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Proposal for zero energy housing designs in Jordan

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Abstract

Background Achieving zero-energy targets in residential buildings is challenging due to improper energy design and the selection of energy-related systems. Moreover, the absence of benchmarks for zero-energy residential buildings, along with the scarcity of studies tailored to diverse climates and building characteristics, highlights the urgent need for further research. This study aimed to address these gaps by designing zero-energy buildings to suit diverse climate zones in Jordan, acting as benchmarks to enhance energy efficiency and promote renewable energy use in the residential sector.

Methods Energy simulation tools were employed to design and verify zero-energy systems. The energy use intensity (EUI) results from the IDA ICE tool were compared with the reported targets and OpenStudio tool outcomes, ensuring that deviations among the proposed designs within the same climate zone consistently remained within acceptable limits, averaging 2, 1, and 1 kWh/m^2 year in 1B (very hot dry), 2B (hot dry), and 3B (warm dry), respectively. Additionally, an economic evaluation was conducted by comparing the cost estimates of a Jordanian code-compliant house and the most acceptable proposed zero-energy design.

Results The proposed designs exhibited average EUI values of 64.4, 64, and 60 kWh/m^2 in diverse climate zones. Outperforming typical Jordanian houses by 56%, 55%, and 60% in 1B, 2B, and 3B, respectively, these designs surpassed national and international benchmarks by at least 35%. Notably, the proposed zero-energy designs achieved substantial cost savings of 1938 USD, equivalent to 11 USD per square meter, throughout the construction phase.

Conclusions Considering Jordan's ambitious energy strategy for 2030 and the significant energy consumption in the residential sector, the proposed zero-energy building designs play a crucial role in advancing the national transition towards zero-energy buildings. This study provides valuable insights by presenting precise designs, benchmarks, and a comprehensive guide tailored to Jordan's distinctive building and climate characteristics with potential applications beyond its immediate context.

Keywords Proposed, Zero-energy, Housing, Designs, Benchmarks

Background

The global energy resource balance relies heavily on non-renewable sources such as oil, coal, and natural gas, all of which emit greenhouse gases and significantly contribute to climate change [1]. The construction industry, in particular, remains a major consumer of energy, accounting for approximately one-third of the world's energy consumption [2, 3]. Therefore, the design of zero-energy buildings (ZEBs) is essential to reduce energy

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consumption [4]. A ZEB generates sufficient renewable energy to satisfy or exceed its annual energy demand, thereby reducing the use of non-renewable energy in buildings [5, 6]. ZEBs achieve energy balance by optimizing energy efficiency and integrating renewable energy generation [7, 8].

An efficient building design for energy conservation is an essential element in all ZEB projects [9, 10]. Optimising a building's energy efficiency before installing a renewable energy system results in a reduced system size and cost [11]. The use of energy simulation tools permits the design team to simulate zero-energy designs and assess energy-efficiency measures [12]. These measures encompass design strategies by using elements that reduce energy demand, including high-efficiency building envelopes, daylighting, solar shading, window and glazing choices, passive solar heating, and natural ventilation [13]. Once the building's energy loads are minimised, the remaining loads can be further reduced by implementing high-performance equipment and systems such as energy-efficient appliances, lighting controls, highly efficient heating, ventilation, and air conditioning (HVAC) systems, and high-performance water heaters [14]. After implementing efficiency measures, renewable energy systems can fulfil the remaining energy requirements. Common renewable energy systems include photovoltaics (PV) and solar water heaters [4, 13, 15].

Energy and environmental design guides, protocols, and literature such as those referenced in [16–20], provide comprehensive insights into the design and construction of buildings with minimal energy consumption and costs equivalent to those of conventional buildings. However, advanced innovative technologies are not always essential for ZEBs. In practice, simplifying a building system increases the likelihood of the building being operated and implemented correctly [17].

Jordan's significant dependence on imported oil and gas, which constitute 94% of its energy supply, makes it vulnerable to price fluctuations. Consequently, the Ministry of Energy and Mineral Resources has crafted an updated master strategy for the energy sector for 2020–2030. The objectives of the strategy are ambitious, aiming to achieve a 30% share of renewables in the total electricity generation capacity and 14% contribution to the total energy mix by 2030 [21]. Moreover, the nation benefits from abundant solar energy potential, with annual daily solar irradiance ranging from 5 to 7 kWh/m^2 and 330 sunny days each year. The country has implemented a comprehensive framework encompassing policies, regulatory measures, financial incentives, and tax exemptions to promote the adoption of renewable energy sources, especially PV and onshore wind energy [22]. Their cost-effectiveness, particularly for buildings consuming more than 5000 kWh annually, makes them a financially attractive choice, with a payback period of less than 6 years [23].

According to the Ministry of Energy and Mineral Resources, residential buildings are the second-largest energy consumers in Jordan [24]. They constitute 72% of the total building stock in the country, and their numbers have increased due to population growth. Jordan must accommodate more than 44,000 new households annually, with an estimated total of more than 352,000 new households by 2030. Hence, residential buildings present a remarkable opportunity for achieving significant energy savings. By incorporating low-energy use intensity (EUI) design principles, the energy consumption of residential buildings can be reduced by 70% [25]. For instance, Jordan's traditional households, which do not adhere to the national energy code and constitute 63% of residential buildings, have an average energy consumption of 267 kWh/m^2 year. In contrast, a typical dwelling that complies with the national energy standard consumes approximately 100–150 kWh/m^2 per year [26].

Although the implementation of energy-efficient practices in Jordanian residential buildings remains limited, particularly in terms of technologies such as photovoltaic (PV) systems, daylight systems, and advanced insulation, the existing national energy code provides a foundation for energy-conscious design. However, the absence of clear zero-energy benchmarks in the residential sector creates an opportunity to pioneer zero-energy designs that can serve as exemplars and catalysts for sustainable construction practices [27].

Jordan's residential sector comprises a diverse range of housing types, primarily located in suburban and rural areas, accounting for approximately 78% of the total. In suburban areas, houses (DAR), apartments, and villas accounted for 55%, 42%, and 2.4% of the housing distribution, respectively, whereas in rural areas, the distributions were 88.9%, 9.9%, and 1.2% [28]. Jordan's climate varies from mixed to extremely hot and is characterised by arid conditions. Summers are characterised by high temperatures and approximately 75% of the annual rainfall occurs during the winter months. In addition, the Jordanian climate is influenced by dry winds, leading to significant temperature fluctuations [29].

To promote ZEBs, it is common practice to design proposals for acceptable building typologies. The designs of the proposed buildings must be tailored to each geographic region and represented a major building type within that region [30, 31]. However, before proceeding with the zero-energy design of these proposals, it is imperative to conduct statistical studies on current building design features. These studies should focus on occupant requirements and building energy performance. Furthermore, a prominent approach for achieving zero-energy design involves statistical building analysis, architectural design, and the subsequent design and selection of various energy-related systems [32].

Several studies have contributed to the understanding of energy efficiency and ZEBs [33–54]. For instance, Zhou [33] investigated the operational performance of ZEBs, involving energy end-use simulations during the design stage and the subsequent selection of PV systems. The study also compared the actual energy consumption of operational ZEBs with the simulated design-phase results.

Deng and Attia [34, 35] contributed to the field by providing energy-oriented tools and procedures that incorporated meteorological parameters, offering valuable support for the promotion and evaluation of ZEBs. Energy modelling techniques were employed to establish benchmarks, enabling engineers to assess the energy performance of the initial design strategies. Notably, these methods were primarily designed for use during the early design phase.

Albdour and Alalouch [26, 36] explored the potential of implementing energy conservation standards to enhance the energy efficiency of residential buildings in both Jordan and Oman. Their findings, generated using energy simulation software, demonstrated the substantial positive effect of applying these codes on annual energy consumption, showing a reduction of up to 48%. The implications of implementing minimum energy requirements in regions characterised by warm and hot climates were assessed by the authors.

Liu and Danza [37, 38] developed field measurement and evaluation methods for ZEBs, focusing on factors related to indoor environmental quality and energy usage of HVAC systems. The average energy consumption of the HVAC system was approximately 33 kWh/m^2.This research led to significant reductions in cooling and heating loads, with decreases of up to 55% and 54%, respectively. They concluded that NZBs provide acceptable thermal comfort and good indoor air quality (IAQ) while maintaining low energy consumption. However, it is important to note that the articles primarily concentrated on IAQ and HVAC system performance, with other systems such as lighting and water heating not being covered.

Hoseinzadeh, Lohwanitchai, Zahedi, Wang, and Hu [39–43] conducted a study on buildings with zero-energy design systems, with a particular focus on the economic viability of the installed systems. A typical residential building served as the baseline, and energy efficiency and cost analyses were performed using both qualitative and quantitative methods. The findings revealed no substantial difference between the actual cost of a ZEB and that of a conventional building.

Zhang, Gao, and Delavar [44–46] laid the groundwork for ZEB research by conducting a comprehensive review of mathematical modelling and control strategies. These studies seamlessly integrated building physics and energy technologies and explored their synergy with rule-based and model predictive controls. Targeting researchers, designers, and engineers, these studies established a foundational map for cohesive building modelling and control within the context of ZEBs.

Okonkwo and Zhu [47–49] delivered a comprehensive overview of ZEBs and the challenges impeding their commercialisation. The reviews provided suggestions for enhancing existing technologies in the building sector, specifically targeting barriers to widespread adoption. Additionally, the studies developed scenarios to analyse building energy consumption, emphasising the significance of adopting ultralow-energy buildings, nearly ZEBs, and ZEBs for substantial reductions in overall building energy consumption.

Marszal, Hernandez, and D'Agostino [50–52] conducted a critical review of the existing definitions of ZEBs and explored various approaches to calculating ZEBs and assessing their progress in Europe. Inconsistencies in the NZEB definitions were also examined, and EU-NZEBs were compared with US-NZEBs definitions. Additionally, key issues such as the balance metric, balancing period, types of energy use, renewable energy supply options, connection to energy infrastructure, requirements for energy efficiency, and indoor climate were addressed in the reviews.

Bataineh and Abu Qadourah [53, 54] conducted studies focusing on the reduction in energy demand in residential buildings located in a warm-dry climate zone (Amman). Passive design measures were employed, and building simulation techniques were used to investigate various design measures. The impact of each measure on the energy demand of residential buildings was assessed both separately and in combination with other measures to identify the optimal solution for reducing energy consumption. The findings revealed a significant potential for energy savings, with annual usage reductions of 53% for cooling, 71% for heating, and 78% for lighting.

However, there is a lack of research on the design of ZEBs. Most studies [33–54], have focused on theories, definitions, evaluation processes, validation techniques, IAQ, mathematical models, cost estimations, and thermal comfort. Nonetheless, previous studies have largely overlooked the holistic design of ZEBs suitable for different climates and building characteristics. The absence of benchmarks for zero-energy residential buildings, coupled with a shortage of studies tailored to diverse climates and building characteristics, highlights the pressing need for this current study.

A solution emerges through the provision of precise zero-energy designs that serve as benchmarks for enhancing energy efficiency and promoting renewable energy use in the residential sector. This is crucial in countries where the residential sector lacks clear zero-energy benchmarks and has a substantial proportion of new buildings falling short of achieving the zero-energy target, often owing to deficiencies in architectural design and the selection of energy-related systems. To achieve the study's main goal, two objectives were established: (1) to produce region-specific zero-energy housing designs tailored to diverse Jordanian climate zones and (2) to establish practical benchmarks for enhancing energy efficiency and promoting renewable energy adoption in residential buildings. To guide this study, the following questions were posed:

To what extent can zero-energy designs reduce energy consumption across the Jordanian climate zones?

What are the comparative costs of zero-energy houses and conventional buildings that comply with Jordan's national energy code?

By conducting comprehensive statistical studies on current building design features, addressing occupant needs, and analysing building energy performance, the current study guarantees a practical and environmentally conscious ZEB design. This study also lays the foundation for a novel Jordanian zero-energy design guide for residential buildings and provides designers, builders, and owners with unparalleled resources for designing and constructing zero-energy buildings in regions with similar climatic zones and building characteristics.

Methods

Statistics and surveys are valuable tools for understanding building characteristics [55–58]. In this study, a combination of national statistics and an online survey were employed to inform the design of the proposed architectural models. Recent statistical data were acquired from the Jordanian Department of Statistics (DOS) [59] with a focus on various design features and owner preferences, including building sites, areas, number of stories, ceiling height, colour, materials, and building type. Insights from previous studies [30, 60–62] guided the establishment of design boundaries and architectural processes. To complement the DOS data, an online survey was conducted to gather responses from approximately 2500 homeowners undertaking home construction by 2022 out of an estimated 44,000 registered owners throughout Jordan during the same year [59]. The survey was delivered via social media platforms and emails over a 10-week period. The goal was to capture insights into building and roof shapes–aspects not covered by the DOS data. To achieve a 95% confidence level, a 5% margin of error, and a sample proportion of 0.5, the minimum required survey sample size was calculated to be 381 participants. The simplicity of the survey, which focused on preferred building shapes and roof types, contributed to the high participation rate.

Considering the limited opportunities for experimental work in the proposed buildings, primarily owing to financial constraints, energy simulation tools (IDA ICE, OpenStudio, Revit Daylighting Analysis, and PVWatts) were also used to model zero-energy systems and verify energy end-use [63–65]. The conceptual design process is summarised in Fig. 1, with detailed explanations provided in subsequent sections outlining the steps that incrementally move the designs towards the zero-energy goal.

Proposed architectural designs

The data gathered from the DOS and responses from the homeowners survey shed light on the prevalent preferences for residential building characteristics, indicating a preference for suburban or rural settings (78%) over infill or constrained sites. Cubic building shapes were the most popular choice (79%), with a significant majority indicating a preference for buildings and spaces ranging from 120 to 250 square meters (85%). Bedrooms 16–20 square meters (64%) and kitchens 15–20 square meters (57%) were the top choices. The majority favoured homes with to 3–4 bedrooms (72%), and there was an overwhelming preference for flat roofs (84%). Single-story buildings were preferred (60%) to multi-storey buildings. White emerged as the preferred building colour (over 98%), and materials such as local stones and cement bricks were widely preferred (82%). The most common residential building configurations were DAR and Villa (73%), as listed in Tables 1 and 2, respectively.

The results played a crucial role in the design and modelling of four representative flat-roofed cubic residential buildings. These designs included two single-story houses with average areas ranging from 150 to 200 m^2 and 200 to 250 m^2, along with two two-story houses falling within similar area brackets. These designs align with the predominant architectural style of Jordan. Typically, these residences feature a floor plan starting with an entrance leading to the reception and living room, followed by a corridor guiding to the bedroom. In addition, there are usually two exterior doors: one near the kitchen and the other close at main entrance. Figure 2 illustrates the conceptual zoning of these proposed designs, and detailed architectural plans used for creating Building Information Modelling (BIM) architectural models are provided in Fig. 3. However, it is important to note that Design 1 represents a typical newly designed house in Jordan using locally available materials. The proposed designs (Design

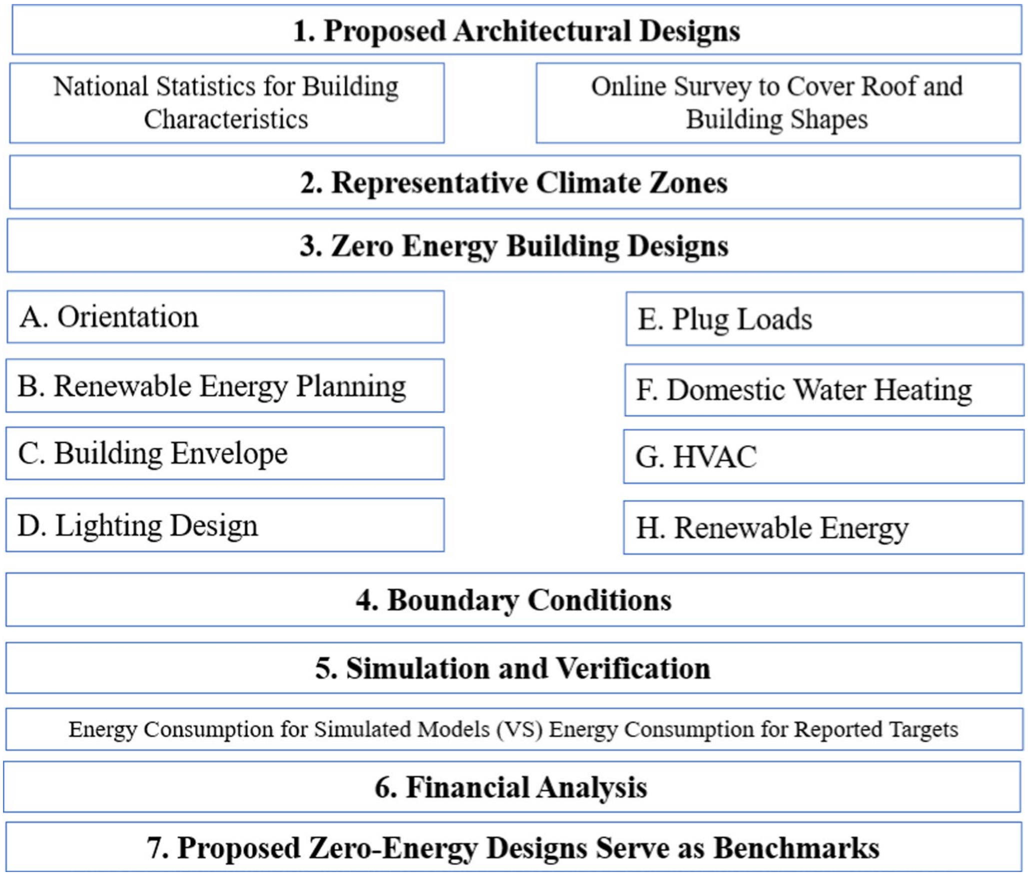


Fig. 1 Design process flowchart

1, Design 2, Design 3, and Design 4) shared several common features such as the building site, building shape, roof shape, building colour, local raw materials, and ceiling height. However, there were variations in certain parameters, such as floor area and number of stories, as listed in Table 2.

Representative climate zones

The consideration of typical weather conditions rather than extreme weather days is crucial when sizing the equipment [66]. The representative climate zones identified in Jordan are (1B), (2B), and (3B), as indicated in Table 3 and Fig. 4, based on the ASHRAE Standard 169-2020, Section A3: Climate Zone Definitions [67].

Zero-energy design

Building orientation

Suburban and rural areas offer favourable conditions for orientation strategies, impacting on-site energy production and passive solar design parameters such as sunlight, shading, and thermal mass. Sun control systems have proven to be more effective on north and south façades. Therefore, for optimal solar orientation across diverse Jordanian climates and designs [68], the orientation of the building along the east–west axis was selected. This orientation minimises challenges with respect to solar gain and glare on the east- and west-facing façades. This orientation also maximises shading strategies on the south-facing façade. A prudent design strategy also advocates windows that enhance natural lighting within a space. This goal was achieved by increasing the glazing area on both the north and south surfaces in comparison with that on the east and west surfaces. It is important to note that the east–west axis of the building can be shifted by up to 20° without significantly affecting the total energy consumption, as shown in Fig. 5 [69].

Renewable energy planning

Although there are other forms of clean energy, photovoltaic (PV) systems are widely used and can be installed in most buildings. Solar panels, which are a crucial component of PV systems, are strategically placed on flat roofs to minimise their footprint and ensure ample roof space for renewable energy generation [70]. Flat roofs were chosen based on the strong support from property owners and their suitability for PV system installation.

Table 1 National statistical and survey results represent approved design features and housing types

Site selection	
Infill	10%
Suburban and rural	*78%*
Constrained site	12%
Building shape[a]	
L	7%
U	3%
Cubic	*79%*
Z	1%
T-shape	1%
Triangle	2%
Circle	2%
Courtyard	5%
Building and space area m^2	
Less than 60	2%
60–110	8%
120–200	*63%*
200–250	*22%*
250–299 or above	5%
Bedroom area m^2	
Less than 12	3%
12–15	15%
16–20	*64%*
20–24	11%
25 or more	7%
Kitchen size m^2	
Less than 6	3%
7–10	9%
10–15	17%
15–20	*57%*
20–25	9%
25–20	3%
More than 25	2%
Number of bedrooms	
1–2	17%
3–4	*72%*
5–6	8%
6 or more	3%
Roof shape[a]	
Gable or cross-hipped roof	9%
Dutch	2%
Flat	*84%*
Dormer	Less than 1%
Shed	Less than 1%
Dome Roof	Less than 3%
Number of stories	
One	*60%*
Two	*37%*
Three or more	3%
Ceiling height m	
3–3.25	*85%*
3.25–3.50	12%
3.50–3.75	3%
Building colour	
White scheme colour	*More than 98%*
Building materials	
Local stone and cement brick	*82%*
Stone and reinforced concrete	8%
Reinforced concrete	7%
Stone and clay	2%
Other	3%
Residential building types	
Apartment	25%
Dar & Villa	*73%*
Others	2%

[a] All data were obtained from the DOS except for the building and roof shapes, which were derived from the survey

Optimal locations on the roof, free from obstructions, such as mechanical or plumbing vents, were selected to simplify the installation process [71], as illustrated in Fig. 6.

The calculated roof area required for the installation of PV panels was determined for each climate zone using data from the National Renewable Energy Laboratory (NREL), as outlined in Tables 4 and 5 [69]. A multiplier of 1.25 was applied to the calculated area of the PV system to accommodate clearances, aisles, and other typical installation requirements for buildings. The process of determining the necessary roof area for PV systems is described by the following equation (see Tables 4 and 5):

$$\begin{aligned}&\text{Roof area required for PVs}\\&=\text{Gross Floor Area}\times\text{PV Area \%}\times 1.25\end{aligned}\quad(1)$$

Building envelope

a. Envelope thermal performance factors

In ZEBs, it is essential to design components that satisfy the U-factor target of the building envelope [72]. Increasing the insulation beyond the required levels can lead to energy savings. However, this benefit may be minimal due to additional construction costs and increased cooling energy loads during mild weather conditions [17, 20]. The U-factor values and the materials for the envelope components listed in Table 6 were used to gradually achieve zero energy in the proposed designs. For detailed

Table 2 Proposed designs' building characteristics and features

Proposed Design	Design 1	Design 2	Design 3	Design 4
Building site	Suburban and rural	Suburban and rural	Suburban and rural	Suburban and rural
Building shape	Cubic	Cubic	Cubic	Cubic
Roof shape	Flat	Flat	Flat	Flat
Floor area (m^2)	175	228	224	170
Ground area (m^2)	183	239	233	178
Number of stories	1	1	2	2
Ceiling height (m)	3	3	3	3
Building colour	White scheme	White scheme	White scheme	White scheme
Building materials	Local stone and cement brick	Local stone and cement brick	Local stone and cement brick	Local stone and cement brick
Number of occupants (Person)	4–6	4–6	5–7	5–7

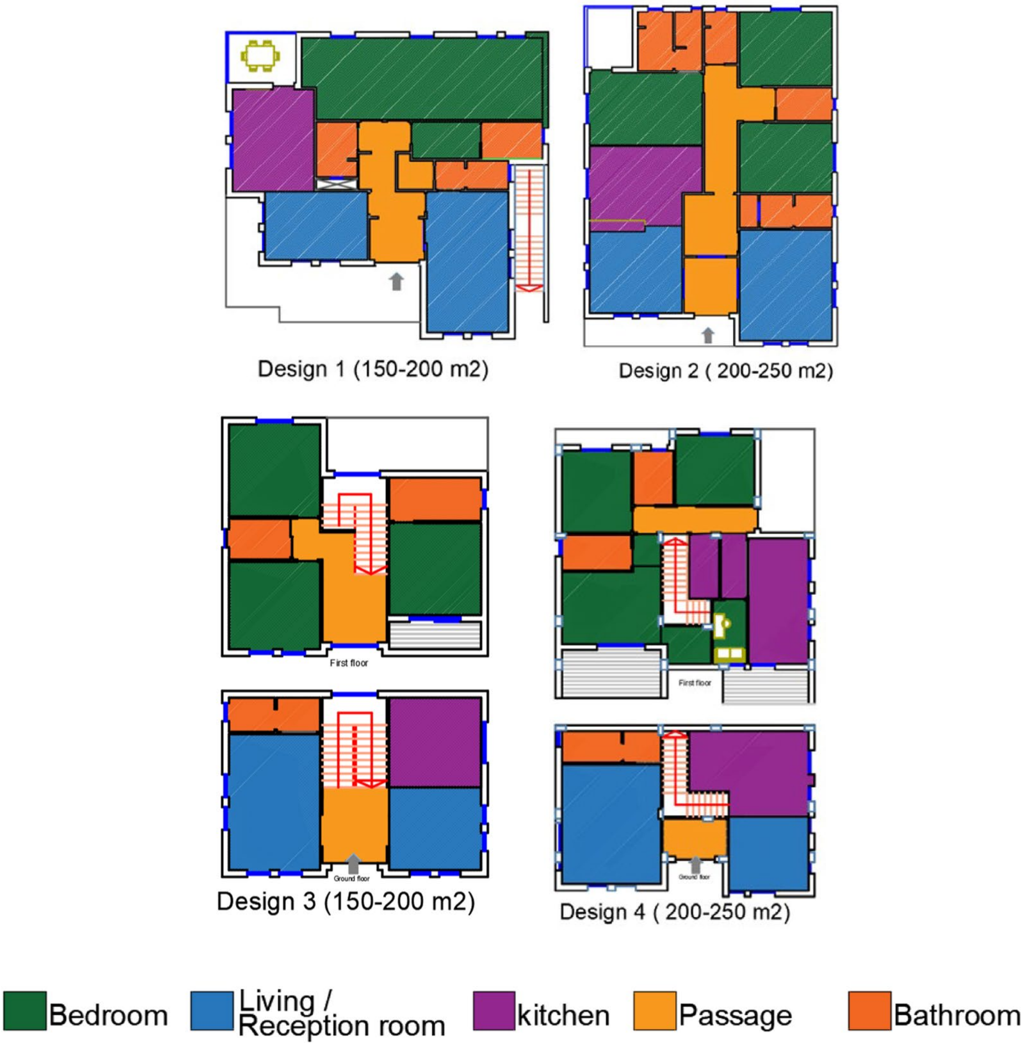
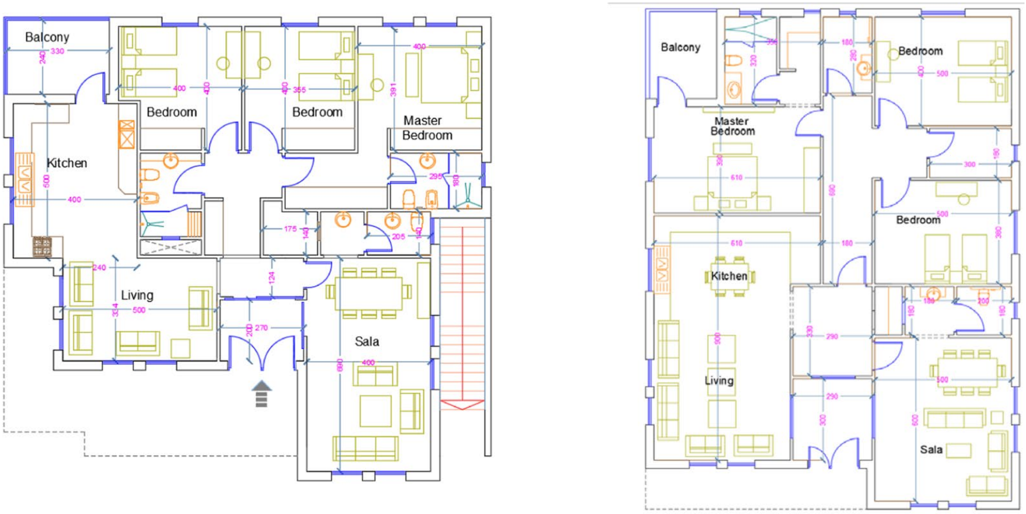


Fig. 2 Conceptual zoning of the proposed houses 1–4 (from left to right)



Design 1

Design 2

Design 3

Design 4

Fig. 3 Architectural plans of designed households 1–4 (from left to right)

components and cross-sections of typical envelope components, refer to Appendix Fig. 15.

b Thermal performance of fenestration and doors

In the pursuit of a ZEB envelope, it is critical to achieve the correct window size for natural lighting, ventilation, and effective heat management [73]. As shown in Table 7, the key window specifications, including the solar heat gain coefficient (SHGC), U-factor, visible transmittance (VT), VT/SHGC ratio, window-to-wall ratio (WWR), and projection factor (PF) play pivotal roles in crafting zero-energy designs. An excessive solar heat gain can result in glare and increased energy consumption. Therefore, effective strategies for controlling the solar gain are essential. Among these strategies, exterior shading

Table 3 Jordan's representative climate zones

Location	World meteorological organization number	Zone symbol	Climate zone	Heating degree days (HDD) and cooling degree days (CDD)	Governorates
Queen Alia Intl	402720	3B	Warm-Dry	2500 < CDD 10 °C < 3500	Amman, Irbid, Ajloun, Jerash, Madaba, Balqa,Karak, Tafileh
Aqaba king Hussein Intl	403400	1B	Very Hot-Dry	5000 < CDD 10 °C	Maan, Aqaba,
Prince Hasan H-5	402600	2B	Hot-Dry	3500 < CDD 10 °C ≤ 5000	Mafraq, Zarqa

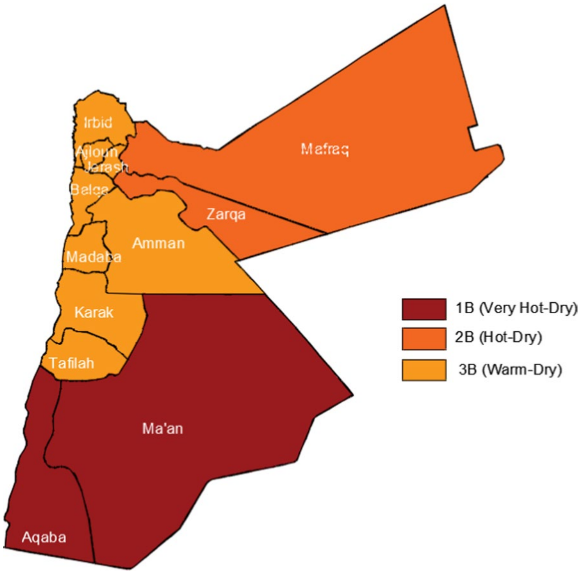


Fig. 4 Jordan's climate zones

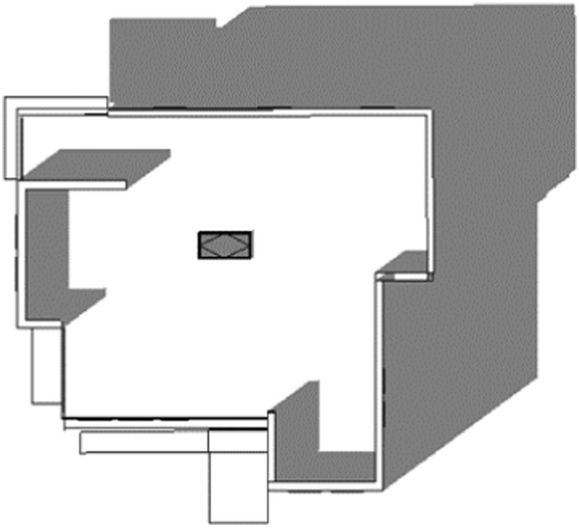


Fig. 6 Roof area for PV system (design 1,3B)

Table 4 Roof area for PV installations

Renewable energy system	Solar systems or PV systems
Orientation	30° of south with a slope ranging from latitude minus 30° to latitude plus 10°
PV percent area of gross floor area	1B = 24% 2B = 17%,3B = 16%

devices have proven to be highly efficient in pre-emptively blocking sunlight before it reaches the windows, thereby preventing undesirable solar gain and glare. Adjustable shading solutions, such as roller shutters and retractable sunshades, offer precise control and allow the manipulation of daylight, sunlight, and outdoor views. These devices are widely accepted and installed across

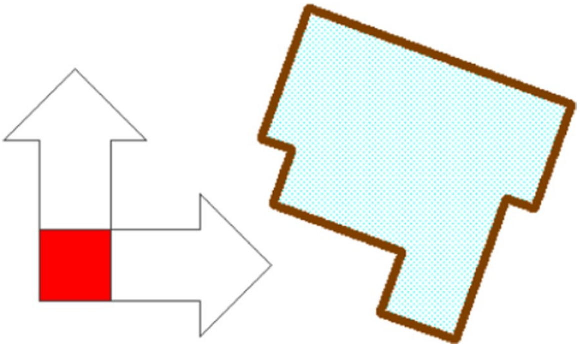


Fig. 5 Building orientation via IDA ICE simulation tool (design 1)

Table 5 Reserved roof area for renewable energy

Climate zone	Design case	PV percent area of gross floor area (%)	Planned Area for PV systems
1B	1.3	24	56 m^2
2B	1.3	17	43 m^2
3B	1.3	16	40 m^2
1B	2.4	24	75 m^2
2B	2.4	17	53 m^2
3B	2.4	16	50 m^2

Table 6 Envelope construction components and materials

Component W/m^{2}K[a]	Climate zone	Materials	Thickness	Used U-Factor[b]	Recommended U-Factor
Mass wall above grade U-factor	1B	1 cm plaster + 15 cm brick + 14 cm insulation (Rigid board) + 7 cm concrete + 5 cm stone	42 cm	0.216	0.22
	2B	1 cm plaster + 15 cm brick + 12 cm insulation (Rigid board) + 7 cm concrete + 5 cm stone	40 cm	0.26	0.3
	3B	1 cm plaster + 15 cm brick + 12 cm insulation (Rigid board) + 7 cm concrete + 5 cm stone	40 cm	0.26	0.27
Roof U-factor (continuous)	1B	2 cm cement tiles + 10 cm fine aggregate and normal concrete + water proofing rolls + 16 cm Insulation (Rigid board) + 27 cm reinforced concrete + 1 cm plaster + 2 cm gypsum board	58 cm	0.202	0.21
	2B	2 cm cement tiles + 10 cm fine aggregate and normal concrete + water proofing rolls + 17 cm Insulation (Rigid board) + 27 cm reinforced concrete + 1 cm plaster + 2 cm gypsum board	59 cm	0.191	0.20
	3B	2 cm cement tiles + 10 cm fine aggregate and normal concrete + water proofing rolls + 17 cm Insulation (Rigid board) + 27 cm reinforced concrete + 1 cm plaster + 2 cm gypsum board	59 cm	0.191	0.19
Slab U-factor	1B, 2B, 3B	1 cm tiles + 9 cm fine aggregate and normal concrete + 10 cm reinforced concrete + 12 cm Insulation (Rigid board)	32 cm	0.243	0.27
Roof solar reflectance		White-scheme colours	–	0.8	0.7

[a] Continuous insulation must be implemented to reduce thermal bridges

[b] U-factor represents the overall thermal transmittance for an opaque assembly

Table 7 Window specifications and ventilation criteria

Component	Climate zone		
	1B	2B	3B
U-factor (operable) W/m^{2}K[a]	3.2	1.98	1.7
SHGC (operable)	0.2	0.22	0.22
Ratio of VT/ SHGC	1.1	1.1	1.1
Projection factor[b]	0.9–1	0.9–1	0.9–1
Window wall ratio %	20–30	20–30	20–30
Double sided ventilation	Depth up to 5 times the height of the room, the opening area must 2% of the floor area (1% on each side of the space)		
Single sided ventilation	Depths up to 2.5 times the height of the room, ventilation opening area should be between 5 and 10% of the room's floor area		

[a] The U-factor for windows signifies the rate at which thermal energy is transmitted through a window assembly, influenced by the temperature variations on each side of the window

[b] The projection factor is defined as the ratio of the horizontal depth of the external shading projection to the sum of the height of the fenestration and the distance from the top of the fenestration to the bottom of the farthest point of the external shading projection, all measured in consistent units (refer to Appendix Fig. 16 for more details)

the country, making them the preferred choices among residents. Although many energy modelling tools can automatically design basic solar shading systems using the ASHRAE shading algorithm, a simplified projection factor method was employed for manual design, as detailed in Appendix A.

Several strategies were also considered:

- Shading devices: shading devices crafted from lightweight and reflective materials with a low heat storage capacity were utilised.
- Window style: casement windows known for their high energy efficiency and ability to provide a tight seal on all sides when closed were selected.

- Window material: uPVC windows were chosen because of their low conductivity and excellent sealing properties, which make them the most energy-efficient choice for Jordanian buildings.
- Window orientation: the window-to-wall ratio on the east- and west-facing surfaces compared to the north- and south-facing surfaces were adjusted to enhance the energy efficiency.
- The shutters of the eastern-facing rooms between 10 am and 2 pm and the shutters of the western-facing rooms after 4 pm were kept closed during summer to prevent solar radiation from heating the rooms.

Lighting design

a Electric lighting and lighting controls

Electric lighting is a key energy-efficient design measure aimed at delivering sufficient illumination while minimising energy consumption. In pursuit of this objective, adherence to the Illuminating Engineering Society (IES) recommended lighting power density (LPD) target for diverse residential space types is crucial, which is set at 2 W/m^2 [74]. Individual spaces within residential buildings may feature distinct lighting power levels, as shown in Table 8, depending on their specific requirements. These variations were meticulously balanced to guarantee comprehensive energy efficiency across the entire building, as shown in Figs 16 and 17.

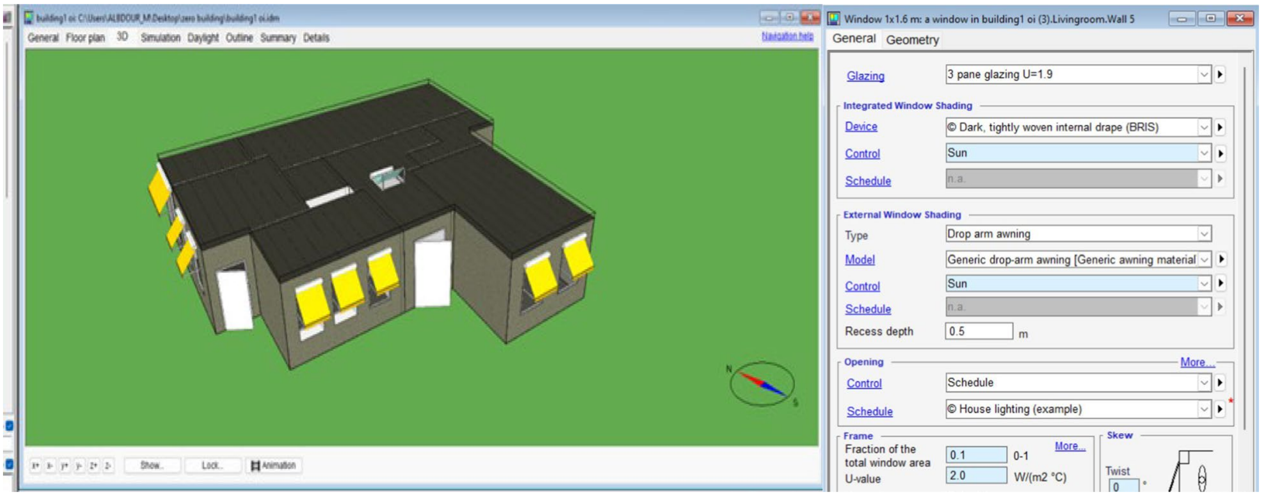
Table 8 Interior and exterior lighting power densities

Interior space	LPA, W/m^2	Daylight priority
Dwelling units	1.78	1
Corridor	4.3	2
Stairway	4.3	2
Restroom	4.3	3
Exterior (parking garage)	1.1	–

Emphasis has been placed on providing electric lighting only when and to the extent needed for the occupants' visual comfort [74]. Although hardwired automated controls have limited applicability in residential buildings, networked lighting systems that are timed and controlled by the residents offer adaptability and help reduce utility costs. A control system that adjusted the intensity of electric lighting to meet occupant needs (LED-capable dimmers) was selected, allowing residents to tailor the lighting to their visual comfort. Motion sensors were employed outdoors to reduce electricity wastage and the likelihood of lights being left on. Additionally, all surfaces were highly reflective, with ceilings featuring a reflectance of at least 90% and walls maintaining an average reflectance of at least 50%. All wall and ceiling surfaces were designed using a white scheme.

b Daylighting

Daylighting in residential spaces serves a dual purpose: connecting occupants to the outdoors and reducing reliance on electrical lighting. To meet these goals, manually adjustable sun control systems have been strategically installed in frequently occupied areas in accordance with the LEED v4 guidelines [75]. This design approach strikes a balance between harnessing



Window 1x1.6 m: a window in building1 oi (3).Livingroom.Wall 5

Glazing: 3 pane glazing U=1.9

Integrated Window Shading
Device: © Dark, tightly woven internal drape (BRIS)
Control: Sun
Schedule: n.a.

External Window Shading
Type: Drop arm awning
Model: Generic drop-arm awning [Generic awning material
Control: Sun
Schedule: n.a.
Recess depth: 0.5 m

Opening
Control: Schedule
Schedule: © House lighting (example)

Frame
Fraction of the total window area: 0.1 0-1
U-value: 2.0 W/(m2 °C)

Skew
Twist: 0 °

Fig. 7 Manual glare-control system (design 1,3B) natural daylight and controlling solar exposure, thereby enhancing occupant comfort, and reducing lighting energy consumption. For detailed information and illustrations, please refer to Figs. 7 and 18 (Appendix). Using Revit Daylighting Analysis 2022 [64], verification was conducted to achieve a spatial daylighting autonomy (sDA) of at least 55% in frequently occupied spaces. This implies that at least 55% of the space receives at least 300 lx of daylight annually for at least 50% of the operating hours. Additionally, an annual sunlight exposure (ASE) of no more than 10% was ensured, signifying that less than 10% of the area received more than 1,000 lx for 250 h per year. The analysis considered permanent interior partitions and outdoor solar shading systems, excluding movable furniture, as shown in Fig. 8.

Consideration was given to the following daylighting strategies to optimize natural light utilisation:

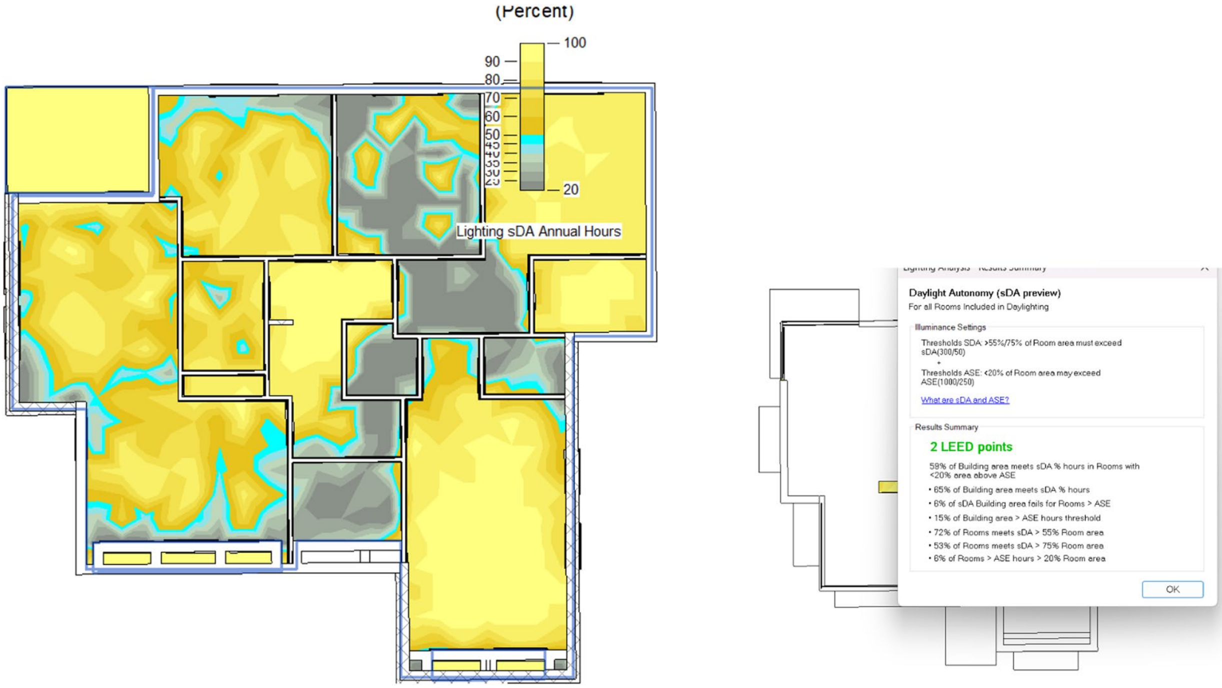
- The viewing windows were positioned at eye level with visible transmittance (VT) ranging from 60 to 100%, depending on the brightness of the view.
- Window-to-wall ratios between 25 and 35% were employed to provide sufficient daylight and outdoor views while minimising excessive heat transmission.
- Utilising the ability to turn off lights when daylight is available through vestibules, skylights, and glazed interior doors.

Plug and process loads

Plug and process loads (PPLs) represent a significant opportunity to contribute to overall energy savings in buildings. These loads generate heat, which is typically removed by the HVAC system, thereby increasing the overall energy consumption of buildings. However, two primary strategies have been employed to reduce plug loads.

- Selecting equipment with lower energy demands.
- Implementing control measures to ensure equipment is turned off when not in use.

The estimated equipment loads and schedules were projected using data from the Building America House Simulation Protocols report [76], which indicated that the total energy consumption of the equipment was approximately 18 kWh/m^2 year, as shown in Fig. 19 (appendix). In the absence of actual equipment load data, the estimated loads are considered acceptable substitutes. Additionally, it is worth noting that devices classified as ENERGY STAR can be employed to meet or even exceed the maximum energy consumption requirements for devices. ENERGY STAR devices operate at low power and can incorporate improved sleep-mode algorithms [77].



Daylight Autonomy (sDA preview)
For all Rooms Included in Daylighting

Illuminance Settings

Thresholds SDA: >55%/75% of Room area must exceed sDA(300/50)
+
Thresholds ASE: <20% of Room area may exceed ASE(1000/250)

What are sDA and ASE?

Results Summary

2 LEED points

59% of Building area meets sDA % hours in Rooms with <20% area above ASE

- 65% of Building area meets sDA % hours
- 6% of sDA Building area fails for Rooms > ASE
- 15% of Building area > ASE hours threshold
- 72% of Rooms meets sDA > 55% Room area
- 53% of Rooms meets sDA > 75% Room area
- 6% of Rooms > ASE hours > 20% Room area

Fig. 8 Spatial daylight autonomy via annual computer simulations (design 1,3B)

Domestic water heating

Energy efficiency strategies for hot water systems focus on two key aspects: minimising the hot water usage and improving the production efficiency. Minimising hot water use involves the selection of fixtures and equipment with low water consumption, as shown in Table 9 [78]. Reducing the water operating loads requires the use of high-efficiency water heaters and, where suitable, solar water heaters. However, individual water heaters offer the advantage of enabling the measurement of hot water use and costs for each unit. Furthermore, Table 10 provides the specifications for the water heater types and capacities, as outlined in references [17, 79, 80].

Solar water heaters are often deemed a crucial energy-saving equipment, particularly in residential buildings with high hot water requirements. The use of solar hot water systems is a significant solution for reducing energy costs. However, it is generally not feasible to design systems that can fulfil the entire domestic water demand. These systems are typically more cost-effective when they meet 50–80% of the annual demand [81]. In Jordan, the average hot water consumption is approximately 60 L per person in accordance with the local code for water supply and sewage in the residential sector [82]. It is important to note that a simple solar power system can effectively cover approximately 65% of the total hot water demand in warm-dry climate zones, 75% in hot-dry climate zones, and 80% in very hot-dry climate zones (see Fig. 20) [83].

HVAC system and equipment

The primary goal of HVAC systems in buildings is to improve the comfort of occupants when outdoor conditions fall below acceptable comfort levels. These systems must consider various factors, including plug loads and necessary HVAC settings, to ensure comfort and ventilation. The use of natural ventilation via window operation is a viable option. Recognising that it is possible to achieve zero energy using readily available system types in the market can encourage a broader range of building owners to embrace zero-energy principles. Table 11 provides recommendations for the HVAC system types based on different climate zones. Two systems were considered in this study: (A) an air-source heat pump multi-split system, and (B) a water-source heat pump. System (A) was chosen for its versatility and suitability across a wide range of climatic zones [84].

System A incorporated a dedicated outdoor air system (DOAS) to guarantee sufficient natural ventilation in each living area. DOAS systems streamline ventilation control and design, improve humidity control and IAQ, and reduce energy consumption. Table 12 provides details of the minimum efficiency standards for the selected system type, as specified in references [17, 85, 86].

Renewable energy system

In most ZEBs, an onsite renewable energy system, typically a PV system, represents the final system required to transition a project from a low-EUI building to a zero-energy or positive-energy building [87]. To determine the size of this system, the calculations aimed to generate approximately 110% of the projected EUI for the designed buildings. Various variables were considered, including snow, ice, breaker trips, dirt accumulation, and year-to-year variations in output. The determination of the system size and output potential involved the use of the PVWatts calculator, which considers factors such as location, local weather, module type, and inverter specifications [65].

Table 9 Criteria for faucets and sprayers

Fixture type	Maximum allowable flow LPM
Lavatory faucet	1.9
Showerhead	6.7
Kitchen sink	3.8

Table 11 HVAC system type by climate zone

Climate Zone	HVAC System Types
1B	System A or B
2B	System A
3B	System A or B

Table 10 Water heater by climate zone, and indoor air-source water-to-water heat pump performance

Climate zone number	System type
1, 2, 3	Local indoor single package
Storage volume in litres	**Uniform energy factor**
Equal or greater than 208.2 L	3.45
Schedules	See Appendix Fig. 17

Table 12 Minimum efficiency by system type

Required for each system type: dedicated outdoor air system	
Air-cooled direct expansion efficiency	> 5.2 ISMRE @ AHRI 920 (2020) conditions
Multistage or variable-speed drive compressor	Multistage or variable-speed drive compressor Minimum turndown ≤ 20% of compressor capacity
Supply fan	Minimum turndown 30% of design flow
Exhaust energy recovery	B (dry) zones: 72% dry-bulb temperature reduction
Direct expansion heat pump	> 3.8 ISCOP @ AHRI 920 (2020) conditions
System a-air-source heat pump (ASHP) multisplit	
Air-source variable refrigerant flow multisplit (cooling mode)	< 19 kW/h; 20 SEER
	> 19 kW/h and < 39.5 kW/h; 13.1 EER; 15 IEER[a]
	> 39.5 kW/h and < 70.3 kW/h; 11.0 SEER; 14.0 IEER[a]
Air-source variable refrigerant flow multisplit (heating mode)	< 19 kW/h; 14 HSPF[a]
	> 19 kW/h and < 39.5 kW/h; 3.7 COP[a]
Terminal fan	electronically commutated motor fans and < 0.38 W/cfm at design
Temperature set point	Heating 21, cooling 23 oC
Maximum air leakage rate	0.1 L/S
Activity (Metabolism rate)	1.2 (residential)
Clothing	Summer 0.5, Winter 1
Occupancy heat gains	40–70 w/m^2 (sleeping-seated)

[a] Minimum levels: certification for air conditioning, heating, and refrigeration (AHRI) standard

Boundary conditions

This study examined the design of zero-energy low-rise residential buildings across various climate zones of Jordan. It is important to note that the outcomes of this research may not be universally applicable to all climate zones or building typologies. The designs proposed here are primarily intended for rural and suburban areas and feature cubic shapes and flat roofs. Consequently, the considerations of infill development, constrained sites, and alternative building configurations were not within the scope of this study. A combination of grid electricity and onsite PV systems is assumed to be integral for achieving zero-energy designs. It is imperative to acknowledge that the effectiveness of this approach may vary depending on the accessibility and availability of local energy resources.

Simulation and verification

In this study, we employed IDA ICE, an advanced whole-building energy simulation tool, using an EQUA engine [63]. It seamlessly imports 2D and 3D CAD files, is compatible with industry foundation class (IFC) models from BIM tools, and incorporates algorithms for building components, complying with ANSI/ASHRAE/IES Standards 90.1-2016 [88]. The IDA ICE offers features such as providing annual energy usage data for 8760 h, hourly modelling of occupancy changes, considering lighting and equipment power, accounting for thermostat set points, detailed HVAC system representation, assessing thermal mass effects, and dividing the building into 10 or more thermal zones. The study utilised the IDA ICE version 4.8 SP2 expert edition to simulate the annual energy consumption [63], ensuring alignment with energy design guidelines and standards for accurate and reliable results.

To ensure the accuracy of the proposed zero-energy designs with construction principles and targets, two verification methods were employed, as follows: the EUI results from IDA ICE simulations were compared with the energy targets set by the New Buildings Institute (NBI) [89], as outlined in Table 13. The NBI database provides the EUI recommendations for zero-energy construction projects across various climatic zones and building types. This approach has been adopted by previous researchers [55, 90].

As a complementary step, OpenStudio, another whole-building energy modelling tool that uses the EnergyPlus engine [91], was employed to validate the proposed designs further. This involved assessing the energy consumption results from the OpenStudio simulations

Table 13 Target use intensity

Climate zone	Site energy. kWh/m^2 year
1B	66.6
2B	63.1
3B	59.9

and comparing them with the results of the IDA ICE simulations.

Figure 9 presents a comparative analysis of the simulated EUI values for each of the four proposed designs and the recommended EUI targets in similar climate zones. The analysis revealed that deviations among the proposed designs within the same climate zone remained within acceptable limits, which is consistent with the ASHRAE Guideline 14 recommendations. Notably, the highest observed deviation was approximately 4%, which occurred in climate zone 1B. Notably, climate zone 1B exhibited the highest energy consumption among the proposed designs, which can be attributed to the extreme heat conditions prevalent there. Specifically, the EUI for climate zone 1B was, on average, 4 kWh/m^2/year higher than that for climate zone 3B and 1 kWh/m^2/year higher than that for climate zone 2B.

As a complementary step, a peer comparison was conducted to assess the total energy consumption generated by the OpenStudio simulations by compare it with the results of the IDA ICE simulations. The highest recorded deviation is approximately 3%, which aligned with the industry's acceptable range of 10% and met the criteria for reliable simulation results according to ASHRAE Guideline 14. This analysis verifies the robustness of the proposed designs and underscores the precision and reliability of the selected simulation tools for assessing their energy performance.

Financial analysis

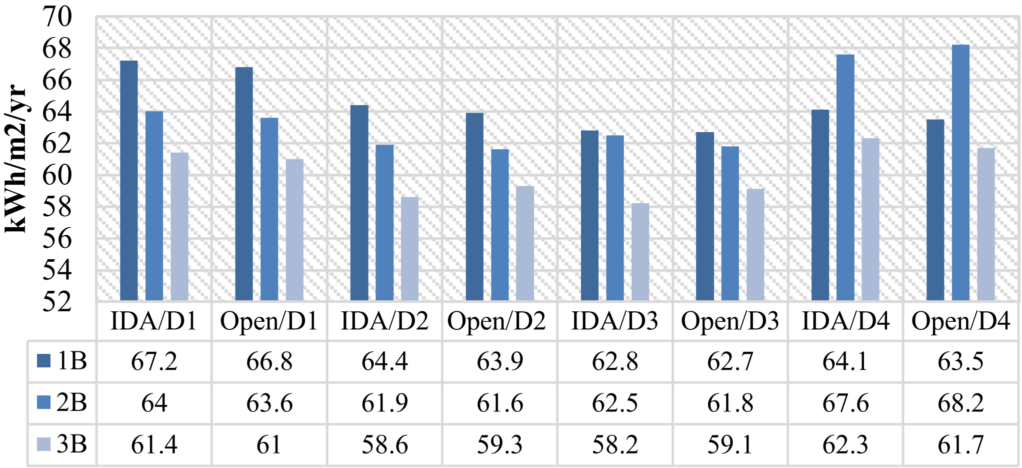
Assessing the cost implications and feasibility of the proposed designs is crucial to determine their practicality. Meaningful perspectives on the economic viability of implementing ZEB designs can be acquired by comparing the cost estimates between a conventional Jordanian house compliant with the national energy code [26], and the proposed most favourable zero-energy design. This thorough analysis encompasses various building systems, with a specific emphasis on four critical elements: the envelope system (including insulation, windows, and doors), lighting system (prioritising energy-efficient lighting solutions), water heating and HVAC systems (assessing costs related to high-efficiency HVAC and water heating systems), and renewable energy systems, particularly solar panels.

The financial aspects of these systems were examined to understand their influence on overall project costs. Specific elements, including shading devices, solar water heating systems, and plug-load systems, remained constant across both scenarios and were omitted from the analysis. Deliberate exclusion focuses on core systems that exert the most substantial influence on the energy consumption and economic viability of zero-energy housing. Moreover, these designs maintain an average area of 175 m^2 and are situated in climate zone 3B, as typified by Amman. By 2023, Amman alone will constitute 43% of all completed dwellings, highlighting a substantial portion of the ongoing construction surge.

Results

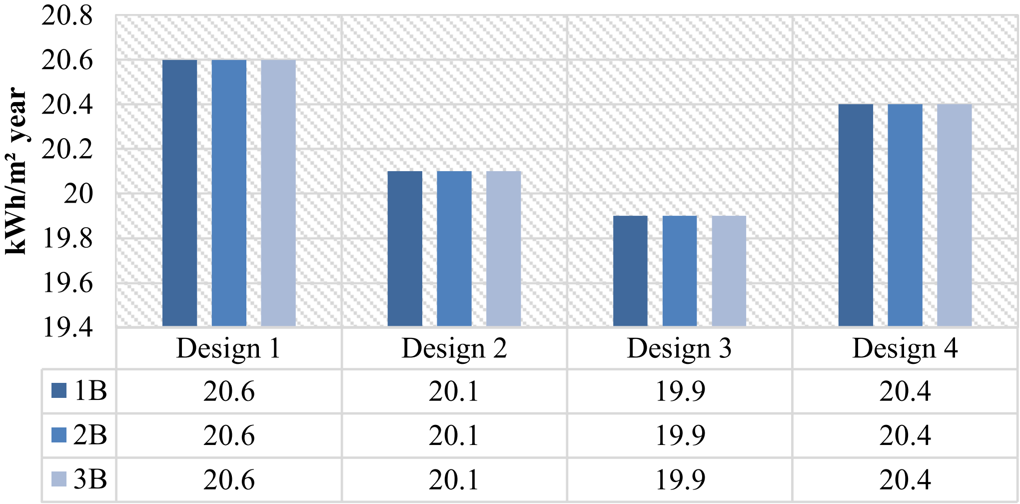
Energy consumption for lighting and equipment

The energy consumption associated with lighting and equipment was thoroughly assessed for each proposed design variant across different climate zones in Jordan. Figure 10 provides a comprehensive comparison of the EUI values for lighting and equipment, highlighting the variations across the climate zones. Notably, the EUI values for lighting and equipment demonstrate remarkable



	IDA/D1	Open/D1	IDA/D2	Open/D2	IDA/D3	Open/D3	IDA/D4	Open/D4
■ 1B	67.2	66.8	64.4	63.9	62.8	62.7	64.1	63.5
■ 2B	64	63.6	61.9	61.6	62.5	61.8	67.6	68.2
■ 3B	61.4	61	58.6	59.3	58.2	59.1	62.3	61.7

Fig. 9 Comparison of energy consumption for proposed designs using different simulation tools



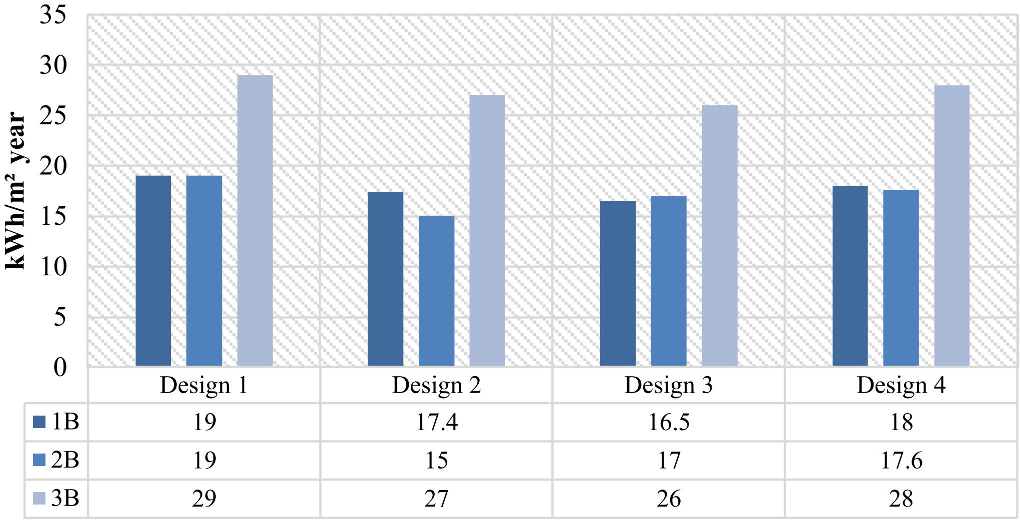
	Design 1	Design 2	Design 3	Design 4
■ 1B	20.6	20.1	19.9	20.4
■ 2B	20.6	20.1	19.9	20.4
■ 3B	20.6	20.1	19.9	20.4

Fig. 10 Energy use intensity for lighting and equipment of the proposed designs

consistency in each climate zone. The highest average variance of 0.7 kWh/m^2 year was observed across various climate zones, reflecting subtle variations. The slight differences can be primarily attributed to variations in window specifications. These values can serve as benchmarks for assessing lighting and equipment performance in future designs and studies in specific climate zones.

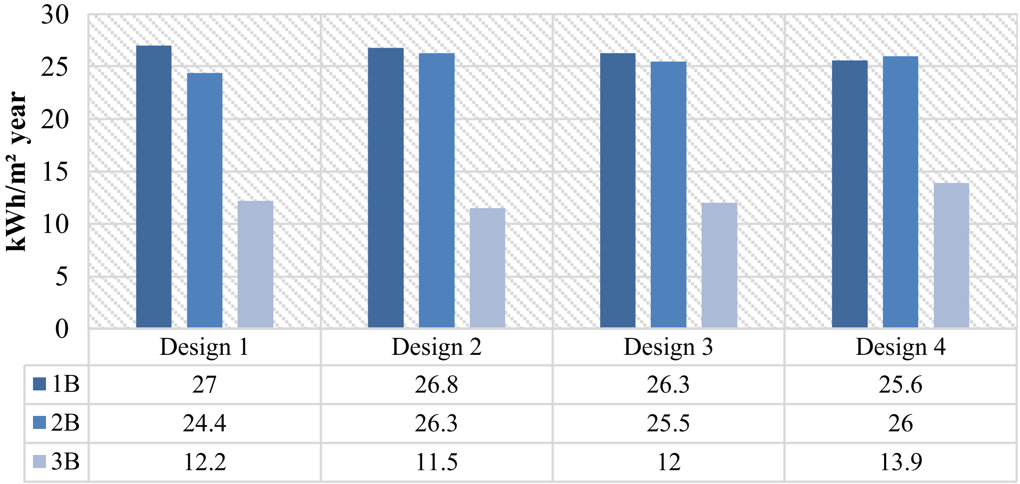
Energy consumption for electric heating

The analysis of the proposed designs is visually represented in Fig. 11, which illustrates the EUI values for electric heating across different climate zones. Climate Zone 3B, distinguished by its mild and dry conditions, stands out with the highest EUI, averaging 27.5 kWh/m^2 year for heating. Conversely, climate zones 1B and 2B, characterised as very hot dry and hot dry, respectively, demonstrated relatively lower heating energy demands, with EUI values of 17.7 and 17.1 kWh/m^2 year, respectively, in comparison to zone 3B. Additionally, when examining the proposed designs within the same climate zone, minimal variations of approximately 2.7 kWh/m^2 year in the EUI were observed, as shown in Fig. 11. These EUI values for the heating loads can serve as benchmarks for assessing the heating performance of future building designs and studies within specific climate zones.



	Design 1	Design 2	Design 3	Design 4
■ 1B	19	17.4	16.5	18
■ 2B	19	15	17	17.6
■ 3B	29	27	26	28

Fig. 11 Energy use intensity for heating of the proposed designs



	Design 1	Design 2	Design 3	Design 4
■ 1B	27	26.8	26.3	25.6
■ 2B	24.4	26.3	25.5	26
■ 3B	12.2	11.5	12	13.9

Fig. 12 Energy use intensity for electric cooling in the proposed designs

Energy consumption for electric cooling

The EUIs for cooling exhibit a pattern opposite to that of heating demand, as illustrated in Fig. 12, with the lowest values observed in climate zone 3B (12.2, 11.5, 12, and 13.9 kWh/m^2 year). Conversely, the highest EUIs were recorded in climate zone 1B (27, 26.8, 26.3, and 25.6 kWh/m^2 year) due to extreme heat, necessitating greater energy for cooling. However, the EUI values for the proposed designs within the same climate zone are nearly identical, as shown in Fig. 12. These values can serve as benchmarks for assessing the cooling performances of future designs and studies specific to climate zones.

Comparison of energy consumption in proposed designs and reported cases

A comparison of the average EUIs of the proposed designs in climate zones 1B, 2B, and 3B with those reported for typical houses in Jordan, Saudi Arabia, and the United States: 1 (very hot), 2 (hot), and 3 (warm) [26, 54, 92]. The proposed designs outperformed typical houses in Jordan by 56%, 55%, and 60% in 1B, 2B, and 3B, respectively, and exceeded international benchmarks by at least 47%, as illustrated in Fig. 13. This underscores their effectiveness in significantly reducing energy consumption even in regions with extreme weather conditions. Furthermore, the designs surpassed the code-compliant houses in Amman by at least 35%, unequivocally

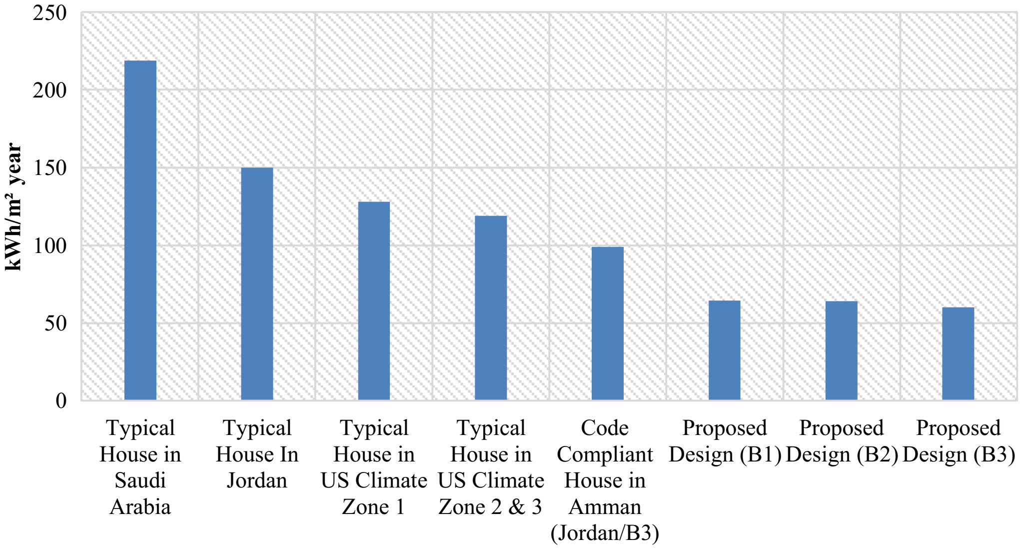


Fig. 13 Average energy use for proposed designs and reported cases

demonstrating their superior energy efficiency. These EUIs can be used as benchmarks to evaluate the energy performance of future designs and studies in Jordan.

Renewable energy system

Renewable energy systems integrated into designed houses play a crucial role in attaining zero-energy targets. The sizing of the PV systems was determined using the PVWatts calculator, encompassing diverse outputs, such as area range, DC system size (kW), module type, number of solar panels, required roof area (m^2), annual DC energy output (kWh), and annual DC energy production per square meter (kWh/m^2 year). The sizing details for different designs across various climate zones are presented in Table 14, including the annual energy production for each design within a specific climate zone. It is important to highlight that the PV systems were sized to cover approximately 110% of the simulated energy consumption for each design. To streamline the calculations, designs with similar average areas were considered.

Financial analysis

To evaluate the financial implications and economic feasibility of implementing ZEB designs in Jordan, a cost comparison was conducted between a typical Jordanian house meeting national energy code standards and the proposed zero-energy design (Design 1). Both scenarios, situated in Amman, have an average area of 175 m^2. The comparison considered the average costs associated with the code-compliant house and those associated with the proposed zero-energy design, considering the disparities in building materials and systems. Additionally, supplementary expenses related to the adoption of zero-energy features and their overall impact on the study were carefully examined. After installing the PV system, the proposed zero-energy design demonstrated savings of 1938 USD, equating to 11 USD per square meter, when juxtaposed with a code-compliant house. This financial analysis, outlined in Table 15, highlights the economic feasibility and substantial financial benefits of embracing zero-energy designs in Jordan.

Proposed designs and building characteristics

The designs were modelled to meet the preferences and needs of homeowners. A distinctive feature of Jordanian architecture is the use of locally sourced materials. Consequently, the proposed zero-energy designs prominently incorporate natural stones and concrete bricks, as illustrated in Fig. 14. Additionally, a white scheme was chosen to minimise heat absorption and enhance reflectivity, demonstrating the deliberate integration of climatic considerations into architectural choices.

Discussion

In this study, we established benchmarks for zero-energy residential buildings in Jordan, emphasising energy efficiency and cost-effectiveness over conventional code-compliant houses. Across diverse Jordanian climate zones, the average EUIs of the proposed designs surpassed those of typical houses in Jordan, Saudi Arabia, and the United States (one, two, and three climate zones, respectively) [26, 54, 92]. The lighting, equipment, heating, cooling, and the overall energy demands were aligned with the reported targets [89].

Minimal variations in the EUIs within the same climate zone highlight the stability of cooling, heating, lighting, and overall energy performance, thereby emphasising the importance of the proposed designs in different climate zones. In climate zone B1, the highest average energy consumption was observed at 64.4 kWh/m^2 year, surpassing those of B2 (64 kWh/m^2 year) and B3 (60 kWh/m^2 year). This discrepancy is attributed to extreme weather conditions, which contributed to an average increase of 4 kWh/m^2 compared to B3 and 1 kWh/m^2 compared to B2.

The EUI values for lighting and equipment demonstrated notable consistency within each climate zone, which is consistent with previous studies on lighting in Jordan [53, 54]. Climate zone 3B, characterised by warm and dry conditions, stands out with the highest EUI for heating, averaging 27.5 kWh/m^2 year, reflecting an elevated demand for heating energy. Conversely, climate zones 1B and 2B, demonstrated relatively lower heating loads, with EUI values of 17.7 and 17.1 kWh/

Table 14 PV System size and output potential

Design number/ climate zone	Location	Area range	DC system size (kW)	Module type	Solar panels number	Roof area (m^2)	Annual DC Energy Output (kWh)	Annual DC Energy (kWh/m^2 year)
1,3/B1	Maan	170–175	8	Standard	20–24	36–42	12,892	73.6
1,3/B2	Zarqa	170–175	8	Standard	20–24	36–42	12,892	73.6
1,3/B3	Amman	170–175	7	Standard	20–24	32–38	11,650	66.5
2,4/B1	Maan	224–228	10	Standard	29–32	50–55	16,634	73
2,4/B2	Zarqa	224–228	10	Standard	29–32	50–55	16,634	73
2,4/B3	Amman	224–228	9	Standard	26–30	45–50	14,850	65.7

Table 15 Cost estimation comparison: code compliant vs. zero-energy houses in Amman

Components/Building systems	Average cost of code compliant house (USD)	Average cost of proposed zero energy house (USD)	Average additional cost of zero energy house (USD)	Average additional cost per m^2 (USD)	Area/No
Envelope[a]					
Walls insulation	637(5 cm)	1527 (12 cm)	890	7.75	113
Slab insulation	1031 (5 cm)	2476 (12 cm)	1444	7.9	183
Roof insulation	987 (5 cm)	3354 (17 cm)	2367	13.5	175
Windows and doors	6977 (Double)	8914 (Triple)	1938	35.3	55
Lighting	352	493	141	0.85	50
Water heating, Heating and cooling system	14,094 (Diesel Central Heating Radiators + Mini Split Air Conditioners)	7047 (air-to-air heat pump for heating, cooling, hot water) [93]	– 7047	– 41	175
Total cost (Before installing PV system)	24,077	23,811	– 227	– 1.3	–
Total energy consumption	26,250 kWh year	10,500 kWh year	– 15,750 kWh year	–	–
Renewable energy system[c]	4180	2508	– 1672	– 9.4	1
Total cost (After installing PV system)	**28,257**	**26,319**	**– 1938**	**– 11**	**–**

Plug equipment was excluded owing to negligible variations in price and energy consumption, and the focus was on cost savings throughout the construction phase

[a] The cost of 1 m^3 of rigid foam was 113 USD (average price in October 2023). All prices are in United States dollars (1 $ = 0.71 JD)

[b] Central heating radiators using diesel are the most common used space heating methods in Amman

[c] Given that the building code doesn't mandate a renewable energy system, assessing only one scenario with renewable energy systems may lead to an incomplete comparison

Fig. 14 Proposed designs and architecture features (1–4 from left to right)

m^2 year, respectively, compared to zone 3B. Furthermore, within the same climate zone, minimal variations of approximately 2.7 kWh/m^2 year in EUI are observed when examining the proposed designs. In terms of cooling, the lowest values are observed in climate zone 3B (12.2, 11.5, 12, and 13.9 kWh/m^2 year), while the highest EUIs are recorded in climate zone 1B (27, 26.8, 26.3, and 25.6 kWh/m^2 year) due to extreme heat, necessitating greater energy for cooling. Despite these variations, the EUI values for the proposed designs within the same climate zone were nearly identical, indicating a consistent performance owing to the shared building characteristics. These findings were consistent with those of a previous study conducted in Jordan [26].

Emphasising the integration of renewable energy systems, particularly PV systems, is crucial for achieving zero-energy targets. The sizing results for various designs in different climate zones are detailed in Table 14 and are aligned with reported PV targets [69]. Furthermore, the economic feasibility analysis considers the costs associated with building materials, energy systems, and additional expenses related to zero-energy features. After installing the PV system, the zero-energy design demonstrated substantial savings of 1938 USD, equivalent to 11 USD per square meter (see Table 15 for more details), aligning with findings from previous studies [39–43]. The design of the proposed houses significantly influenced indoor thermal comfort, with thermal satisfaction levels reaching a minimum of 80% of the total number of occupants.

The strength of this study lies in the design of zero-energy residential buildings across all the climate zones in Jordan, offering specific benchmarks and designs tailored to the building and climate characteristics of Jordan. The identified inputs and proposed designs serve as valuable resources for future studies by enabling more accurate energy analyses, improved thermal comfort assessments, and IAQ evaluations. Additionally, this work contributes to raising the awareness of energy efficiency and lays the foundation for a new Jordanian guide to zero-energy design for residential buildings.

Although this study provides valuable insights into various aspects of zero-energy residential building design, it is essential to acknowledge its limitations. Notably, IAQ was not within the scope of this study, and a more thorough investigation of indoor thermal comfort is necessary. However, previous studies [37, 38] have affirmed that ZEBs offer satisfactory thermal comfort and high IAQ while maintaining low energy consumption. In addition, the proposed designs were specifically tailored for unconstrained sites and low-rise residential buildings. To address these limitations, future research efforts should encompass a comprehensive assessment of IAQ and indoor thermal comfort in zero-energy residential buildings with a focus on unique climatic conditions. Furthermore, exploring different building types and night-time ventilation strategies, understanding occupant behaviour in adapting to extreme weather conditions, and evaluating equipment loads and scheduling would contribute to a more holistic understanding of zero-energy design in diverse contexts.

Conclusions

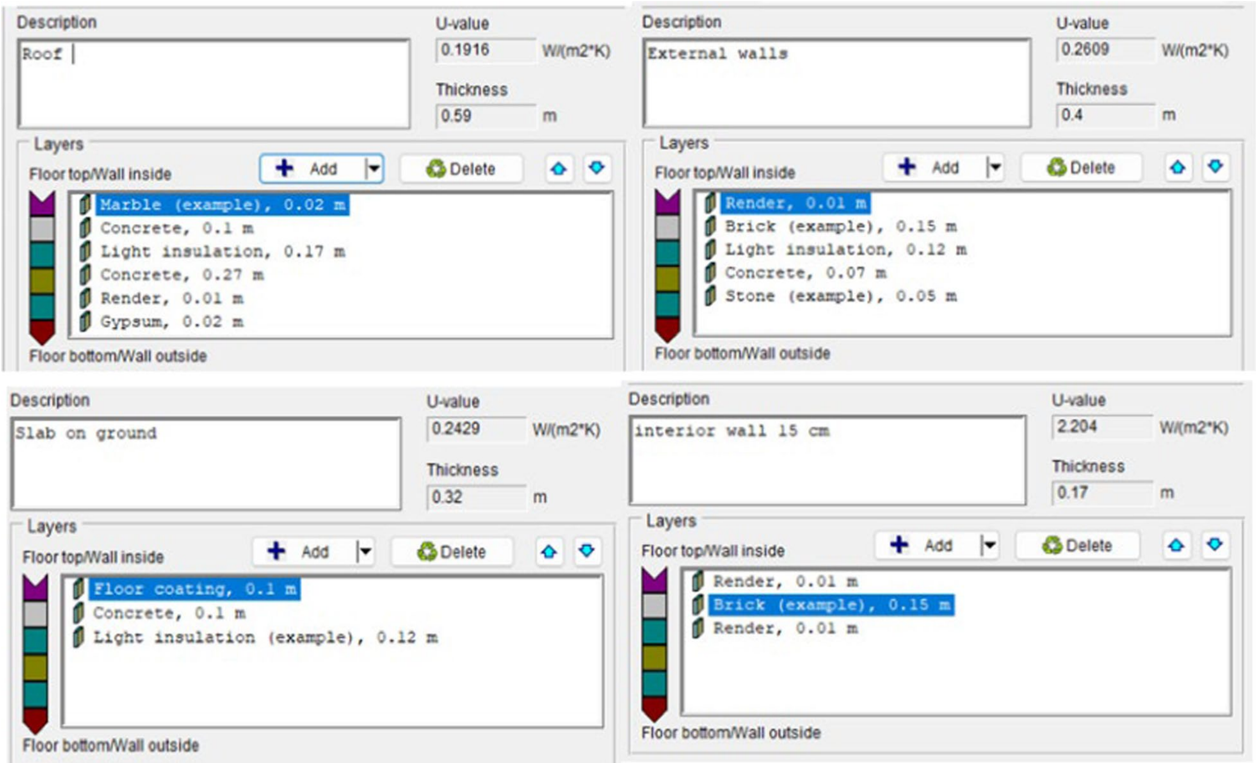
In this study, we established robust benchmarks for zero-energy residential buildings across various climate zones in Jordan. The main goal was to develop designs that act as benchmarks, advocating for maximum energy efficiency and the adoption of renewable energy in residential construction. The findings highlighted that the proposed designs significantly surpassed the performances of typical houses in different countries. This underscores the effectiveness of zero-energy designs under the diverse climatic conditions in the country. The integration of renewable energy systems, particularly PV systems, plays a pivotal role in achieving zero-energy goals. The calculated generation of approximately 110% of the projected EUI using the PV Watts calculator highlights the efficacy of this approach. The economic feasibility assessment demonstrates not only substantial energy savings but also significant cost savings. In addition, the design of the proposed houses played a crucial role in the indoor thermal comfort, with at least 80% of the total number of occupants experiencing thermal satisfaction.

Validation of the proposed designs using IDA ICE and OpenStudio building energy tools revealed their resilience and consistently met energy performance targets across diverse climate zones. This holistic approach, which amalgamates architectural preferences, climate considerations, and energy-efficient technologies lays the foundation for a practical Jordanian zero-energy design. This guide is envisioned as a valuable resource for designers, builders, and owners to promote the construction of environmentally conscious and energy-efficient buildings in similar climates.

Considering Jordan's ambitious energy strategy for 2030 and its substantial energy consumption within the residential sector, this study addresses the critical gaps in sustainable construction practices. The proposed zero-energy designs serve as benchmarks, and guide future construction practices, contributing to the global transition towards ZEBs. This study provides valuable insights into the field, offering specific benchmarks, designs, and a holistic guide tailored to Jordan's unique building and climate characteristics with potential applications beyond its immediate context.

Appendix A

See Figs. 15, 16, 17, 18, 19, 20



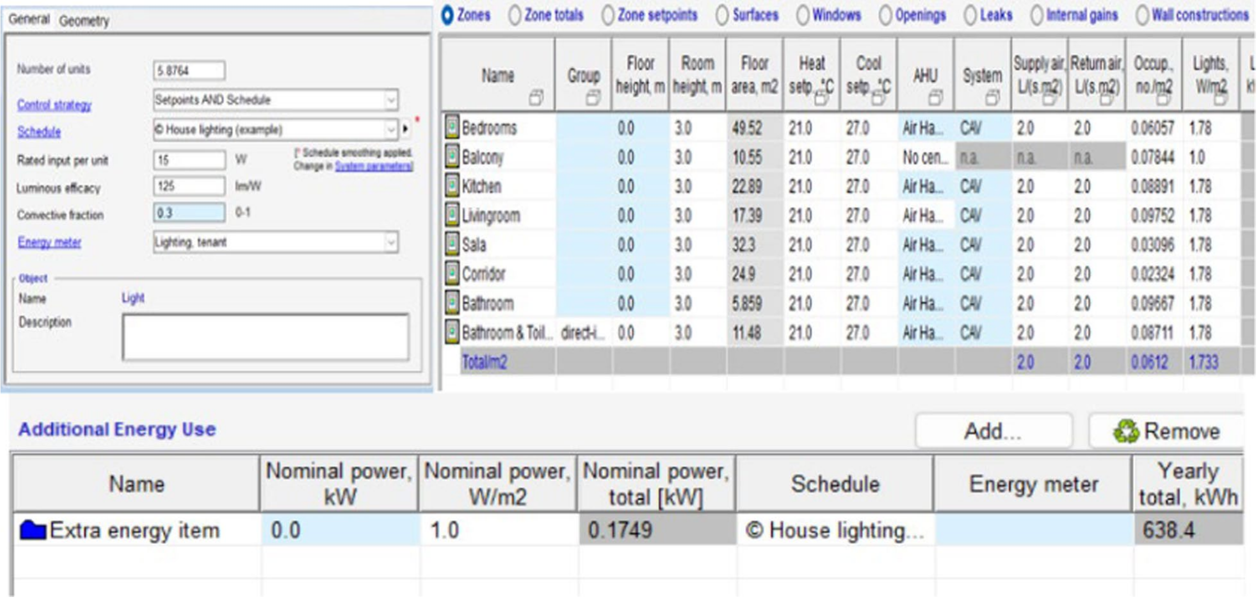
Description: Roof
U-value: 0.1916 W/(m2*K)
Thickness: 0.59 m
Layers:
- Marble (example), 0.02 m
- Concrete, 0.1 m
- Light insulation, 0.17 m
- Concrete, 0.27 m
- Render, 0.01 m
- Gypsum, 0.02 m

Description: External walls
U-value: 0.2609 W/(m2*K)
Thickness: 0.4 m
Layers:
- Render, 0.01 m
- Brick (example), 0.15 m
- Light insulation, 0.12 m
- Concrete, 0.07 m
- Stone (example), 0.05 m

Description: Slab on ground
U-value: 0.2429 W/(m2*K)
Thickness: 0.32 m
Layers:
- Floor coating, 0.1 m
- Concrete, 0.1 m
- Light insulation (example), 0.12 m

Description: interior wall 15 cm
U-value: 2.204 W/(m2*K)
Thickness: 0.17 m
Layers:
- Render, 0.01 m
- Brick (example), 0.15 m
- Render, 0.01 m

Fig. 15 Detailed envelope specifications via IDA ICE software (design 1,3B)



Number of units: 5.8764
Control strategy: Setpoints AND Schedule
Schedule: © House lighting (example) *
Rated input per unit: 15 W
Luminous efficacy: 125 lm/W
Convective fraction: 0.3 0-1
Energy meter: Lighting, tenant
[* Schedule smoothing applied. Change in System parameters]

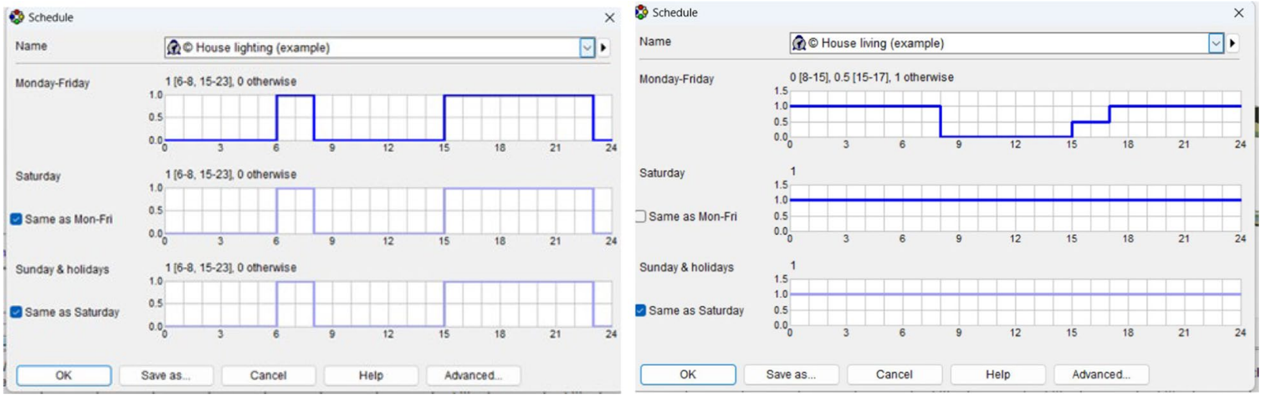
Object
Name: Light
Description:

Name	Group	Floor height, m	Room height, m	Floor area, m2	Heat setp., °C	Cool setp., °C	AHU	System	Supply air, L/(s.m2)	Return air, L/(s.m2)	Occup., no./m2	Lights, W/m2
Bedrooms		0.0	3.0	49.52	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.06057	1.78
Balcony		0.0	3.0	10.55	21.0	27.0	No cen...	n.a.	n.a.	n.a.	0.07844	1.0
Kitchen		0.0	3.0	22.89	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.08891	1.78
Livingroom		0.0	3.0	17.39	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.09752	1.78
Sala		0.0	3.0	32.3	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.03096	1.78
Corridor		0.0	3.0	24.9	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.02324	1.78
Bathroom		0.0	3.0	5.859	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.09667	1.78
Bathroom & Toil...	direct-i...	0.0	3.0	11.48	21.0	27.0	Air Ha...	CAV	2.0	2.0	0.08711	1.78
Total/m2									2.0	2.0	0.0612	1.733

Additional Energy Use

Name	Nominal power, kW	Nominal power, W/m2	Nominal power, total [kW]	Schedule	Energy meter	Yearly total, kWh
Extra energy item	0.0	1.0	0.1749	© House lighting...		638.4

Fig. 16 Interior and exterior lighting power densities for different units



Schedule

Name: © House lighting (example)

Monday-Friday: 1 [6-8, 15-23], 0 otherwise

Saturday: 1 [6-8, 15-23], 0 otherwise

☑ Same as Mon-Fri

Sunday & holidays: 1 [6-8, 15-23], 0 otherwise

☑ Same as Saturday

Schedule

Name: © House living (example)

Monday-Friday: 0 [8-15], 0.5 [15-17], 1 otherwise

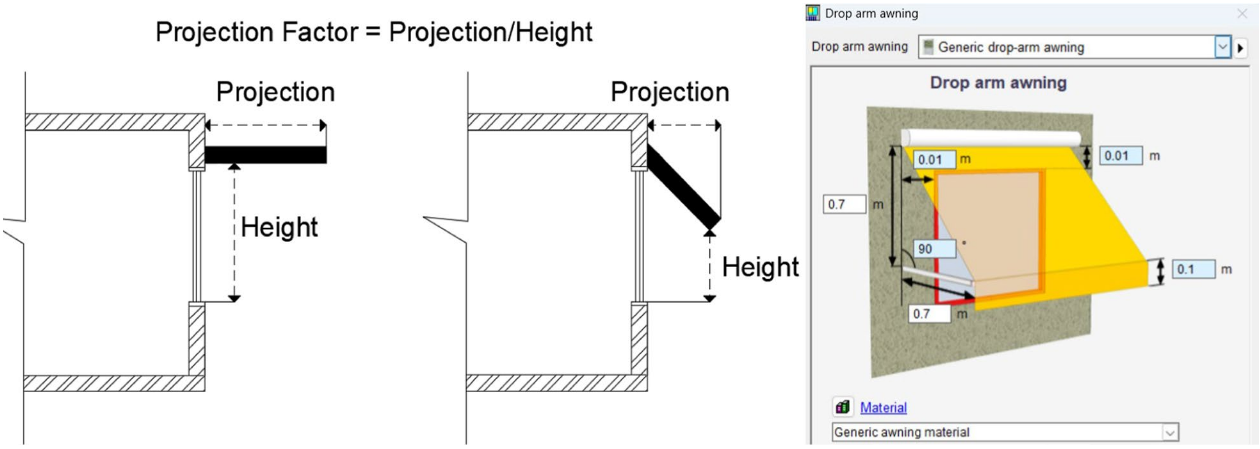
Saturday: 1

☐ Same as Mon-Fri

Sunday & holidays: 1

☑ Same as Saturday

Fig. 17 Lighting, house living schedules

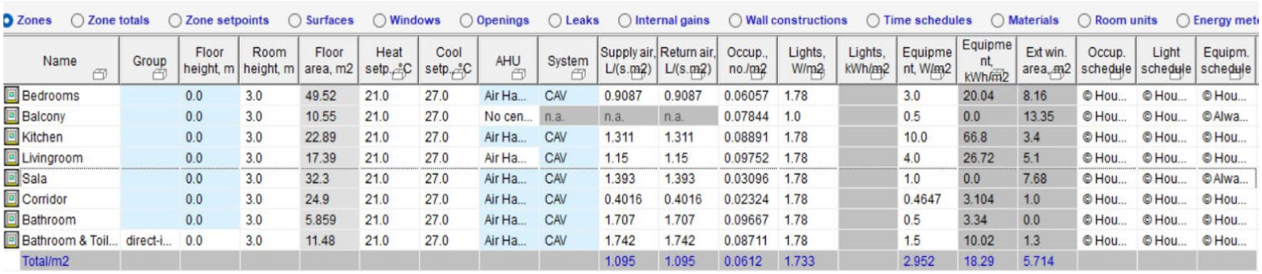


Drop arm awning

Drop arm awning: Generic drop-arm awning

Material: Generic awning material

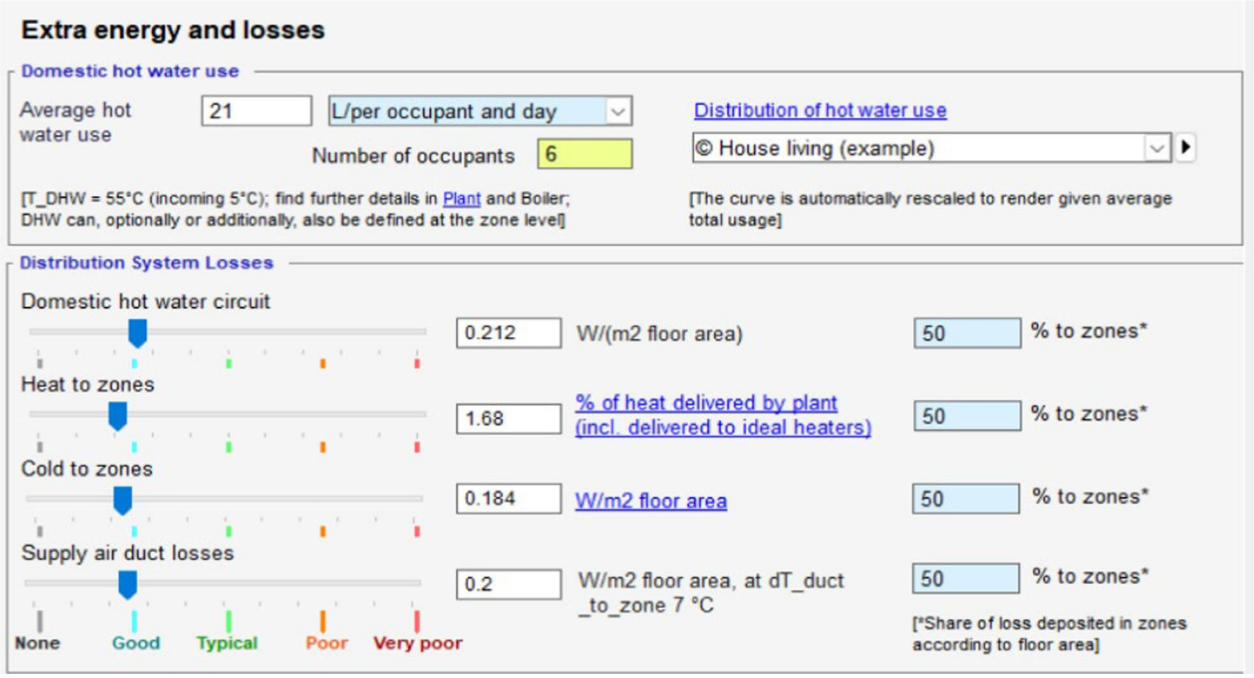
Fig. 18 Detailed exterior shading specification inputs on IDA ICE software (design 1,3B)



● Zones ○ Zone totals ○ Zone setpoints ○ Surfaces ○ Windows ○ Openings ○ Leaks ○ Internal gains ○ Wall constructions ○ Time schedules ○ Materials ○ Room units ○ Energy met

Name	Group	Floor height, m	Room height, m	Floor area, m2	Heat setp., °C	Cool setp., °C	AHU	System	Supply air, L/(s.m2)	Return air, L/(s.m2)	Occup., no./m2	Lights, W/m2	Lights, kWh/m2	Equipment, W/m2	Equipment, kWh/m2	Ext win. area, m2	Occup. schedule	Light schedule	Equipm. schedule
Bedrooms		0.0	3.0	49.52	21.0	27.0	Air Ha...	CAV	0.9087	0.9087	0.06057	1.78		3.0	20.04	8.16	© Hou...	© Hou...	© Hou...
Balcony		0.0	3.0	10.55	21.0	27.0	No cen...	n.a.	n.a.	n.a.	0.07844	1.0		0.5	0.0	13.35	© Hou...	© Hou...	© Alwa...
Kitchen		0.0	3.0	22.89	21.0	27.0	Air Ha...	CAV	1.311	1.311	0.08891	1.78		10.0	66.8	3.4	© Hou...	© Hou...	© Hou...
Livingroom		0.0	3.0	17.39	21.0	27.0	Air Ha...	CAV	1.15	1.15	0.09752	1.78		4.0	26.72	5.1	© Hou...	© Hou...	© Hou...
Sala		0.0	3.0	32.3	21.0	27.0	Air Ha...	CAV	1.393	1.393	0.03096	1.78		1.0	0.0	7.68	© Hou...	© Hou...	© Alwa...
Corridor		0.0	3.0	24.9	21.0	27.0	Air Ha...	CAV	0.4016	0.4016	0.02324	1.78		0.4647	3.104	1.0	© Hou...	© Hou...	© Hou...
Bathroom		0.0	3.0	5.859	21.0	27.0	Air Ha...	CAV	1.707	1.707	0.09667	1.78		0.5	3.34	0.0	© Hou...	© Hou...	© Hou...
Bathroom & Toil...	direct-i...	0.0	3.0	11.48	21.0	27.0	Air Ha...	CAV	1.742	1.742	0.08711	1.78		1.5	10.02	1.3	© Hou...	© Hou...	© Hou...
Total/m2									1.095	1.095	0.0612	1.733		2.952	18.29	5.714			

Fig. 19 Estimated loads based on Building America House Simulation Protocols Report



Extra energy and losses

Domestic hot water use

Average hot water use: 21 L/per occupant and day

Number of occupants: 6

[T_DHW = 55°C (incoming 5°C); find further details in Plant and Boiler; DHW can, optionally or additionally, also be defined at the zone level]

Distribution of hot water use: © House living (example)

[The curve is automatically rescaled to render given average total usage]

Distribution System Losses

Domestic hot water circuit	0.212	W/(m2 floor area)	50	% to zones*
Heat to zones	1.68	% of heat delivered by plant (incl. delivered to ideal heaters)	50	% to zones*
Cold to zones	0.184	W/m2 floor area	50	% to zones*
Supply air duct losses	0.2	W/m2 floor area, at dT_duct _to_zone 7 °C	50	% to zones*

[*Share of loss deposited in zones according to floor area]

Fig. 20 Average hot water use (design 1,3B) Via IDA ICE

Abbreviations

ISMRE	Integrated seasonal moisture removal efficiency
ISCOP	Integrated seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
EER	Energy efficiency ratio
IEER	Integrated energy efficiency ratio
HSPF	Heating seasonal performance factor
COP	Coefficient of performance

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Author contributions

Conceptualisation, M.S.A. and F.A.; methodology, M.S.A.; software, M. S. A.; validation, M. S.; formal analysis, M. S. A.; investigation, H.S.; resources, S. A. and F.A.; data curation, M.S.A. and F.A.; writing-review and editing, M.S.A., M.S., and F.A; visualisation, M.S.; supervision, M.S.A. and F.A; project administration, M. S. and M. S.; F.H.,M.S, H.S, and S.A. All the authors have read and agreed to the published version of the manuscript.

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The datasets used and/or analysed in the current study is available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing Interests

We declare that the authors have no competing interests as defined by the BMC, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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