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House of the Future: Designing a Net-Zero Energy Housing Archetype for Emirati Families

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Abstract

This paper documents the design of a concrete 3D-printed net-zero energy housing archetype in the United Arab Emirates (UAE). The net-zero energy target was achieved by combining active and passive design strategies, such as cross-ventilation, improved thermal performance of the building envelope, exterior shading devices, and a geothermal cooling system. Meeting the requirements of Estidama's Pearl Rating System—particularly the thermal transmittance (U-values) for building envelope components—was a challenge due to the use of 3D-printed walls and prefabricated hollow-core slabs. To address this, a parametric analysis was conducted using LBNL Therm thermal performance modeling software to optimize the U-values of walls and roofs. A U-value of 0.22 W/m²·K was achieved, which is 30% more efficient than the minimum required by Estidama. Subsequently, whole-building energy simulations were performed using the Home Energy Efficient Design (HEED) software. The simulations show that implementing the active and passive design strategies yielded a minimum energy use intensity (EUI) of 87 kWh/m^2. Yr, which was later supplemented by onsite solar energy generation to achieve the NetZero target. Performance evaluations demonstrate that compliance with local sustainability requirements, such as Estidama, and achieving the net-zero energy goal are possible, proving the feasibility of 3D-printed sustainable housing in the UAE. The findings of this research show that achieving net-zero energy in housing is possible in the UAE, even with 3D printing, and advocate for its wider adoption and implementation. The study results support the local and international pursuit to achieve environmental sustainability through achieving energy efficiency and transitioning to clean energy sources. The findings also align with and contribute to the achievement of the United Nations Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

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Keywords

Net-Zero Energy; Archetype; Housing; 3D printing; U-value; UAE; Hot arid climate

Introduction

1.1. Background

Housing demand in the United Arab Emirates (UAE) has been increasing throughout the last few decades, as 71% of existing buildings are mainly categorized as residential (*Abu Dhabi | The Official Portal of the UAE Government*, 2024). For example, the Emirate of Abu Dhabi had an existing total of 253 thousand residential units by the year 2022

(Statista, 2023). The UAE is home to people from more than two hundred countries around the world who move to the UAE primarily for work, investment, or to seek a better lifestyle. Housing options in the UAE vary depending on the socioeconomic situation of people, including family structure and affordability. The housing options include mid- and high-rise multi-unit residential buildings, semi-detached (known also as townhouses), and single-family detached houses (i.e., villas). The single-family detached houses are the most common type of Emirati family housing and will be the focus of this study. The government has been acting as the main housing provider for its citizens since the establishment of the country in the early 1970s (Damluji, 2006; Agrawal et al, 2020). In the early seventies of the last century, the government of the UAE started providing traditional houses (Sha'biya), which are a form of housing that consists of one floor with a large outdoor living space. This housing archetype then responded to family needs and traditional lifestyle. Following that, in the 1980s until recently, and with the introduction of new construction materials and technologies and the lifestyle changes, the government-provided housing archetypes were developed from traditional to modern and then contemporary styles that take the style of 2-3 story detached single family houses (Remali et al., 2016)(Remali et al., 2016). These new housing archetypes are typically imported from different climates and cultures and are heavily dependent on mechanical and electrical systems for indoor climate control. Consequently, the demand for energy to operate these buildings skyrocketed. Therefore, there has been a necessity to develop more efficient alternatives with lower energy demands and environmental impact.

In recent years, several housing programs have been established to provide Emirati families with decent housing. For instance, the North Ban Yas Project and Balghaiylam Residential Development were launched by the emirate of Abu Dhabi Housing Authority (ADHA) (UAE: Residential Unit Supply in Abu Dhabi 2022 | Statista, 2021 This growing demand for housing is expected to continue as a natural result of population growth and the attractive environment for investors and job seekers in the UAE. This growth of demand for housing mandates a need for continuous development of housing infrastructure and improves their performance to stay in line with the UAE's future vision and the emerging global challenges, such as climate change, highlighted in the UAE's Green Agenda 2030 and its commitment to sustainability and greenhouse gas (GHG) emission reduction. (UAE Government, 2025)

On another front, 3D printing is revolutionizing the construction industry by offering a faster, more cost-effective, and sustainable approach to constructing buildings. (Deshmukh *et al.*, 2020). This innovative technology transforms computer-aided drafting (CAD) designs into real structures using large-scale printers with minimal involvement of manpower. By automating the layering of concrete or other printing materials, 3D printing enables the creation of complex architectural forms while significantly reducing construction time and material waste. (Kabir, Mathur and Seyam, 2020) Additionally, using locally sourced materials enhances sustainability, minimizing the environmental impact of projects.

As advancements continue, 3D printing is set to play a crucial role in the future of building construction. This role is expected to achieve significant advances in cost savings and construction waste reduction. Therefore, introducing 3D printing in the construction industry in the UAE offers great potential for contributing to the continuous pursuit of environmental sustainability, energy, and cost efficiency.

Further, the need for net-zero energy housing is becoming increasingly critical as the world faces environmental challenges, rising energy costs, and resource depletion. (Voss et al., 2011). Net-zero energy houses are designed to generate as much energy as they consume, reducing reliance on traditional active systems such as mechanical cooling and ventilation. This can be achieved by incorporating passive design strategies and renewable energy sources such as solar power. This form of housing offers long-term cost savings by cutting utility bills and environmental benefits through lowering the reliance on energy generated by burning fossil fuels.

In hot arid regions like the UAE, where high energy consumption is driven by high cooling demands, net-zero housing is essential for promoting environmental sustainability, enhancing energy security, and creating resilient, eco-friendly communities for the future. (Bojarajan *et al.*, 2024). Net-zero energy housing was achievable in many cases and in different regions in the world by implementing various passive and active design strategies and energy conservation measures (see Table 1).

In the UAE, where the government is considered the largest provider of housing to its citizens, and where typical housing designs are implemented in hundreds and sometimes thousands, designing a net-zero housing archetype would be of great importance to achieve substantial energy savings and reduction of greenhouse gas emissions. Our proposed project is in line with the Emirate of Abu Dhabi's objective for sustainable development and innovation, as it promotes the use of sustainable approaches for constructing housing units, such as 3D printing.

Table 1: Example of similar net-zero housing buildings (by the authors)

Net-zero energy case study	Location	Strategies implemented	Source
Single-Family (703 Heliotrope)	Corona del Mar, CA, USA	Enhanced wall system (closed cell spray insulation); enhanced air tightness; efficient HVAC system; use of natural ventilation; high efficiency lighting	(Dean, 2018)
Oak Haven Modular House	Ojai, CA, USA	Enhanced wall, roof, and window thermal transmittance; enhanced envelope air tightness; use of daylight and high-efficiency electric lights; EnergyStar-rated HVAC system and electric equipment; On-site energy generation (PV)	(Dean, 2018)
Carlsson Family Home Portland, OR	Portland, OR, USA	Enhanced envelope thermal transmittance; enhanced air tightness; On-site energy generation (PV)	(Elemental Green, 2025)
ÉcoTerra house	Eastman, QC, Canada	Thermal mass; Solar passive heating; geothermal heating; heat recovery system; enhanced thermal transmittance of windows and walls; Onsite energy generation (photovoltaics);	(Noguchi *et al.*, 2008)

1.2. Objectives and paper structure

The main objective of the project is to develop a net-zero energy housing archetype that achieves the lowest possible Energy Use Intensity (EUI) while generating equivalent energy on site. The housing archetype will be of single-family detached houses that are typically provided through the governmental housing projects in the UAE. Designing a housing archetype that is self-sustaining in terms of energy lowers the operational costs of the housing sector. This pursuit to reduce the ecological footprint of housing aligns with the UAE's plan to achieve sustainability and reduce Greenhouse gas (GHG) emissions. (*The UAE's Green Agenda - 2030 | The Official Portal of the UAE Government*, 2024). On the other hand, using 3D printing during construction is expected to minimize construction time and materials waste. Additionally, the proposed archetype is designed to meet the needs of Emirati families. Figure 1 Outlines the main objectives of this research-based design.

The following section outlines the methodology followed to design and evaluate the housing archetype performance, including the parametric analysis and performance optimization. Then the results of the different performance evaluation processes are presented and discussed. Finally, conclusions and recommendations are drawn based on the findings. Figure 2 Outlines the whole paper structure.

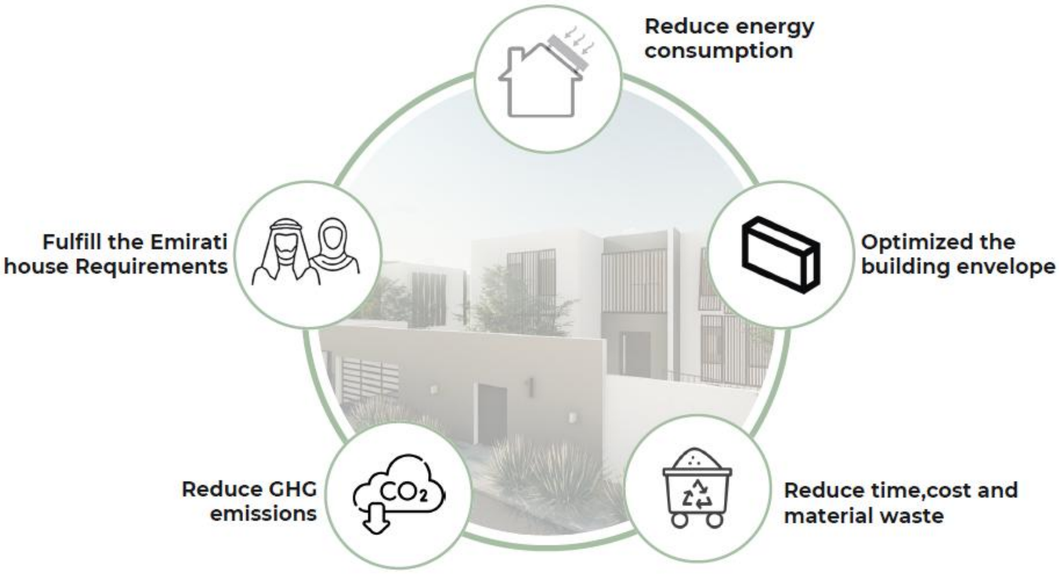

Figure 1: The main objectives of this research-based design project (by the authors)

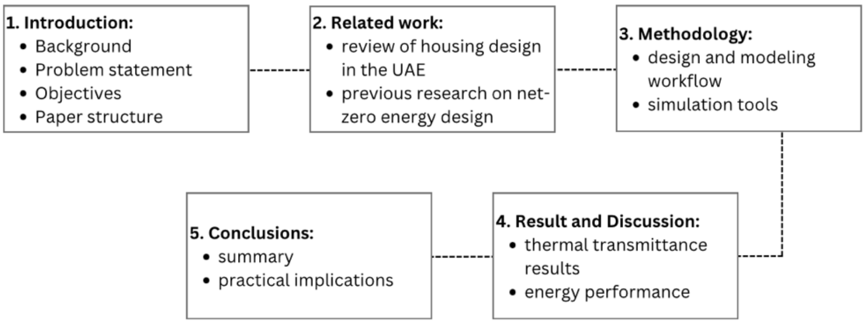

Figure 2: The paper structure (by the authors)

Materials and Methods

This section covers the steps that were followed to design the net-zero housing archetype. The research methodology builds upon the net-zero energy framework that pursues reducing emissions and energy demand by designing buildings that produce the same amount of energy they use. (WBDG, 2025). In the UAE's hot-arid climate, the basics of the bioclimatic design theory to reach optimal passive cooling techniques, such as shading, thermal mass, and natural ventilation, were implemented. (Beskonakli, 2024). This approach has been proven to be successful in similar building types and climatic conditions.

The design process is also adopting the well-known performance-based design approach and simulation-aided building design that relies on performance evaluation as the base of design decision-making. (Clarke, 2007; Galinski, 2025). The methodology and design approach also took into account social aspects of housing in design, and every possible effort was made to make design decisions that reflect the local culture and suit the family structure of the Emirati family and their needs.

The methodology revolves around the verification of the design performance of the housing archetype designed by the authors to meet and exceed the local energy codes in the Emirate of Abu Dhabi in the UAE. Since this study is a documentation of a design and modelling process of a net-zero housing archetype, a quantitative analysis approach was followed throughout the simulation and performance modelling of the whole building and its components. Numerous performance modelling iterations were performed, and the resulting performance was compared to the local code and standards requirements. The design and modeling workflow is described first, then the modeling and simulation tools are described. Figure 4 Outlines the major steps of the design process.

2.1. Design and modelling workflow

(1) Building concept design was the initial stage of architectural development, where functional and aesthetic aspects were integrated. This stage involved analyzing client needs, site constraints, and functionality to guide decisions on layout, materials, and technology. Key factors such as sustainability, energy efficiency, and environmental integration that influence the design were thoroughly studied. The goal was to create a harmonious, efficient, and inspiring space while balancing practicality, feasibility, and cost-effectiveness.

a. Inspired by Sheikh Zayed's quote, "Give me agriculture, and I will guarantee you civilization." Our project highlights the role of agriculture and water in the UAE's development. The Shabhana tree, a symbol of heritage and connection, served as our inspiration, representing gathering and growth. Its five branches reflect family development, emphasizing Emirati heritage in shaping the future.

b. The courtyard building configuration was selected to provide privacy and serve to passively cool the building.

c. Since this housing archetype is intended for implementation in mega housing projects, which implies applying the archetype in various orientations, the archetype was configured using five (5) modules that can be arranged in different ways around the courtyard in a way that ensures that passive cooling is achieved with all orientations (see Figure 3).

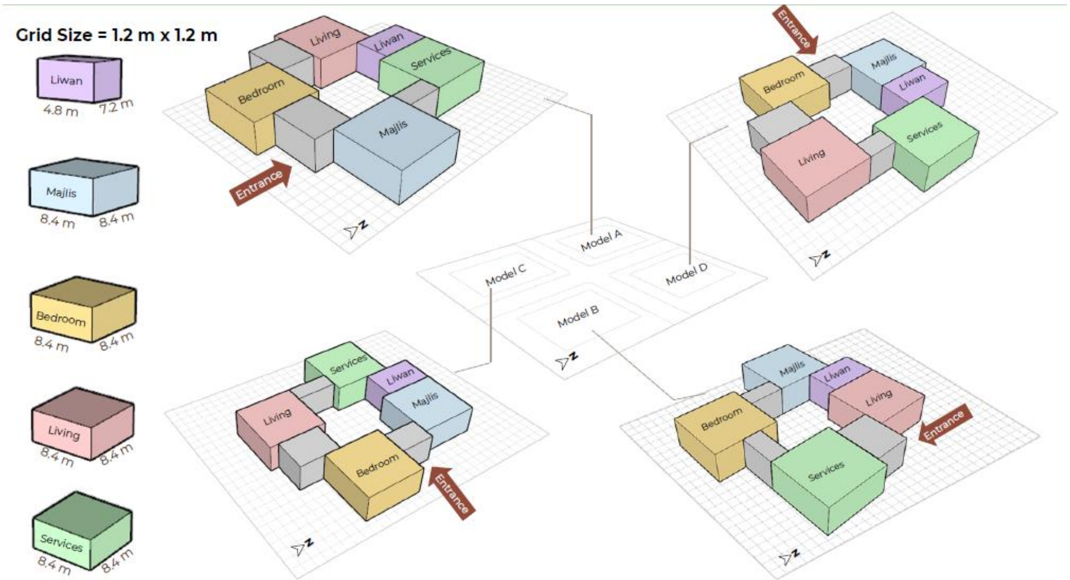

Figure 3: The archetype modules and configurations (by the authors)

(2) The optimization of the building systems stage was focused on optimizing the performance of the building envelope, heating, ventilation, and air conditioning (HVAC), and lighting systems performance.

a. Parametric analysis was conducted to optimize the thermal transmittance (U-Value) of the building envelope components: walls, windows, and roof. Three alternative concrete mix designs and three different insulation materials were tested. The concrete mix designs were obtained from Suntharalingam et al. (2021). Nine (9) different combinations of wall assemblies were created by varying the concrete mix, insulation material, and the number of wall layers.

b. A geothermal ground source heat pump, with desiccant for dehumidification, was selected as the cooling system.

c. Exterior shading was applied to all orientations as the first line of blocking solar radiation. Heat avoidance by using exterior shading is well known for its effectiveness in lowering cooling loads (Lechner, 2014).

(3) The whole building simulation was performed to evaluate the whole building EUI and the integrated effectiveness of the optimized building systems. Various passive and active strategies were combined in the final simulations.

(4) On-site energy generation was planned to be in the form of solar photovoltaics. Solar analysis was performed to determine the sun exposure of the archetype, and the number of photovoltaics was determined based on the needed electric power to make up for energy use. Power Net-metering method was selected for the archetype where the generated electricity is supplied to the grid while the house is using power from the grid. The selection of this method was driven by the need to overcome the reliability of solar energy at low/no generation time (night and severely overcast weather).

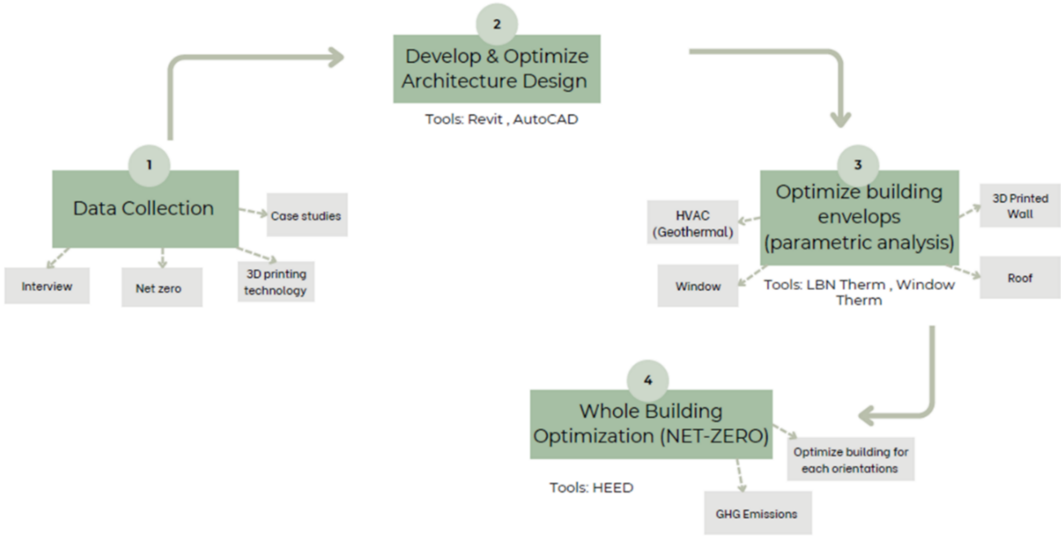

Figure 4: Research-based design process (by the authors)

2.2. Simulation tools

In the process of designing and optimizing the net-zero housing archetype, several software tools were used in different stages of development. Below is a list of these software with a brief description:

1. **Autodesk Revit** is a 4D Building Information Modeling (BIM) software equipped with tools for planning and monitoring different phases of a building's lifecycle, from initial concept and construction to maintenance and potential demolition (Autodesk, 2025). In our project, we primarily utilized Revit for designing our archetype and developing its construction details. Revit, as a BIM software, was selected as it enables the creation of an integrated building model that combines architectural, structural, and mechanical systems in one model, which facilitates coordination and minimizes discrepancies between building systems.

2. **SketchUp** is a 3D modeling software that provides intuitive tools for designing, visualizing, and rendering architectural, interior, and landscape projects. It is widely used by architects, designers, and engineers for conceptual design, documentation, and presentation(Trimble, 2025). SketchUp was used for 3D modeling of the building archetype. The SketchUp software was used during the schematic design process for quick visualization of building spaces and form.

3. **Climate Consultant** is a user-friendly, graphics-based software designed to assist architects, builders, contractors, homeowners, and students in analyzing and understanding their local climate (Sbse, 2018) . The software was used to visualize and analyze climate data of the UAE, which was used as the basis of designing passive and active design strategies, selection, and application

4. **Home Energy Efficient Design (HEED)** is a whole-building energy simulation software that visually illustrates potential energy, cost, and carbon emissions savings by exploring various design alternatives or implementing and modeling changes to a home (SBSE, 2018). HEED is a noncommercial simulation software that was developed by researchers of the University of California, Los Angeles (UCLA). HEED was used in the final stages to simulate the whole building performance and optimize the EUI.

5. **LBNL Therm & LBNL Window** are research-grade software that were developed by the Lawrence Berkeley National Laboratory (LBNL) in the United States of America (USA) and are used to analyze two-dimensional

heat transport through building assemblies, including windows, walls, and roofs, and other assemblies. It is especially useful for calculating U-values and R-values of building materials as well as for assessing thermal bridges (LBNL, 2024). Additionally, this software is useful in visualizing heat flow through building assemblies. LBNL Therm was used to evaluate, visualize, and optimize the thermal transmittance (U-Values) of the housing archetype wall and roof assemblies.

3. Results and discussion

This section presents the results of the research-based design of the housing archetype, including the envelope components optimization, whole building energy use optimization, and the onsite energy generation.

3.1. Envelope thermal transmittance (U-value) results

Enhancing the thermal performance of the building envelope is a fundamental step that is commonly sought and implemented by the designers of high-performing and net-zero buildings, as can be seen in Table 1 . The main objective of improving the thermal transmittance of building envelope is to minimize the amount of heat admitted of heat admited through opaque and transparent surfaces, which consequently reduces the cooling demand. In this study, wall, windows, and roof thermal performance were optimized using the modelling tools specified earlier.

- **3D Printed Wall Modelling using (LBNL Therm)**

Figure 5 Presents the results of the parametric analysis conducted to optimize the thermal transmittance of the 3D printed wall assembly. The target was to achieve a U-Value of 0.32 W/m2K specified by the local sustainability framework Estidama (Pearl rating system). Three different mix designs and insulation materials were used to create alternative wall assemblies. The different assemblies were simulated in LBNL Therm. Our Final 3D-printed wall assembly has a 30 cm double-wall construction with a continuous layer of Extruded Polystyrene Insulation (XPS) sandwiched between two layers of Polyurethane Foam Spray (PUF) insulation. The assembly simulated U-value was 0.22 W/m²·K, which is 30% better than the Estidama requirement.

- **Roof Modelling using (LBNL Therm)**

Prefabricated hollow core concrete slabs were selected for the flooring and roofing systems of the housing archetype. We created a multi-layered roof assembly with thermal insulation and a hollow core slab in order to satisfy Estidama requirements for roof construction. Alternatives of the assembly were tested in two separate scenarios, each with varying insulation thicknesses. Given the roof's continuous exposure to solar radiation, we thickened the Extruded Polystyrene (XPS) thermal insulation layer from 50 mm to 150 mm in order to improve the roof's thermal resistance. After adjusting the insulating layer, the final computed U-value improved to 0.1302 W/m²·K. (see Figure 7)

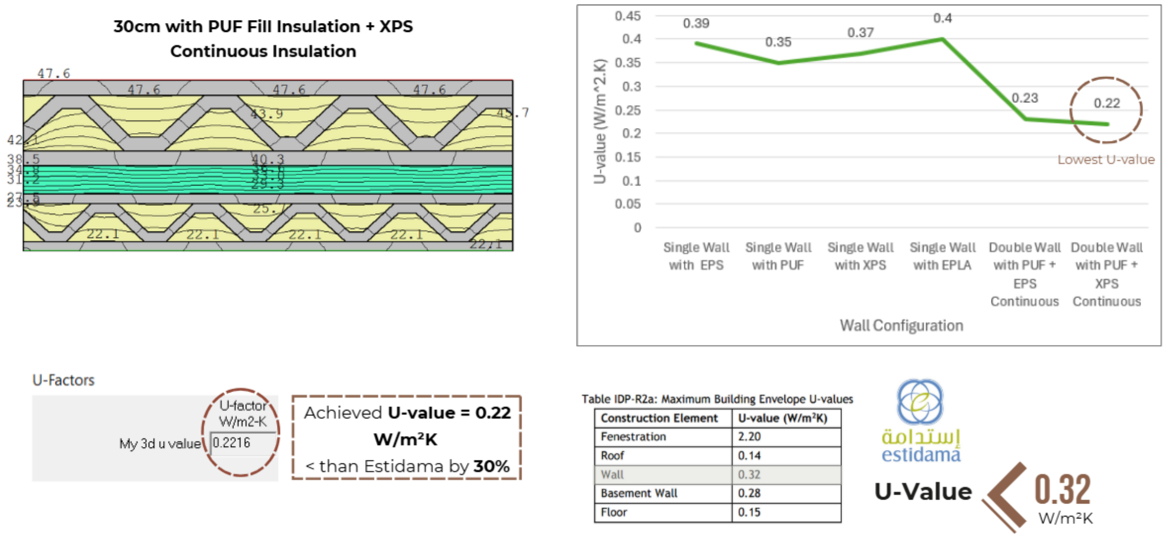

Figure 5: Results of optimizing the 3D printed wall assembly to achieve the target thermal transmittance (U-Value) (by the authors)

Figure 6: 3D printed mockup of the final wall assembly (scale 1:1). The mockup was created by the study authors using a small-scale 3D printer.

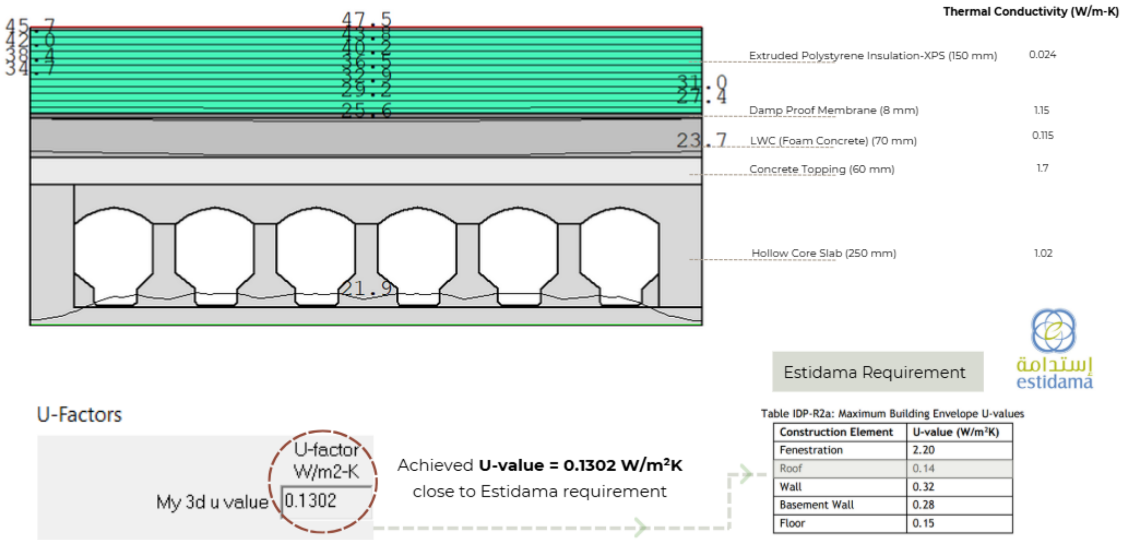

Figure 7: Results of optimizing the prefabricated hollow core concrete slab assembly to achieve the target thermal transmittance (U-Value). The results are extracted from the LBNL Therm energy modeling software

- **Window using (LBNL Window)**

Windows play a crucial role in determining the energy efficiency of a building as they are considered the least resistant to conductive heat transfer, as well as transparent to direct solar radiation. All reviewed net-zero case studies (see Table 1 They had windows with thermal performance optimization at the core of their design approach. This simulation and analysis were also conducted to evaluate two custom window glazing options for the 3D-printed housing archetype, ensuring they meet the U-value requirements specified by Estidama. We used the LBNL Window program to simulate the two window options with varying parameters, including the gas fill type, to identify the best option for the villa's windows. Option 1 consists of double glazing with a 6.4 mm Low-E coating and an air gap of 12.7 mm. While option 2 involves a change in one parameter: the gas infill between the glazing layers is replaced with Xenon, while the rest of the configuration remains the same. It consists of double glazing with a 6.4 mm Low-E coating and a 12.7 mm Xenon gas gap. After running the simulations, the results were analyzed and presented in the flow chart below. The decision was made to select Option 2 due to its lower U-value compared to Option 1, ensuring better thermal performance and compliance with Estidama's energy efficiency standards. (see Figure 8).

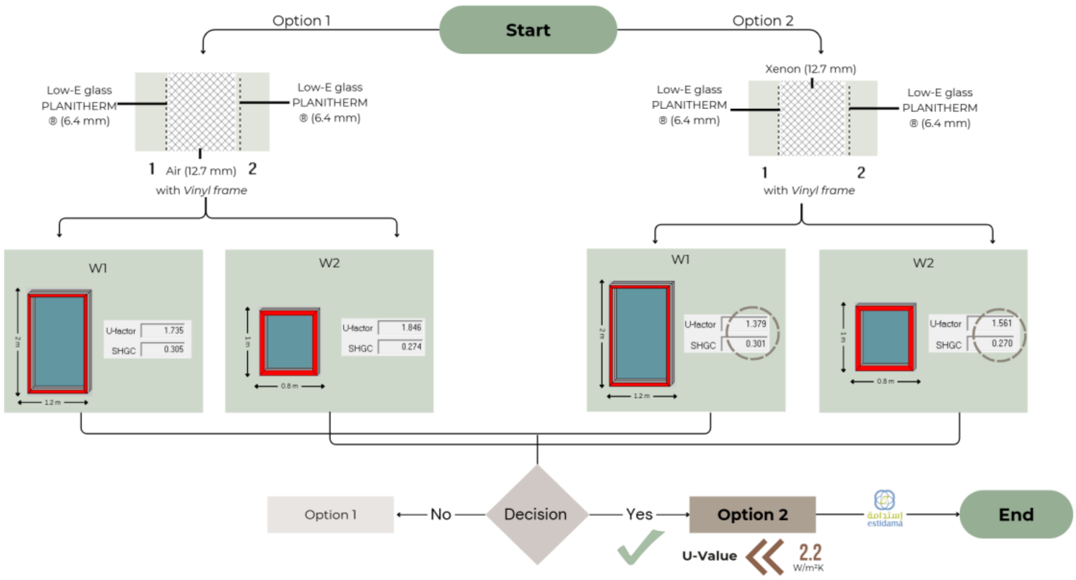

Figure 8: Results of optimizing window assembly to achieve the target thermal transmittance (U-Value). The results were extracted from the LBNL Window software.

3.2. Whole building simulation results

Building performance simulation (BPS) has become an essential technique that aids designers in evaluating their design decisions and achieving design objectives. (Clarke, 2007). Following the performance optimization of the different building components/systems, such as walls, windows, and roof, a whole building performance simulation was performed using a combination of passive and active design strategies. Home Energy Efficient Design (HEED) Software was used to conduct simulations. For a cooling-dominated climate such as the UAE, applying enhancements to the building envelope (walls, windows, and roof) is essential for minimizing heat gain and lowering cooling loads, as it has been proven in several net-zero housing projects and studies(refer to examples in Table 1). Figure 9 Shows the results of the simulation iterations, including the baseline and the improved model by applying the passive and active design strategies. The results show that the baseline energy model had an energy use intensity (EUI) of 120 kWh/m²/yr. Figure 9 Also shows that the lowest achievable EUI without on-site energy generation was 87 kWh/m^{2,} which is lower than the EUI specified by the Emirates Green Building Council (EmiratesGBC) for energy-efficient buildings (90 kWh/m^2) (EmiratesGBC, 2017). The integration of photovoltaics (PV) arrays into the model to generate electrical energy from solar radiation was able to supplement the required EUI (i.e., the 87 kWh/m²) and allowed reaching an EUI of 0 kWh/m²/yr. To overcome the issues of reliability (overcast days), availability (at night), and storage of solar energy (using batteries), the researchers/designers selected the net-metering approach, where generated electric energy is instantly supplied to the grid, and the housing archetype is operated using the grid electricity.

Since the housing prototype is intended to be implemented in governmental housing projects where hundreds or sometimes thousands of units are/will be built, the whole building simulation was repeated for all four cardinal orientations (South, North, East, and West) to evaluate the impact of orientation on the energy performance of the housing archetype. Figure 10 demonstrates the results of the whole building simulation for the four cardinal orientations. Observing the results indicate a small difference in EUI between the different orientations, with the highest when the archetype is facing the west, when relatively large windows are facing the low sun of the west, which increases the heat gain. On the contrary, the lowest was observed when the archetype is facing the north, where limited direct solar gains occur.

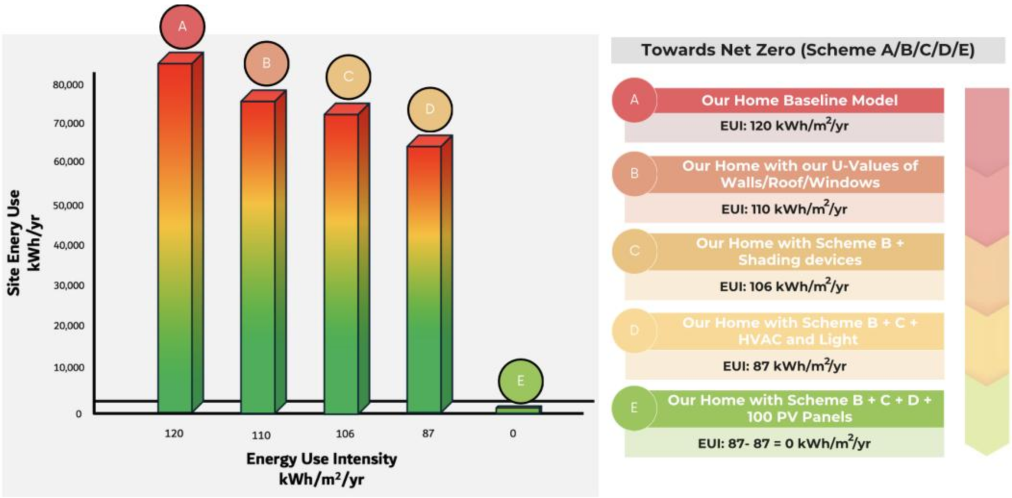

Figure 9: Results of optimization simulations using various passive design strategies, active design strategies, and on-site energy generation to achieve optimal building performance. (extracted from HEED simulation software)

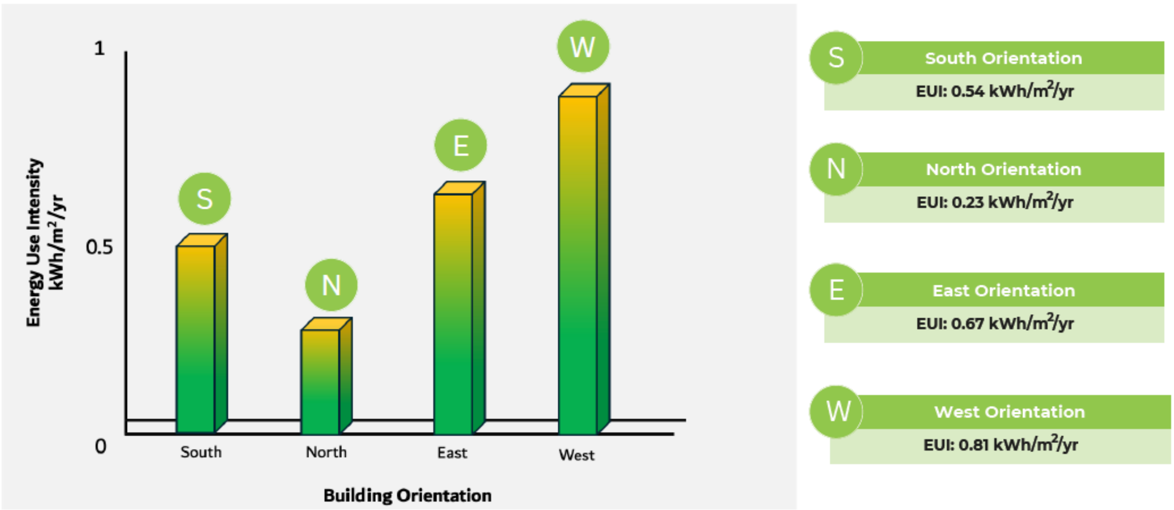

Figure 10: Whole building simulation results for the housing archetype facing the four cardinal orientations (extracted from HEED simulation software)

3.3. On-site energy generation

Rooftop solar photovoltaics (PV) were used for energy generation. Figure 11 demonstrates the placement number and arrangement of the rooftop PV panels. The total usable rooftop area was calculated to be 485m2, and the targeted total amount of required energy generation was ~ 42,200 kWh/year. The total possible annually generated energy from PVs was simulated to be ~112,880 kWh/year, which is 270% of what is needed to run the housing archetype. Therefore, only around 50% of the rooftop area needs to be covered with PVs (see Figure 11).

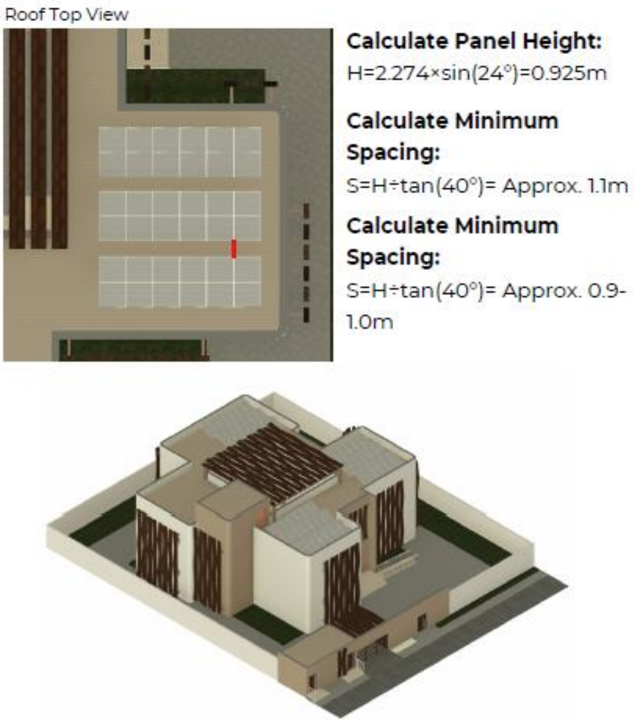

Figure 11: Roof top PVs arrangement ~ 50% of the roof area. (by the authors)

4. Limitations and recommendations for future research

Although achieving net-zero energy in housing in the UAE is possible, it comes with a number of challenges that include increased initial cost, technical difficulty, and challenges regarding social acceptance and occupants' behavior. The design and construction of net-zero housing requires an integrated process, such as the integrated design process (IDP), where all design stakeholders are involved throughout the process. This design approach is yet to be widely adopted in the design and construction industry due to cost and feasibility issues. (Abuimara *et al.*, 2018). Additionally, net-zero buildings have a higher initial cost due to the use of high-quality, efficient materials and systems, which, in some cases, impose an additional financial burden that clients may not be ready to afford (Dwaikat and Ali, 2016).

On the other hand, achieving the net-zero target for housing/buildings relies on the social acceptance and building occupants' behavior. Occupants' behavior and use of buildings (i.e., use and interaction with systems and components) can affect building performance largely and can cause what is known as the performance gap. Performance gap is the mismatch between the predicted/simulated and the actual building performance. (van Dronkelaar *et al.*, 2016). Bridging the performance gap can be achieved through involving occupants in the design process and increasing the awareness of the use and purpose of different building features.

Overall, the results of this study indicated the need, possibility, and the benefits of designing housing that can reach the net-zero goal. However, the study had several limitations that the authors acknowledge and are providing recommendations for future research:

1. The investigation was limited to a housing archetype that is constructed using 3D concrete printing. Future research should consider applying the methodology followed in this study to other construction methods/ assemblies common in the region, such as precast concrete construction, cast-in-place concrete building, and steel construction.

2. The cost associated with the use of an emerging construction technology is still relatively high due to the costs of 3D printers. The cost can be assimilated if the project is implemented on a large scale for housing projects. Further research is required in the area of estimating and evaluating the cost-effectiveness of these emerging construction technologies.

3. The achieved savings of the implemented design strategies are evaluated using building performance simulation. Future research should perform validation using field testing in buildings that have these design strategies in place.
4. The results of this study are specific to the single-family housing archetype in hot arid climates. Future research should consider testing different housing typologies in different climate zones.
5. Achieving net-zero energy in reality can be influenced by many factors during building operation. Notably, occupants/building users' behavior and interaction with building systems are a very influential factor that has been proven in many studies (O'Brien et al., 2020; Yan et al., 2015)(O'Brien et al., 2020; Yan et al., 2015)(O'Brien et al., 2020; Yan et al., 2015)(O'Brien et al., 2020; Yan et al., 2015). Increasing the awareness of building users about the importance of lowering the impact of their buildings and their behaviour, and the way they should operate their buildings, is crucial in achieving the net-zero energy targets.

5. Conclusion

In this paper, we conducted a comprehensive research-based design of a net-zero energy 3D printed housing archetype in the United Arab Emirates. During the design process, achieving net-zero energy was feasible through the integration of active and passive design strategies, including geothermal cooling systems, enhanced building envelope performance, exterior shading devices, and onsite energy generation. A notable achievement was the development of a 3D printed wall assembly that complies with the local code of the Estidama Pearl rating system in Abu Dhabi in terms of thermal transmittance. The U-value achieved was 30% better than the value specified by the code. The study also demonstrated that combining well-studied and evaluated passive and active strategies would lead to minimizing the EUI to the level that can be compensated with onsite energy generation. The study also demonstrates the viability of 3D printing in sustainable residential construction and opens new possibilities for its broader application in the UAE's housing sector. Future research should consider applying the same strategies and approach to other common construction methods in the UAE, such as modular 2D and 3D concrete construction and the traditional cast-in-situ approach. This would encourage further implementation of net-zero energy housing, which contributes largely to achieving the country's goal of achieving environmental sustainability and sustainable development. Overall, the study's findings represent a step forward toward achieving both local and international environmental sustainability goals, such as Abu Dhabi Vision 2030 and the United Nations Sustainable Development Goals (SDGs).

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Conflict of interest:

The authors declare that there is no competing interest.

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