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Sustainable Off-Site Construction in Desert Environments: Zero-Energy Houses as Case Studies

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Abstract: The construction industry is one of the largest consumers of natural resources, and the building sector accounts for around 40% of energy consumption and CO_2 emissions. To contribute to the need for more sustainable solutions, this research analyzed and highlighted the benefits of off-site construction, utilizing eleven zero-energy prefabricated houses from the Solar Decathlon Middle East competition as case studies. The study used construction data documented by the competition organizers, such as drawings, manuals, photos, and in-person observations during the assembly process. The comparative analysis focused on the construction categories, types of solutions, structural materials, façade types, and building materials. The case studies featured both heavy and lightweight construction and three types of off-site construction: panelized, volumetric, and hybrid. The hybrid construction was the most utilized since it combines the advantages of less intensive on-site work of the volumetric solutions with the transportation benefits of 2D elements. The designers justified their selection of timber as a structural material based on its low environmental impact. In addition, they enhanced the environmental benefits of off-site construction by selecting eco-friendly materials and solutions that increase the efficiency of the houses.

Keywords: modular construction; prefabricated houses; off-site construction; sustainable construction; zero energy; solar decathlon

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1. Introduction

The building construction industry has a high environmental footprint due to its high energy consumption, high rates of GHG emissions, waste, elevated health and safety risks, and high cost [1,2]. In 2020, this industry was responsible for 6% of global final energy usage and 10% of energy-related CO_2 emissions [3]. On the other hand, as Figure 1 shows, buildings accounted for 30% of global final energy usage and 27% of energy-related CO_2 emissions. Therefore, the construction and building sectors have become priorities for addressing climate change [4]. In addition, the need for new buildings is increasing due to rapid urbanization and population growth. This means that unless there is a change in the construction industry, their energy demand and associated GHG emissions will also increase [3]. This fact is noticeable, especially in the Middle East, which has had one of the fastest-growing urban populations in the world in the last few decades [5].

Developing more restrictive building codes, requiring nearly zero-energy buildings (on the path towards zero-energy ones), is crucial for maintaining a country's competitiveness, securing energy supplies, and reducing the built environment's carbon emissions. There are several definitions of nearly and zero-energy buildings and two of them are most widely recognized. The European Parliament and Council of the European Union published one, and the United States Department of Energy created the other [6,7].

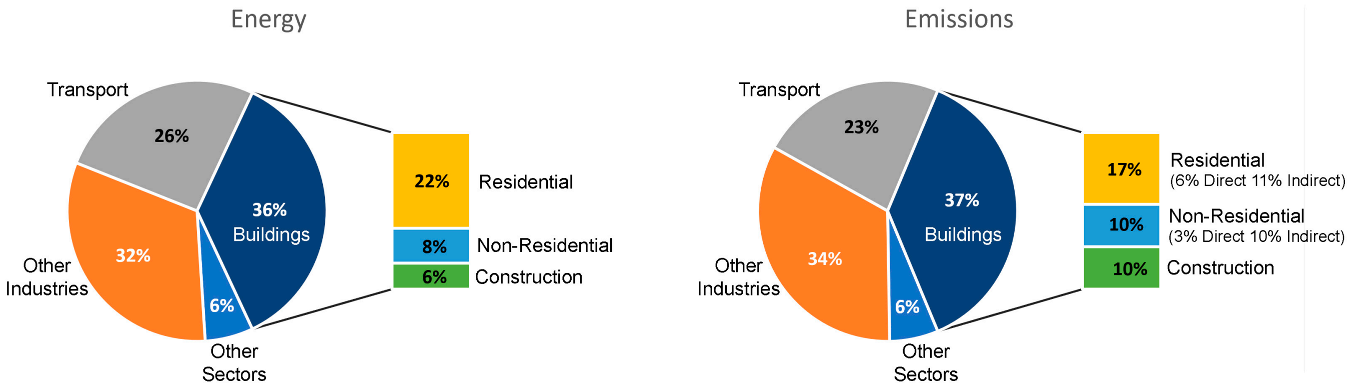

Figure 1. Global share of buildings and construction final energy and emissions—2020. (By the authors from [3]).

These definitions coincide on two points: the prerequisite of very high energy performance and the need to fully (or significantly) cover the reduced amount of energy required by the building using renewable energy sources. Most energy consumption in buildings is linked to protection from the external climate and the need to use mechanical systems to maintain a healthy and comfortable indoor environment. That fact is even more critical in regions with extreme climates, particularly hot arid ones. Therefore, the first and most cost-effective step to reaching the necessary high-energy performance is the application of passive design strategies, starting with the proper design, or refurbishing, of the building's thermal envelope. These strategies help enhance the building's energy efficiency, reducing the need for renewables to meet its energy demands.

As in other Middle Eastern countries, the United Arab Emirates' (UAE) construction industry continues to expand [8]. With a stronger focus on sustainable development by the UAE government, federal and local agencies have established initiatives to improve building efficiency. In addition, the UAE regulators periodically revise their energy conservation codes, drawing progressively closer to the Nearly Zero Energy Buildings goal [9]. For instance, Dubai was the first city in the Middle East to commit to the Building Efficiency Accelerator (BEA) project, aiming to accelerate building efficiency policies and programs and double the global energy efficiency improvement rate by 2030 [10]. The governmental organizations and the private sector are also moving towards the zero-carbon vision of the government of the UAE and have started to develop early adopters of sustainable nearly zero-energy offices, universities, and residential projects. Two good examples of early adopters in the residential sector are the Masdar City Eco-Villa [11], constructed in Abu Dhabi, and The Sustainable City, an environment-friendly community developed in Dubai [12].

Up to now, most efforts to reduce the emissions of buildings are concentrated in their operational phase. However, as buildings become more efficient in terms of energy consumption, the environmental impact of construction becomes more significant. Material extraction and production, transportation of materials and components, construction equipment, and waste disposal are the most prevalent sources of energy use and CO_2 emissions in building construction. Therefore, it is also essential to focus on construction methods and materials to achieve zero-carbon buildings [13].

There is no single solution to address complex issues like sustainability in the built environment. However, it has been found that one way to contribute to the sustainability of both the construction industry and the building sector is increasing the implementation of prefabrication and modularized solutions [14]. The penetration of off-site construction in the UAE and other Middle Eastern countries is very low. Most regional companies that provide off-site solutions offer precast concrete elements [15], such as wall panels and prestressed hollow-core slabs. In addition, there is a general lack of information about off-site construction, its benefits, and how it can respond to the region's harsh climate. Consequently, more studies are needed to determine the potential contributions of prefabrication and modular construction to a more sustainable built environment in the Middle East.

This study analyzes and compares eleven zero-energy, sustainable houses that participated in the 2018 Solar Decathlon Middle East to contribute to the knowledge of off-site construction in the region. Studying these houses' different prefabrication and modularized approaches will help building professionals and developers identify new possibilities for improving the sustainability level of their new projects.

The remainder of this article is organized as follows: Section 2 summarizes some relevant topics about off-site construction; Section 3 presents the utilized methodology; Section 4 introduces the cases and their classification; Section 5 explains the classified cases in detail; Section 6 includes the analysis and discussion of the case studies; and Section 7 presents the conclusions and explains future work.

2. Off-Site Construction

Off-site construction permits rapid and efficient site assembly with high-quality finishing. However, it requires changing how buildings are designed, planned, fabricated, and assembled [16]. Innovative design and management software (like the ones based on BIM) [17], advanced materials, robotics, automated processes, additive manufacturing, and other novel technologies have increased off-site construction potential [18]. However, more research, prototyping, and testing will ensure the optimization and successful implementation of the off-site construction solutions.

Numerous studies have been published on prefabricated and modular house construction. For example, Meuser et al. conducted in-depth research on historical, architectural, and structural aspects of industrialized housing construction [19]. Their work included an overview of different prefabricated housing technologies and a comprehensive collection of case studies of multi-story housing developments. Similarly, Albus studied the existing prefabricated building systems, focusing on the processes and sustainability aspects of the construction methods, including the efficient use of the materials [20]. Using many case studies, Lawson et al. presented a comprehensive overview of modular construction, analyzing its advantages and demonstrating its ability to create flexible and diverse designs [21]. Ferdous et al. studied the advancements in multi-story modular buildings, aiming to unlock their potential [22]. Kamali et al. compared the environmental performance of modular integrated construction (MiC) to that of conventional residential construction [23]. Other authors focused their studies on organizing the information published in the literature and determining future research directions, as in the case of Jin et al. [24].

The following sections present a summarized literature review focusing on off-site construction types, the classification of structural systems, and a brief comparison between off-site and conventional construction.

2.1. Off-Site Construction Classification

Several authors have proposed diverse ways of classifying off-site construction [21]. For example, the book Construction and Design—Prefabricated Housing presents a classification for prefabricated construction systems based on a combination of load-bearing elements and materials [19]. This classification includes three main typologies (skeleton frame, walls, floors, and prefabricated spatial units) and three materials (wood, concrete, and steel). Considering their weight, off-site construction systems can be classified into two categories: heavyweight and lightweight. Typically, heavyweight construction employs concrete, earth, or other dense materials. In contrast, typical light systems rely on steel, wood, or polymeric materials.

Based on the type of solution, the heavy and lightweight offside constructions can be classified as 2D (panelized), 3D (volumetric spatial units), or hybrid (a combination of both) [25]. 2D off-site construction consists of structural or non-structural prefabricated panels, such as walls, slabs, and partitions [26]. In comparison, the components of 3D off-site construction are structural or non-structural three-dimensional modules [21]. The structural 3D modules are load-bearing spatial units, and the pods are non-structural volumetric units. Typically, the pods are functional spaces supported on the floors of the buildings [21].

Hybrid off-site constructions combine 3D modules with industrialized 2D panels [21]. Usually, the 3D modules contain spaces requiring intensive labor and numerous equipment or appliances, such as bathrooms, kitchens, and mechanical and electrical rooms. The remaining spaces' walls, floors, and roofs are assembled using 2D components. Tall buildings usually require prefabricated skeletons (primary structure) that are "filled" or "closed" using 2D elements, 3D modules, or a combination of both.

2.2. Benefits of Off-Site Construction Methods Related to Their Classification

The benefits of both off-site construction and the selection of the method vary according to the project characteristics, location, site conditions, space availability, cost of personnel, availability of auxiliary equipment, and time requirements [27]. Table 1 summarizes the expected benefits of off-site construction based on the chosen solution. 3D off-site solutions typically require less construction time and fewer workers on-site than hybrid and 2D solutions. However, 2D panels require less transport space than 3D solutions. In addition, compared with typical 3D modules, 2D panels are easier to accommodate in containers and transport in standard vehicles. Consequently, transporting 2D panels is typically less expensive.

Table 1. Comparison of the expected level of benefits of the off-site construction solutions.

Parameters	The Expected Level of Benefits
Time on site	3D < Hybrid < 2D
Crane size	2D < Hybrid < 3D
Use of crane and auxiliary equipment	3D < Hybrid < 2D
Auxiliary equipment time of use	3D < Hybrid < 2D
Free space around the building	2D < Hybrid < 3D
Effort and number of workers on site	3D < Hybrid < 2D
Site deliveries cost	2D < Hybrid < 3D

Regarding auxiliary equipment, 2D solutions necessitate a smaller crane capacity but a longer use time than 3D modules. In conclusion, projects utilizing structural 3D modules can reduce the on-site time and labor. However, the shipping and assembly of modular components increase risks and costs [28].

2.3. Comparisons between Conventional and Off-Site Construction

Off-site construction offers several benefits compared with conventional construction. For example, modular construction companies can deliver high-quality buildings in less time and with more control over the final project's costs [27]. In addition, the potential for further improvements in off-site construction over conventional methods is significant, as Figure 2 shows [27,29].

Off-site construction methods have several economic advantages, including reduced construction time and expenses, improved cash flow, and higher-quality results. These incentives should be enough to consider a shift towards off-site construction, which can also bring social and environmental benefits [29].

Indeed, it is safe to say that off-site construction has the potential to contribute to a sustainable built environment by providing social, environmental, and economic benefits, which are the World Business Council on Sustainable Development's three pillars of sustainability [29,30]. The social benefits of off-site construction include better working conditions and a safe and healthy workspace. In addition, off-site construction opens new opportunities for in-factory and on-site jobs. The environmental benefits include reduced road traffic movements, on-site energy use, waste materials, water consumption, noise, dust, and GHG emissions [27]. Additionally, prefabrication improves the fabrication quality of building components [20]. Its systematized planning and optimized use of materials substantially enhance the reusability and recyclability qualities of buildings and their components.

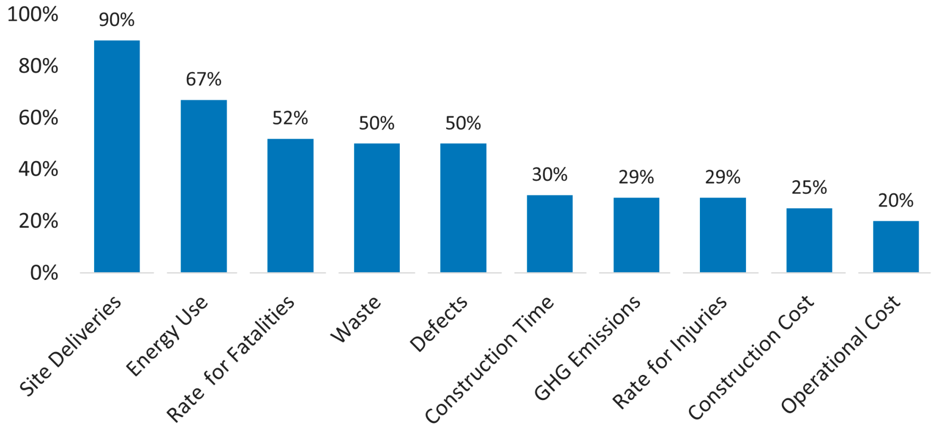

Figure 2. Potential for improvement of off-site construction compared with conventional construction. Actual savings will depend on the project's characteristics. (By authors from [27]).

Off-site construction does not conflict with producing highly efficient or zero-energy buildings (ZEB). M. Nabi and I. El-Adaway investigated and defined the selection criteria for modular construction. In the category of environment-related issues, they include energy efficiency as one of the factors [31].

Several research studies conducted Life Cycle Assessments (LCA) of off-site construction and compared them with more conventional methods. After conducting a comprehensive critical literature review on modular construction, Kamali and Hewage concluded that, in most cases, off-site modular buildings exhibit better life cycle performance than traditional ones [32]. A study in the United States also found that the average impacts of modular houses are less than those of conventional construction. However, this study highlights significant variation between projects and construction companies [33]. Table 2 summarizes the potential sustainability benefits of off-site construction based on the study by D. Krug as well as that by J. Miles, and J. Wilson [27,29]. It is important to clarify that the fact that a building was constructed using off-site or modular construction methods does not necessarily mean that it is more sustainable than a similar one built using more traditional solutions. However, as shown in the studies presented above, off-site construction can help increase sustainability levels in many ways. Therefore, building professionals and developers in all latitudes should consider using this construction type in their projects [34].

Off-site construction methods also present challenges and some disadvantages [32]. First and foremost, as relatively new construction methods, they must gain space in one of the most traditional industries and demonstrate a history of successful implementation. In addition, off-site methods require a high initial investment to set up the production factory, more coordination throughout all project stages, and more pre-construction planning and additional engineering efforts than conventional construction. In the case of modular construction, as mentioned before, there are other challenges related to dimension limitations, the risks of moving heavy and oversized elements, and the monetary and energy costs of shipping, transportation, and assembly [28].

Sustainable on-site and off-site construction both involve using sustainable materials (with a low environmental impact throughout their life cycle, from the extraction of raw materials to the disposal, reuse, or recycling of the finished product). Using this type of material is a way in which builders can help reduce the environmental impact of their projects while creating more energy-efficient and healthy buildings. However, as Table 3 shows, there are some challenges and drawbacks related to sustainable construction materials.

Table 2. Summary of the potential benefits of off-site construction. The black rectangles indicate the sustainability pillars to which each one of the benefits is related. (Source: based on [27,29].)

Parameters		Sustainability Benefits		
J. Wilson [27]	**D. Krug and J. Miles [29]**	**Economic**	**Environmental**	**Social**
More efficient process		■		
Better quality control	Reduction in snagging and defects	■	■	
	Faster construction	■		■
	Improvement in the cash-flow	■		
Reduction in material waste	Reduction in waste	■	■	■
Construction cost saving		■		
Reduction in energy use for construction	Reduction in energy used on site	■	■	
Reduction in life-cycle embodied energy and carbon	Reduction in energy use	■	■	■
Reduction in operational impacts		■		■
Reduction in transportation-related impacts	Reduction in road traffic movements	■	■	■
Support for adaptation, reuse, and recycling		■	■	
Reduction in disruption to the surrounding community			■	■
Support for resilience		■		■
Reduction in indoor environmental quality issues			■	■
	Health and safety	■		■
	Improved working conditions			■
Contribution towards affordable housing shortage				■

Table 3. Challenges and drawbacks of sustainable materials.

Potential Drawbacks	Brief Explanation
Higher initial cost	They can often be more expensive than traditional materials, especially when they are first introduced to the market. They may require more specialized manufacturing processes or be produced in smaller quantities.
Limited availability	They may not be as widely available as traditional materials, especially in certain regions. This can make it more difficult to find contractors and suppliers who are familiar with working with them.
Performance	They may not always perform as well as traditional materials in terms of strength, durability, or fire resistance.
Lack of research	There is still a lack of research on the long-term performance of some sustainable materials. This can make it difficult to assess their true environmental impact and durability.
Acceptance	There may be some resistance to using sustainable materials from contractors, builders, or building owners unfamiliar with them.

To conclude, off-site construction consists of two categories, heavyweight and lightweight, based on the selected structural materials. The off-site construction solutions are classified into 2D elements, 3D modules, and hybrid (2D and 3D). Off-site construction emphasizes innovative and novel technologies through the use of Building Information Modeling (BIM) and robotics while planning, designing, fabricating, and assembling. The benefits of off-site construction identified in this literature review are improvements in site deliveries, energy use, fatality rates, waste, defects, construction time, GHG emissions, injury rates, construction costs, and operational costs, alongside other environmental, social, and economic benefits.

The undeniable benefits of off-site construction depend on the project characteristics, materials selection, location, cost, availability of auxiliary equipment, and time. There is no surprise that such a relatively new solution in the construction industry faces some challenges. Investing time and effort in the pre-construction planning phase, the cost of the construction factory, and their acceptance are some of the challenges of off-site construction.

3. Methods

The following steps were taken in the current study to analyze the building cases:

1. Selection of case studies. The case studies were chosen based on two criteria: First, the case had to be a zero-energy house that took part in the 2018 Solar Decathlon Middle East, and second, the project had to be pre-constructed and assembled utilizing off-site systems.
2. Data collection. The authors studied the cases using the construction data from the participating teams, such as construction drawings and project manuals, in addition to photos, videos, and in-person observations during the houses' assembly process.
3. Classification of the cases. The authors developed a classification based on a literature review and organized the cases around it.
4. Case analysis. The authors analyzed each house independently, including the off-site construction system types and categories, architectural concepts, structure, façade system, materials, and how the teams assembled their houses. To illustrate the houses' design, interior distribution, and off-site construction elements, the authors drew the floor plan in AutoCAD for each of the cases, as well as some of their construction details. In the case of houses constructed using 3D modules and hybrid solutions, the volumetric units (modules, pods, and cartridges) were color-coded in the floor plans.
5. Comparison and discussion. The case studies were compared and discussed based on their categories, solutions, structural materials, and how these choices relate to the transportation method used in each case. Also, the façade types and building materials were examined. Lastly, the cases were compared in relation to the applicable Dubai building regulation and two early adopters of sustainable zero-energy houses.

Before proceeding to the case studies and their comparison, the following sections will explain the Solar Decathlon Middle East and the off-site construction classification utilized in this study.

3.1. Solar Decathlon Middle East

The Solar Decathlon Middle East (SDME) is an international project that challenges university teams to design, construct, and test sustainable solar houses that respond to the local climate. In the final phase of the project, the participating teams assemble their projects at the competition/exhibition site called the Solar Hai. The SDME Solar Hai is in Dubai at the Mohammed bin Rashid Al Maktoum Solar Park (Figure 3).

Figure 3. Solar Decathlon Middle East 2018—Dubai, UAE. (Source: SDME 2018 Organization).

The participating teams have only 15 days to assemble their sustainable houses and test that all their systems are fully operational. After passing all inspections, the houses are evaluated through ten contests, the decathlon, for ten days. As Figure 4 shows, there are three types of contests in the SDME: juried, monitored, and monitored/measured tasks.

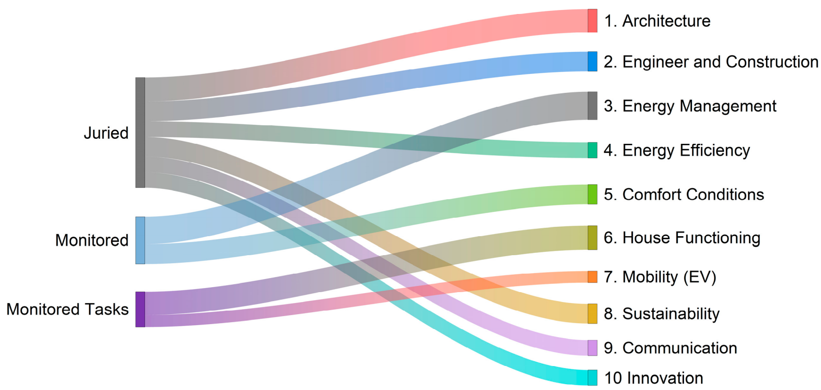

Figure 4. Solar Decathlon Middle East contest structure. (By the authors).

Six groups of jurors, each comprising at least three international experts, evaluate the juried contests. During the ten days of competition, participating students carry out typical tasks and chores of a standard household, following the competition rules. Appendix A summarizes the teams' responsibilities during the competition period. Simultaneously, the projects' indoor environmental quality (IEQ) and energy performance are continuously monitored. Details about the monitoring and instrumentation systems utilized in the SDME 2018 are presented in Appendix D. Sustainability is not just one of the contests of the SDME; it is its fundamental pillar. All the other contests are also related to a sustainable built environment and lifestyle. Considering this and the restricted time of the assembly phase, Solar Decathlon teams strive to create sustainable projects.

The SDME organizers are aware that transporting the houses' modules and components from considerable distances, even across oceans, requires much energy and related carbon emissions, and they do not want to encourage this practice. However, to increase social awareness of zero-energy and sustainable buildings and foster knowledge sharing between experts and students from around the world, the SDME organizers ask the participating teams to assemble their houses on the same site. Building professionals and developers should look for local off-site factories for their projects and, if there are no nearby factories, consider the energy required for the modules and components' transportation. Like in the SDME, the participating teams in the American Solar Decathlon had to transport and assemble their houses at a designated site. However, in its last two editions (SD 2021 and SD 2023), houses were constructed in each participating team's respective city to reduce transportation costs and carbon emissions.

The motivation to participate in the Solar Decathlon Middle East, like in other solar decathlons worldwide, is that it offers a unique learning experience. As a way of rewarding the hard work of participating teams and helping with their expenses, the SDME organization provides monetary prizes to all the teams that reach the final phase and enter the contest period. The top five teams were awarded prizes from USD 245,000 to USD 123,000. All the other teams received USD 110,000, regardless of their ranking.

3.2. Off-Site Construction Classification

Considering the diverse types of off-site construction presented in international solar decathlon competitions and the information collected from the literature review, the authors created a structure to classify the SDME off-site construction case studies, which can be applied to other low-rise buildings. The case studies were organized following a three-level classification, as Figure 5 shows. The main categories (heavy and lightweight construction) are followed by the primary structural material and the type of solution (2D, 3D, or hybrid). Additionally, the projects' façades were classified as non-ventilated or ventilated (a suitable construction for hot climates).

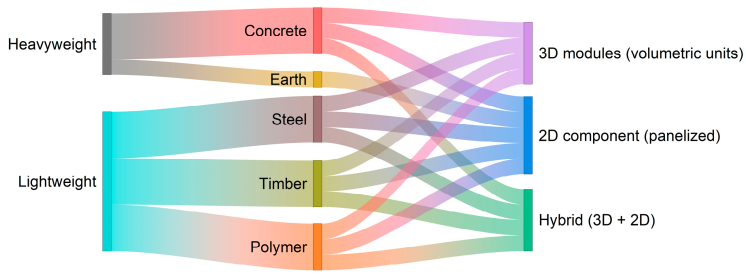

Figure 5. Off-site construction classification. (By the authors, based on [21] and the cases in the international solar decathlon competitions).

4. Case Characteristics and Classifications

The selected cases correspond to eleven of the fifteen zero-energy houses designed and constructed by the Solar Decathlon Middle East 2018 competitors (Table 4). All the SDME 2018 projects had some level of off-site construction, including pre-cut and pre-assembled elements. However, only those with prefabricated spatial units or 2D components that require low-intensive work during the assembly period were selected.

Table 4. Brief of the case studies: the participating teams, the house names, and their floor area.

House	ID	Team Name	Participating Universities and Countries	Unique Features	Floor Area (m^2)
H01	AST	Aqua Green	- Ajman University (UAE)		84.0
H02	KSU	KSU	- King Saud University (UAE)		101.4
H03		AURAK	- American University of Ras Al Khaimah (UAE)	Roof terrace	92.6
H04	BX	Baity Kool	- University of Bordeaux (France) - Amity University (UAE) - An-Najah National University (Palestine)		105.5
H05	UOW	UOW	- University of Wollongong (Australia) - TAFE Illawarra (Australia) - University of Wollongong (UAE)		120.0
H06	VT	Virginia Tech	- Virginia Tech University (USA)		99.1
H07	UOS	KNOW HOWse	- University of Sharjah (UAE) - University of Ferrara (Italy)	Two floors	120.0
H08	SUR	Sapienza	- Sapienza University of Rome (Italy)		103.1
H09	NCT	TDIS	- National Chiao Tung University (Taiwan)	Roof terrace	75.9
H10	BU	Efden	- Ion Mincu University of Architecture and Urbanism (Romania) - Technical University of Civil Engineering Bucharest (Romania) - University Politehnica of Bucharest (Romania) - Birla Institute of Technology and Science Pilani (Dubai)		97.1
H11	TUE	Virtue	- Eindhoven University of Technology (Netherlands)	Apartment	82.5

4.1. Cases' General Characteristics

The chosen houses were designed and built by university teams from four continents (America, Europe, Asia, and Australia). With a few exceptions, most projects in the 2018 edition were single-story detached villas with one or two bedrooms. For example, the KNOW HOWse was a two-story villa, while the TDIS and AURAK projects had covered and semi-covered roof terraces. Although the Team Virtue house was a single-story structure, it was designed as a prototype for a one-bedroom apartment in a multi-story residential building. Table 4 provides an overview of each house, including the names of the teams and universities, the size of the houses, and the countries of origin.

4.2. Classification of the Cases

In the SDME 2018, almost all the off-site construction possibilities shown in Figure 5 were represented, except for industrialized earth panels and polymeric solutions. These possibilities were exhibited in previous Solar Decathlon editions. For example, an SD Europe 2010 competition team constructed their house using industrialized earth panels. Furthermore, several projects using polymeric 3D modules were part of the extra-competition exhibition at SD Europe 2014. The polymeric elements can be extruded, molded, or 3D printed. Table 5 indicates each house's category, solution, and structural materials, following the structure of Figure 5.

Table 5. Off-site classification of the case studies.

House #	Team Name	Category	Solution	Structural Material
H01	Aqua Green	Heavyweight	2D (panelized)	Concrete
H02	KSU	Heavyweight	3D (volumetric units)	Steel [1]
H03	AURAK	Lightweight	3D (volumetric units)	Steel
H04	Baity Kool	Lightweight	3D (volumetric units)	Timber
H05	UOW	Lightweight	Hybrid	Light Steel Frame
H06	Virginia Tech	Lightweight	Hybrid [2]	Timber
H07	KNOW HOWse	Lightweight	Hybrid	Timber
H08	Sapienza	Lightweight	Hybrid	Timber
H09	TDIS	Lightweight	Hybrid	Timber
H10	Efden	Lightweight	Hybrid	Timber
H11	Virtue	Lightweight	Hybrid	Timber

[1] Team KSU used steel structure and Autoclaved Aerated Concrete (AAC) plates to build the floors and roofs of their 3D modules. [2] Virginia Tech team built their house using primarily 3D modules named "cartridges".

5. Case Details

This section presents an analysis of each case based on its off-site construction type. First, the 2D solutions, then the 3D solutions, and lastly, the hybrid solutions are discussed in the order shown in Table 5.

5.1. Solutions 2D

Team Aqua Green

Team Aqua Green based its house's architectural concept on the region's vernacular villas, using trellises to provide privacy and shading (visual and light screening). The southern terraces add a more contemporary buffer and transitional space. There are no openings in the east or west of the house, and the south openings are well-protected to prevent overheating. As shown in Figure 6, the service areas (kitchen and bathroom) are in the dwelling's center, separating the social and private spaces.

Team Aqua Green is the only team that utilized a heavyweight structure and the only one that built its house using only 2D elements.

This team used precast light green concrete panels for the house's walls and prefabricated hollow-core concrete slabs for its floor and roof. In addition, the terrace's structure and screens were constructed using prefabricated metal components. The terraces are covered with PV modules, providing shade for the south façade.

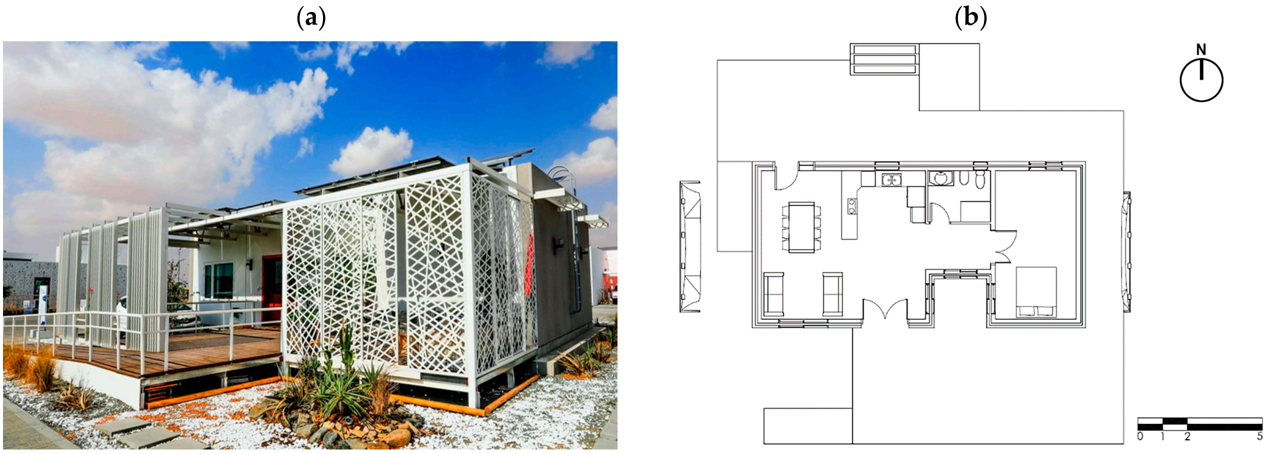

Figure 6. Team Aqua Green's house. (**a**) Exterior photo. (**b**) Floor plan. (Photo: SDME 2018 Organization. Floor plan: by authors based on team Aqua Green drawings).

The passive indoor conditioning of Middle Eastern wind towers inspired this team's novel cooling solution. Using evaporative cooler pumps, they circulated cool air through the core of the dwelling's concrete roof and cavity walls. Also, cool air is circulated through the space between the house's double window system, thereby reducing thermal gains through the fenestrations.

The team began their house's assembly by placing the 25 prefabricated concrete foundations and installing the 11 hollow core floor slabs. Then, they fixed the 14 wall panels to the floor slabs, set the 11 roof slabs on top of them, and sealed all the joints. Then, different crews worked on the interior and exterior of the house. The team members on the exterior placed the roof membrane, installed the PV modules, and assembled the deck and terrace elements. Those in the interior carried out the MEP work and continued with finishing and furnishing. Finally, the team cleaned up their lot.

5.2. 3D Solutions

5.2.1. Team KSU

Team KSU's house is one of three constructed with 3D modules. This project is based on the heritage of the Arabian Peninsula's architecture, giving a modern reinterpretation to the traditional courtyard house, as it is closed to the exterior but open to the patio. As indicated in Figure 7, the team designed their house with four distinct 3D modules. The three main modules were arranged in a U-shape to generate a shaded north-facing patio. The first includes private spaces (the bedroom, a full bathroom, and a powder room) and a storage area. The second module contains the kitchen and dining area. The third comprises the public areas (the foyer, living room, and workspace). The fourth, and smallest, is the technical room.

Team KSU utilized steel elements (W and M shapes) for the structural skeleton of the house's 3D modules, cement boards for the exterior wall cladding, glass-fiber-reinforced gypsum panels for the walls' interior finishing, and lightweight Autoclaved Aerated Concrete (AAC) panels for the floors.

The team filled the wall cavities between the cement and gypsum boards with an insulation material they developed composed of date palm tree fiber. The 3D modules arrived at the site fully finished. The 3D modules are interconnected using a bolting method that facilitates the assembly and disassembly of the house. Similarly, the MEP systems include module-to-module plug-and-play connections.

The team started the assembly by setting up the prefabricated concrete foundations and placing the three main modules of the house. After that, the team placed the technical module and proceeded with the interconnection of the MEP fixtures, piping, and wiring.

Then they installed and interconnected the PV modules. Finally, the team completed the project by installing exterior fixtures, assembling ramps and terraces, and cleaning the site.

(**a**) (**b**)

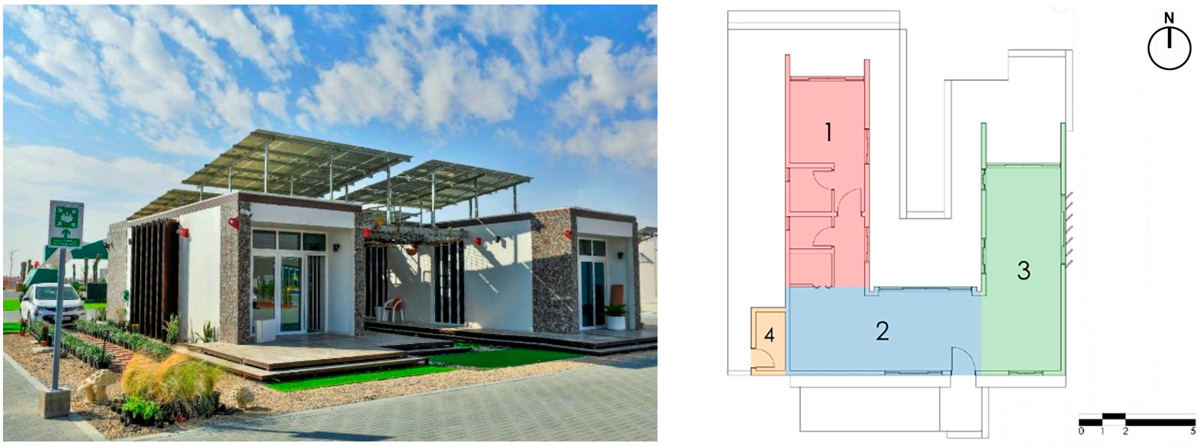

Figure 7. Team KSU's house. (**a**) Exterior photo. (**b**) Floor plan—1: bedroom, two bathrooms, storage; 2: kitchen, dining area; 3: entrance, living room, workstation; 4: technical room. (Photo: SDME 2018 Organization. Floor plan: by authors based on the teams as per drawings).

5.2.2. Team AURAK

Team AURAK's house, like the KSU one, utilizes steel elements as the main structure of its 3D modules. The team named their house "Al Bayt Al Kamel," which means "the perfect or completed house." Following the style of an Emirati traditional house, their main concepts are privacy and protection. As shown in Figure 8, privacy and sun protection are present in indoor and outdoor spaces. The team installed "Arish screens" in the house's windows. These palm-leaf screens connect historical culture to contemporary house design and provide privacy and protection from the harsh desert climate. Similarly, tall green walls offer privacy and sun protection for the courtyard. The green wall's shade and evapotranspiration improve the courtyard's microclimate.

(**a**) (**b**)

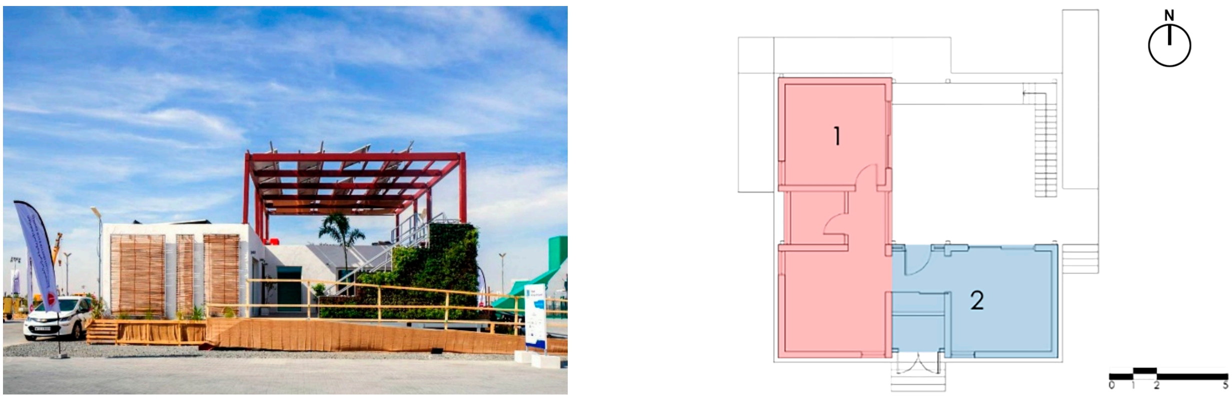

Figure 8. Team AURAK's house. (**a**) Exterior photo. (**b**) Floor plan—1: bedroom, bathroom, kitchen, dining area; 2: entrance, living room, electrical closet, mechanical room. (Photo: SDME 2018 Organization. Floor plan: by authors based on team AURAK drawings).

As the floor plan in Figure 8 shows, this L-shaped house comprises two 3D modules. The first includes the bedroom, bathroom, kitchen, and dining room, while the second consists of the foyer, living room, and technical rooms. The house also has a metal structure supporting the green wall and the photovoltaic canopy. This canopy provides shade for the courtyard and the roof terrace. In addition, this terrace has a green roof (hydroponic farming).

The AURAK team used a steel structure and the EVG-3D construction system to build the 3D modules of their house. The EVG-3D panels consist of EPS (expanded polystyrene) cores between two galvanized mesh sheets connected with steel diagonal wires that are finished with cement mortar on both sides. The result is a sandwich-type construction. Before applying the mortar, the team installed all the required MEP pipes, conduits, and boxes (including the radiant cooling system). Finally, the fully finished 3D modules were transported to the site.

The team started the assembly by setting up the prefabricated concrete foundations and placing the two 3D modules. Then, they installed the steel supports and connection beams in the courtyard area and connected the modules' MEP elements. The following step was assembling the courtyard floor, ramps, stairs, and steel canopy structure. After that, they installed the outdoor HVAC units, PV modules, green roofs, and walls. Finally, the team cleaned up their lot.

5.2.3. Team Baity Kool

As in the previous two cases, the Baity Kool team built their house utilizing 3D modules. However, unlike them, they used cross-laminated timber panels as the primary structural material. The team Aqua Green based their architectural concept on the Medina traditional house and prioritized protection from the harsh exterior environment and control of the admission of solar radiation. As shown in Figure 9, they organized the 3D modules in a U-shape configuration, creating a protected courtyard. The result is a house closed to the harsh exterior and open to a sheltered courtyard. The courtyard is covered with a mobile PV pergola and wooden louvers at the north to ensure solar radiation protection, optimize daylight harvesting, facilitate natural ventilation, and provide privacy. The wooden louvers also define the house's entrance within its welcoming-shaped wooden panels, creating a shaded threshold. Spatial flexibility is the central concept of the house's interior spaces and furniture. The occupants can convert the living–dining area and bedroom into offices or shared workspaces.

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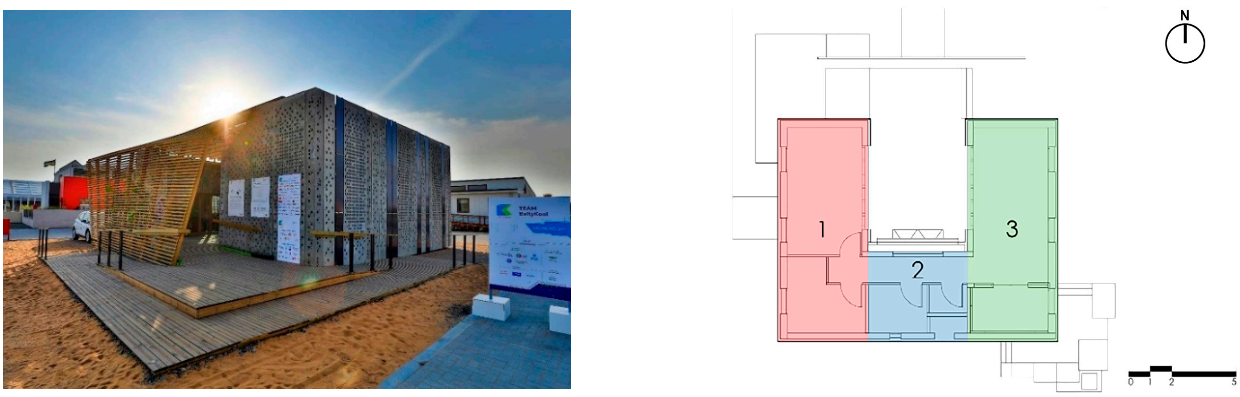

Figure 9. Team Baity Kool's house. (**a**) Exterior photo. (**b**) Floor plan—1: bedroom/office; 2: corridor, bathroom, technical room; 3: entrance, living-dining room/workspace, and kitchen. (Photo: SDME 2018 Organization. Floor plan: by authors based on team Baity Kool drawings).

Team Baity Kool constructed their house using three pre-wired, pre-plumbed, and furnished 3D modules. The first module contains the bedrooms. The second module, strategically located at the center of the house, includes the connection corridor, the bathroom, and the technical room (HVAC, plumbing, electricity, and PV system equipment). In addition, the team installed a large aquarium on the north wall of this module, facing the courtyard. This aquarium, the courtyard green wall, and the rooftop vegetable garden are part of the house's aquaponic system [35]. Finally, the third module contains the living–dining room and the kitchen area. All the house service areas (kitchen, bathroom, and mechanical room) are next to each other in the south.

The house has ventilated façades with exterior panels inspired by the "Mashrabiya", traditional Islamic privacy wood screens made of intricately turned wood pieces. The team reinterpreted this Middle Eastern architectural element into perforated fiber-reinforced concrete panels that function as the exterior skin of the ventilated façade and bring privacy and protection to the house windows.

Another element of the ventilated façade is the six vertical strips of photovoltaic modules alternating with the concrete panels on the east, south, and west façades. The team aimed to develop a multifunctional façade (overheating control, shading, privacy screen, and energy production) suitable for future Middle Eastern buildings.

To reduce the embedded energy of their house, the team utilized both bio-sourced and locally sourced materials. In addition to the cross-laminated timber structure, they used compressed mud bricks, a tensed canvas acoustic ceiling, textile finishing, wooden furniture, and bio-based insulation materials [35].

The Baity Kool team started their assembly by placing the house's foundations. Then they set the three modules. After that, the team installed the precast façade panels, the green roof, the PV module trellis (over the courtyard), the terrace and ramps, the shading and screening system, and the wooden wall in the north. Finally, they cleaned their site.

5.3. Hybrid Solutions

5.3.1. Team UOW

Team UOW named their house Desert Rose and used the motto "A House for Life." The house's design principles merged Australian and Middle Eastern cultures while meeting the needs of people with age-related disabilities, including dementia. Based on Middle Eastern traditions, team UOW divided Desert Rose House into three zones: guest, family, and individual. The foyer and the plant room complemented the living spaces, as shown in Figure 10. The living room and the powder room constitute the guests' zone, while the dining room and kitchen are the family zone. Finally, the individual zone comprises the bedroom, bathroom, and study room. The house lacks corridors, and all rooms are visually connected to facilitate the orientation of elderly occupants. On the exterior, the east, south, and west walls are finished with a ventilated façade that shades the house's thermal envelope and reduces indoor overheating.

(**a**) (**b**)

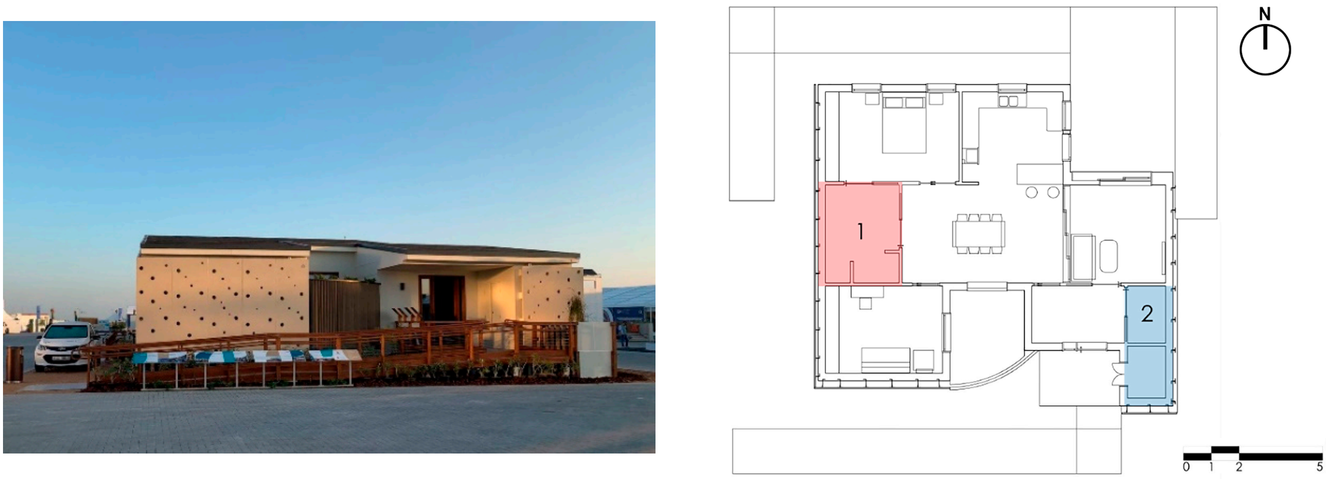

Figure 10. (**a**) Team UOW's house photo. (**b**) Floor plan—1: bathroom; 2: bathroom and plant room. (Photo: SDME 2018 Organization. Floor plan: by authors based on team UOW's drawings).

The Team UOW used lightweight steel frame elements to build the 3D modules and 2D industrialized panels. The designers worked with structural material suppliers to minimize material waste. The outside layer of the ventilated façade was built using perforated lightweight concrete panels, Figure 11. These perforated panels were made of foamed concrete combined with recycled crushed glass and reinforced with carbon fiber mesh. The foamed concrete is half the weight of standard-grade concrete, and the carbon fiber permitted a reduction in the wall thickness from 75 mm to 50 mm. This reduced the weight and volume of material transported and allowed a 40% reduction in these elements' carbon footprint.

The assembly process was started by placing the prefabricated footing elements and the two 3D modules. Then, the team installed the floor panels around the 3D modules using bolted connections. As the next step, the team placed the walls and made the electrical and plumbing interconnections. After that, they assembled the roof panels, followed by the HVAC, mechanical, and PV connections. Finally, they installed the deck and ramps and cleaned up the site.

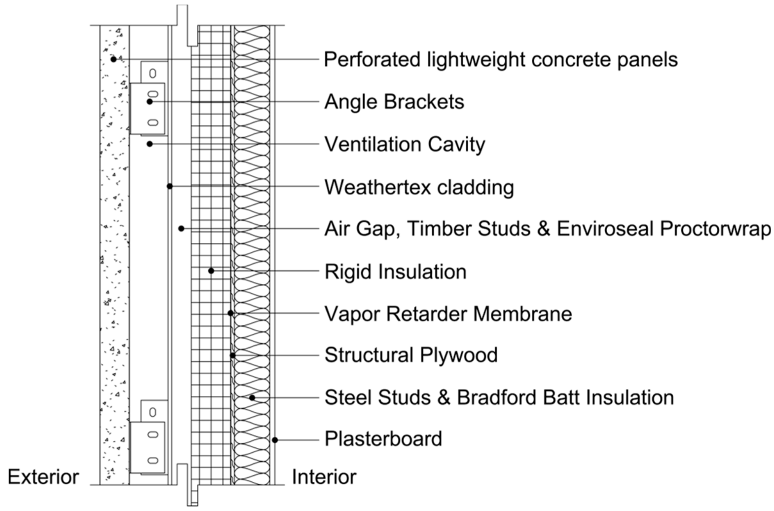

Figure 11. UOW's house: vertical section of the exterior wall. (By authors based on the team UOW's drawings).

5.3.2. Team Virginia Tech

Instead of the typical large 3D modules, this team developed a series of compact "smart plug-and-play modules." They call these modules "cartridges." These cartridges were transported fully finished with appliances, technical systems, and furniture. The idea is to ship technology to the construction site, not just space. Due to their dimensions and weight, they can be transported on standard flatbed trailers and placed using forklifts or small cranes. More than a house, the Virginia Tech team designed a system suitable for detached villas or multi-dwelling buildings with multiple space options. The team claims their solution makes producing smarter, more efficient, and more cost-effective dwellings possible.

FutureHaus, the competition prototype, stands out for its spatially efficient distribution, flexibility, and successful technological integration. The house has two well-defined zones separated by a central corridor, comprising service and served areas, as shown in Figure 12. The service areas (the bathrooms, kitchen, and technical room) have fixed elements. In contrast, the served areas (the office, the living room, and the bedroom) are more flexible. The occupants can reconfigure, enlarge, or shrink these spaces according to their required programmatic needs. For example, they can transform the house into an office during the day, expand the living room at dusk, or increase the bedroom area at night. In addition, the served areas have a seamless connection with the house's outdoor terrace, which is screened by a stainless-steel fence inspired by the Islamic "Mashrabiyah".

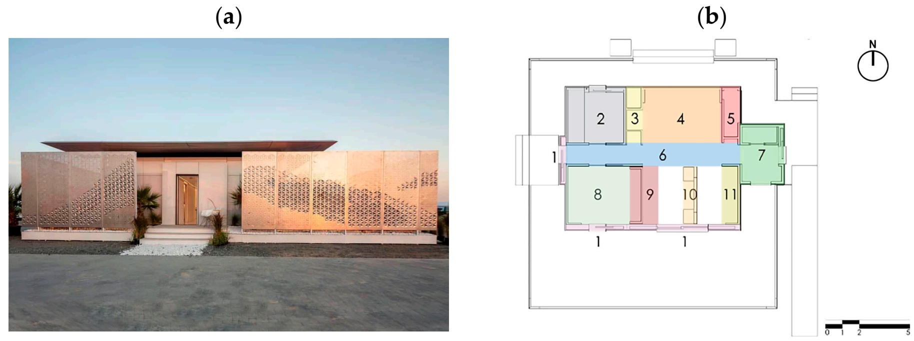

Figure 12. Team Virginia Tech's house. (**a**) Exterior photo. (**b**) Floor plan—1: door cartridge; 2: bathroom; 3: wet mechanical room; 4: kitchen, dining area; 5: dry mechanical room; 6: corridor; 7: entry, powder room; 8: bedroom; 9: mobile closet; 10: mobile AV wall, living area; 11: office. (Photo: SDME 2018 Organization. Floor plan: by authors based on team Virginia Tech drawings).

The Virginia Tech team built their cartridges using structural insulated panels (SIP), consisting of closed-cell polyurethane rigid foam sandwiched between two oriented strand boards (OSB). The walls of the cartridges that make up the house's thermal envelope were finished with ventilated façades. The team selected the house materials, considering their environmental impact. In the case of materials with high environmental effects that they cannot substitute, such as metals, they looked for those with the highest recycled content.

The team built the competition prototype, connecting the following 3D cartridges: entry, kitchen, bathroom, office, AV wall, closet, dry and wet mechanical, master bedroom, and spine cartridge, as shown in Figure 13. They also utilized three 2D cartridges, paneled like industrialized elements, to close the house's living, bedroom, and back doors. The "spine cartridge", the corridor ceiling, functions as the house's central nervous system. It includes the HVAC ducting, communication lines, and the interconnections between the cartridges' electrical sub-panels and the house's main distribution board. The team also integrated the PV modules into long-horizontal pre-wired cartridges that arrived at the site ready for façade installation. All the house foundations and modules were transported using only five trailers.

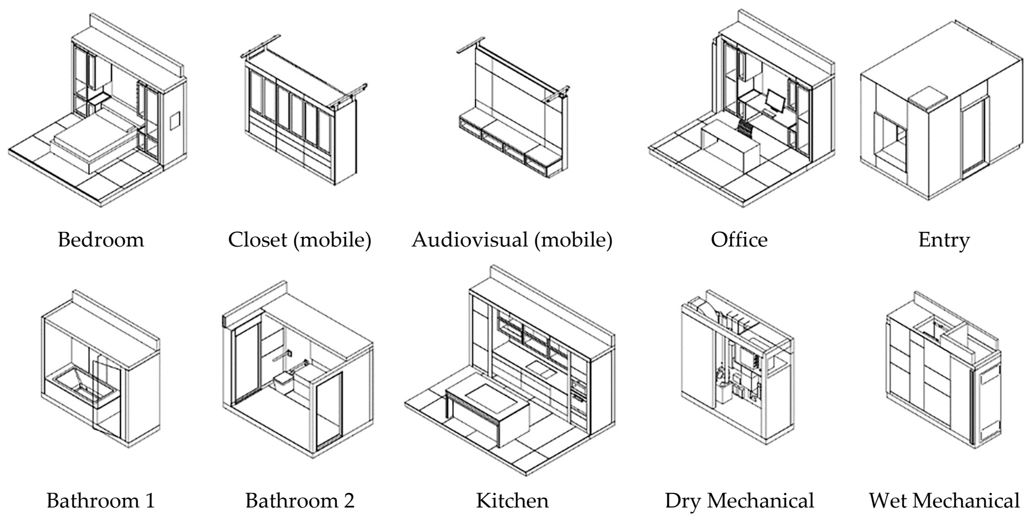

Figure 13. 3D cartridges of team Virginia Tech. The design also includes other cartridges such as the ceiling spine, exterior doors (lateral façades), and PV. (By authors based on team Virginia Tech drawings).

The assembly started with the installation of the house's prefabricated footing. Then the team continued with the set-up of the vertical cartridges and the assembly of the spine cartridge over the corridor. After that, they installed the PV cartridges and the roof canopy and made MEP the interconnections. Then, they installed the deck, ramps, fences, and landscape elements. The final tasks included cladding the ventilated façades and cleaning the site.

5.3.3. Team KNOW HOWse

The team KNOW HOWse presented the only two-story house in the SDME 2018 competition. The team aimed to design an innovative and energy-efficient house, combining a reinterpretation of a traditional tent of Emirati Bedouins with the traditional Emirati house layout (Figure 14). Recognizing that privacy is a relevant aspect of Emirati life, they installed mobile divisions (curtains) to separate the ground floor living areas, the entrance zone, the Majlis (double-height living), and the dining room. Following the same approach, the house's first floor resembles the private "family area" of the Emirati house. The occupants can increase this area through an innovative sliding floor that moves over the Majlis. The house exterior has a ventilated façade cladding with light-colored removable tensile fabric panels that resemble the Bedouin tent material and improve the façade's thermal performance.

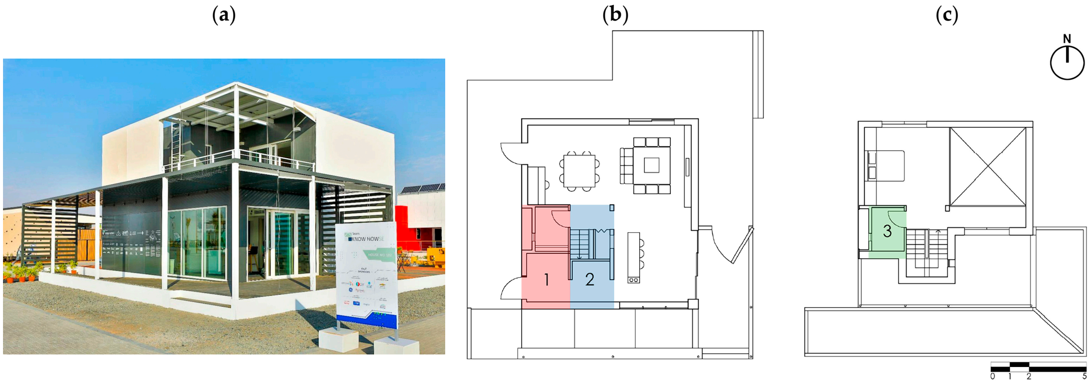

Figure 14. Team KNOW HOWse project. (**a**) Exterior view (**b**) Ground floor plan—1: bathroom, utility room, kitchen (first part); 2. stairs, kitchen (second part). (**c**) First-floor plan—3: bathroom. (Photo: SDME 2018 Organization. Floor plans: by authors based on team KNOW HOWse drawings).

This team's hybrid solution is mainly based on paneled 2D elements combined with three container-size volumetric units. These 3D units arrived on site finished, with all the MEP components installed. As shown in Figure 14, one of these units contains the ground-floor bathroom, the part of the kitchen with plumbing installations, and the technical room (accessible from the exterior). The other unit includes the staircase, storage, and the other part of the kitchen. Finally, the third unit contains the first-floor bathroom.

The exterior walls of the 2D elements and the envelope of the 3D modules consist of magnesium oxide boards (house interior finishing), rigid insulation (15–20 cm), CLT panels (10 cm thick), vapor barriers, magnesium oxide boards, and the ventilated textile façade system [36]. In addition, soundproof buffers are installed at the junctions between the panels to break the sound wave transmission between the rooms. The team chose the house materials considering their environmental aspects and potential impacts throughout their life cycle. For instance, the selected cross-laminated timber (CLT) panels have a low environmental impact and come from a controlled forest production chain. Likewise, the magnesium oxide boards combine strength and versatility with sustainability and recyclability.

The assembly commenced with the installation of the steel footings. Then, the team set up the 3D modules for the ground floor and placed this level's flooring and wall panels. The team then installed the first floor's bathroom module, slabs, and sliding floor. After that, the team assembled the first-floor walls, roof panels, and plenum, and made the MEP connections. At last, they installed the exterior components (the PV modules, the south and east sheds, the overhang shading device, and the textile panels) and cleaned up their lot.

5.3.4. Team Sapienza

Team Sapienza utilized a hybrid off-site construction based primarily on 2D panels in combination with three small 3D modules, as Figure 15 shows. Its architecture blends modernity with a reinterpretation of typical elements of the traditional Arabic house: square shape, central courtyard (patio), wind tower, and privacy screens (Mashrabiya). The result is an elegant design that successfully responds to the regional culture and harsh climate, providing privacy, protection from solar radiation, and other passive cooling strategies. Furthermore, the house's indoor and outdoor spaces are functionally flexible. The occupants, for example, can divide the central patio into two zones, one with a more public character and the other more private, with direct access to the interior spaces. These adjacent courtyards are a reinterpretation of the "takhtabush", a passive conditioning strategy [37]. In traditional Arab architecture, a takhtabush is a covered outdoor sitting area between a shaded courtyard and an entirely open courtyard. The different thermal conditions and sizes of the covered and uncovered spaces ensure steady airflow through convection. In addition, the courtyard also has an automatic adaptive solar shading system. Similarly, the openings on the south façade are protected with external semi-transparent fiberglass mesh roller blinds.

(**a**) (**b**)

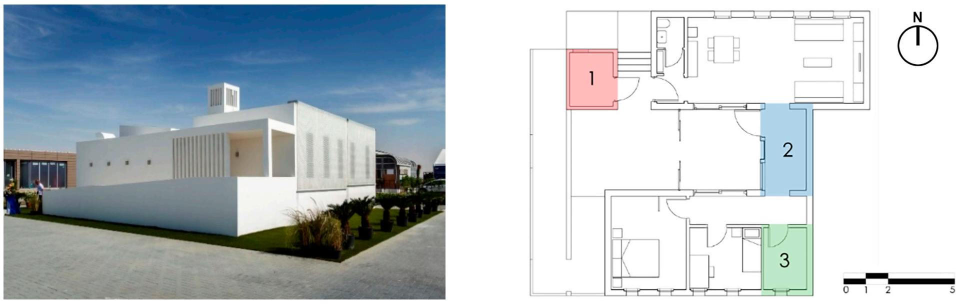

Figure 15. Team Sapienza's house. (**a**) Exterior photo. (**b**) Floor plan—1: technical room; 2: kitchen; 3: bathroom. (Photo: SDME 2018 Organization. Floor plan: by authors based on team Sapienza's drawings).

The indoor spaces are organized into two well-defined zones: the social zone (including the powder room and the living-dining area) and the private zone (including two bedrooms and a bathroom). These two zones are separated by the patio and connected by the kitchen, as Figure 15 shows. The team constructed the 2D and 3D elements using cross-laminated timber (CLT) panels joined with innovative steel connections. They used wall-to-floor ventilated steel connections to protect the CLT panels from moisture and wet/dry cycles. In addition, they increased the structural resistance of the CLT panels by applying a post-stress technique (Press-Lam). This technique also allows the structure to be adjusted to the required seismic class, facilitates future changes (adding openings or removing noncritical walls), and permits the construction of multi-story buildings [37].

The team designed a multilayer solution for the house façade, whose components, from the interior to the exterior, are plasterboard, cavity (tech space), CLT panels, insulation (fiber-reinforced aerogel blanket), vapor barrier, and cement board finished with a photocatalytic paint.

The team selected environmentally friendly products and materials considering their whole life cycle. They prioritized renewable, recycled, and recyclable materials, as well as those that were bio-sourced and free of hazardous substances. For instance, the wood used on the structure, doors, and finishings came from a well-managed forest. In addition, they use low-embodied-energy thermal insulation (fiber-reinforced aerogel blankets) made from amorphous silica. Similarly, they chose the paints based on the embodied energy and chemical components they contained.

The assembly began with placing the prefabricated foundations and installing the underfloor piping. Then, they placed the three 3D modules and the floor slabs. After that, they assembled the walls and roof panels. After completing the roof, they installed the PV modules and the solar thermal panel and made the MEP system interconnections. Next, they worked on the internal finishing, furniture, green wall, and landscaping. Finally, the team cleaned up the lot.

5.3.5. Team TDIS

Team TDIS developed an urban rehabilitation project to transform deteriorated areas into co-working villages based on sharing sustainable resources. More than a house, their competition prototype is a flexible co-living space. It was constructed using a hybrid solution. Most of its construction components are prefabricated panels (2D elements) combined with two aligned 3D modules, named the "energy bar," which includes all the MEP systems of the prototype.

The prototype has two stories. The main indoor space on the ground floor connects to an uncovered terrace on the north side and a covered outdoor area on the south side (Figure 16). This space contains the preparation area of the kitchen, the dining room, and the living room. It is a flexible space that can be converted into a co-working space with workstations and meeting areas. Perpendicular to this space, to the west, is located the energy bar, which includes the MEP technical room, kitchen, laundry, and bathroom. The foyer and the bedroom are next to the main indoor space. The stairs are located at the south and lead to a PV canopy-covered open terrace.

(**a**)

(**b**)

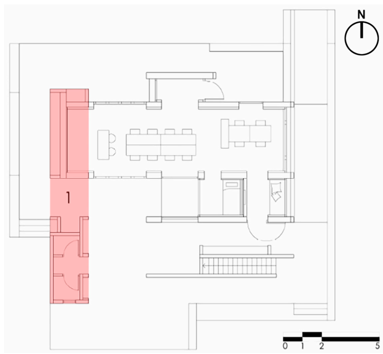

Figure 16. Team TDIS house. (**a**) Exterior photo. (**b**) Floor plan—1: Energy bar (storage room, technical room, kitchen, charging station, laundry room, bathroom). (Photo: by authors. Floor plan: by authors based on team TDIS drawings).

This prototype was designed with lightweight timber construction. Its Insulation Panel System (IPS) contributes to the prototype's high thermal insulation, light weight, fast assembly, and low cost. The exterior wall components from the interior are fire-retardant antimicrobial grade panels, wooden bars, IPS, waterproof felt, and a ventilated façade with composite panels as external wall cladding. These composite panels have UV film protection and reduce dust deposition due to low static electricity.

As shown in Figure 17, the assembly process started by placing the prefabricated foundation, the energy bar module, and the floor elements. After that, the team installed the walls, roof, stairs, and PV system. Next, the outdoor deck, ramps, and steps were assembled. Then, the team fixed the windows and doors, worked on the interior finishing, placed the vegetation, and cleaned up the site.

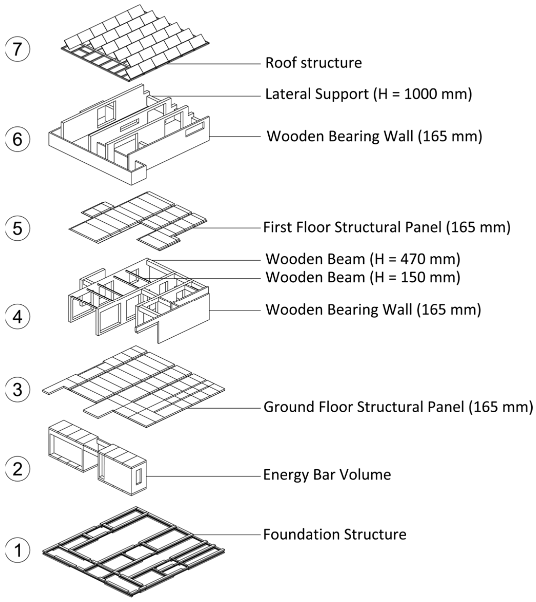

Figure 17. Blow-up of TDIS house, indicating the main components and the assembly process. The numbers indicate the assembly sequence. (By authors based on team TDIS drawings).

5.3.6. Team EFDEN

Team Efden conceived their house construction system as a hybrid off-site system, consisting primarily of 2D timber elements and one 3D timber module (the technical room). They designed a flexible house based on the "less is more" philosophy and the biophilia concept to promote a sustainable lifestyle. As shown in Figure 18, the main zone of the house is an open space containing five areas: the living space, kitchen, workstation, dining space, and bedroom. The only separated areas are the bathroom, technical room, and storage. In the open space zone, the only fixed function is the kitchen, and the rest of the space is adaptable, allowing the occupants to choose where to eat, sleep, work, and sit.

(**a**) (**b**)

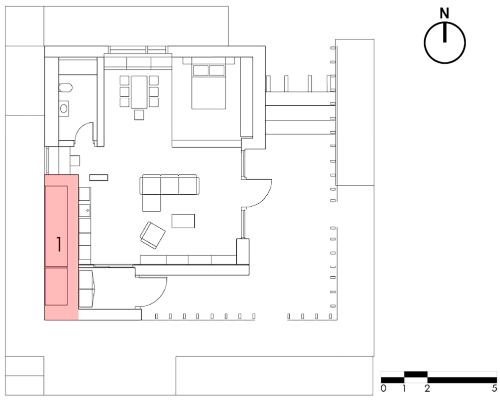

Figure 18. Team Efden house. (**a**) Exterior photo. (**b**) Floor plan—1: technical room. (Photo: SDME 2018 Organization. Floor plan: by authors based on team Efden's drawings).

The team selected the house's materials considering four aspects: materials with an Environmental Product Declaration (EPD), metals with very high recycled content, wood with Forest Stewardship Council (FSC) certification, and finishes with low volatile organic compounds (VOC). After analyzing different options, they selected cork for the interior finishes, mineral wool as an insulation material, and timber as the primary material. The wood was used in many ways, including in cross-laminated timber elements, timber frame panels, and glued laminated wood (Glulam) beams. The latter were used to create an ample indoor space free of columns. In addition, they use an almost 100% dry assembly, utilizing wet finishing only for 26% of the wall surface, resulting in a total consumption of 80 L of water for the whole construction process.

Efden's house has opaque ventilated façades with aluminum panel cladding, as Figure 19 shows. The walls comprise two cross-laminated timber panels (CLT) connected by timber mullions. The team claims this wall system is lighter and uses 20% less wood than standard CLT while maintaining the same structural resistance.

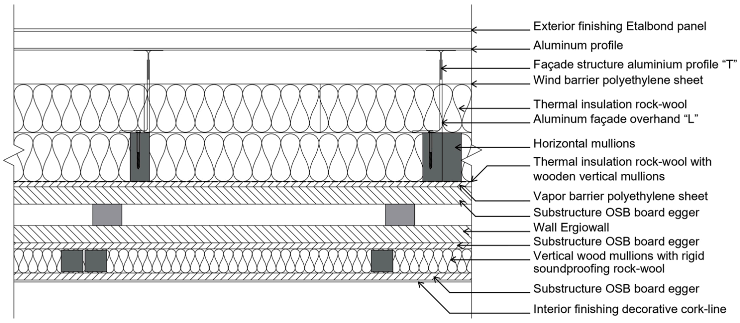

Figure 19. EFDEN house—horizontal section of the exterior wall. (By authors based on the EFDEN team drawings).

The team started the assembly by laying the foundations and their only 3D module (the technical room). Then, they assembled the floor, walls, and roof panels. After setting up the main structural elements, they installed the insulation layers and interconnected the MEP components. Then, they set up the terrace shell structure (columns and beams) and assembled the deck. Finally, they installed the ventilated façade cladding panels and the solar system before they cleaned up their lot.

5.3.7. Team Virtue

Team Virtue designed a six-story apartment building named LINQ ("connecting" in English). They assembled one of the apartments and part of the building atrium, including its curved green wall, at the competition site (Figure 20). The building has three zones: the atrium, the vertical circulation core, and the apartments. Similarly, its apartments have three zones: the public area, the bedroom, and the service core. The service core is at the center of the apartment and combines the kitchen, technical room, bathroom, and entertainment unit. It contains the primary electrical, plumbing, and HVAC components. The service core is also essential to the structure. It supports the floors and roof elements.

(**a**) (**b**)

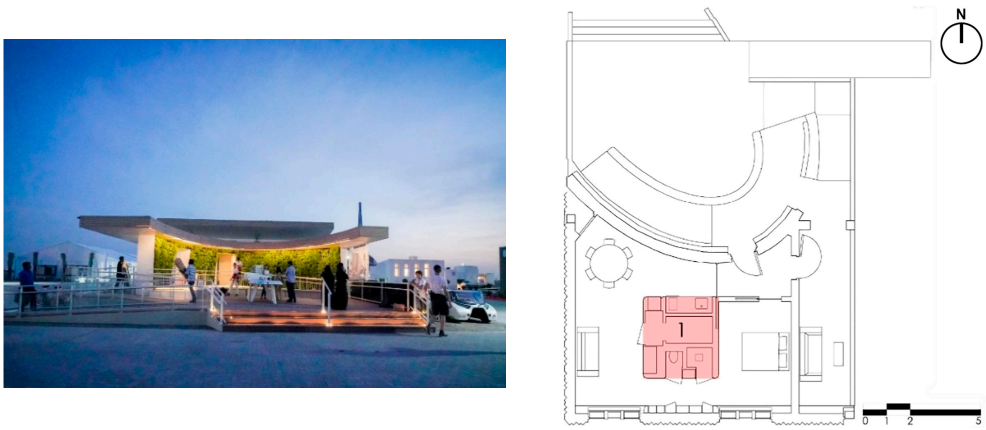

Figure 20. Team Virtue's house. (**a**) Exterior photo. (**b**) Floor plan—1: kitchen, technical room, bathroom, entertainment unit. (Photo: SDME 2018 Organization. Floor plan: by authors).

LINQ was conceived as a lightweight hybrid off-site construction using 2D industrialized elements and 3D fully equipped service modules. The walls, roofs, and floors were made using prefabricated 2D elements. These elements have a core of engineered OSB joists and bio-foam insulation boards that are skinned on both sides with solid laminated wood panels.

The apartments have two façade systems: a green wall façade at the north elevation and a bio-composite façade system at the south and west. The light-colored bio-composite cladding elements are three-dimensional pieces made from organic materials, including rice and oil. This cladding system shades and ventilates the apartment's thermal envelope while contributing to its external appearance.

The assembly began with placing and leveling the foundation elements. After that, the team installed the 3D service module. Then, they installed the prefabricated floor panels and assembled the wall elements. The next step was placing the roof panels and completing the ductwork connections. Finally, the team installed the finishings and the green wall and cleaned up the site.

6. Discussion

The following sections summarize the findings, considering the construction category, type of solution, structural material, optimum design, façade types, thermal envelope, and non-structural materials. In addition, the energy performance and sustainability assessment during the competition are discussed. The last part of the discussion compares SDME 2018 houses with two nearly zero-energy early adopters in the UAE and the Dubai Green Building Regulations (Al Sa'fat).

6.1. Category, Type of Solution, and Primary Structural Material

Figure 21 presents the proportions of designs within each off-site category, solution type, and primary structural material. The first figure shows that most teams selected lightweight construction systems (nine out of the eleven projects (82%)). The use of lightweight off-site construction provides clear benefits in terms of transportation, handling, and assembly. Usually, these solutions require smaller cranes, and the module assembly is safer, easier, and more affordable. They also provide some environmental benefits related to their typical dry construction systems, which facilitate the reuse and recycling of materials and components.

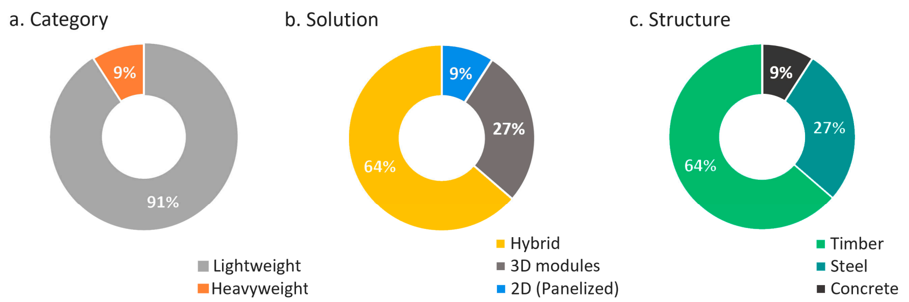

Figure 21. Case studies: categories, solution types, and primary structural materials.

The studied cases feature different off-site methods, including panelized (2D), volumetric (3D), and hybrid solutions (a combination of 2D and 3D solutions). However, only one of the houses used fully 2D solutions, three used 3D solutions, and the other seven (64%) used hybrid solutions.

Regarding the primary structural materials, seven houses used timber, three used steel, and one used concrete. One of the cases with a steel structure used a light steel frame (Team UOW). Timber was by far the most frequently used material (64%). The teams justified its selection as the primary structural material based on its light weight and environmental advantages. Timber is a lightweight building material that outperforms steel and concrete regarding embodied energy and air and water pollution [38,39].

Other justifications for timber include its design flexibility, high thermal performance, environmental friendliness, reduced waste, fast installation, and good seismic and acoustic performance. However, timber is not produced in desert areas like the UAE; consequently, there is no construction tradition connected with this material in the region. The GHG emissions associated with transporting timber cannot be denied. Therefore, further analyses must be carried out including Life Cycle Analysis (LCA) and Life Cycle Cost (LCC) of timber in comparison with standard solutions (on-site concrete, concrete blocks) and other prefabricated solutions for the UAE.

Team Aqua Green was the only team that used concrete as its primary structural material. However, seeking a low environmental impact alternative solution to standard concrete, they selected a light precast option denominated "green concrete". This lightweight concrete has the highest possible ratio of ground granulated blast-furnace slag (GGBS). Use of this concrete reduces the house's environmental impact by cutting the CO2 emissions associated with standard concrete while helping to conserve natural resources. GGBS also increases the strength and durability of the concrete elements, improves mix workability, and reduces the risk of thermal and shrinkage cracks. Similarly, Team KSU used reinforced Autoclaved Aerated Concrete (AAC) panels for the floors and roofs of their 3D modules and lightweight concrete prefabricated hollow-core panels for their walls. AAC comprises quartz sand, calcined gypsum, lime, cement, water, and aluminum powder. Compared with traditional concrete, it produces less solid waste and greenhouse gas emissions.

As explained in Section 3.1, SDME is an international competition that requires the participating teams to assemble their houses in Dubai. In the 2018 edition, teams from Australia, America, Europe, the Far East, and the Middle East participated in the competition. During the analysis of the cases, the authors found that the selected off-site solution (category, type, and material) and the transportation are related to the place of pre-construction. As Table 6 shows, out of eleven houses, five used only land transportation. Interestingly, only two heavyweight houses and the three houses that used only 3D volumes were in this group.

Table 6. Relation between the country of pre-construction, type of transportation, and the utilized off-site construction.

House	Team Name	Country of Off-Site Preparation	Transportation	Category	Solution	Structural Material
H01	Aqua Green	UAE	Land	Heavyweight	2D (panelized)	Concrete
H02	KSU	Saudi Arabia	Land	Heavyweight	3D (volumetric units)	Steel [1]
H03	AURAK	UAE	Land	Lightweight	3D (volumetric units)	Steel
H04	Baity Kool	France and UAE	Land [2]	Lightweight	3D (volumetric units)	Timber
H05	UOW	Australia	Maritime and Land	Lightweight	Hybrid	Light Steel Frame
H06	Virginia Tech	US	Maritime and Land	Lightweight	Hybrid [3]	Timber
H07	KNOW HOWse	Italy and UAE	Land [4]	Lightweight	Hybrid	Timber
H08	Sapienza	Italy	Maritime and Land	Lightweight	Hybrid	Timber
H09	TDIS	Taiwan	Maritime and Land	Lightweight	Hybrid	Timber
H10	Efden	Romania	Maritime and Land	Lightweight	Hybrid	Timber
H11	Virtue	Netherlands	Maritime and Land	Lightweight	Hybrid	Timber

[1] Team KSU used steel structure and Autoclaved Aerated Concrete (AAC) plates to build the floors and roofs of their modules. [2] House components were prepared in France and shipped to the UAE, where the team completed the off-site preparation. [3] Virginia Tech team built their house using primarily 3D modules named "cartridges". [4] The 2D units (based on cross-laminated timber panels) were prepared in Italy and shipped to the UAE, where the team completed the off-site preparation.

The teams from abroad did not select heavy elements or large 3D modules due to the difficulties and cost of transporting them. As a result, all the houses transported via sea routes were lightweight and used hybrid solutions.

Several teams were composed of universities from different countries. Among them, Baity Kool and KNOW HOWse decided to pre-construct their houses in the UAE, requiring only land transportation and giving them more flexibility with their off-site solutions. Most of the Baity Kool house components were prepared in France and shipped to the UAE, where the team completed the off-site preparation of the 2D units and 3D modules. In the case of KNOW HOWse, the 2D units (based on cross-laminated timber panels) were prepared in Italy and shipped to the UAE. They also made the necessary arrangements to find a permanent site for their projects in the UAE. The strategies of these two teams surely reduced the overall energy and related carbon emissions of their houses' transportation. However, no data are available to analyze this reduction in detail or compare it with the energy consumption of other designs fully transported from abroad.

6.2. Projects' Passive Strategies, Thermal Envelopes, and Materials

Incorporating passive design strategies is crucial to reducing the energy required for their operation when developing sustainable zero-energy buildings. These strategies help enhance a building's energy efficiency, reducing the need for renewable energy sources to meet its energy demands. The study of the climate and the site where the building will be erected is fundamental to selecting suitable passive strategies. The climate in the GCC region is characterized by long and very hot summers and warm winters. It corresponds to the Bwh (Hot Desert Climate) in the Köppen–Geiger climate classification. Due to the elevated temperatures and extremely low annual precipitation, the climate of most cities in the region is classified as 0B (Extremely Hot and Dry), as in the case of Dubai. Due to its proximity to the Arabian Gulf, Dubai has fewer temperature fluctuations, and the humidity reaches higher levels than cities in the peninsula's interior. Therefore, passive strategies must focus on blocking solar radiation, reducing the thermal exchange surface area with the exterior, and identifying envelopes with very low thermal transmittance. The use of transitional and thermal buffer spaces is also helpful. Table 7 presents the passive strategies selected by the participating teams in the SDME 2018, organized into three categories: volume and geometric design, envelope, and passive cooling.

In extreme climates, most of the time, it is not possible to achieve interior comfort conditions without the support of active ventilation and conditioning systems. However, passive strategies can significantly reduce these systems' energy consumption. Due to the harsh exterior conditions, if the site and the function allow it, the most appropriate is to design compact buildings with a lower surface area of thermal envelope relative to volume. As can be learned from Middle Eastern vernacular architecture, the use of a patio that can be covered during the day is also an effective strategy. This strategy reduces the openings to the hash exterior and connects the interior spaces with the shaded patio, which has a much better microclimate. A third option is to develop a slightly elongated building with its long axis running east–west. This option can be improved by attaching a porch or covered terrace to the south. Almost half of the SDME 2018 teams opted for the use of a patio, designing U-shape houses with the patio opened to the north, O-shape houses with a central patio, L-shape houses with a north-east patio, or houses with lateral covered patios. The houses' envelopes are discussed separately in Sections 6.1 and 6.5. Only three teams included openings in the east and west façades, and they designed small openings that were suitably protected from solar radiation. Also, for glazing in desert environments, in addition to the low U-value, having low solar heat gain coefficients (SHGC) is crucial. This is especially critical for unprotected or partially protected glazing.

Regarding passive cooling strategies, providing shading to both opaque and translucent parts of the envelope is the most effective strategy. On the other hand, natural ventilation has limited value in hot arid climates since the ambient temperature is too high most of the year.

Table 7. SDME 2018 Passive strategies. The black rectangles indicate the strategies utilized in each house.

SDME 2018 Houses Passive Strategies	**Aqua Green**	**KSU**	**AURAK**	**Baity Kool**	**UOW**	**Virginia Tech**	**KNOW HOWse**	**Sapienza**	**TDIS**	**Efden**	**Virtue**
Volume and geometric											
Compact						■	■			■	■
Around or next to a covered patio		■	■	■				■		■	
Elongated along east–west axis (with south protected by a covered open space)	■								■		
Envelope											
Ventilated Façade				■	■	■	■		■	■	■
Wall U-value (60% or lower than the code)	■	■	■	■	■	■	■	■	■	■	■
Roof U-value (30% or lower than the code)	■	■	■	■	■	■	■	■	■	■	■
High-performance glazing	■	■	■	■	■	■	■	■	■	■	■
No windows in the east or west	■				■	■		■	■	■	■
Fully (parallel) protected east or west windows		■	■	■			■				
Green roof		■	■	■						■	
Green wall			■	■	■			■		■	■
Cool roof and high reflective walls		■			■			■			
Passive Cooling											
Fixed solar shading	■	■	■	■	■	■	■	■	■	■	■
Operable solar shading				■			■	■			
Shaded roof	■	■	■	■	■	■	■	■	■	■	■
Covered roof terrace			■						■		
Natural ventilation	■	■	■	■	■	■	■	■	■	■	■
Night ventilation (natural night cooling)	■	■	■	■	■	■	■	■	■	■	■
Ventilation (Ventury or stack effect)					■		■	■			
Passive space planning											
Foyer or entrance vestibule					■	■			■		■
Living areas north- or south-oriented	■					■	■		■	■	
Living areas open to covered patio		■						■		■	
Interior buffer zones				■			■			■	
Attached covered spaces (terraces, porches)	■						■	■	■	■	■
Thermal Energy Storage (TES)											
Sensible thermal mass	■	■	■	■			■	■			
Passive latent TES											

Passive strategies related to space planning can be highly effective and usually do not require increasing the budget of a project. Some effective planning strategies include using foyers or separate vestibules, and using storage areas, closets, and service rooms as thermal buffer spaces.

Moreover, incorporating thermal mass can effectively minimize fluctuations in indoor temperature, particularly in areas with significant variations between day and night temperatures. Some strategies integrate both passive solutions and active systems, known as "hybrid or semi-passive strategies". The hybrid design strategies utilized by the SDME teams are summarized in Table 8.

Table 8. SDME 2018 hybrid solutions (semi-passive: combination of passives and active solutions). The black rectangles indicate the strategies utilized in each house.

Passive Strategies in SDME 2018 Houses	**Aqua Green**	**KSU**	**AURAK**	**Baity Kool**	**UOW**	**Virginia Tech**	**KNOW HOWse**	**Sapienza**	**TDIS**	**Efden**	**Virtue**
Motorized solar shading				■			■	■			
Ventilation with heat recovery				■					■		■
Ventilation with energy recovery		■	■		■	■		■		■	
Evaporative cooling	■										■
Radiant cooling	■		■	■	■				■		■
Night or day sky radiation				■							■
HVAC buffer tank (sensible)				■							■
HVAC with PCM					■	■					

Due to the importance of the building envelope, the following sections present the analysis of the façade types, wall materials, bio-composites, natural materials, and high-performance insulation materials. This section concludes with a comparative analysis between the SDME houses' thermal envelop characteristics, the Dubai building regulations, and two early adopters of sustainable zero-energy residences.

6.2.1. Façades Types and Exterior Wall Materials

The performance of the thermal envelope is one of the most significant elements influencing the energy consumption and CO2 emissions of buildings [40,41]. However, the environmental impact of the façade types and materials is determined not only by their thermal performance but also by their durability, multifunctionality, and embodied energy. Table 9 presents information regarding the façades and insulation of the case studies. Seven out of eleven teams used opaque ventilated façades (OVF) for their houses (64%).

Opaque-ventilated façade systems offer a wide variety of cladding and can be used on both new construction and renovations. Additionally, these systems provide hygrothermal and construction benefits due to the installation of a continuous thermal insulation layer and the naturally ventilated cavity [41]. The scientific literature about opaque ventilated façades points out that they are effective in reducing cooling loads since they perform as a shield against the heat flows (solar radiation, reflections, and ambient temperature) that typically have a negative impact on indoor conditions in the summer months and hot climates [41]. Most teams utilized thermal energy storage in the walls, ceilings, and floors to reduce temperature fluctuations and energy demand.

Furthermore, in regions with elevated temperatures, such as the UAE, incorporating a heavy mass into building structures and increasing insulation can minimize fluctuations in indoor temperature and decrease the cooling loads [42]. In these climates, buildings with heavy mass perform better than those with moderate or light mass. The use of thermal mass provides a third advantage: energy flexibility. A study in the UAE also found that modulating the setpoint for certain hours allows the use of the building's thermal mass for load management. Under the conditions of this study, the energy flexibility achieved using thermal mass allowed the peak demand to be shifted from 1.70 to 3.0 h [43].

Table 9. Categorization of the case studies' façade types and envelope materials.

Type	ID	Team	Façade Materials: Exterior Finishing	Façade Materials: Insulation Type	Insulation Location	Indoor Finishing Mat.
Non-ventilated Façade	H01	Aqua Green [1]	Precast concrete	Extruded polystyrene	Wall core	Concrete
	H02	KSU	Cement board w/coated glass fiber mesh	Date palm tree surface fibers	Wall core	Gypsum board
	H03	AURAK	Cement–mortar layer (applied over three-dimension welded wire mesh with insulation panel at the core)	Rigid insulation panels and semi-rigid wood fiber insulation	Exterior	Shotcrete
	H08	Sapienza [2]	Cement board with coated glass fiber mesh	Fiber-reinforced aerogel blankets	Ext. and Int.	Gypsum board
Opaque Ventilated Façade	H04	UOW	Foamed concrete mixed with recycled crushed glass and carbon fiber mesh reinforcement	Extruded polystyrene insulation Board (closed cells) and insulation batts (recycled glass and natural organic binders)	Ext. and Int.	Gypsum board
	H05	Baity Kool	Cement mortar precast panels	Expanded polystyrene insulation (EPS)	Wall core	Raw clay bricks
	H06	Virginia Tech	Glass rainscreen	Polyurethane foam	Wall core	Glass panels
	H07	KNOW HOWse	Tensile fabric	Polyurethane foam	Interior	Magnesium board
	H11	Virtue	Tridimensional cladding (Bio-composite materials)	Biofoam	Wall core	MDF wall panels
	H09	TDIS	Rainscreen composite panels (resins reinforced cellulose fiber)	Extruded polystyrene insulation board (closed cells) and vacuum insulation panels (VIP)	Wall core	Glass–fiber–wood laminated panels
	H10	Efden	Aluminum (Etalbond)	Rock-based mineral fiber insulation	Ext. and Int.	OSB with cork panels

[1] Team Aqua Green exterior walls were prefabricated concrete panels with a cavity. [2] Team Sapienza's south façade had a ventilated shading system.

In conclusion, all SDME teams made a heroic effort to design high-performance envelopes for their houses to respond to Dubai's extreme climate while minimizing energy consumption. The thermal properties of their houses' walls, floors, roofs, and glazing are discussed in Section 6.5 and summarized in Table 8.

As previously explained, wood, steel, and concrete were the structural materials in the studied cases. Nevertheless, the teams utilized a variety of other materials in their projects' façades, including light concrete and cement boards, bio-composites and natural materials, and high-performance insulation materials. These materials and phase change materials (PCMs) are discussed in the following sections.

6.2.2. Bio-Composite and Natural Materials

In the last decades, motivations for material selection have increased beyond the traditional parameters of cost, strength, and thermal performance to include sustainability parameters such as embodied energy, recyclability, and biodegradation [44]. Boosted by environmental concerns and regulations, bio-composites, biodegradable plastics, and bio-based polymers are emerging as sustainable alternatives to conventional petroleum-based materials and nonbiodegradable composites [45]. These "eco-friendly" and biocompatible materials help reduce raw materials and non-renewable waste.

Aiming to contribute to sustainable construction, several SDME teams utilized bio-composite and natural building materials for exterior cladding, finishings, and insulation. For example, Team Virtue used bio-composite organic materials for the house façade, composed of rice and other plant materials. They also used cork on the floors and "bio-foam" as insulation material. This "bio-foam" is a combination of recycled expanded polystyrene and biopolymers coming from raw vegetable material. The panels of the ventilated façade of the TDIS house are composite panels made of resins reinforced with cellulose fiber. Team KSU utilized the surface fiber waste of date palms as insulation. Team KSU developed date palm fiber insulation and used it to fill the core of their prefabricated light concrete panel. A study conducted in Morocco found that a thermal insulation material made from date palm fibers reduced the cooling and heating energy consumption of a two-story villa by 25% and 18%, respectively [46]. Team AURAK also used date palm-based materials. In this case, the team used date palm leaves to build the windows' sun and privacy screens, known in Middle Eastern vernacular architecture as "Arish".

6.2.3. High-Performance Insulation Materials

Team Sapienza used fiber-reinforced aerogel blankets consisting of silica aerogel and fiberglass, a resilient and durable material with high thermal resistance and sound insulation. On the other hand, Team UOW and TDIS used extruded polystyrene insulation board featuring closed-cell insulation, which has high vapor transmission resistance. Team TDIS also utilized vacuum insulation panels (VIPs), a type of thermal insulation comprising a gas-tight enclosure surrounding a rigid core from which the air has been evacuated. The VIPs have excellent thermal performance and are thinner and lighter than conventional insulation materials [47]. In addition, the VIPs are durable and can withstand extreme weather conditions. Current work on VIPs primarily centers on auto-healing enclosures and production cost reduction. The use of such innovative insulation solutions is the reason for the low U-values of these SDME houses.

6.2.4. Phase Change Materials

Since the first editions of the Solar Decathlon, many teams have used phase change materials (PCM) in many ways, either integrated into their houses' thermal envelopes or as a component of their HVAC systems [48]. PCMs have a relatively large thermal energy storage capacity in a temperature range close to their switch point. They present an almost isothermal behavior during the charging and discharging processes. Therefore, they provide many benefits for building applications, including low weight, high heat storage density, and thermal energy storage and release at a nearly constant temperature [49].

In the SDME 2018 edition, three teams used PCM. Two of them, UOW and MizanHome, used PCM in thermal storage tanks as part of their HVAC systems. (MizanHome is an excellent project designed by Malaysian students from the Islamic Science University of Malaysia and the University of Technology.) The third team was Virginia Tech, which used PCM on the house plenum over the ceiling tiles. In this case, they can charge the PCM using the HVAC system when reasonable (e.g., where there is a low electricity price, out-of-peak period, or excess energy production) and then absorb the heat from space when required without needing additional energy.

6.3. Energy Performance during the Competition

Before assembling their houses on the competition site, the teams used simulation software to validate their design decisions and, in some cases, conducted a series of experiments to determine the performance of the house components and systems. During the final phase of the competition, the organizers monitored the houses' comfort conditions and energy behavior, as well as the functioning of their systems and appliances. Appendix D includes details of the monitoring and instrumentation system utilized in the SDME 2018.

Implementing all-electric buildings is an efficient way to reduce carbon emissions from the building sector in a shorter period of time. Therefore, as per SDME rules, participating houses must be all-electric solar houses. The SDME 2018 houses demonstrated outstanding energy performance during the ten-day competition period, as shown in Figure 22. The energy balance shown in this figure includes the energy consumed to charge an electric vehicle (EV). The SDME organization provided one EV for each team for the contest period. It is also important to explain that during the competition, the capacity of the electrical inversion of all the houses was restricted (physically or via firmware) to 8 kW. Appendix B summarizes the PV solar systems of the SDME houses. Two of the projects functioned as nearly zero-energy houses. In contrast, the remaining eight behaved as zero-energy or positive-energy houses since they could export more energy to the grid than they imported from it.

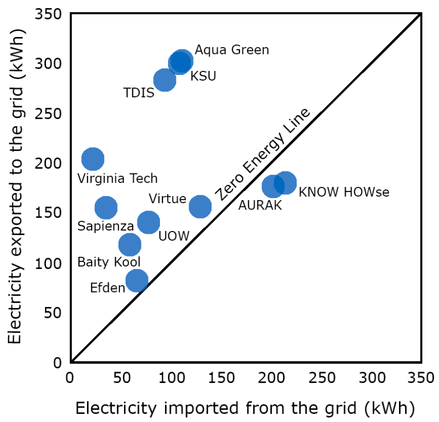

Figure 22. Electrical energy balance (exported vs. imported from the grid) during the ten days of competition of the SDME 2018. (By the authors).

Figure 23 compares the points earned by the teams for maintaining indoor comfort conditions and carrying out tasks related to energy consumption. Details about the teams' tasks and responsibilities during the contest period can be found in Appendix A. As shown in Figure 22, Virginia Tech, Sapienza, and Baity Kool were the houses that imported less energy from the grid. Virginia was also the house with the highest score in both the comfort sub-contests and the energy consumption tasks, as seen in Figure 23. UOW and Sapienza also achieved excellent scores in the comfort parameters and energy-related tasks. Appendix C summarizes the information about the HVAC systems installed in the SDME 2018 houses.

On the other hand, Aqua Green was the team that exported the most to the grid. This team did excellent work maintaining the air quality levels. However, it did not rank among the top teams in other comfort parameters such as lighting and humidity level or among the top teams in hot water draws, ovens, or clothes-washing tasks. Achieving high scores for lighting and humidity was challenging for many teams. Similarly, the oven and the dishwashing task were challenging for some teams. The other two teams that exported the most energy to the grid were KSU and TDIS, and as explained in Section 6.4, TDIS' house had the lowest wall and roof U-values.

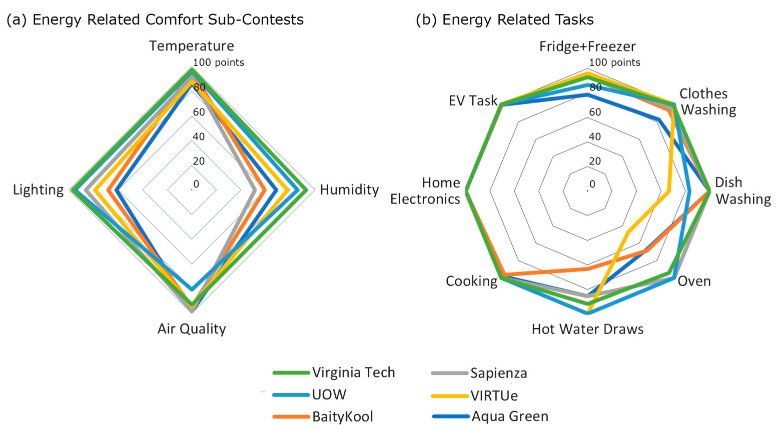

Figure 23. Points earned by the teams in sub-contests related to energy consumption. (**a**) Comfort conditions sub-contests. (**b**) Tasks sub-contests. (By the authors from SDME 2018 results).

6.4. Sustainability Evaluation during the Competition

According to the SDME regulations, three international experts must evaluate the degree of sustainability of projects throughout their life cycles, considering nine concepts: sustainability approach, construction systems, materials, bioclimatic strategies, active systems and equipment, solar systems, water, vegetation, and waste.

Off-site construction offers many sustainability benefits, including environmental, social, and economic aspects, as explained in Section 2.2. It is likely that these advantages, along with the quick assembly process, contributed to most teams opting for this construction method. Table 10 summarizes the evaluation criteria of the SDME sustainability contest.

Table 10. Sustainability contest evaluation criteria at the SDME.

	Criteria	Description
1	Sustainability and the project concept	Relationship between the general concepts of the house and sustainability, assessing the team's understanding of the sustainable built environment and how this understanding is incorporated into their project.
2	Construction system	Sustainability merits of the selected system, considering aspects such as water use, solid waste, time, recyclability, and health and safety.
3	Materials	Sourcing and the environmental impact of selected materials, also considering their content and possibilities for reuse or recycling, embodied energy, durability, and maintenance requirements.
4	Bioclimatic strategies	Application of passive design strategies to maintain a healthy and comfortable indoor environment, minimizing energy requirements.
5	Active systems	Selection of equipment, HVAC, and lighting systems that effectively maintain a healthy, functional, and comfortable indoor environment while minimizing environmental impact.
6	Solar systems	Evaluation of the thermal solar, PV, and energy storage systems, including their environmental benefits and impacts, as well as their energy recovery time, CO_2 emissions reduction, and durability.
7	Water	House and landscaping water conservation strategies, including low-flow or water-saving fixtures, high-efficiency irrigation solutions, greywater systems, water treatment, and water reuse.
8	Vegetation	Use of native and low-water-use locally adapted plants and low-maintenance solutions, as well as the use of plants, green walls, or roofs, to reduce the surrounding heat and the house's energy demand.
9	Waste	Waste reduction, collection, and management, as well as its reuse or recycling possibilities, during the project's construction, use, and end-of-life phases.

However, using an off-site construction method does not solve all the sustainability requirements. Therefore, all participating teams made a great effort to utilize materials with low embedded energy, apply passive design strategies, select high-efficiency appliances and systems, use environmentally friendly refrigerants, and integrate solar technologies. Additionally, their contemporary designs were adapted to the climate, responded to the Middle East's culture, and included reinterpretations of the valuable aspects of the region's vernacular architecture.

As a result, all the off-site construction projects in SDME 2018 achieved good to excellent scores in sustainability, averaging 85%. Indeed, the first four places corresponded to off-site construction houses (Figure 24). However, as clarified in Section 2.3, using off-site or modular construction methods does not guarantee that a building is more sustainable than a similar one built primarily on-site. This was also observed in SDME 2018; two houses constructed with intense on-site work received a higher score in the sustainability contest than some houses built using off-site construction.

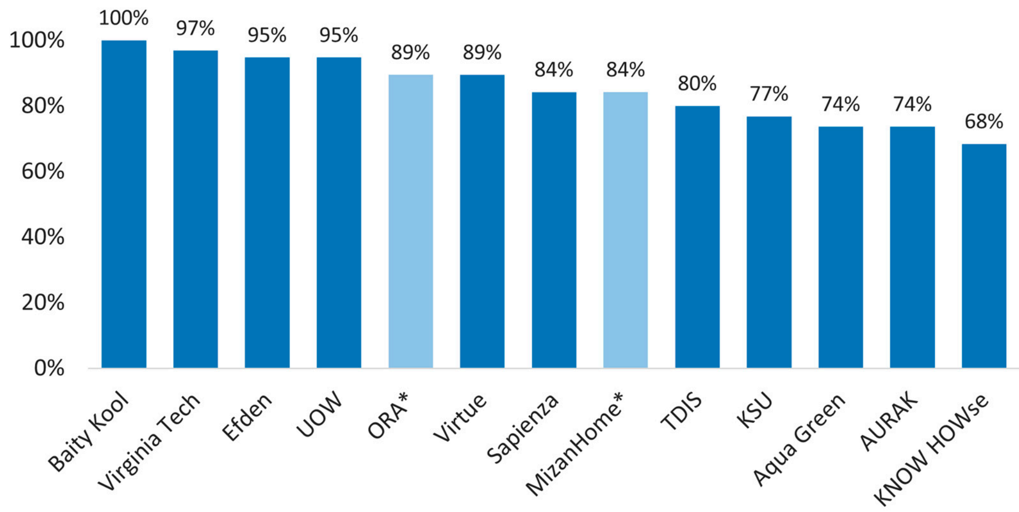

Figure 24. Sustainability score and ranking of the houses that used off-site construction in the SDME 2018. (Source: by authors from the result published on the SDME website). * The Teams ORA and MizanHome houses required intensive on-site work; thus, they are not part of the present study.

As shown in Figure 24, Team ORA, comprised of students from Herriot Watt University (Dubai and the UK), tied for the fifth position and outpaced six teams utilizing off-site construction. Meanwhile, Team MizanHome, comprised of students from the Islamic Science University of Malaysia and the University of Technology, surpassed five other teams.

6.5. Comparison between SDME 2018 Houses, Nearly Zero Energy Early Adopters in the UAE, and the Dubai Green Building Regulations

A critical aspect of sustainable zero-energy buildings is their thermal performance since it is responsible for most of their energy consumption and associated carbon emissions. Therefore, utilizing high-performance thermal envelopes that respond to the local climate is crucial. To gain a better understanding of the thermal envelope and energy performance of the case studies, this section compares these cases with the Dubai energy conservation code and two early adopters of sustainable zero-energy residential projects that were mentioned in the introduction: The Sustainable City and the Masdar City Eco-villa.

Dubai's applicable building code during the SDME 2018 competition was the Dubai Green Building Regulations Al Sa'fat, which was updated in 2017 [50]. This regulation aims to enhance the sustainability level of buildings and reduce their consumption by at least 30%. It comprises both mandatory and voluntary requirements, including a rating system. The Dubai Building Code was launched in 2021 [51], and aligned with this code, and the latest update of Al Sa'fat started to apply in 2023. These two new regulations further improved the previous codes. However, there have been no changes in the thermal envelope transmittance requirements (U-values of walls, roofs, floors, and glazing).

The Sustainable City (TSC) in Dubai was conceived as a low-carbon residential and mixed-use community. It comprises 500 villas, 89 apartments, and many facilities, including an urban farm, a school, a mosque, and recreational facilities [12]. Its villas incorporate passive strategies and highly efficient systems. The best performance was registered on the largest four-bedroom villas. They consume about 100 kWh/m^2 per year, 65% lower in electricity use intensity (EUI) than similar villas in Dubai. The TSC villas also have solar PV canopies that can generate up to 40% of their total energy demand. The fact that The Sustainable City is a successful real estate development means that the local market is prepared for nearly zero-energy houses.

The Eco-Villa in Masdar City offers a residence designed to meet a typical Emirati family's needs and expectations while being highly energy-efficient [11]. This house was constructed using insulated concrete forms (ICF) and includes high-efficiency equipment and energy management systems to maintain consumption below 97 kWh/m^2 per year. Most of the project materials (90%) were locally sourced. Moreover, its PV system can generate up to 102% of the house's energy demand.

As shown in Figure 25, the U-values of the exterior walls of SDME 2018, Eco-Villa, and TSC Villas are significantly lower than the Al Sa'fat rating system's upper limit for opaque surfaces. The U-value of the walls of the TSC Villas is more than 40% lower than the required maximum limit. However, the Masdar City Eco-Villa value, 0.16 w/m^{2}k, is even lower (Table 8). Indeed, this value also exceeds the stricter requirements of the Abu Dhabi Estidama rating system (0.320 w/m^{2}k). Additionally, the Eco-Villa walls' thermal transmittance is similar to that of the UOW house, which is also lower than in the three SDME 2018 cases. However, four SDME houses have the lowest values. The TDIS house stands out with its exceptionally low U-value thanks to combining closed-cell extruded polystyrene boards and vacuum insulation panels (VIP), as explained in Section 6.2.3.

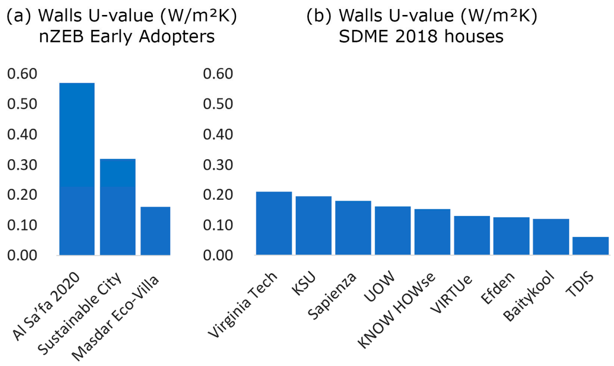

Figure 25. Wall U-value comparison between Dubai Green Buildings Regulations, nearly zero energy early adopters in the UAE, and SDME 2018 houses. (Source: by authors).

The roof's thermal performance is critical in tropical and sub-tropical areas due to the high sun exposure and the high angles. As Figure 26 shows, the U-values of the TSC villas, Masdar Eco-villa, and the SDME houses again significantly exceed the requirements of Al Sa'fat. The roofs' thermal transmittance of the TSC villas is 30% lower than the Alsa'fat requirements. This value is even lower in the SDME houses. As with the walls, the lowest value was achieved by the TDIS house. It is essential to explain that the roofs of the SMDE houses are shaded by PV panels, roof terrace canopies, and roof gardens. The protection from solar radiation and the use of highly reflective finishes drastically reduce the overheating of their roofs, improving the energy performance of these houses.

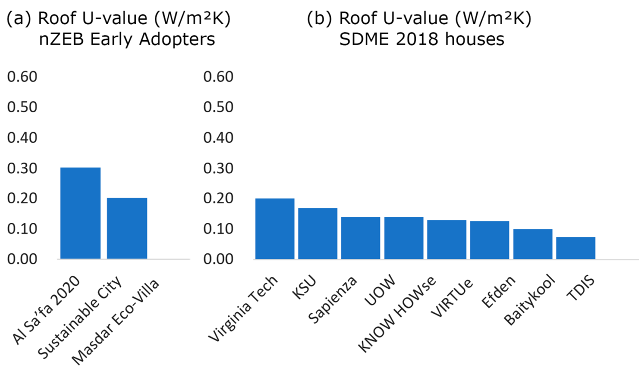

Figure 26. Roof U-value comparison between Dubai Green Buildings Regulations, nearly zero energy early adopters in the UAE, and SDME 2018 houses. (Source: by authors).

On the other hand, Table 8 shows that the U-values of the floors in all the SDME houses were notably lower than those in the TSC. In buildings located in hot arid areas, glazing is a critical element since it is the major contributor to indoor overheating, not only due to its thermal transmittance but also from direct solar gains. Table 11 shows that the windows' U-values in the TSC and UOW houses are more than 30% lower than the required levels. The values of these houses are 1.3 and 1.4 (w/m^{2}k), respectively. These values are sufficient in buildings with an appropriate window-to-wall ratio. However, some SDME teams went further, using triple-glazed windows with inert gas filling, low emissivity coatings, and low thermal transmittance frames, reaching U-values as low as 1.0 w/m^{2}k.

Table 11. Comparison of the thermal envelopes of SDME 2018 houses, two nearly zero energy early adopters in the UAE, and Dubai Green building Regulations (Al Sa'fat).

	Name		U-Value	(W/m^{2}k)		
			Opaque		Transparency	SHGC
		Wall	Roof	Floor		
Dubai Green Building Regulations	Al Sa'fat	0.570	0.300	-	2.100/1.900	0.350/0.280/0.220
Sustainable nZEB	The Sustainable City	0.320	0.200	1.300	1.300	-
Early Adopter	Masdar City Eco-Villa	0.160	-	-	-	-
SDME 2018	Viginia Tech	0.210	0.100	0.140	-	-
	KNOW HOWse	0.153	0.169	0.309	1.666	0.450
	KSU	0.195/0.192	-	-	1.533	0.270
	Sapienza	0.180	0.130	0.280	1.000	-
	UOW	0.161	0.200/0.164 [a]	0.163	1.400	-
	Virtue	0.133/0.127 [b]	0.127	0.131	-	-
	Efden	0.126/0.133	0.126	0.193	1.000	0.280
	Baity Kool	0.120	0.140	0.160	-	-
	TDIS	0.060	0.075	0.072	-	-

[a] U-value of tilted roof = 0.200 (w/m^{2}k), flat roof = 0.164 (w/m^{2}k). [b] U-value of north wall = 0.133 (w/m^{2}k), east west south walls = 0.127 (w/m^{2}k).

Due to the transparency of the glazing, it is also relevant to the percentage of solar energy that is directly and indirectly transferred indoors through it, which is known as the solar heat gain coefficient (SHGC). This parameter loses its criticality in cases like the SDME houses where the designer took special care to protect the glazing from direct solar radiation using architectural elements and shading devices. In any case, to use glazing with an SHGC value larger than the one prescribed in Al Sa'fat, the designer must demonstrate that the performance of their solution is equal to or better than the one required by the regulation. That is the case with KNOW HOWse with an SHSC equal to 0.45 and a code maximum requirement of 0.35 (low window-to-wall ratio). This house has no windows in the west and very low and well-protected glazing in the east and south. A porch and rolling shading protect these glazings. Other teams like Efden and KSU greatly surpass the code requirements, with SHSC equal to 0.28 and 0.27, respectively. The envelope of the two UAE's early adopters of sustainable nearly or zero-energy houses greatly exceeds the Al Sa'fat requirements, consuming 65% or less of a similar house in the Emirates. Comparing them with the SDME cases, it was found that the SDME houses' envelopes surpass those of the TSC, and almost half of them also surpass the Eco-villa characteristics. Additionally, unlike the TSC house and the Eco-villa, six SDME houses have ventilated façades that enhance the performance of their thermal envelope and keep it always shaded (Table 9). As a result of these factors, the SDME houses have better energy performance than these two high-performing comparison cases.

The quality of thermal insulation installation in walls, floors, and roofs is higher in a factory than on-site. This gives a thermal performance advantage to prefabricated and modular construction over traditional methods. Also, the support elements of the ventilated façades can be installed in the factory, significantly reducing the installation time on site. Additionally, exterior and interior motorized shading solutions can be integrated into 2D wall panels and prefabricated 3D modules.

6.6. Additional Solutions to Those Utilized by the SDME 2018 Houses

For most projects, integrating suitable passive solutions and using readily available finishing and insulation materials in the prefabricated panels and 3D volumes is sufficient to achieve the energy efficiency required for zero- and nearly zero-energy buildings. The SDME 2018 houses demonstrate numerous approaches and materials that can be employed to attain this objective. The previous sections presented some not-so-typical materials utilized by the SDME 2018, passing from advanced insulations and bio-composites to hybrid solutions with phase change materials (PCM).

However, for special situations, singular buildings, or developers that want to go further, there are other options not utilized by the SDME that can be integrated into 2D and 3D offsite construction elements that can be appropriate for desert environments and cities such as Dubai with higher relative humidity than other hot arid areas. Table 12 includes some solutions that might apply to specific projects and can be integrated into prefabricated building volumes or 2D components.

Table 12. Additional solutions that can be integrated into prefabricated 2D panels and 3D volumes.

Category	Solutions
Responsive shading	Integrated into the 3D volumes and 2D wall panels are responsive shutters and solar protection devices that move, change, or adjust themselves as required. Use of dynamic solutions inspired by nature—biomimicry building envelopes.
Interior finishing	Integrate phase change materials (PCM) into the indoor boards to add dynamic thermal mass. Reduce the CO_2 levels of the interior spaces, including CO_2 adsorption materials as well as super-porous materials. The prefabricated elements can also utilize natural materials with humidity-control capabilities.
Advanced insulation	In addition to vacuum insulation panels (VIP) and insulation with aerogel utilized by SDME 2018 houses, prefabricated envelope elements can use other high-performance insulation, such as gas-filled panels (GFP). They can also use insulation enhanced with nanomaterials. For example, lightweight and highly effective insulation materials can be created using carbon nanotubes.
Dynamic glazing	Integrate photochromic or electrochromic glazing into the prefabricated panels and modules. Also, PCM, or polymer-filled glazing, can be integrated.
Renewables integration	Seamless integration of photovoltaic (PV), solar thermal, photovoltaic thermal (PVT), as well as daytime and night radiative cooling technology into prefabricated walls, roofs, or 3D modules.

7. Conclusions

Aiming to explore the possibilities of developing off-site-constructed sustainable zero-energy houses for arid climates, eleven 2018 Solar Decathlon Middle East (SDME) projects were utilized as case studies. These projects used a variety of off-site solutions, allowing the authors to conduct interesting cross-case research. The study analyzed the construction category, type of solution, and primary structural materials, as well as their thermal envelope, façade types, and non-structural materials.

It was found that the type of transportation greatly influenced the selection of off-site construction systems. For instance, one of these five projects with only land transportation was the only one that used precast concrete panels. Also, three of these projects were the only ones that utilized large 3D modules. In contrast, all the maritime transported projects opted for hybrid systems. These systems took advantage of the less intensive on-site work of the 3D modules and the transportation benefits of 2D elements. In these cases, the teams constructed 3D modules only for the spaces that required the most intensive work and included more equipment, such as kitchens, bathrooms, and technical rooms. Unfortunately, this information about the energy consumed in the transportation and construction of the SDME 2018 houses is unavailable.

Nine projects were built using lightweight solutions, and eight were constructed using only dry construction techniques. Dry construction increases the sustainability of the designs, facilitating the reuse and recycling of the materials. The teams also selected their materials considering their sustainability level, preferring those with low environmental impacts. In connection with this, seven cases utilized timber as the primary structural material, justifying their selection based on the ecological advantages of this material.

Another way the sustainability level of their projects was increased was by adding sustainability and energy conservation parameters to the selection of the type, materials, and thermal performance of their projects' envelopes and by using passive design strategies such as self-shading and thermal mass. As a result, the energy performance and the hygrothermal comfort were excellent in the building simulation and during the competition's monitoring period. Nine cases reached a positive energy level, and the other two reached a nearly zero-energy level.

The SDME 2018 projects showcased different ways to apply prefabrication and modular construction to develop sustainable zero-energy buildings in hot arid climates. Their characteristics and performance surpassed the sustainable nearly zero-energy early adopter houses at The Sustainable City in Dubai. Similarly, they matched or exceeded the Abu Dhabi Masdar City Eco-villa, an excellent example of a sustainable zero-energy house.

It was found that the economic, social, and environmental benefits of offsite construction can be an excellent way to increase the sustainability level of the construction sector. These methods are not exclusive to one architectural style or specific construction materials, as seen in the SDME cases. However, it was also found that the fact that a building was constructed using off-site or modular construction methods does not necessarily mean it is more sustainable than a similar one built using more traditional solutions.

Two future research areas were identified through the present study's development. The first is related to the fact that many SDME 2018 teams utilized lightweight systems and timber structures for their lower embodied energy and reuse and recycling possibilities. However, lightweight construction is not typical in the Middle Eastern region, and given the lack of local wood sources, timber construction is not common either. Therefore, further research is required on the life cycle analysis (LCA) and life cycle cost (LCC) of lightweight and off-site timber solutions for the UAE and neighboring countries, including material transportation. The second comes from the interest of some teams in improving the use of concrete and other cementitious materials. More research must be conducted on optimizing their mixtures or wall compositions to obtain lighter and less carbon-intensive solutions.

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Appendix A. SDME 2018 Houses Occupancy and Energy-Related Tasks

During the ten days of competition, the houses were occupied from 8:00 a.m. to 8:30 p.m.; this time was extended during the three days the teams offered special dinners (dinner parties, as they are called in the SDME rules). Per the rules, at least three people will be inside the houses during the occupancy period (two team members and the SDME organizer observer). However, in most cases, more team members were inside the houses carrying out the tasks listed in Table A1, reaching eight or more during the dinner parties and the visits of the nine groups of juries.

Table A1. Summary of the teams' tasks and responsibilities during the ten days of competition. (Source: SDME 2018 Rules).

Teams' Tasks and Responsibilities	During the Competition (10 days)	Weekly Average
Maintain temperature, humidity, CO_2, and lighting levels	240 h	168 h
Use of TV and other house entertainment equipment	69 h (min)	48 h (min)
Use of computers	69 h (min)	48 h (min)
Maintain fridge and freezer temperature	240 h	168 h
Cooking tasks	7 times	5 times
Oven tasks	6 times	4 times
Special dinners for eight people	3 times	2 times
Loads of dishwashing machines	6 times	4 times
Hot water for showers 50 L	700 L (min)	490 L (min)
Loads of washing machine (using hot water)	7 times	5 times
Clothes drying	7 times	5 times
Turn on all artificial lights (interior and exterior)	33 h (min)	23 h (min)
Drive and charge an electric vehicle (EV)	430 km (min)	301 km (min)

Appendix B. SDME 2018 Houses PV Solar Systems

In addition to the most typical Building Attached Photovoltaics (BAPV), the SDME teams did their best to integrate the PV modules in their roofs, canopies, façades, and glazing. Table A2 summarizes the photovoltaic systems of these houses.

Table A2. SDME 2018 Houses' PV Solar Systems. All teams' PV system production was restricted during the contest period, limiting the inverters to 8 kW.

Team	Module Type	Modules Location	Orientation	System Size (kWp)
Virginia	Mono & polycrystalline Silicon	Roof & entryway window [1]	Top & South (vertical)	13.55
UOW	Monocrystalline Silicon	South facing part of the roof [2]	Top (South tilted)	10.4
BaityKool	Polycrystalline Silicon	Façades [1] (S, E, and W) & patio shading [1]	S, E, and W (vert.) & S (tilted)	7.34
EFdeN	Polycrystalline Silicon	Roof	Top	8.96
Sapienza	Mono HIT	Roof [1]	Top (South tilted)	10.56
VIRTUe	Thin Film (CIGS)	Roof [2]	Top (South tilted)	7.77
TDIS	Monocrystalline Silicon	Roof terrace canopy [1]	Top (adjustable tilt)	9.36
KNOW HOWse	Monocrystalline Silicon	Roof	Top	9.6
Aqua Green	Polycrystalline Silicon	Roof and terrace shading [1]	Top (south tilted)	9.6
KSU	Monocrystalline Silicon	Roof and patio shading [1]	Top (South tilted)	17.4
AURAK	Monocrystalline Silicon	Roof and patio shading [1]	Top (South tilted)	11.4

[1] BIPV (Building Integrated Photovoltaic). [2] BIPVT (Building Integrated Photovoltaic Thermal–Hybrid).

Appendix C. HVAC Systems of the SDME 2018

Table A3. HVAC systems installed in SDME2018 houses. The black rectangles indicate the HVAC systems utilized in each house.

Team	Cooling Only	Heat Pump	Centralized	Decentralized	ERV	HRV	R32	R410A	R134a	Air/Water	Air/Air	Single OD Units	Multiple OD Units	Non-Ducted System	Ducted Network	Chilled Water Network
Aqua Green	■			■				■			■		■	■		
AURAK	■			■	■		■				■		■	■		
KNOW HOWse		■		■					■		■	■		■		
EFdeN		■		■	■		■				■	■		■		
TDIS		■		■		■		■			■	■		■		
KSU		■	■		■			■			■	■			■	
Virginia Tech		■	■		■			■			■	■			■	
Baity Kool		■	■			■		■		■		■			■	
VIRTUe		■	■			■		■		■		■			■	
UOW		■	■		■			■		■		■				■
Sapienza		■	■		■			■		■		■				■

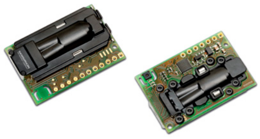
Appendix D. SDME 2018 Instrumentation and Monitoring

A significant part of the SDME competition's scoring is related to the houses' energy behavior, their capacity to maintain a healthy and comfortable indoor environment, and the correct execution of the tasks required by the rules. The SDME monitoring system is responsible for collecting these measurements (Table A4). The organization installs in each house a monitoring panel and all the necessary equipment (meters, sensors, wiring, and tripods). The monitoring panels are wall-mounted enclosures that contain data loggers, data acquisition modules, main electrical meters, internal memory, battery backup, and other components of the SDME monitoring system. The information collected by the monitoring system is readily accessible to the public in real time on the SDME website.

Table A4. SDME 2018 sensors and meters. (Source: SDME 2018 monitoring procedures).

Image	Type	Accuracy	Location
	Globe temperature (PT1000) Range (−5 to 60 °C)	Class B (DIN EN 60751) PT1000 ±0.3° C	Living room and bedroom (tripod)

Table A4. *Cont.*

Image	Type	Accuracy	Location
	Relative humidity and temp. sensor (temperature-compensated digital output)	RH 1.5% (typ.) Temp. ± 0.1 (typ. 20 °C to 60 °C)	Living room and bedroom (tripod)
	Multi-parameter ambient sensor CO2 range 0–10,000 ppm Temp. range: −40 °C to 120 °C RH range: 0 to 100%	CO_2 ±30 ppm ±3% Temp. ±0.5 °C, RH ±2%	Living room, kitchen, and bedroom (tripod)
	Ambient light sensor (with high-precision human-eye response)	<0.2% (typ. matching between ranges)	Living room and kitchen
	Insulated thermocouples Type J (exposed junction)	Class 1 (EN 60584-2)	Inside oven, fridge, freezer, clothes washing, and dishwashing machines
	Smart bidirectional energy meter Rated current: 63 A Frequency: 50 and 60 Hz	Class B (EN 50470) Class 1 (IEC 61557-12) Class 1 (IEC 62053-21)	SDME Monitoring Box (3 units) Houses electrical panels (2 units)
	Smart static ultrasonic water meter	Class 2—T30, T50: ±2% (range Q2 ≤ Q ≤ Q4)	Outside of the houses

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