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Innovation in Sustainable Solar-Powered Net-Zero Energy Solar Decathlon Houses: A Review and Showcase

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Abstract: Solar Decathlon is a showcase of cutting-edge residential buildings containing innovative solutions and technologies. This study reviewed, identified, and categorized technological innovations from past Solar Decathlon competitions. The review was based on publicly available data of the top five houses from each U.S. and international Solar Decathlon competition. The most prolific innovations identified were from building services systems and architectural design and construction. It was observed that most innovations within building services systems were in heating, ventilation, and air-conditioning, and home automation, while architectural design and construction innovations focused on building adaptability, façade, structure, and building materials. It was found that although there is no fixed relationship between the numbers of innovations in the houses and their overall competition points, there is a high probability for an innovative house to be placed within the top five houses. This study also provides information about technological innovations within Solar Decathlon houses and offers an innovation classification scheme to guide Solar Decathletes to understand what innovations could be implemented in their future entries.

Keywords: technological innovation; sustainability; architectural innovation; construction innovation; building services innovation; building; net-zero energy; Solar Decathlon

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1. Introduction

1.1. Innovation

Sustainable development is part of the solution to high resource consumption in the building sector [1]. Hence, engineers in the building and construction industry need to think more innovatively to achieve sustainable development. Innovation enables companies to increase competitiveness [2,3], grow market share [4], and avoid lagging behind international perspectives or disappearing [3].

Eurostat and the Organization for Economic Co-operation and Development (OECD) jointly developed the "Oslo Manual" in order to study innovation [5]. Early editions of the manual focused on technological innovation in manufacturing from a product and process point of view, and later in 2005, organizational innovation was added. Based on this manual, the definition of innovation used through this research is "the implementation of a new or significantly improved product, or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations" [5]. The international Solar Decathlon (SD) competition houses were used as the data source in this study, since SD is a platform for implementation and showcase of technological innovations within the building and construction sector.

1.2. Solar Decathlon

SD is an international competition that challenges students to design, build and operate full-size solar-powered sustainable homes. Students involved in the project ranged from the undergraduate through to the Ph.D. levels from different disciplines. The SD competition, first held in 2002 by the U.S. Dept. of Energy, has intended to provide communities with information and education about opportunities and advantages of clean energy products for designing and building sustainable and high-energy efficient solar-powered houses and help encourage the implementation of net-zero energy homes. The competition is a showcase of affordability and comfort that combines energy-efficient construction and appliances with the renewable energy systems available today [6].

In SD, each house is judged based on 10 sub-contests (thus the term decathlon). Between 2002 and 2019, 16 competitions were held across nearly all continents. The location and innovation sub-contest detail for each competition are summarized in Table 1.

Table 1. Solar Decathlon competitions' sub-contests related to innovation. The asterisk indicates competitions that were considered for the analysis in this study.

Solar Decathlon Competition	Sub-Contests or Sub-Contest Component (Innovation Related Points/Total Points)
Europe 2019	Innovation & Viability Sub-contest (100/1000)
Middle East 2018 *	Innovation Sub-contest (80/1000)
China 2018	Innovation Sub-contest (100/1000)
U.S. 2017 *	Innovation Sub-contest (100/1000)
Latin America 2015	Viability & Innovation Sub-contest (100/1000)
U.S. 2015 *	No specific innovation contest criteria
China 2013	No specific innovation contest criteria
Europe 2014 *	Innovation Sub-contest (80/1000)
U.S. 2013 *	No specific innovation contest criteria
Europe 2012 *	Innovation Sub-contest (80/1000)
U.S. 2011 *	No specific innovation contest criteria
EUR 2010 *	Innovation Sub-contest (80/1000)
U.S. 2009 *	No specific innovation contest criteria
U.S. 2007 *	No specific innovation contest criteria
U.S. 2005 *	No specific innovation contest criteria
U.S. 2002 *	Presentation & Simulation (15/1100), Comfort zone (30/1100), Refrigeration (30/1100), Hot water (30/1100), Lighting (20/1100)

1.3. *Importance of Innovation in the Solar Decathlon Competition*

SD is an innovation-based competition with multiple aims: (i) challenge students to develop innovative solutions; (ii) encourage professionals to reduce the environmental impact of their buildings by selecting the best materials and technologies; and (iii) educate the public about renewable energy, energy efficiency, responsible energy use, and available technologies in these areas [7]. SD is also a good way for government agencies to support/seed innovation [8]. In the SD competition, innovation is embedded in all project areas such as engineering, energy production, construction, and architecture [6–12]. Although innovation is important in SD contests, there is a lack of studies that highlight and summarize the innovations arising from SD competitions.

Innovation is increasingly becoming an important factor for the success of a project. While studies such as [13,14] have reviewed specific innovative technologies in buildings, this paper is the first to document and analyse the concept of innovation in the SD competitions and offer a new classification method for technological innovations. It is expected that the findings obtained from this study can be used to facilitate the development and implementation of innovations in future Solar Decathlon competitions and innovations in the built environment.

2. Method for Analysis and Classification of Innovation

The proposed methodology for analysing the data on innovation from past SD contests is a qualitative research method using thematic analysis [15,16]. For this process, as there were approximately from 12 to 22 teams in each competition and there have been 16 competitions since the inaugural event in 2002, the scope was limited to the top five ranked houses (by the competition points). The documents used for undertaking this research were: U.S. Dept. of Energy Solar Decathlon web-page [6], contest codes/rules [17–24], and reviews [8,9,25] available from the various competitions as well as reports and house manuals from individual entrant web-pages, academic papers, and multimedia.

In order to analyse the data, general themes of the innovative technologies were first categorized and then applied to the individual SD house (Top 5). In the last step, the data was analysed by finding the number of innovations in each house and calculating the percentage of each innovation in the two main classifications of "building services" (BS) and "architecture and construction". The detail of the analysis is provided in Figure 1 and discussed in the following sections.

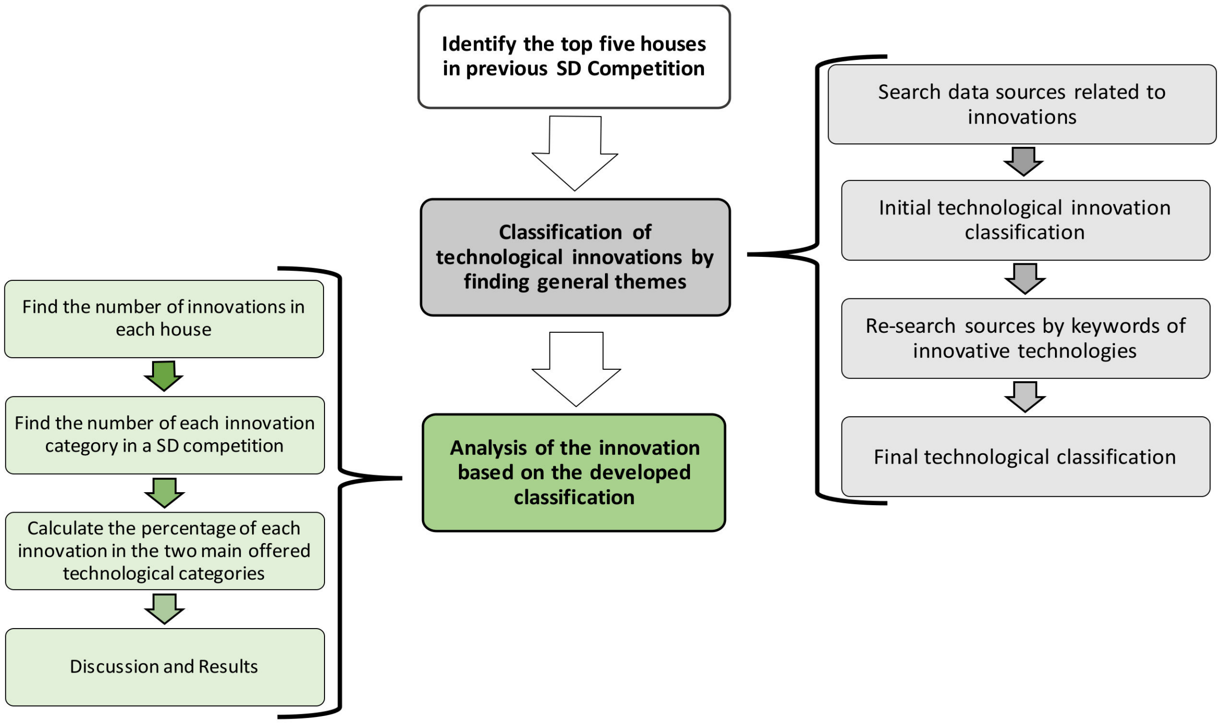

Figure 1. Data analysis methodology used in this study.

3. Analysis of Solar Decathlon Competitions 2002–2019

3.1. Innovation Concept from the Perspective of Time in SD Contests

From the perspective of time, the competition process can be divided into four temporal phases of pre-contest, competition development, contest period, and post-event (refer to Figure 2). The first phase can contain innovations in the conceptual design, name, and marketing of the house. Innovations in this phase determine the qualification to enter the competition. This is followed by the development and implementation phase, which stretches from early development to prototyping. In this phase, almost all elements such as communication, architecture, and building services are involved. This is followed by the period in which contestants build and operate the house at the competition location. The post-event phase mostly involves communications; however, there can be a major innovation in the destination of the house after the competition. Considering all these phases, the most significant opportunity for major technological innovations occurs in the development and implementation phase.

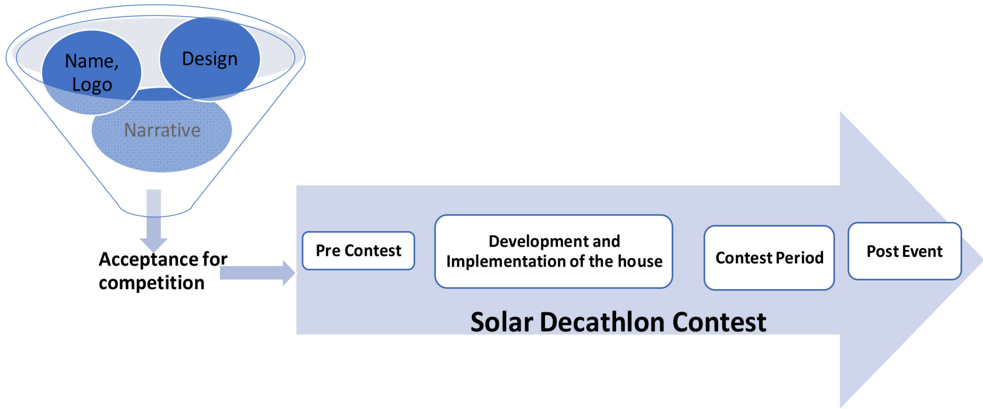

Figure 2. Innovation from the perspective of time during the SD Contest.

3.2. Innovation Concept from the Perspective of Judgement in SD Contests

In all SD competitions, the houses were judged based on 10 sub-contests. These sub-contests vary from one competition to another, and scores or judgment categories also change. Generally, the five sub-contests of architecture, engineering, energy balance (efficiency), thermal comfort, and house functioning have remained in all competitions.

There are various scoring methods for sub-contests: successful completion of tasks (e.g., washing dishes, cooking, and laundry to simulate real-life activities); measuring performance and monitoring (e.g., meeting certain CO_2 levels, humidity, and temperature for thermal comfort); or expert jury perceptions. Jurors assess the house based on their expertise in the specific field in which specific measurements cannot, such as aesthetics, innovation, and design inspiration [9]. There were no fixed or certain identifiers for innovation judgement except for the expertise of the jury members.

Over the history of SD, innovation has been judged in two main ways: a scoring system (as part of a sub-contest or a separate sub-contest by itself); and special award. In the U.S. 2002 competition, "innovation and consumer appeal" was considered as part of the design presentation and simulation, comfort zone, refrigeration, hot water, communication, and lighting sub-contests. Innovation was not part of a U.S. SD competition sub-contest or a separate sub-contest until 2017. For the SD competitions held in other countries, innovation has remained a separate sub-contest, except for China 2013. Table 1 shows how the innovation judgment approach was changed over time from one SD to another. The innovation-related sub-contest has gained more attention and is considered a separate sub-contest in the last five SD competitions.

4. Review of Innovations in Solar Decathlon Competitions

The main innovations within the analysed SD contests, considering the top five houses, can be categorized as per Figure 3. This classification was developed through thematic analysis as explained in Section 2. As innovation into passive design features was previously analysed [26], the classification of technological innovation in the present study (from the subject of passive design) only considers building envelope, façade, and passive use of phase change materials (PCMs).

As shown in Figure 3, the two main categories of innovation are architectural design and construction and building services systems. In Sections 4.1 and 4.2, these classifications are evaluated by being applied to the cohort of the top five SD houses.

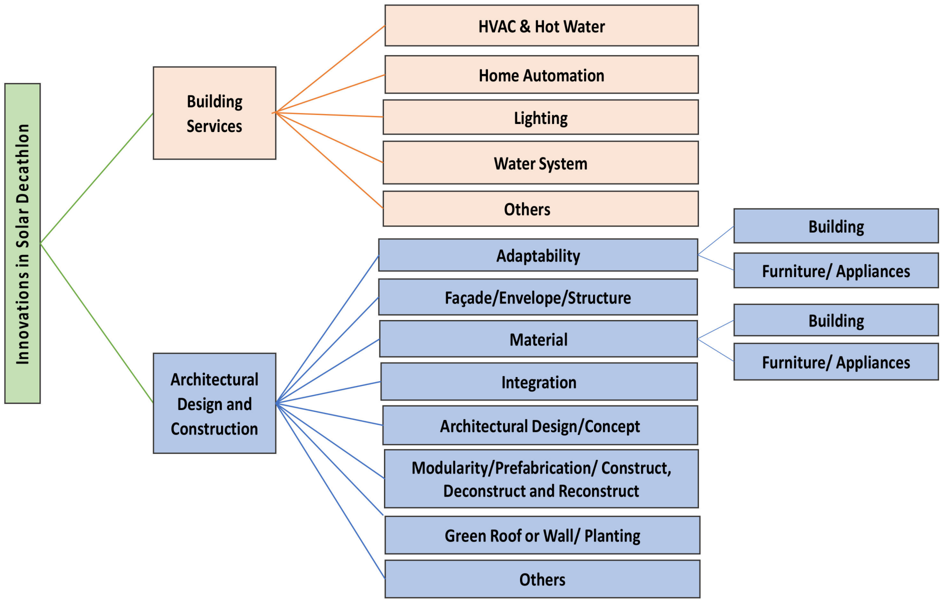

Figure 3. Classification of the technological innovations in SD competitions.

4.1. Innovations in Building Services

The abovementioned classification of innovations was applied to the cohort of the top five houses. Details of each classification are shown in Table 2. The percentage of each classified innovation within building services is shown in Figure 4.

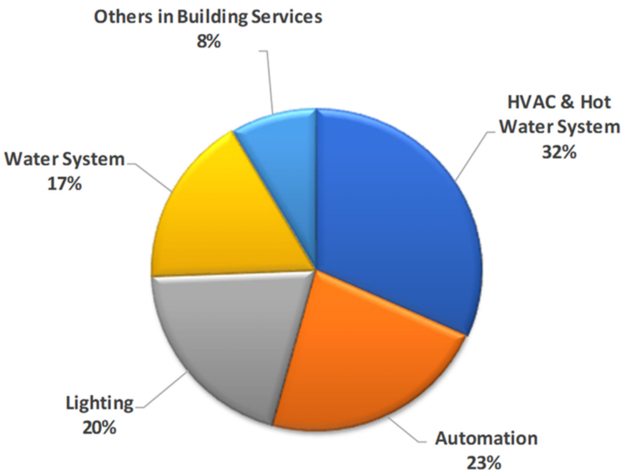

Figure 4. Building services innovations within the top five houses of SD competitions.

The highest percentage of innovations within building services has been in the area of heating, ventilation and air conditioning (HVAC) and hot water systems. This high percentage confirms opportunities for innovation in the HVAC area, and that innovative solutions are needed to maintain thermal comfort conditions while minimizing energy use. As an example, an energy-efficient HVAC system for the harsh desert climate of -Solar Decathlon Middle East (SDME) 2018 was difficult to design as HVAC systems are high energy users and mandatory for thermal comfort conditions. Increasing efficiency can raise the chance of success in innovation sub-contests. As such using a novel HVAC [27] system was key to the University of Wollongong Desert Rose Solar Decathlon house in winning the innovation sub-contest in SD Middle East 2018. The main innovations within the building services are presented in Table 2.

Table 2. Main innovations in building services.

Innovation Category	Main Innovations in Building Services	
HVAC & Hot Water System	• Energy recovery ventilator (ERV) unit, desiccant energy recovery ventilator (DERV) unit, heat recovery ventilator (HRV), [9,27–48] • Geothermal/ground source heat pump [8,9] • Radiant (cooling/heating) floor/ceiling [9,10,27,29,35,37–39,49–53]. • Evacuated tube solar thermal collector [32,33,38,41,54–56]	• Desiccant system: desiccant wheel, waterfall, desiccant cooling [27,30,35,36,57–59] • PCMs [11,27,29,34,36,40,41,45,47,50,51,56,60–67] • Other HVAC Creative Solution [8,39,58,59,68]. • Cooling/ventilation tower, evapotranspiration cooling [49,51,69,70]
Home Automation	• Control system senses conditions and takes inputs lighting, temperature, moisture, and CO_2 inside the house and adjusts mechanical systems accordingly by sending commands to receivers, motors, and valves, Controls shading, lighting, and HVAC systems [9,27,29,31,32,34,38,40,41,43–45,47–49,52,53,57,59,69–82]. • Predictive control strategies [27,41,47].	• Designed/produced gateways as a mediator between two different protocols [27]. • Smartphone/touch-pad applications allow for instant modifications such as energy use, and power up the house, usage of touch-pads [9,10,29,38,47,80].
Lighting	• Ambient natural lighting: skylight/Solatube/optical fiber/sky-wall (made of translucent aerogel allowing daylight into the interior spaces) [8,52,76,78,81,83–85]. • Light emitting diode (LED)/LED strip/LED framed in the plexiglass [8,9,27,36,42,43,47–49,51,57,60,63,69,70,74,78,79,86–88].	• Dimming features [44,52,57,82,89,90] • Lighting design, where switches with Radio Frequency (RF) emitters are used, along with RF adapters placed on the lights [78].
Water System	• Hydroponic wetland/garden [10,35,44,87,91]. • Recovering and harvesting of the rainwater [41,43,45,48,52,53,74,80]. • Aquaponics [49,80]. • Usage of natural domestic purifying plant/photo-ozonolysis/charcoal/bio-microbic recovering system [53,82,85]	• Grey/black water collecting/treatment and re-use: irrigation, flushing, etc. [27,36,39,40,43,45,47,48,52,59,70,74,79,82,85,91–96]. • Joulia shower: shower pan with heat recovery [37,41,52,97]. • Orbital system [47].
Others	• Hydronic dryer cupboard using the hot water generating from the sun for drying clothes [98]. • Zeolites in dishwasher [11,52]. • Hybrid application [30,79,99]. • Home smart sensors including face recognition able to activate operations within the house based on the people detected [70]. • Interactive/Smart mirror [47,48,59]. • Plug and play cable installation [27,100].	• Sun-tracking photovoltaics, which also serves as sunscreen on the rooftop terrace [41]. • Dye-sensitized solar panel [81]. • Innovative combination of the classical residual current device (RCD) and main circuit breaker (MCB) devices in the electrical system of the house, innovative RCD installation [79,100]. • Photoluminescent ceramic tiles [53]. • Luminous solar collector (LSC) [101]

As an HVAC system is a set of different technologies and components, innovation could occur at different levels. For instance, for the dissipation of hot air, a heat recovery unit was located behind the refrigerator by the University of Colorado in the U.S. in 2002. This engineering design was marketable as it used off-the-shelf technologies [8]. Auburn University designed and decorated a room of their house with large water-filled cylinders and used them as thermal mass to moderate the building temperature by staying cooler in the summer and warmer in the winter [8]. The idea of grouping appliances together on a specific wall was implemented by Virginia Tech University to not only use them as serving tools but also consider them as a thermal buffer [8]. Radiant floor heating [9], ground source heat pumps [8,9], and evacuated tubes for hot water systems [9,54] are among the technologies that have been used extensively and could be considered as the innovations at the time. An ERV [102] unit was used to minimize cooling and heating load. A custom manufactured DERV made of a non-toxic silica gel wheel, which exchanged heat and humidity between the intake and exhaust air was used by the Cornell University [28]. The liquid desiccant made up of calcium chloride mixed into the waterfall was an outstanding creative solution for controlling the humidity level in the house [57]. A prototype absorption chiller sized for residential use and designed to be tied up with the solar thermal system was a feature of the Santa Clara University HVAC system [103].

Phase Change Material has been applied in SD buildings in various ways to cool down or heat them up. Phase change gel was used under the floor as thermal mass by Universidad Politécnica de Madrid. The phase change gel helped heat the internal area by realizing the thermal energy on a winter night (Figure 5-left) and cool the house on a summer night (Figure 5-right) [55]. The same technology was applied by the Team Deutschland through microscopic-sized phase change material as Micronal plasterboards in their house. More innovation related to the HVAC innovations can be found in the study conducted by Ma et al. [104].

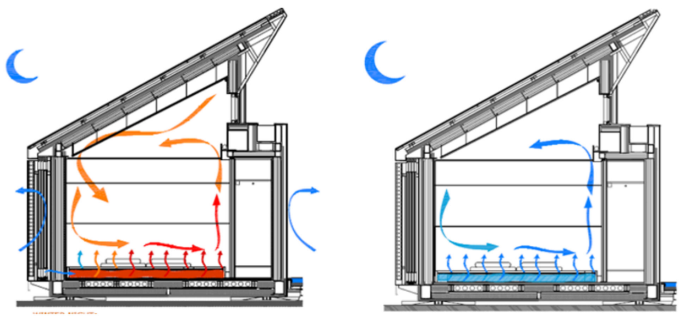

Figure 5. (**Left**): Winter night heating of phase change gel in the floor. (**Right**): Summer night cooling. Adapted from ref. [55].

Over the past SD competitions, innovations in automation systems have changed dramatically from simple controls to developed building management systems (BMS). In the U.S. in 2005, Cornell university used an automatic computerized control system for an ERV and its HVAC system [9]. Recently, the University of Wollongong's automation systems used KNX and digital addressable lighting interface (DALI) lighting protocols systems integrated with the Internet of Things (IoT), implemented in the Solar Decathlon house for the SDME 2018 [27].

Lighting the house is an important feature in any building. The usage of electrochromic windows allowed occupants to block or let the sun's rays pass through. Applying small voltage to the electrochromic glass results in darkening or lightening the house [105]. One of the specifications of Santa Clara University in the U.S. 2007 was applying Solatube, an innovation in daylighting system. As shown in Figure 6, it transferred the captured sunlight from the roof and distributed it throughout the room [83].

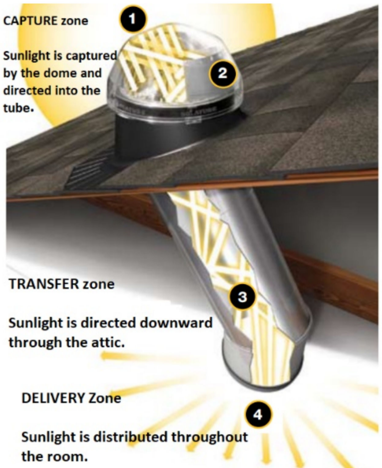

Figure 6. Solatube daylighting system. Adapted from ref. [83].

Auburn University skylight, which was filled with prisms to amplify sunlight for daylighting, was a different technique. Another interesting daylighting system was Skywall used by Virginia Tech. These outer walls were made up of a translucent aerogel material allowing daylight into the interior spaces [8,9]. The University of Virginia used a light-emitting diode wall as a climate control aspect [8]. This wall reflected the building's environmental condition through colour changes, showing whether the house is cool or warm.

Water is a precious and limited resource. Therefore, it is crucial to harvest, treat and reuse water. Many innovative solutions were implemented in the water waste systems and irrigation of the SD houses. As an example, water can be referred to as irrigation of the roof garden through the treated greywater from appliances [106]. More details about technological innovations in the SD houses are provided in Table 2. In conjunction with the innovations from building services, the second most significant collection of technological innovations came from architecture and construction, which will be discussed in the next section.

4.2. Innovations in Architectural Design and Construction

Applying the pre-offered classification shown in Figure 3 in the top five SD houses, the percentage of the categorized innovations in the architecture and construction was found and is presented in Figure 7.

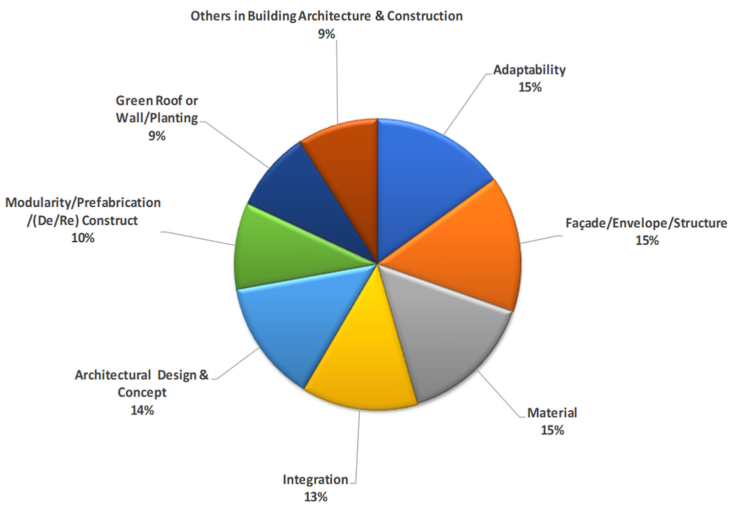

Figure 7. Architecture and construction innovations within the top five houses of SD competitions.

The main innovations for architectural design and construction are listed in Table 3.

Table 3. Main innovations in architectural design and constructions.

Innovation Category	Main Innovations in Architectural Design and Construction	
Adaptability	• Moveable roof/wall [9,27,57,82,107]. • NanaWall and shutters [9,42,45,80,108]. • Sliding/folding door/Photovoltaic panel/Screen [27,37,43,45,52,55,80,87,109]. • Automated awning system/curtain [41,75]. • Folding façade [79].	• Fold down-slide out/adjustable cabinets [10,47]. • Reconfigurable blocks/furniture/spaces such as workstation, bed, toilet, etc. [10,11,30,32,41,48,53,59,74,78,79,85,87,107]. • Two-faced/extended/combined (usage of rolling cart and locking caster) table [30,43,59,107].
Façade/Envelope/Structure	• SIP [9,32,40–45,47,110]. • Trombe wall [102]. • Integrated PV on façade [111,112]. • Large operable shutter [42,81]. • Sand/hemp infilled cavities in the building structure [11,52]. • Oriented strand board (OSB) [73,92]. • Exchangeable façade [41]. • Innovative skin wall [27,49,78]. • Ventilated façade [27,113]. • Bend-proof wooden rigid corner joints [114]. • Mashrabiyah shade screen [47].	• Circular façade of laser-cut holes with folded tabs, laser cut-innovative screen [72,95]. • Façade layer of nanogel filled polycarbonate panels [72]. • Zigzag/jagged façade structure [96]. • Vacuum insulated panel [11]. • Façade made of disused CDs [36]. • Lucido façade system [52]. • Texture façade [37]. • Structural bamboo (I-beams)/Lamboo frame [29,57,115].
Material	• Aerogel material [8,70]. • Bamboo, spruce, hemp, veneer, cork, compressed wheat straw/sawdust, soybean, pine, cellulose wadding, oak wood [9,27,29,39,45,52,62,73,79,85,92,116]. • Durable and water resistance composite materials adapted from the boating industry [42]. • Texsteel (magnetic and conductive) [11]. • Innovative cement [83].	• Milk bottles [57]. • Recycled steel, stone, glass, wood, aluminium [27,49,53,57,69,79,117]. • Harvested timber [36]. • Reclaimed wood, redwood plywood [36,40,49]. • Innovative (crushed, hemp, recycled, foamed) concrete [27,41,57,99]. • Sustainable lyptus flooring [118]. • 3D printing material [47].
Integration	• Integrated solar panel and awning [8,9,47,48,106]. • Building integrated photovoltaic (BIPV) in different elements, such as shutters, façade, roof, etc. [27,29,37,41,42,48,49,56,57,79,81,99,100,119,120].	• Integrated solar shingles [64]. • Bifacial PV in the façade [45]. • Integration of the evacuated solar collectors in the envelope [121].

Table 3. *Cont.*

Innovation Category	Main Innovations in Architectural Design and Construction	
Architectural Design and Concept	• Core concept [9,11,40,45,53,79,99]. • Onion-like design [57]. • Skin system design blended in the green house [78]. • Single-room house [111]. • Butterfly roof [122,123]. • Health-related designs [27,118]. • 'Dry-flood-proofing' approach design [42]. • Design of self-supporting, custom-made ceiling elements used for distribution of conditioned air [81].	• Conceptual landscape design [124]. • Saferoom design [59]. • Loggia with the modern application [53]. • A bent tubular design which controls the light entry [29]. • Home as a place of food production [43]. • A penthouse design as a solution to the city restoration and more living space in the old buildings [79]. • Greencourt [91].
Modularity/Prefabrication/De-Construction/Construction	• House on a chassis so it could be moved to and from the location of competition in one piece/usage of the transportation system, built into house structure [9,56].	• A container as part of the house [9]. • Prefabricated constructions, modular wall, roof [9,27,45,49,52,53,70,79,81,116].
Green roof or wall/planting	• Green roof, wall [9,27,37,48,55,64,70,71,81,82,85,115,125,126]. • Vertical farm [11].	• Greenhouse [43,78]. • Permaculture companion planting [91].
Others	• Composting bin with included worms in the kitchen [9,106]. • Triple/quadruple-glazed, krypton/argon fill, low-e film windows [27,29,49,62,85,89]. • Spider-shaped anchor for the anchoring system of the house [37].	• Heat-trapping planters, canning table [43]. • Composting toilet [81,91]. • Solar dryer [43,81,91]. • Electro-chromic windows [105].

The integration of solar panels in a building was an innovation as it is adding extra value, such as shading and insulation to the building, while providing electricity. As an example, PV awning acted as a shading element (Figure 8) [9]. Also, providing overhangs through PV on the roof shaded the south-facing windows, which let the tenants enjoy better indoor comfort by having winter sun and omitting summer solar gain [106]. One of the most innovative integrations of PV in the building (BIPV) was implemented by team Technische Universität Darmstadt through applying PV into louvered oak shutters around the building, which provided adjustable shading (Figure 9) [71].

Figure 8. California Polytechnic PV awning. Reprinted from ref. [9].

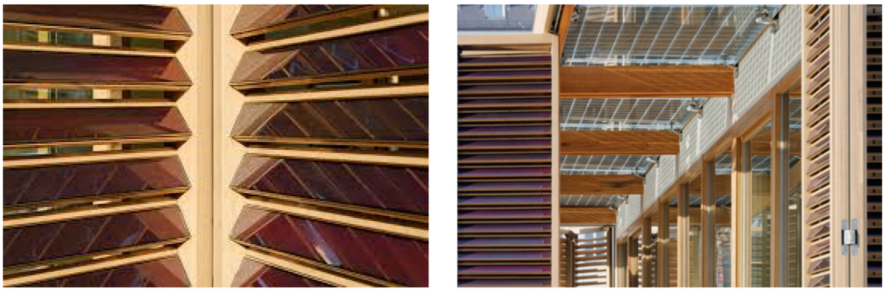

Figure 9. Technische Universität Darmstadt: (**Left**): BIPV in louvered oak shutters. Adapted from ref. [127]. (**Right**): BIPV awning. Adapted from ref. [128].

Moveable elements in the building could be considered innovative ideas. Moveable roof from [49] provided their house with the capability of adjusting openness and daylight entering the house. Moreover, NanaWall (i.e., a folding, rather than sliding glass wall between the living room and patio) provided a thermal seal as well as connected the interior and exterior spaces together [9]. Sliding doors and gliding room dividers [27] were other examples of moveable building elements that provide the building with more flexibility.

Usage of Structurally Insulated Panel (SIP) made up of various materials, as a primary building envelope/insulation, has been repeated [9]. The structure of SIP and materials used for its production can be considered innovative. Agriboard, a structurally insulated panel made of compressed wheat straw between two pieces of the oriented strand board [92], and BioSIP [129], were examples of SIP, as an innovative material for building construction used by the University of Colorado. More building construction system details can be found in the study conducted by Liu et al. [114].

Fast and economical ways to construct, deconstruct and reconstruct a building were another area for innovation. Prefabricated building structure [27] allows components to be built while minimizing the use of fossil fuels and construction logistics. As another solution, the New York Institute of Technology [9] used the transport shipping container to form the primary part of the house and contained the kitchen, bathroom, and mechanical systems. It included all the expensive components in a central core section. This prefabricated core was observed as adding market potential [9].

The selection of building materials played an important role in SD houses. The previously mentioned BioSIP, a patented wall type, was produced using lightweight but strong panels made from recycled materials which were filled with lightweight foam insulation (produced from soybean oil and waste paper) [9]. Usage of bio-fuel (bio-diesel) for transportation, as well as making furniture and tableware from natural materials such as soy, wheat, corn, and coffee [9] in civil and urban communities and cities can be considered as an innovation. Similarly, other material innovations included engineered wall panels, furniture, and cabinets using fast-growing woods from managed forests [129], and soybean-based insulation sprayed between wall studs, ceiling, and floor joists [92]. Innovative materials considering durability and sustainability included Lyptus [118] and bamboo flooring, and Trespa wall panels built by paper, wood fibre, and resin-based composite used for exterior and interior walls [116]. Homes have also featured a recycled milk bottle wall and structural bamboo I-beams [57]. Newly developed cement containing recycled material [83] is another example of innovation. More details on the skin material of the building have been offered by Zhang et al. [130] through case studies of Solar Decathlon Europe 2010.

Other innovations included: roof garden [9], green wall [49,70], usage of hydrogen fuel cell on the premises [9], composting bin with included worms in the kitchen [129], composting toilet [91], and Trombe wall [102].

The abovementioned innovations were identified and categorized. This classification could be used to develop the technological component of an innovation management framework.

4.3. Innovations at Solar Decathlon Middle East 2018

In November 2018, the Solar Decathlon competition was held for the first time in the Middle East. This competition was different from other Solar Decathlon competitions in terms of its location, where it was in a dry and humid climate of the desert. In the following section, some of the outstanding innovations of this competition are reviewed.

In SDME 2018, Virginia Tech University received first overall rank by presenting FutureHAUS, a prototype smart house built with smart construction techniques. The house was made of prefabricated modular structures that were pre-wired and pre-plumbed. These cartridges were designed in a way to be finished off-site and hooked up on-site using a plug-and-play assembly method [47]. The suites of the cartridges are shown in Figure 10. This assembly method using prefabricated cartridges could provide a construction project with minimal site pollution, fast construction, and accurate scheduling, timeline, and pricing.

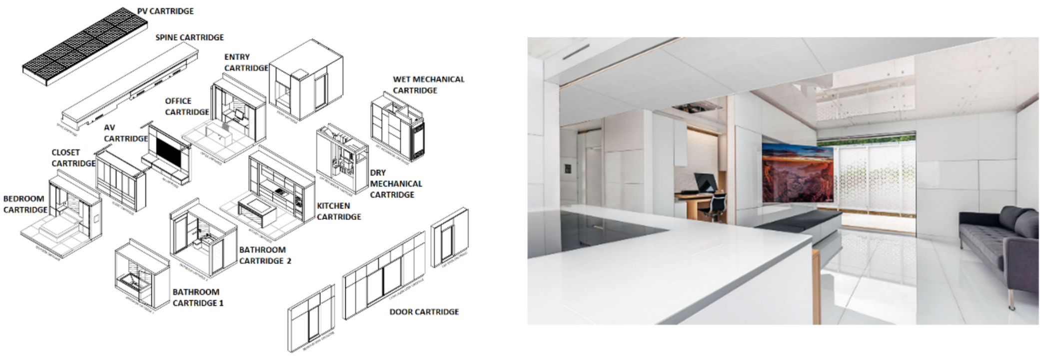

Figure 10. FutureHAUS. (**Left**): Suite of cartridges. Adapted from ref. [47]. (**Right**): Office and living room flex-space with rotating audio-visual (AV) wall, which could be moved mechanically. Reprinted from ref. [47].

The bathroom cartridge contained innovative features such as a smart mirror interface, a one-piece 3-D printed sink and countertop, and the toilet and vanity were height adjustable.

Team Virginia Tech implemented creative spatial flexibility in FutureHAUS called Flex-space. In this space, three program spaces of a home office, a bedroom, and a living room could be created through movable walls. The walls were powered by direct current (DC) through the conductive rail integrated to the house central spine cartridge which contained all home-run communication and electrical lines and all ductwork of the HVAC system. In the flex-space, the rotating AV wall shown in Figure 10 allowed the user to share the television and audio-visual technology between the living room and home office modes [47].

Team UOW from the University of Wollongong won second place in SDME 2018. Team UOW had a strong aim to change the way the world views homes for the elderly. Their innovative smart solar-powered Desert Rose was designed and developed to provide for occupants with age-related disabilities and diseases including dementia. The Desert Rose house innovative air to water HVAC system making use of on-site thermal storage and desiccant system provided the house with thermal comfort and suitable air conditioning based on the Dubai climate. The building integrated photovoltaic thermal (BIPVT) system of the house was innovative as they not only provided the house with electricity and hot water, they were also the roof structure of the house by themselves. The developed Model Predictive Control (MPC) was the major energy management strategy of the house. This MPC system along with the usage of KNX, DALI protocols, and IoT techniques led to the innovative smart automation system of the house. The digital water taps shown in Figure 11 include features like "tap on and off" functionality and free-spinning tapware. These novel taps could improve the quality of life for people with arthritis and dementia [131].

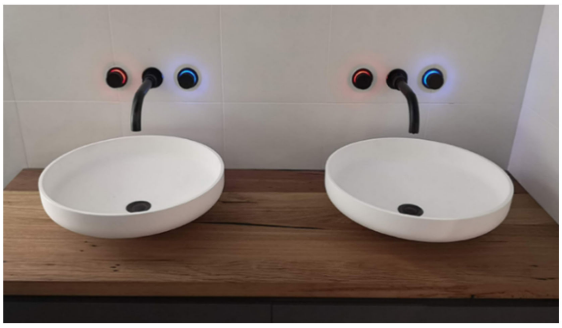

Figure 11. Innovative Desert Rose water tap. Reprinted from ref. [131].

In the Middle Eastern culture, having privacy is important. Considering this cultural aspect as well as reducing the heat gain from the harsh climate, an innovative façade was used. As an illustration, Team UOW Desert Rose house was wrapped by an innovative second skin wall made of a foamed concrete containing recycled crushed glass as a cement replacement. For the construction of this wall, instead of conventional steel reinforcement, carbon-fibre mesh reinforcement was used [27]. BAITYKOOL house, which won third place in the competition, had a similar envelope around it. This façade was made of ultra-high performance fibre-reinforced concrete [49]. The biomimetic solar cells [126] of this house were integrated in two different ways into the building. The first integration was within the façade and the second innovative way was BIPV in a movable roof over the patio. As shown in Figure 12, this movable roof could be closed and acts as a shading element throughout the day.

Figure 12. Movable PV integrated roof over BAITYKOOL house. Adapted from ref. [49].

A hybrid innovation was implemented in the water recycling system (Figure 13) of the BAITYKOOL house. The greywater could go through two ecological processes for filtration. The first stage was waste filtration through earthworms called lumbri-filtration, followed by treatment via Ultraviolet (UV) rays from the sun (bio-solar purification) [49]. The recycled water fed the ecosystems of the house, including the aquaponics system of the house for growing vegetables and raising edible fish.

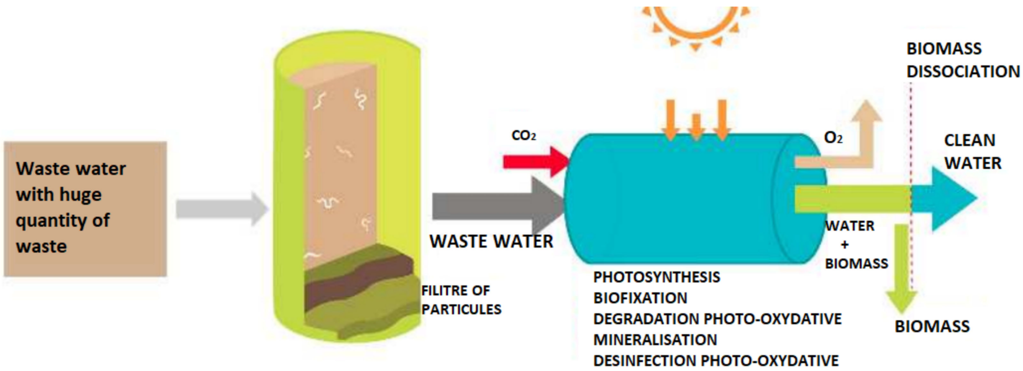

Figure 13. Greywater filtration of BAITYKOOL house. Adapted from ref. [49].

The Efden team won fourth overall rank in SDME 2018. They implemented hybrid innovative home automation based on energy efficiency and user experience. The automation system integrated the entire equipment into a programming logic controller (PLC), which runs the logic behind the automation scenarios. Integration of gateways for converting DALI to KNX and EnOcean to Modbus module made DALI and EnOcean compatible with the controller. A voice support system through which the occupants could use simple voice commands to find out the temperature and humidity of the house, access the lighting control system or operate the doors/windows open/closing mechanisms was created. This voice system was integrated into the automation via message queuing telemetry transport (MQTT)protocol; a Smart Mirror that displayed news, date and time, the weather forecast was developed. However, the most interesting feature about this mirror was the face recognition and understanding of the person's mood [48].

The University of Rome Sapienza implemented the concept of "innovative within tradition" by designing and building their smart solar house blended in with the Arab tradition and heritage. They combined a traditional internal patio with a green wall and a smart wall fountain integrated with the home automation system. Also, innovative augmentation of a wind tower (Figure 14) with an active air conditioning system was used. These combinations of modernity and tradition were implemented through an innovative building construction system with Cross Laminated Timber augmented with post-tensioning technique (Press-Lam), ventilated floor-wall connection technology, and innovative selective windows with advanced aluminium-wood frames enriched with aerogel thermal breaks [70]. The adaptive shading system with automated semitransparent light-reflective blinds and the car shading were other aesthetic innovative features of this house [70]. This electrical car canopy included a demonstrative off-grid PV system based on LSC [101] technology.

The above review showed that innovation has become an essential component in Solar Decathlon competitions to demonstrate how to use and implement innovative solutions and technologies to achieve net-zero energy consumption of solar-powered houses and how innovations assisted student teams in winning the competition.

Figure 14. Sapienza house with semitransparent blinds and the wind tower. Reprinted from ref. [70].

5. Discussion

As part of the innovative solution, flexible designs such as a Murphy bed, moveable roof, and wall have been developed, which provide the building and furniture with more flexibility and adaptability. Another key innovation is to find efficient and fast ways to construct, deconstruct and reconstruct SD houses. For example, prefabricated constructed components, modular designs that fit into a shipping container, usage of the container as part of the building, and number-coded prefabricated construction systems, which allow non-builders to construct a house and/or reduce the construction logistics, are among the methods being considered.

There is no linear or fixed relationship between the technological innovation features of an SD house and its overall ranking in the contest. However, it can be concluded that innovation can assist the house to stay among the top five. As an example, the University of Maryland participated in four SD competitions (2002-4th, 2007-2nd, 2011-1st and 2017-2nd). The innovations of their entries were radical and incremental. The liquid desiccant waterfall (LDW) system was first used in LEAFHouse in 2007; and later in 2011, the improved LDW was employed in the WaterShed house. Although each time their entry had innovative features, the overall rankings did not follow any trend (other than being highly rated) (shown in Figure 15). One reason is that innovative features do not necessarily help houses to function to competition requirements. Another reason is that the innovation concept is quite broad; contests, sub-contests, and judgment, as well as grading approaches, change from one SD to another. In summary, there is a lack of fixed/equal identifiers for innovation judgment.

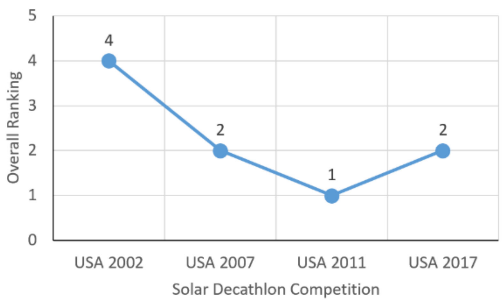

Figure 15. The overall ranking of the University of Maryland in four Solar Decathlons.

In SDME 2018, Desert Rose won first place in the innovation sub-contest and second overall. Figure 16 shows the details of the innovation sub-contest in that competition. Team Virginia Tech won the overall competition and Team UOW and Baitykool were respectively placed in the second and third overall. Figure 17 also confirms the abovementioned assertion in that there is no direct relationship between the ranking and number of innovations in the top five houses within any of the SD competitions.

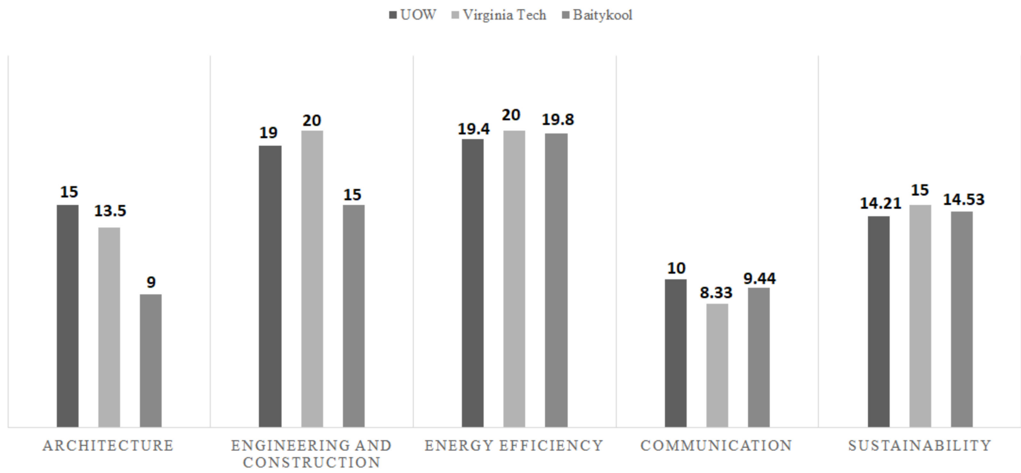

Figure 16. Innovation contest scoring for Team UOW and place getters in SD Middle East 2018.

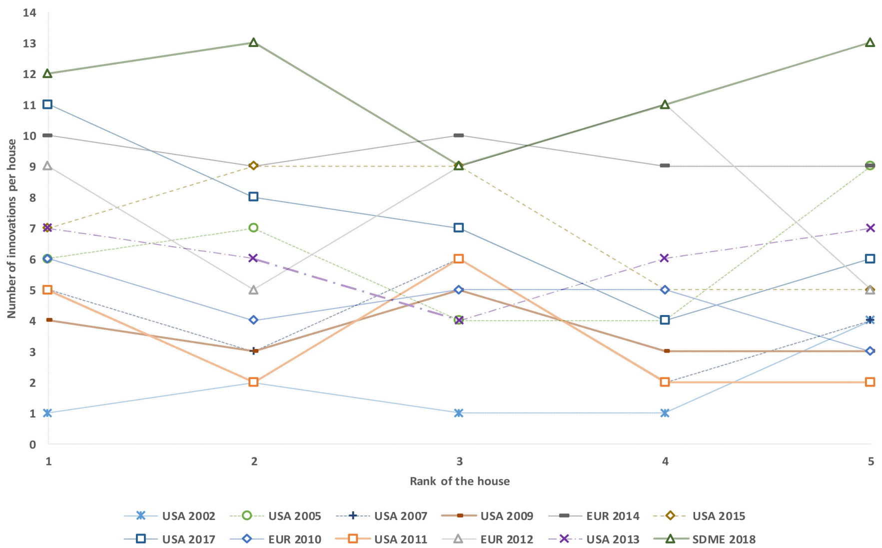

Figure 17. Innovations versus the ranking of the houses in the competition.

In general, it was found that the most innovations were implemented in HVAC, architectural design, adaptability of the building appliances to different lifestyles and climates, building materials, and integration of different features into the body of the building.

Figure 18 illustrates the number of total innovations in the first top-five houses in the SD competitions. Overall, before 2015, the competitions in Europe had more innovations than those held in the U.S. In recent years, the total innovations in the houses ranked 1st to 5th were increased. This could be due to the advances in technology innovations providing teams with easier and economical ways to implement their ideas. As discussed in the previous sections, SD competitions commenced in 2002, and this long history provides teams with more data and information compared to the teams in the early stages of competitions. Therefore, being more familiar with the process and rules of competitions can have an impact on the selection of a successful innovative idea or process of implementation. As an illustration, new teams are able to add values to a previously defined and developed innovative idea from the past SD houses, such as usage of DALI protocol for LED strips which was an innovation from early competitions, or integrating Google Home to the BMS of the house. Figure 18 also shows that most innovations occurred in the 1st-placed houses.

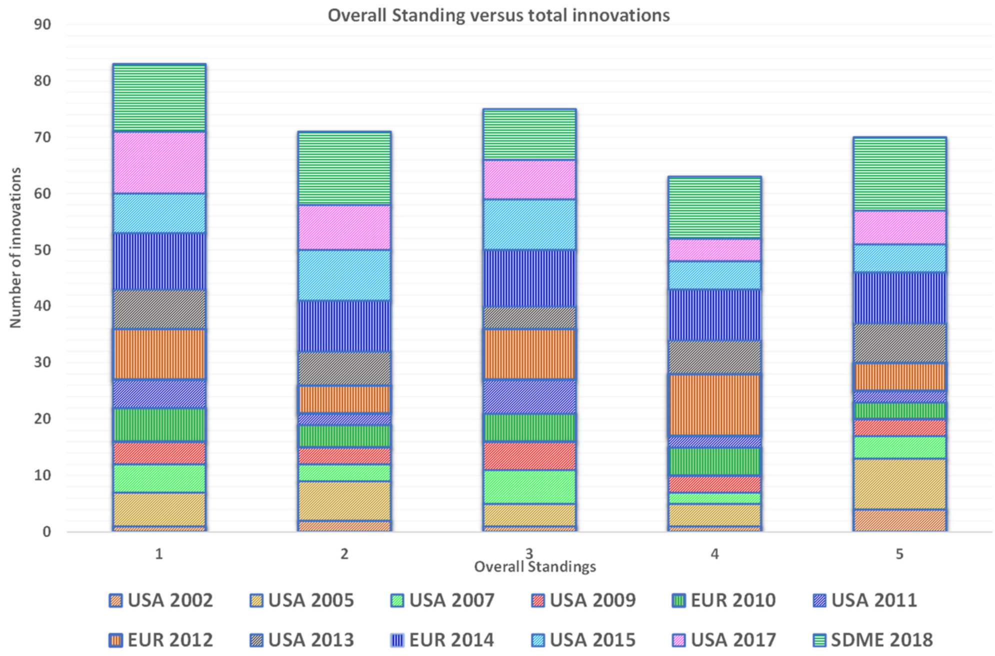

Figure 18. Overall standing versus total innovations in SD competitions.

As shown in Table 4 and mentioned above, more innovations were implemented in building services than those in architecture and construction. The innovation percentages increase as the competition time approaches the year 2017. This table has been compiled by considering only the top five houses in each of the SD competitions.

Table 4. Percentage of innovations in SD competitions between 2002 and 2018.

SD Competition	HVAC & Hot Water System	Automation	Lighting	Water System	Others in Building Services	Adaptability	Façade/Envelope/Structure	Material	Integration	Architectural Design & Concept	Modularity/Prefabrication/(De/Re) Construct	Green Roof or Wall/Planting	Others in Building Architecture & Construction
USA 2002	80%	0%	60%	0%	0%	0%	0%	10%	10%	0%	0%	0%	0%
USA 2005	100%	10%	40%	10%	0%	40%	80%	80%	40%	10%	80%	10%	60%
USA 2007	80%	60%	60%	0%	40%	10%	40%	0%	10%	10%	0%	40%	10%
USA 2009	100%	40%	0%	0%	0%	0%	40%	40%	60%	40%	0%	10%	10%
EUR 2010	80%	10%	40%	10%	10%	40%	60%	40%	40%	40%	40%	0%	10%
USA 2011	100%	80%	0%	0%	10%	40%	10%	0%	10%	40%	0%	10%	0%
EUR 2012	100%	80%	60%	80%	40%	60%	60%	100%	10%	60%	60%	10%	40%
USA 2013	100%	80%	10%	60%	0%	40%	40%	60%	40%	40%	10%	40%	10%
EUR 2018	100%	100%	100%	80%	80%	100%	80%	60%	80%	80%	40%	40%	10%
USA 2015	100%	80%	100%	80%	0%	80%	60%	40%	40%	60%	10%	10%	10%
USA 2017	10%	80%	80%	100%	40%	80%	10%	10%	40%	80%	40%	60%	60%
SDME 2018	100%	100%	100%	100%	80%	80%	100%	100%	100%	60%	80%	80%	80%

Innovation is a broad topic and its concept can change over time, i.e., a product which is considered as a novel technology this year, may not be an innovation in the next year. In some cases, adding value to previous innovations can result in a new product or service which will be an incremental innovation. Successful innovations may continue to be included in newly built houses.

It is worthy to mention that innovative technologies in a house are not limited to the building itself. As an example, building an electrical vehicle (EV) [132] charger can provide energy for electric transportation systems. SDME 2018 competition provided the competition teams with testing ground for new ideas in housing as well as urban planning and sustainable transportation. Therefore, the solar-powered houses are required to produce enough energy to cover the demand of the building and the eco-friendly vehicle. The energy consumption for EV chargers should be monitored and controlled through the BMS of the house. For instance, the Desert Rose house BMS is able to control and monitor HVAC systems, EV charger, windows, lighting, smart appliances and the renewable energy systems [27].

SD is a suitable vehicle for showcasing and making innovative prototypes as the scientific and business sectors can come together and make changes by offering prototypes that will be operated and tested during competition and prepared for market.

6. Conclusions

In this study, technological innovations in the top five ranked sustainable net-zero houses in the Solar Decathlon competitions have been analysed. This was completed by applying thematic qualitative analysis. Consequently, the final classification has been derived. The classifications identified the areas where technological innovations have happened the most. It was found that the innovations in HVAC and home automation were the most focused technological innovations within building services, while within architectural design and construction, most innovations were in the adaptability of the building to lifestyles and climates, façade and structure, and building materials.

Based on this study, there is no direct relationship between the technological innovation features of SD houses and their overall ranking in the competition. However, it can be concluded that innovation helped the student teams to be placed among the top five houses in the competition. For example, the Desert Rose house in the Solar Decathlon Middle East 2018 won first place in the innovation sub-contest; however, it received the second overall ranking. Also, it was observed in recent years, specifically after 2017, that the innovation percentages have increased. This can be because of the advances in technology which provide SD teams with economical and improved ways to implement their innovative idea. The greater usage of incremental innovations can be another reason for this increase.

In this review, a technological innovations classification was developed that is a suitable tool for researchers, building and construction sector practitioners, and future Solar Decathletes. The developed classification is a fundamental starting point for establishing standards for an innovative net-zero sustainable house. It can also be used for future solar decathlon judgment criteria (with respect to both identifiers and weightings). Furthermore, the classification is a key component for developing the technological component of a sustainability-oriented innovation management framework for buildings. Moreover, the offered innovation quantification shows where in the building and construction sector, innovative sustainable technologies are more needed and can be applied in order to address sustainable developments needs of this sector.

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Abbreviations

AV	Audio-visual
BIPV/T	Building Integrated Photovoltaic Thermal System
BMS	Building Management System
BS	Building Services
DALI	Digital Addressable Lighting Interface
DC	Direct Current
DERV	Desiccant Energy Recovery Ventilator
ERV	Enthalpy Recovery Ventilator
EV	Electrical Vehicle
HVAC	Heating Ventilation and Air Conditioning
HRV	Heat Recovery Ventilator
IoT	Internet of Things
LSC	Luminous Solar Collector
LED	Light-Emitting Diode
LDW	Liquid Desiccant Waterfall
MCB	Main Circuit Breaker
MQTT	Message Queuing Telemetry Transport
OECD	Organization for Economic Co-operation and Development
OSB	Oriented-Strand Board
PV	Photovoltaic
PCM	Phase Change Material
PLC	Programming Logic Controller
RCD	Residual Current Device
RF	Radio Frequency
SD	Solar Decathlon
SDME	Solar Decathlon Middle East
SIP	Structurally Insulated Panel
UV	Ultraviolet

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