Energy use in residential buildings for sustainable development: The fifth Solar Decathlon Europe revelations

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Research article

Energy use in residential buildings for sustainable development: The fifth Solar Decathlon Europe revelations

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ABSTRACT

This research focuses on achieving sustainable development in residential buildings with energy use. Under the influence of the energy crisis and related problems, research on residential buildings for less energy use has great potential. The literature review, according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses, and including VOSviewer analysis, shows the research is increasing and meaningful. Solar Decathlon buildings are used as the main objects in this research. The fifth Solar Decathlon Europe energy use technologies are examined through onsite investigation and online searching. The Analytic Hierarchy Process method for multi-criteria decision analysis is used for sustainability assessment. Moreover, the Ladybug and ClimateStudio plugins simulated respectively the annual solar radiation and the best angle for receiving it. The main findings show that 34 kinds of technologies used in these buildings can be classified into two categories in three directions. Passive technologies should be applied and prioritized, but generating renewable energy is also important. Some infrequently used technologies are not insignificant. The research shows that the combination of technologies decides sustainability performance, but the quantity used does not. Furthermore, energy use also needs to be balanced and coordinated in combination with architectural aesthetics. This research on energy use in residential buildings is beneficial for achieving sustainable development.

1. Introduction

1.1. Research background

Sustainable development has become a common goal worldwide. The United Nations agreed 17 Sustainable Development Goals (SDGs) in 2015. Goal 7 “Affordable and Clean Energy” and Goal 11 “Sustainable Cities and Communities” focus on energy and buildings, respectively [1]. They are the focuses closely related to this cross-sectional research about energy use in buildings [2].

From the energy aspect, the energy crisis and related problems are intensifying [3]. According to Our World in Data, the remaining

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years from 2020 of global coal, gas and oil are only 139, 49 and 57, respectively [4]. Since 2016, the International Energy Agency (IEA) has interlinked energy, air pollution and health issues in the World Energy Outlook [5]. Energy use is often accompanied by environmental pollution, which is harmful to human health, and in addition massive greenhouse gas emissions exacerbate global warming [6]. This results in climate change with frequent extreme weather, further prompting people to use more energy to resist problems such as overheating in summer, causing a vicious circle. Excessive energy use is not conducive to sustainable development and inefficient energy use also causes energy waste. Improper energy use and related problems should be reduced.

From the building aspect, buildings were responsible for 34 % of energy demand globally and 37 % of energy and process related CO_2 emissions in 2021 [7]. Even under COVID-19 in the last few years, global energy demand and emissions have declined [8]. However, there is still considerable potential for less energy use in buildings, in terms of reducing energy demand, improving energy efficiency and generating renewable energy [9]. The residential building constitutes the most significant proportion of all building types. The total energy consumption is higher than other kinds of buildings [10]. Globally in 2021, global residential buildings accounted for 21 % of total final energy consumption, more than twice the proportion used in non-residential buildings (9 %), and the direct and indirect global energy and process emissions (17 %) were also more than those of non-residential buildings (11 %) [11]. So energy saving on residential buildings is necessary and more effective [12–14]. This research aims to improve energy use in residential buildings to make contributions towards sustainable development.

In fact, lots of advanced research from the energy aspect has developed efficient energy management systems to achieve energy saving in buildings. For instance, Alhasnawi et al. developed an Improved Cockroach Swarm Optimization Algorithm (ICSOA) for reducing the cost of electricity and the peak-to-average ratio in apartments [15]; Tang et al. carried out the research using a hybrid optimization algorithm method and a scenario-based stochastic optimization technique to achieve a day-ahead energy management system [16], and Alhasnawi et al. proposed a novel economic dispatch using an improved butterfly optimization algorithm for the energy management of neighborhood smart buildings [17]. These research studies provide advanced guidance for building energy saving. Under these, the research starts from the discipline of architecture, using the fifth Solar Decathlon Europe (SDE) as a case study.

1.2. Research motivation

The fifth SDE [18], which comes from Solar Decathlon (SD) competition, is used as research object. Here, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure is used for systematic reviews. The PRISMA protocol is an evidence-based set of items widely used for academic research to enhance systematic reviews' transparency, consistency, comprehensiveness, and replicability [19–21]. The topic keyword of "Solar Decathlon" was searched on the Web of Science website. The preliminary screening found 230 related papers. After the exact selection related to this research, finally, 95 items of articles and

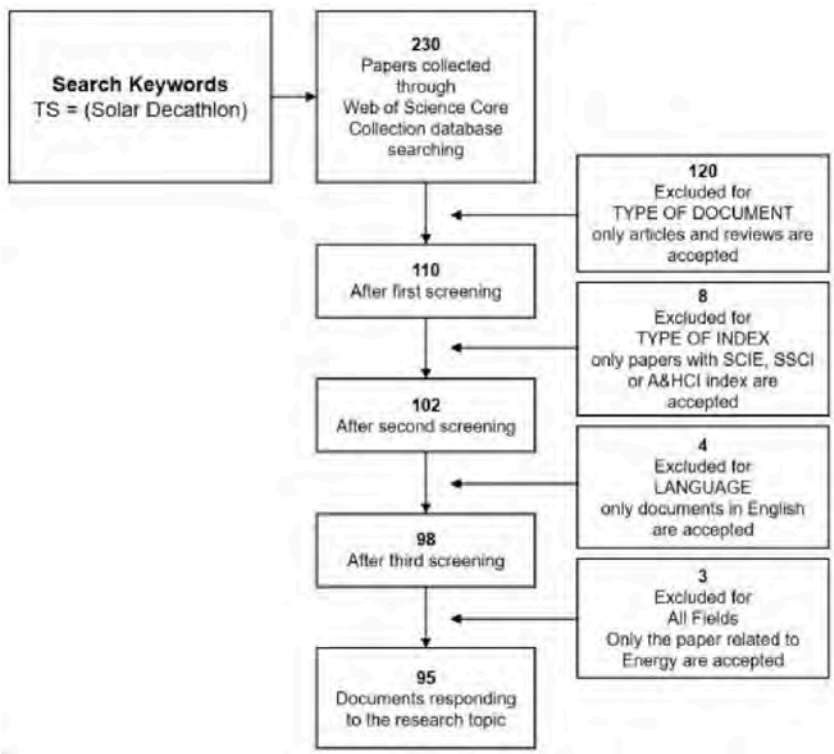


Fig. 1. PRISMA screening flowchart.

review with the index of “SCIE, SSCI or A&HCI” and writing in English by “Energy” classification were established (Fig. 1). According to the data of publication count with the year, Fig. 2 clearly shows the development of publications on SD research with time. The publication exponential trendline is going up overall. The first publication came in 2003, then papers were published every year from 2012. It is worth noting that in 2014, the related publications count reached a peak. This is mainly because of the first edition of the SDE show in 2010 and the following 2012 SDE, an open source that encouraged research and contributed 18 papers, helping publications reach 27 in 2014. Yu et al. defined SD from 2010 to 2011 as a mature period, from 2013 going to a promotion period, which echoed this situation to some extent [22]. With more and more research focusing on this, research on SDE’s residential buildings for sustainable development is needed (Fig. 2).

Moreover, the VOSviewer software analyzed the keywords “Sustainab* and Solar Decathlon” in 124 publications from the Web of Science. Similar bibliometric analysis software such as CiteSpace, SciMAT, VantagePoint, and so on also exist. However, there is no consensus on the best one [23]. VOSviewer is usually considered for mapping the co-occurrence of keywords [24]. The keyword co-occurrence with links shows that the main keywords of these papers are: sustainability, Solar Decathlon, buildings, energy efficiency, performance and so on (Fig. 3). The keyword “sustainability” strongly correlates to other keywords because the original intention of this competition is to achieve sustainable development. Furthermore, the competition’s theme is improving the energy efficiency of residential buildings. Therefore, the fifth SDE is taken as a case study that aims to explore creative and innovative knowledge for energy use in residential buildings, making important contributions to sustainable development.

2. Research objects

2.1. Solar Decathlon Europe

SDE comes from SD, initiated in 2002 by the United States Department of Energy (DOE) [25]. This university-level student competition aims to inspire the next generation of building professionals to design and build high-performance, low-carbon buildings powered by renewables [26,27], and was hailed as the Solar Olympics and the Green Building Expo [28]. Up to now, seven regions, including India without construction, have hosted a total of 25 competitions (Table 1) [29]. In Europe, this is the fifth SDE and the first one hosted in Germany.

For the detail of rules, the fifth SDE regulates the lot size as 18.0 m by 18.0 m with a close operation area of 18.0 m by 10.0 m. The operation area will be used as alleys and pedestrian paths during the competition phase. The height of each building is required to be at most 7.0 m. Moreover, the architectural footprint cannot exceed 150.0 m^2. The net floor area within the thermal envelope shall be at least 45.0 m^2 but shall not exceed 70.0 m^2 for one-storey units and 110.0 m^2 for two-storey units. The contests of SDE include ten separate scored contests with several sub-contests (Table 2). That is why the competition is named the decathlon. The combined approach of the Design Challenge and the Building Challenge is applied. Finally, the team with the highest total points out of 1000 will win the competition [30].

The final ranking, including jury evaluation, task completion, tests and monitored performance of the fifth SDE, is listed in Fig. 4. The ranking is the sum of the individual scores. RoofKIT got the first prize out of all the teams. VIRTUe got the second. SUM and AuRA tied for third place.

2.2. Residential buildings in the fifth SDE

In the fifth SDE, there were 18 teams from worldwide universities, but in the end, only 16 teams finished the competition due to COVID-19. Table 3 shows the information of each team, but some teams’ projects did not give a name. The competition site is located in

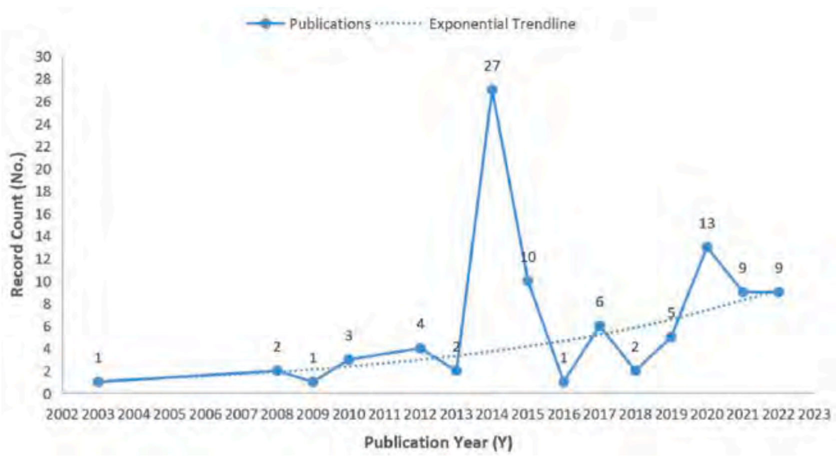


Fig. 2. Related publications trend chart.

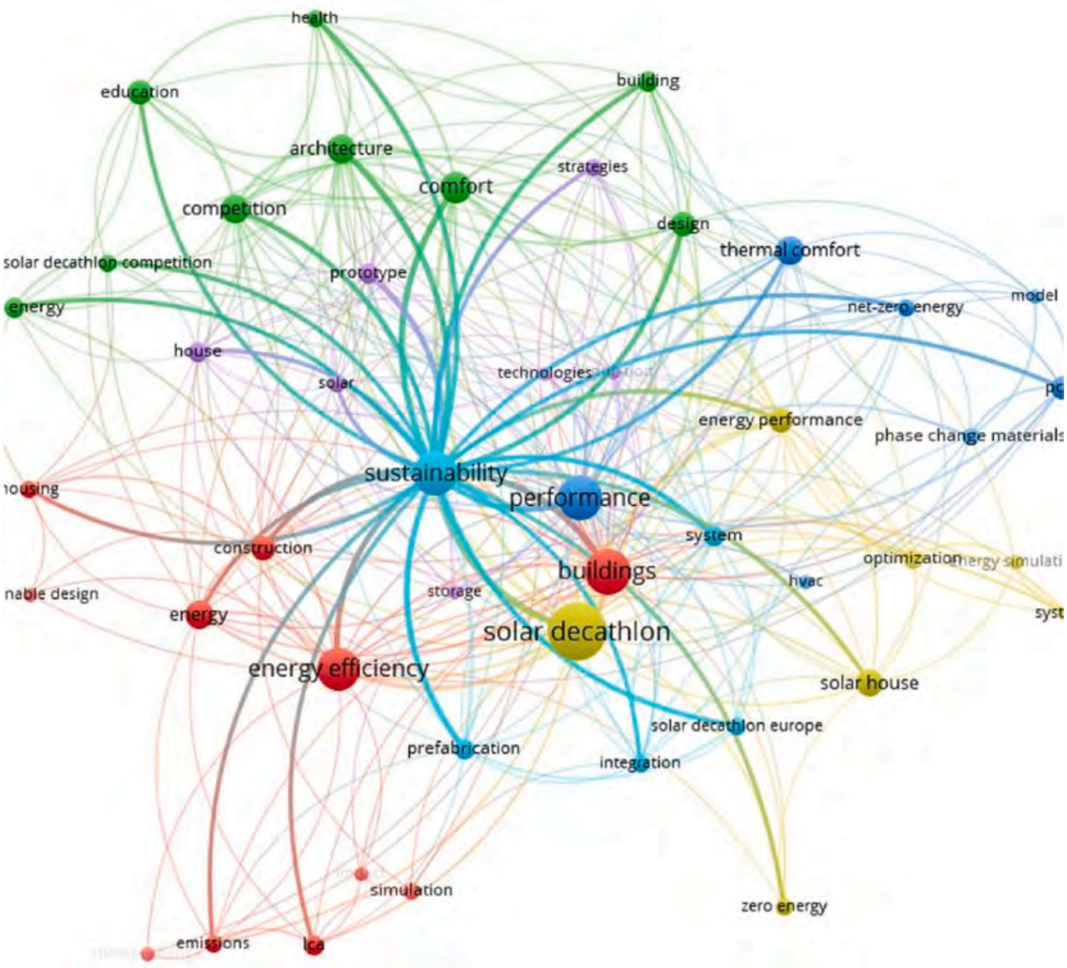


Fig. 3. Keyword co-occurrence with links of 124 papers.

Table 1
Global SD competitions.

Solar Decathlon Competition	Location and year	Times
Solar Decathlon US	Washington D.C. 2002, 2005, 2007, 2009, 2011 and 2013; Irvine (California) 2015; Denver (Colorado) 2017; Golden (Colorado) 2020.	9
Solar Decathlon Latin America and Caribbean	Santiago de Cali (Colombia) 2015 and 2019.	2
Solar Decathlon Europe	Madrid (Spain) 2010 and 2012; Versailles (France) 2014; Szentendre (Hungary) 2019; Wuppertal (Germany) 2021/2022.	5
Solar Decathlon China	Datong 2013; Dezhou 2018; Zhangjiakou 2021/2022.	3
Solar Decathlon Middle East	Dubai (UAE) 2018 and 2020/2021.	2
Solar Decathlon Africa	Ben Guerir (Morocco) 2019.	1
Solar Decathlon India	National Student Competition without Construction: 2020/2021; 2021/2022; 2022/2023.	3

Wuppertal, Germany. It is offset to the east by 26.5°. All buildings are arranged in two rows with aisles. Each building's entrance is facing the aisles (Table 4).

3. Methods

Based on the literature review of sustainable development in the context of the energy crisis and related problems, achieving less energy use has been an explicit goal worldwide. Accordingly, the fifth SDE's residential buildings are used as research objects. Related publications on previous Solar Decathlons were analyzed using PRISMA and VOSviewer software. The literature review shows that research on SD for sustainable development is increasing and needed.

Table 2
The fifth SDE rules.

Contests	Sub-contests	Total Points	Sub-contest Points	Evaluation Type	SDE21 Challenge	
					Design Challenge	Building Challenge
Architecture	site integration	120	20	jury	•	
	building design		60	jury	•	•
	interior & lighting design		20	jury		•
	solar system integration		20	jury	•	•
Engineering & Construction	energy concept	120	60	jury	•	•
	performance analysis		30	jury	•	•
	life cycle carbon footprint		30	jury		•
Energy Performance	energy consumption	120	30	monitoring		•
	energy balance		30	monitoring		•
	self consumption		20	monitoring		•
	PV system performance		20	monitoring		•
	grid interaction		20	task		•
Affordability & Viability	affordability	100	50	jury	•	•
	viability		50	jury	•	•
Communication, Education & Social Awareness	communication	80	40	jury	•	•
	education		20	jury	•	
	social awareness		20	jury	•	•
Sustainability	circularity	100	60	jury		•
	sufficiency, flexibility & environmental performance		40	jury	•	
Comfort	temperature	100	25	monitoring		•
	humidity		5	monitoring		•
	air quality (CO_2)		20	monitoring		•
	lighting		10	monitoring		•
	sound insulation		10	test		•
	air tightness		10	test		•
	performance gap		20	task		•
House Functioning	appliances	80	40	monitoring/ task		•
	water		10	task		•
	dinner		15	guest evaluation		•
	user friendliness		15	guest evaluation		•
Urban Mobility	mobility concept	80	60	jury	•	
	urban mobility tasks		20	task		•
Innovation	5 × 20 points	100	100	jury	•	•

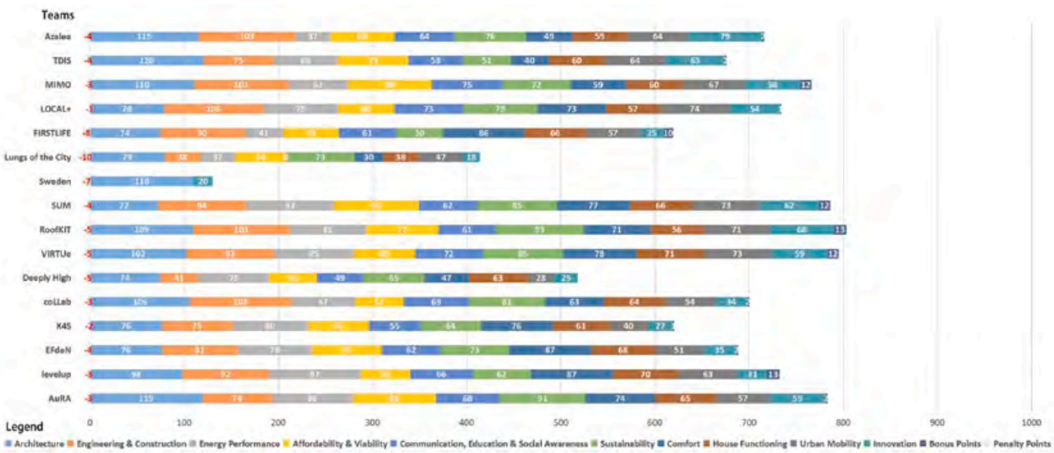


Fig. 4. The ranking of the fifth SDE.

The history, rules and final ranking were examined through onsite investigation and online searches of the SD and fifth SDE. All the teams' buildings are taken for the next step of energy use technologies analysis.

After the qualitative analysis refers to related research, the energy use technologies for achieving less energy use in buildings are

Table 3
The fifth SDE's 16 teams.

No.	Team	Project	University	Country	Homepage
1	Azalea	Escalà	Polytechnic University of Valencia	Spain	https://www.azaleaupv.com/
2	TDIS	1 House for All	National Yang Ming Chiao Tung University	China	https://tdis.nycu.edu.tw/
3	MIMO		Hochschule Düsseldorf, University of Applied Sciences	Germany	https://mimo-hsd.de/
4	LOCAL+		University of Applied Sciences Aachen	Germany	https://www.team-localplus.com/
5	FIRSTLIFE		Czech Technical University in Prague	Czech Republic	http://firstlife.cz/en/homepage/
6	Lungs of the City	Re Greened Blocks - RGB	University of Pécs	Hungary	https://lungsofthecities.com/
7	Sweden	C-Hive	Chalmers University of Technology	Sweden	https://www.c-hive.com/
8	SUM		Delft University of Technology	Netherlands	https://www.delftsolardecathlon.com/
9	RoofKIT		Karlsruhe Institute of Technology	Germany	https://roofkit.de/en/
10	VIRTUe	Ripple	Eindhoven University of Technology	Netherlands	https://teamvirtue.nl/
11	Deeply High		Istanbul Technical University & Lübeck University of Applied Sciences	Turkey & Germany	https://deeply-high.eu/
12	coLLab		Stuttgart University of Applied Sciences	Germany	https://www.collab.hft-stuttgart.de/
13	X4S	Extension for Sustainability	Biberach University of Applied Science	Germany	https://www.team-x4s.de/
14	EFdeN	EFdeN VATRA	"Ion Mincu" University of Architecture and Urbanism	Romania	https://efden.org/
15	levelup		Rosenheim Technical University of Applied Sciences	Germany	https://levelup-ro.de/
16	AuRA		Grenoble School of Architecture	France	http://team-AuRA.org/

divided into passive and active categories in three directions: reduce energy demand, increase energy efficiency and generate renewable energy [31,32]. Then the statistical analysis of the used ratio is calculated. Finally, these results are presented in the Sankey diagram and pie charts.

Furthermore, based on energy use technologies, the Analytic Hierarchy Process (AHP) method is used for multi-criteria decision analysis (MCDA). MCDA is used to rank, select, and compare different alternatives based on multiple criteria. The AHP is the most commonly applied MCDA method [33]. It is designed to build a decision process by multiple independent factors [34]. Based on the three aspects-reducing energy demand, increasing energy efficiency, and generating renewable energy-the Super Decisions software analyzed the top four teams' buildings for sustainability assessment.

Then this research analyzed the design for generating renewable energy in the best-ranked team. The plugins named Ladybug and ClimateStudio for Grasshopper in Rhinoceros software simulated respectively the local annual solar radiation and different slopes of solar panels for receiving radiation. By quantitative study, the building design for generating renewable energy of RoofKIT is learned.

The comparative research method is also used throughout the article, especially in the Discussion and Conclusions part. Finally, the findings from the fifth SDE residential buildings for sustainable development are summarized.

The methods used in the paper include onsite investigation, literature review, forecasting operation, software simulation, qualitative analysis, quantitative analysis and comparative analysis. For the forecasting operation, the rationality of the research flowchart can be proved by our previous research [35]. For the literature review, all the data was uploaded online, and it can be checked [36]. The simulation software uses software recommended by relevant studies that can ensure accuracy [37,38]. Moreover, the simulation result can be verified by related research [39]. The flowchart of this research paper is shown in Fig. 5.

4. Results

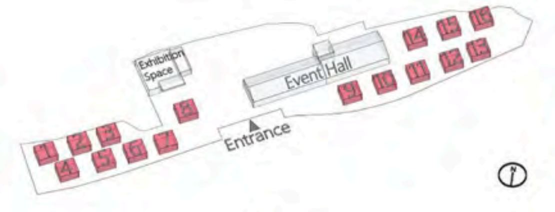
4.1. Examination of the fifth SDE

Based on the context of improving energy use in residential buildings for sustainable development, 16 buildings of the fifth SDE are used as research objects. The energy use technologies of each building and the three directions for passive and active technologies are examined.

Azalea comes from the Polytechnic University of Valencia, Spain. Their project, Escalà, aims to achieve economically, socially and environmentally sustainable solutions to the different problems of the Valencian neighborhood of El Cabanyal. The concept focuses on standardized and scalable wooden housing to adapt to the local situation. The wooden structure with recycled cotton insulation can increase the thermal resistance of the building to save energy. An incorporated space named Escalà is used as a thermal cushion to save heating energy in winter for indoors. A heating system on the roof named Caloret collects incident solar radiation for indoor thermal comfort in the winter and forms natural ventilation in summer without external energy. Moreover, solar panels are used on the walkable roof to generate renewable energy [40].

TDIS comes from National Yang Ming Chiao Tung University, Taiwan province, China. The project "1 House for All" means Net

Table 4
The competition site and 16 competing buildings.



SDE Site

1. Azalea

2. TDIS

3. MIMO

4. LOCAL+

5. FIRSTLIFE

6. Lungs of the City

7. Sweden

8. SUM

9. RoofKIT

10. VIRTUe

11. Deeply High

12. coLLab

13. X4S

14. EFdeN

15. levelup

16. AuRA

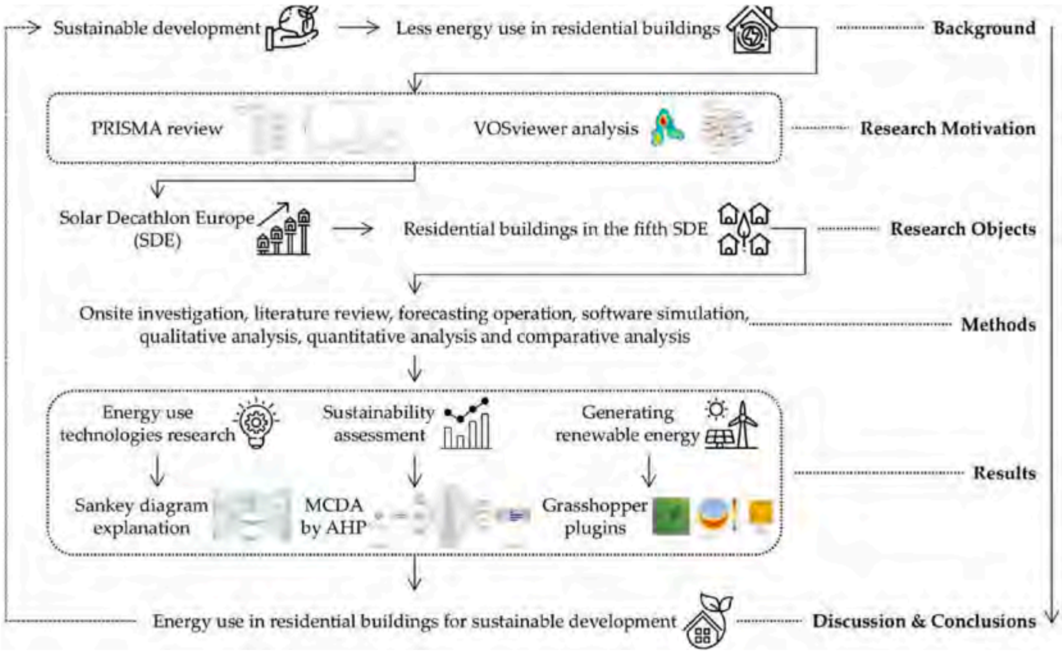


Fig. 5. The flowchart of this research paper.

Zero Mid-way Houses, Social Enterprise Housing and Energy-Efficient Sharing Stations in the city. This house is built with durable and reusable cross-laminated timber (CLT) and glued-laminated timber (GLT) in an assembly way with a circular design. The building's curtain wall uses a recycled steel frame with Low-E double glazed windows. The material of the insulated wall is rock wool for higher thermal resistance. The airbags in the building are manufactured from recycled plastic material and the Soy Wax Lighting System from phase change material (PCM). Interactive thermochromic insulated tiles are used in a replaceable way for a future renewal of the house in case any piece is broken. All the building's materials are used in Building as Material Banks (BAMB) for reuse in the future. Moreover, the roof's solar panels generate renewable energy for sustainability [41].

MIMO comes from Hochschule Düsseldorf, university of applied sciences, Germany. The name of MIMO means Minimal Impact - Maximum Output, and it focuses on the existing warehouse in Wuppertal for redesigning. The residential modules are in a wooden structure. The wall structures and thickness are optimized for noise, fire and heat protection with cork insulation. Cork offers good sound insulation, moisture regulation, thermal conductivity and durability. The clay bricks are used in combination with the plant wall for heat storage, moisture regulation, sound insulation and freedom from harmful substances to achieve a pleasant indoor climate. A semi-public greenhouse on the roof is used to provide vegetables and is a specific shape to collect rainwater for reuse. The energy supply system energiBUS links to a heat pump for energy use in the whole system. Photovoltaic cells in horizontal glass slats form Building Integrated Photovoltaics (BIPV) as the climate shell for energy production. At the same time, the moveable slats can be opened or closed according to different seasons for indoor thermal comfort. Moreover, some areas are kept free to obtain views and daylight into the interior [42].

LOCAL+ comes from the University of Applied Sciences Aachen, Germany. LOCAL+ stands for "Low Carbon Lifecycle +". Wooden modules are used to assemble the building in a prefabrication way which minimizes waste in the construction industry and CO_2 footprint. The ground floor opens from south to north, passively regulating the indoor environment. The outside plant wall on the south offers good thermal insulation to maintain a comfortable thermal environment. The building materials are mainly clay ballast panels, clay building boards, dry screed, clay grooves slabs, brick screed, ceramic tiles, oriented strand board and mineralized wood chip fill. In the case of deconstruction, 85.9 % of the building mass can be taken for high-quality recycling. The hydrogen system in the building offers around 65 % self-sufficiency energy. Furthermore, the roof's PV panels also play an essential role in energy generation [43].

FIRSTLIFE comes from Czech Technical University in Prague, Czech Republic. It aims at Feasible and Innovative Residences for STudent Life. The building by modular design with building system elements is prefabricated before transport to Wuppertal. The building walls used natural materials of CLT construction to save the construction thickness. The external staircase wall was made by each team's donation of the palette to reuse the used elements for a better future. The floor uses recycled materials of linoleum, carpet tiles and vinyl offcuts. The heating system in the floor gains heat from the inverter heat pump for dry-laid floor heating. The overhang of the roof structure is shaded by climbing greenery and sufficient thermal insulation thickness to suppress overheating. The PV lamellas on the roof generate energy for the inverters. The central control system can detect the CO_2 concentration by sensors for active ventilation. The lighting sources are designed to change the spectral composition according to the day and night. During the day, the blue spectral component is added to the light source to increase work productivity. Furthermore, rainwater management and greenery applications also help carbon neutrality [44].

Lungs of the City comes from the University of Pécs, Hungary. The project name is Re Greened Blocks - RGB. The building has a compact shape to reduce the surface area and is airtight to prevent heat loss. A transitional zone between the heated area and the exterior is used for passive energy saving. Strategically orientating the building functions and window sizes prevents the building from overheating. The green facade offers a filter zone by regulating the cleanliness, noise and humidity. The building also uses recycled and natural materials such as cedar wood treated with the Yakisugi method for wall coverings. Solar panels on the roof and facade generate energy for use within the building [45].

Team Sweden comes from Chalmers University of Technology, Sweden. The project is called C-Hive and is constructed with a timber structure combined with 3D-printed wooden cellulose to build a co-living and co-working housing typology. Cellulose is extensively used as a recyclable, renewable resource of waste products from the Swedish forestry industry. Prefabricating the modules makes the units easy to assemble. The roof protrudes beyond the edges on the top of the walls to provide shelter from rain and sun. For solar energy, the PV panels on the roof generate energy for domestic use [46].

SUM comes from Delft University of Technology, Netherlands. It is the abbreviation of the Symbiotic Urban Movement, which aims to achieve a mutual and beneficial relationship between people and the environment. The building consists of modules in prefabricated timber structures with biobased materials. The Laminated Veneer Lumber (LVL) timber used on the building is the strongest wood construction with its weight. The ground floor walls use 90 % recycled cotton sources from old clothing for interior insulation. The cellulose insulation consists of recycled newspaper covered by gypsum fiberboards. The external building envelope uses 2 mm bio-composite sandwich panels with 150 mm recycled plastic (PET) bottles insulation. All the insulation material can be reused. The external facade uses mineral brick slips and prefabricated plaster elements dried at 60 °C to reduce CO_2 by 80 %. The energy-efficient thermal envelope keeps the heat inside during the winter to maintain indoor comfort. Furthermore, sun shading with the PCM battery reduces the summer's cooling demand. The air-to-water heat pump uses the energy in a highly energy-efficient way. The PVT panels on the roof sustainably generate energy and heat water. The southern and western facades are equipped with PV panels, the ceramic print of which can vary as necessary. Rainwater and filtered greywater are used for the toilet and the local plants. The control system is grouped heat pump, ventilation and energy usage to offer an excellent indoor climate. As for the ventilation system, a CO_2 sensor can monitor the indoor air quality to adjust it appropriately [47].

RoofKIT comes from Karlsruhe Institute of Technology, Germany. This project is designed as a top-up to an existing old building in need of renovation. The building is prefabricated and installed with light-weight timber modules in an ecological way without any permanent glues but using a clip-in system. Living mushroom organisms are used for weather protection on the outside facade. Some materials, such as wood elements, slats, girders, tiles and metal plates, come from demolished buildings. The team is trying to achieve 100 % renewable energy use for the building. The solar energy generated by a PVT system with 14 modules is for achieving an energy cycle. It can also be used for a heat pump to feed the under-floor heating system and hot water tank. Oscillating decentralized ventilation systems are integrated into the facades to guarantee fresh air during the winter with heat recovery. Building waste and sewage are also used for energy and heat generation. The energy management system maximizes the grid efficiency and optimizes solar yield, electricity demand and battery charge/discharge. Moreover, skylight windows achieve passive ventilation and lighting energy saving. The louvers in effective shading also achieve passive cooling [48,49].

VIRTUe comes from Eindhoven University of Technology, Netherlands. The Ripple project, inspired by the Ripple Effect, aims to spread sustainable change in existing buildings with renewed and vertical extensions. The building uses high-quality timber for load-bearing core and columns. The flexible design is suitable for replacing with recycled wood in the future. The module includes two small apartments and a communal room with a shared washing machine and dishwasher and others for public use to increase building use efficiency. PV thermal panels generate electricity and warm water for energy use in the so-called Solar Belt. In the communal room, EQUI, a smart control system, helps the user schedule energy use [50].

Deeply High comes from Istanbul Technical University, Turkey and Lübeck University of Applied Sciences, Germany. It aims to develop an environmentally friendly solution for the re-densification of cities. The building consists of prefabricated modules and designs in combination with a vertical energy garden. On the one hand, it is a small greenhouse passively gathering energy from the sun. On the other hand, this space offers natural ventilation indoors with a chimney system. The passive cooling system is also used in this building. The PCM regulates indoor air temperature for energy saving. Biomass (microalgae) technology is implemented to purify wastewater for reuse. The conversion process will convert excess CO_2 into oxygen to contribute to carbon neutrality. Recycled materials such as straw and hemp are used in insulation for low energy consumption. On the roof, the garden is used for rainwater collection and for decreasing the urban heat island effect. Moreover, PV panels are used there for generating renewable energy [51].

The coLLab comes from Stuttgart University of Applied Sciences, Germany. The design focuses on an interdisciplinary extension and redevelopment concept for urban buildings. It uses a wooden structure with recycled wood facades for low carbon and fast construction. The building is integrated with a GRID system which includes regenerative power, heat collection, sun protection, greening, daylight permeable grids and openings. The organic PV (OPV) collectors installed on the modular walls and monocrystalline silicon-based photovoltaic modules on the roof generate energy. The ventilation system consists of decentralized trickle vents with solar chimneys. At the top of the solar chimney, an air-to-water heat pump is implemented to extract heat from the air for energy saving [52,53].

X4S comes from Biberach University of Applied Science, Germany. The project is named Extension for Sustainability. It uses solid timber for prefabrication, fast construction, minimal loads and high fire protection. Windows consist of wood and aluminum materials with triple-glazing. The blinds are integrated with the window to reduce thermal bridges. The roof shielded by solar panels can also be used for gardening. PV and PVT collectors with battery systems adjust electricity use. The heat pump is used. A heat recovery system is used at the exhaust air places. Smart home system controls lighting, window blinds, battery and energy systems [54].

EFdeN comes from the "Ion Mincu" University of Architecture and Urbanism, Romania. The project is named EFdeN VATRA, in which the Romanian word VATRA translates as "the hearth". It means a place full of joy, dance and stories. This building is based on 4mX4m grids with three single living apartment modules and one private greenhouse module to achieve efficiency and scalability. The building uses natural and renewable materials with a minimal ecological footprint. The off-site timber frame with dry assembly process reduces carbon emissions. It also has a façade-integrated optical fiber for indirect natural lighting and an automated blade system for controlling direct light. Wall panels are filled with straw and newspaper insulation. The double wooden frame of the panels easily supports ceilings, roofs and facades without any thermal bridges. The roof shape offers the best angle (35°) and height for bifacial photovoltaic panels (LG Mono) to generate energy on both sides [39].

Levelup comes from Rosenheim Technical University of Applied Sciences, Germany. Levelup focuses on the building renovation on the top using solar energy. It is designed based on modular construction and a flexible floor plan addition of stories in the light-weight wood structure. Glue-free timber with wooden nails ensures green construction. A ventilation system with an enthalpy heat exchanger is installed. A PVT system and semi-transparent PV modules are integrated on the roof to generate energy. Primary temperature control for the building is provided via a propane heat pump. Moreover, the direction of the roof aligns with the sun for good energy generation efficiency. The greening on the roof and facades is helpful for architectural aesthetics and offers shading and cooling functions. On the facades, building-integrated photovoltaics also offer as much renewable energy. The control cabinet for building automation co-ordinates heating, ventilation, lighting, shading, household appliances and other building technology into a smart system. Black and gray water conduct separately to maximize reuse. Furthermore, heat is recovered from used hot water [55,56].

AuRA comes from the Grenoble School of Architecture, France. This project aims to use recycled materials, including bio and geo-

Table 5
16 teams' concept and energy use technologies.

No.	Team	Design Concept	Energy use Technologies
1	Azalea	standardized and scalable wooden house	wooden structure; recycled cotton insulation; thermal cushion space (Escalà); heating system (Caloret); natural ventilation; solar panels
2	TDIS	net zero mid-way houses, social enterprise-housing and energy-efficient sharing stations in the city	cross-laminated timber (CLT); glued-laminated timber (GLT); steel frame; Low-E double glazed windows; rock wool; recycled plastic material; phase change material; interactive thermochromic insulated tiles; Building as Material Banks (BAMB); solar panels
3	MIMO	minimal impact - maximum output	wooden structure; cork insulation; clay bricks plant wall; greenhouse; rainwater use; heat pump system (energiBUS); BIPV; moveable slats
4	LOCAL+	low carbon lifecycle +	prefabricated wooden modules; opening ground floor; plant wall; recyclable materials; hydrogen system; PV panels
5	FIRSTLIFE	feasible and innovative residences for student life	prefabricated modular design; natural materials; recycling materials; overhang roof; plant wall; heat pump; PV lamellas; central control system; spectral composition lighting; rainwater management
6	Lungs of the City	Re Greened Blocks	compact and airtight; transitional zone; strategically orientating and window sizes; green facade; recycled and natural materials; solar panels
7	Sweden	co-living and co-working housing typology	timber structure; 3D-printed wooden cellulose; recyclable, renewable resource of waste products; prefabricated modules; roof protrudes beyond the walls; PV panels
8	SUM	achieve a mutual and beneficial relationship between people and the environment	prefabricated modules; LVL timber; recycled cotton, newspaper, PET insulation; mineral brick slips; sun shading; PCM battery; air-to-water heat pump; PVT and PV panels; rainwater and greywater reuse system; control system; CO_2 sensor
9	RoofKIT	top-up to an existing old building	prefabrication; timber module; clip-in system; mushroom organisms; recycled materials (wood, metal and others); PVT system; heat pump; oscillating decentralized ventilation system; waste and sewage reuse; energy management system; skylight window; louvers shading
10	VIRTUe	spread sustainable change in existing buildings with renewed and vertical extensions	high-quality timber; flexible design; recycled wood; modular units; shared communal room; PV Thermal panels; smart control system (EQUI)
11	Deeply High	develop an environmentally friendly solution for the re-densification of cities	prefabricated modules; greenhouse; natural ventilation; passive cooling system; phase change material; biomass (microalgae) technology; recycled materials (straw and hemp); roof garden; PV panels
12	coLLab	an interdisciplinary extension and redevelopment concept for urban buildings	wooden structure; recycled wood facades; GRID system (regenerative power, heat collection, sun protection, greening, daylight permeable grids and openings); organic PV (OPV); modular walls; monocrystalline silicon-based photovoltaic; ventilation system; solar chimney; air-to-water heat pump
13	X4S	extension for sustainability	prefabricated solid timber; triple-glazed windows with blinds; PV and PVT collectors; heat pump; heat recovery system; smart home system
14	EFdeN	a place full of joy, dance and stories	4mX4m modular grids; natural and renewable materials; off-site timber frame; dry assembly process; optical fiber; automated blade system; straw and newspaper insulation; roof shape; bifacial photovoltaic panels
15	levelup	the building renovation on the top using solar energy	modular construction; flexible floor; lightweight wood structure; glue-free timber; ventilation system; PVT system; semi-transparent PV; propane heat pump; roof direction; greening; BIPV; smart system; black and gray water reuse; heat recovery
16	AuRA	use recycled materials, including bio and geo-sourced and renewable energy	recycled materials; prefabricated wood; straw insulation; reused wooden beams; PV panels

sourced and renewable energy. The prefabricated wood comes from sawmills locally. The fibers come from agricultural waste to make straw insulation. Clay material used for walls regulates the interior hygrometric and thermal comfort. Moreover, the structure uses reused wooden beams. The building modular framework provides the technical core, the skin forms the thermal envelope and the shell integrates the PV panels to generate energy and protect the building [57].

Based on all the projects examined, Table 5 clearly shows that energy use technologies corresponded with the teams and their design concepts.

4.2. Energy use technologies

Under the influence of the energy crisis and related problems, improving energy use is the common goal for sustainable development, especially for residential buildings with greater energy saving potential. In fact, achieving this goal is complementary in multiple ways. The Sankey diagram further categorizes the energy use technologies of the fifth SDE (Fig. 6). Even though different teams used different technical names, the essence is the same. Fig. 6 normalizes them. Each technology's use ratio (UR) is listed in descending order with its percentage (%) on the right of Fig. 6. Although examining all the technologies used in the fifth SDE building is hard, the listed results are mainly based on the onsite investigation and each team's promotion. It is clear that a total of 34 kinds of technologies are used for sustainable development in energy use.

The passive technologies used in the fifth SDE are around 65.93 % of all the energy use technologies. This proportion exceeds the sum of the other two, which demonstrates the principle of passive priority [58]. The frequency of use of each passive technique is shown in Fig. 7(a). Natural material is used and valued by every team. Although building a house is inseparable from materials, the green use of natural materials can better achieve sustainable development. Waste use such as recycled cotton, steel, plastic and others are widely used in various construction places. The prefabrication module is applied in at least in 12 buildings. As for the PCM and optical fiber lighting, even though they only occupy 12.5 % and 6.25 %, respectively, in this competition, this does not mean they are unimportant. These 21 passive technologies are no longer explained one by one. They include several aspects such as material selection, construction method, architectural design and others [59]. In short, all of these help to improve energy use in a passive way. Passive technologies should be a foundation in architectural practice [60].

As for the active technologies used for improving energy efficiency, they account for 13.33 % of all technologies used. The remaining 20.74 % is taken up by generating renewable energy, which is more than the improve energy efficiency element. On the one hand, this competition advocates using renewable energy, such as solar energy. On the other hand, generating more renewable energy is needed under the energy crisis and related background problems. Suppose renewable generation can cover energy use, even providing the excess power to society with cash back. In that case, each family will be willing to let their house be an energy generation building independently. Therefore, solving the energy crisis and related problems will be proactive for everyone.

The frequency of use of "improve energy efficiency" is shown in Fig. 7(b). The most widely used is the control system, which can save energy and offer a healthy environment through big data, the Internet of Things (IoT) and smart algorithms. As for the

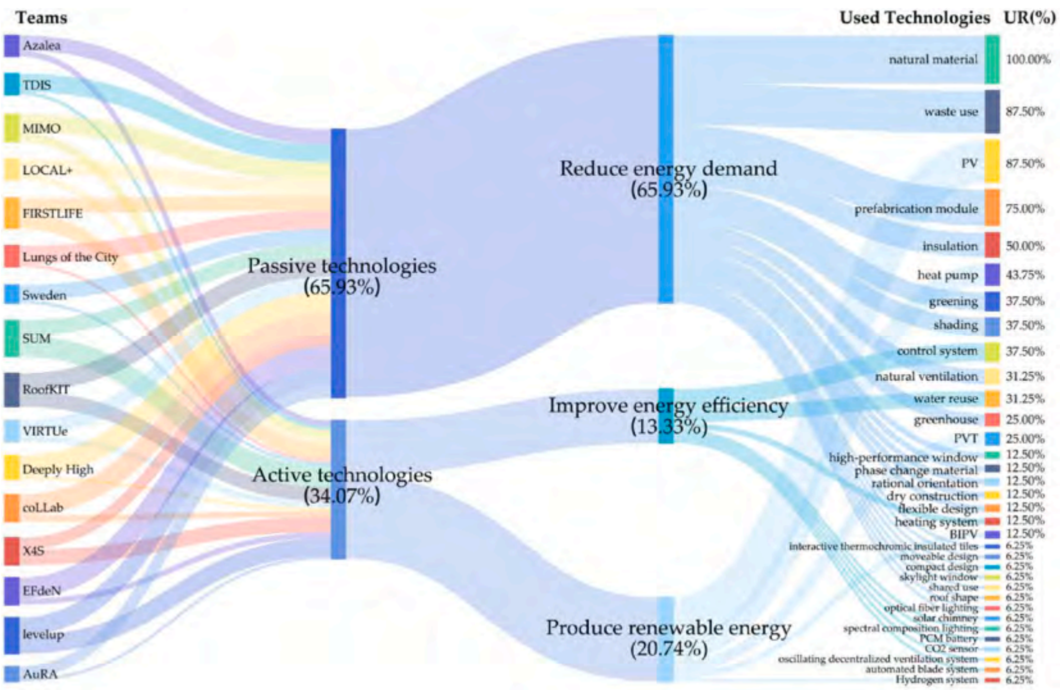


Fig. 6. Energy use technologies analysis.

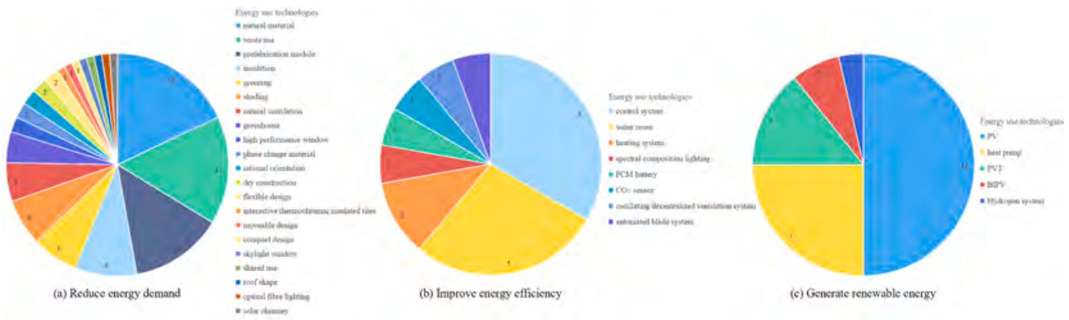


Fig. 7. The frequency of use in three directions: (a) Reduce energy demand, (b) Improve energy efficiency, and (c) Generate renewable energy.

infrequency used in active technologies, such as spectral composition lighting and oscillating decentralized ventilation system, these also merit attention. Despite the principle of passive priority, active is necessary as well. Especially when environmental problems such as global warming are intensifying, active technologies are urgently needed to solve problems that cannot be solved under passive conditions.

The frequency of use of "generate renewable energy" is shown in Fig. 7(c). All the teams used solar panels by PV, PVT, or BIPV, which is the leading renewable energy generation technology. Renewable energy has great significance to sustainable development. This should be applied widely in buildings.

4.3. Sustainability assessment

Based on the fifth SDE ranking for sub-contests of Energy Performance and Sustainability related to this research, the total score is shown in Fig. 8. Team Sweden lost these sub-contests. The top four teams' scores are 1st SUM, 2nd AuRA, 3rd RoofKIT and 4th VIRTUe. Compared with overall ranking results, it can be found that these teams are the same as the top four in the overall ranking, even though the ranking order is slightly changed. These four teams' energy use technologies are used for MCDA for sustainability assessment [61].

For MCDA, of which team's energy use technologies combination it is better to promote, the three criteria of "reduce energy demand," improve energy efficiency" and "generate renewable energy" are established based on the previous research of three directions for energy use. Each team's energy use technologies are normalized as before. These technologies are established in sub-criteria with the same weight for each technology. Finally, the four teams are used for final alternatives by comparing pairwise from the decision elements regarding the importance of their control criterion under the hierarchy construction. Here, Super Decisions software is used for AHP. Fig. 9 shows the workflow, hierarchy and results of the MCDA for these four teams. The results show that the RoofKIT is the best for sustainability assessment of energy use technologies combination. The second is SUM, the third is VIRTUe and the fourth is AuRA. As for the number of energy use technologies used by each team, RoofKIT used 6 passive technologies, 3 active technologies and 2 renewable energy technologies, total 11 kinds of energy use technologies. SUM used 5, 4 and 3 separately, 12 in total. VIRTUe used 5, 1 and 1, 7 in total. AuRA used 4, 0 and 1, 5 in total. So the greatest user of energy use technology is SUM. Nevertheless, based on AHP, the best one is RoofKIT. The results of this analysis prove that the best solution for energy use for

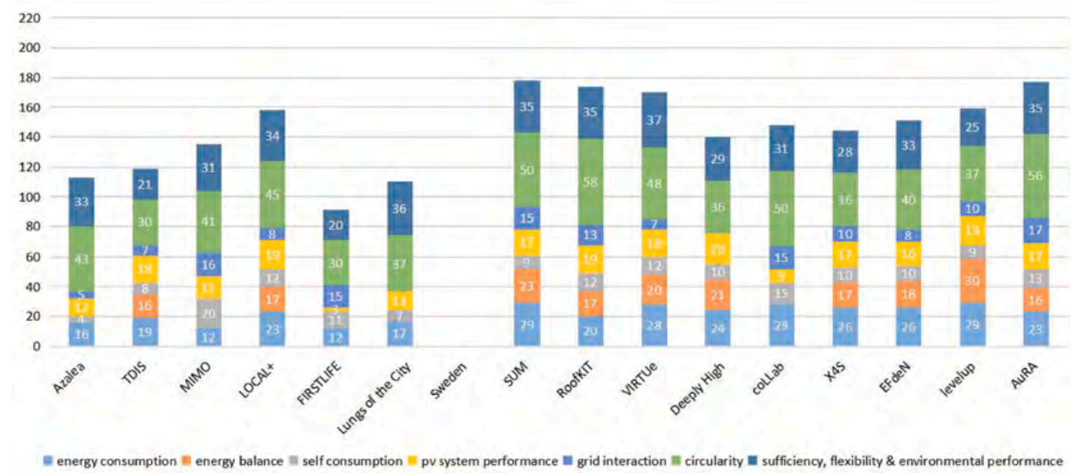


Fig. 8. Total score of sub-contests in Energy Performance and Sustainability.

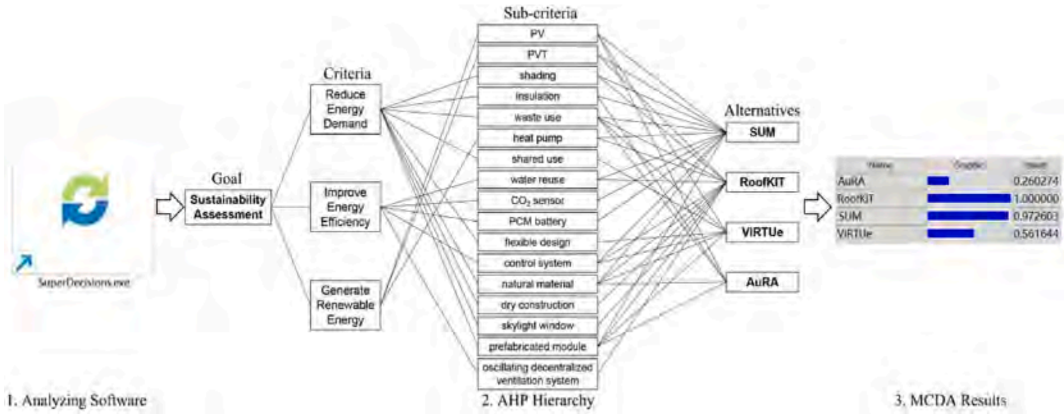


Fig. 9. Workflow of MCDA.

sustainable development depends on the combination method, not just technologies stacking. Tools are neither good nor bad, only for fair use.

4.4. Generating renewable energy for sustainable development

The combination of energy use technologies for sustainable development is a complex issue. Most residents do not have the chance or motivation to buy or build their houses as zero-energy buildings. However, with the development of solar panel technologies, the question of how to generate more renewable energy in buildings, especially for the most significant proportion of building types - residential buildings, needs to be researched. Although the passive energy use technologies accounted for the most significant proportion of energy technologies in the fifth SDE buildings, if the residents can generate enough renewable energy to cover self-use or even sell that to the public, energy use for sustainable development will be an active and autonomous issue [62]. Sustainable development needs an open source to reduce expenditure. Without energy generation, there is no energy use, let alone energy saving. It is essential to generate renewable energy. In addition, the extensive use of clean energy, such as solar energy, wind energy and geothermal energy, reduces carbon emissions, which not only alleviates climate change but also helps solve the energy crisis [63]. Here, the solar energy generated by PV is researched. The best team for the combination of energy use technologies according to the sustainability assessment, RoofKIT, is used for analysis.

The fifth SDE competition site is located in Wuppertal, Germany. According to the Global Horizontal Irradiation (GHI) map of Germany by the World Bank, the GHI in Wuppertal is equivalent to that in Dusseldorf [64]. GHI is considered a simplified approximation of PV power production [65]. The weather data of Dusseldorf near Wuppertal is used for analysis by the Ladybug plugin for Grasshopper in Rhinoceros software [66]. The annual solar radiation, including (a) total radiation, (b) diffuse radiation, and (c) direct radiation, is shown in Fig. 10. It can be easily understood that the south side receives the most radiation during the whole year, and there the maximum total annual radiation reached 30.82 kWh/m^2. So the south face is the most efficient direction to use solar energy. It is worth noting that the angle between 150 and 210, due south plus or minus 30° is the best range for solar radiation use to generate renewable energy.

The fifth SDE site for each building is not oriented north-south. It is offset about 26.5° to the east, which is still in the best range between 150 and 210. Therefore, the solar panels directly facing South can maximize the use of solar radiation. However, solar panels on the roof, combined with the building by adding the solar panels on the flat roof or roof truss, look like temporary installations or additional equipment and are inadvisable from the architectural aesthetics [67,68]. So the solar panels on a pitched roof facing South (parallel to the aisle) are the best way to maximize the use of solar radiation.

From this perspective, RoofKIT did well compared with the other buildings with pitched roofs. Even though TDIS, EFdeN and levelup also used pitched roofs, TDIS and EFdeN have not fully utilized the roof area. The levelup's pitched roof is not in the best direction, which is not suitable for maximizing the use of solar radiation. However, besides the south-facing direction and pitched roof, the roof's angle is another key to the best use of solar radiation for generating renewable energy. This is because the building is immovable, but the solar radiation changes with the sun moving all year round. So the most extensive annual solar radiation receiving angle needs to be analyzed.

The annual solar radiation simulation by the ClimateStudio plugin for Grasshopper in Rhinoceros software analyzes the solar panels in the same area with different slopes between 0 and 50°. It can be seen that the most extensive annual solar radiation received in this competition site is when the slope is between 30 and 40° in Wuppertal (Fig. 11). However, RoofKIT uses a pitched roof with 20° in two sections. This is to avoid the roof being too long, causing one end to be too high to form indoor space waste and increase the energy demand. Meanwhile, skylight windows are set between the two roof sections to utilize the north-facing lighting to form uniform indoor lighting and effectively save energy. This is the result of balancing energy generation and architectural design, which can be seen as a reflection of architectural aesthetics.

All in all, the best one is not accidental. Whether in total ranking or sustainability assessment, RoofKIT is number one. Furthermore,

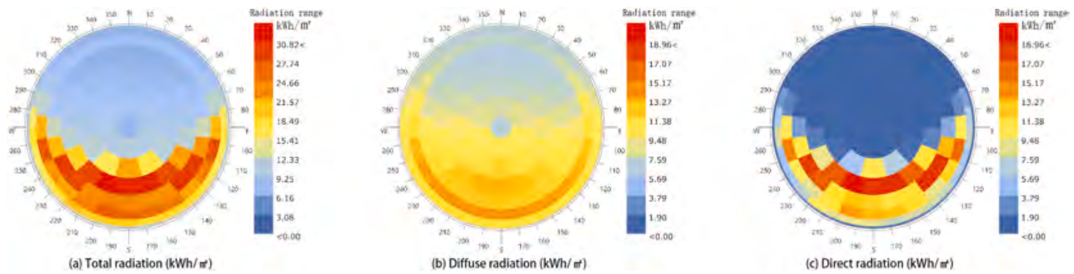


Fig. 10. Top view of hemispherical sky matrix of annual radiation, including (a) Total radiation, (b) Diffuse radiation, and (c) Direct radiation.

Fig. 11. Annual solar radiation received in same area panels with different slopes.

from the renewable energy generation for sustainable development aspect, architectural aesthetics are also subtly reflected.

5. Discussion

This research focuses on energy use in residential buildings for sustainable development. The analysis between energy crisis and climate change revealed that the vicious circle continues to intensify with positively correlated effects. Based on the SDGs, the relationship between energy and buildings shows that less energy use in residential buildings has great potential. These findings echo other scholars' research, such as [69–71].

According to the PRISMA literature review of SD publications and the keyword co-occurrence analysis by VOSviewer, the data demonstrate that the research on SD is increasing and meaningful, especially for the cross-study in buildings and energy aspects [72].

The history of SD, the rules, the ranking and 16 buildings in the fifth SDE were examined. Even though it is hard to list all the energy use technologies in these buildings, the results indicate that they can be divided into passive and active categories in three directions. Although existing research tends to classify building technologies into passive and active [73], or three aspects namely reduce energy demand, increase energy efficiency and generate renewable energy [74], this conclusion does not contradict those findings. Instead, the relationship between them is represented graphically as Fig. 6.

By statistical analysis, 34 kinds of technologies are classified. Passive technologies are the most used in all the buildings, which supports the passive priority principle [75]. However, active technologies are also necessary [76]. Generating renewable energy does not focus on energy saving directly but helps cover energy consumption [77]. This measure should be vigorously promoted to encourage residents to contribute to sustainable development spontaneously. Moreover, some infrequently used technologies, such as PCM, optical fiber lighting and spectral composition lighting, are still worth promoting [78].

Based on the fifth SDE's examined energy use technologies, the AHP method for MCDA was used to analyze the sustainability assessment. The top four teams were analyzed by comparing the final ranking with the sub-contests ranking in Energy Performance and Sustainability. The result demonstrates that the use of the most energy use technologies can not decide the final sustainability performance, but the combination way decides it. This point has yet to be proposed according to a wide range of literature studies. However, this brings a limitation. The advantages and disadvantages of different energy technology combinations need further research.

Then, renewable energy generation with architectural design is analyzed. The primary way to generate renewable energy in buildings is to use solar panels. Therefore, the preferred way to combine the pitched roof with the solar panels was explored. The best team, RoofKit, was used to analyze. Ladybug plugin simulated the local annual solar radiation to find the proper building orientation between 150 and 210. Compared with others, RoofKIT is designed well to maximize solar radiation use. ClimateStudio plugin further analyzed the best slope for solar panels, but the suitable range is between 30 and 40° in Wuppertal. Considering the increasing indoor space waste with energy demand, the pitched roof angle of RoofKIT used 20°. This is acceptable under energy generation with architectural design, sublimated into architectural aesthetics [79]. But this leads to another research topic that can be researched in the future.

Furthermore, this research verified a research paradigm based on the SD and SDE open source data. Yu et al. did the research based on the open data in 2019 [22]. The SD competition not only attracted many teachers and students from all over the world to participate, but also continued architectural education because of its open competition information. This is the meaning of the competition. Even though the authors are also past SD participants, due to the limitations of personal knowledge, there will inevitably be deviations in understanding. Any limitations will be improved once the authors become aware of them.

6. Conclusions

Under the SDGs, this research started from the energy crisis and related problems trying to make contributions to sustainable development from residential buildings. A case study of the fifth SDE is analyzed, based on a series of methods to figure out the energy use technologies, sustainability assessment and generating renewable energy for sustainable development issues. The main findings are:

1. The vicious circle exists between the energy crisis and climate change with a positive correlation effect.
2. Under the influence of the energy crisis and related problems, residential buildings' energy saving can make huge contributions to sustainable development. Research into residential buildings for energy saving should be vigorously developed.
3. The PRISMA literature review and VOSviewer analysis show that the cross-study of building and energy aspects of SD is increasing and meaningful. Further research should follow up the SD progress.
4. The 34 energy use technologies in the fifth SDE can be sorted into passive and active two categories, in three directions.
5. In this competition, the ones most used (65.93 %) are passive technologies, which supports the principle of passive priority. In practice, passive techniques should be applied first.
6. Active technologies are needed. Generating renewable energy should be strongly encouraged, considering residential buildings' great energy saving potential. Importantly, if residential buildings can be self-sufficient in renewable energy, we will be a big step closer to the SDGs.
7. Infrequency used technologies in the SDE are not necessarily unimportant. They need to be considered and promoted, too.
8. Sustainability assessment by the AHP method for MCDA shows that the combination of technologies decides the sustainability performance, but the quantity used does not.
9. To generate as much renewable energy as possible, the direction and angle of solar panels should be considered. However, the energy use also needs to be balanced and coordinated with the architectural aesthetics.
10. The revelations of the fifth SDE residential buildings are helpful in solving the background problems for sustainable development.

More research results may be obtained from different research approaches, such as literature review, sustainability assessment and software simulation. More findings will be achieved in the future, especially on the connection between the quantity and effectiveness of energy-saving technologies, and the balance between renewable energy generation and architectural aesthetics. Furthermore, the research into reducing fossil energy consumption in residential buildings by generating renewable energy should also focus on the balance with passive technologies, the different classifications of residential buildings, the design principles of climate houses with traditional housing, the formulation of rules for residential building design, the possibility of autonomous houses, and the consideration of the volumetric-spatial and functional-planning level for residential buildings as well. These will be the focuses of further research.

Data availability statement

The information on SD and SDE was sourced from relevant public websites. The figures and tables in this paper are all made by the authors. All the quoted data are cited clearly in the context. The data are mainly from sources listed below.

A) SD history comes from https://www.solardecathlon.gov/.
B) SDE information comes from https://sde21.eu/and https://building-competition.org/EU2021.
C) All the photos were shot by the author.
D) The researched dataset generated by the authors has been uploaded to Mendeley Data with the citation as: *Li, Bin; Caneparo, Luca; Zhang, Yuqing (2023), "Dataset for 'Energy use in residential buildings for sustainable development: The fifth Solar Decathlon Europe revelations'", Mendeley Data, V1,* https://data.mendeley.com/datasets/nm2rmn9wrp/1 [36]. The data can be found by this link: https://data.mendeley.com/datasets/nm2rmn9wrp/1

Ethics approval and consent to participate

Not applicable.

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CRediT authorship contribution statement

Bin Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuqing Zhang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Caneparo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition. **Weihong Guo:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Qinglin Meng:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Declaration of competing interest

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

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