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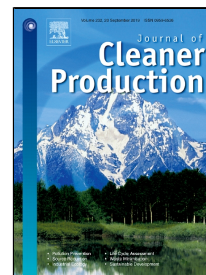
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Towards an optimized zero energy solar house: A critical analysis of passive and active design strategies used in Solar Decathlon Europe in Madrid

Abstract

Solar Decathlon is an international multidisciplinary competition for designing, building and operating Zero Energy Solar House. Based on the existing evaluation framework, this research identifies 7 key decisions and 24 passive and active strategies that lead to an optimized Zero Energy Solar House with better architecture, comfort condition and electrical energy balance performance: selecting passive strategies regarding shape, function layout and microclimate organization, adopting solar systems and heating, ventilation and air-conditioning systems as active strategies, integrating the passive and active with prefabrication systems, and finally evaluating the project against sustainability (energy payback period). Focused on 2010 and 2012 Solar Decathlon Europe in Madrid, this research critically reviewed 33 involved projects using this framework. Furthermore, the research correlated the 24 strategies with their performance results in the competition through multi-criteria analysis. The review generated passive-active integrated empirical models for an optimized Zero Energy Solar House in Mediterranean climate conditions. Beyond the particular competition and climate, the research found five important lessons for integrating passive and active technologies for a solar house. The framework proposed by this research, and the strategies and lessons learnt from reviewing the Solar Decathlon Europe competitions can help to transfer the technologies and related knowledge gained from experiments into practice.

Keywords: Solar Decathlon Europe; zero energy solar house; integrative passive and active design; prefabrication; sustainability

Terminologies

<i>Footprint</i>	Maximum observed area of building and solar energy components during the competition
<i>Insulated area</i>	Area of insulated and well-conditioned space
<i>Shape coefficient</i>	Ratio of building external surface area to the volume it encloses
<i>Aspect ratio</i>	East-west length to north-south width ratio
<i>Opening ratio</i>	Ratio of opening area to the wall, only southward façade is calculated in this paper
<i>Buffer zone/space</i>	Passive space without air-conditioning for pre-treating thermal comfort
<i>Thermal mass</i>	Material to absorb and store heat energy, usually have high density
<i>Buoyancy-driven ventilation</i>	Ventilation arise due to differences of air density, which in large part arises from differences in temperature
<i>Evaporation cooling</i>	Cooling based on the unsaturation of air and the latent heat of evaporation of water
<i>Heat pump</i>	A device that transfers heat energy from a source of heat to what is called a heat sink

<i>SD</i>	solar decathlon
<i>SDE</i>	solar decathlon Europe
<i>SDC</i>	solar decathlon China
<i>DOE</i>	department of energy
<i>ZEB</i>	zero energy building
<i>NZEB</i>	net zero energy building
<i>ZESH</i>	zero energy solar house
<i>SIPs</i>	structural insulated panels
<i>VIP</i>	vacuum insulation panel
<i>EPS</i>	expanded polystyrene
<i>PCM</i>	phase change material
<i>HP</i>	heat pump
<i>HVAC</i>	heating, ventilating and air conditioning
<i>PV</i>	photovoltaic
<i>BIPV</i>	building-integrated photovoltaic
<i>CPV</i>	concentrating photovoltaic
<i>PV/T</i>	photovoltaic/thermal system
<i>Poly-Si</i>	polycrystalline silicon
<i>Mono-Si</i>	monocrystalline silicon
<i>CIS</i>	copper indium selenium solar film
<i>CIGS</i>	copper indium gallium selenium solar film
<i>EPBT</i>	energy payback time
<i>MCA</i>	multi-criteria
<i>AR</i>	contest of architecture
<i>CC</i>	contest of comfort condition
<i>EEB</i>	contest of electrical energy balance
<i>IMV</i>	industrialization & market viability

1 Introduction

Since the invention of silicon photovoltaic (PV) panels in 1954, the integration of rapidly developing solar technologies as new part of the residential system has become a worldwide new trend (Prasad and Snow, 2004). While generating renewable energy through PV is an effective solution for reducing greenhouse emissions, it also raises higher standard for architectural design and mechanical system.

Conceptually, a zero-energy building (ZEB) is understood as an energy efficient building being able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand (Satori et al, 2012). Despite this concept targets at a “zero” balance of energy clearly, the ZEB definitions are still expressed with a wide range of terms and phrases. In order to propose a commonly agreed ZEB definition and a robust calculation methodology, Marszal (2011) identified and presented a set of parameters that differ between 12 ZEB definitions, and indicated that the metric, the period and the types of energy included in the energy balance together with the renewable energy supply options, the connection to the energy infrastructure and energy efficiency, the indoor climate and the building-grid interaction requirements are the most important issues. Comparing to another similar term: net zero energy building (NZEB) which refers to buildings that are connected to the energy infrastructure, ZEB is more general and may include autonomous buildings (Danny et al, 2013). In this work, we use the term ZEB as energy autonomy which better describes some Solar Decathlon Europe (SDE) projects equipped with energy battery packs.

In the 1950s, the first prototype towards ZEB was developed in the form of solar houses attempting to achieve zero-heating (Ferrante, 2011). Early examples include the 1955 “Bliss House” using solar air collectors and rock mass for heat storage and the 1970 “Vagn Korsgaard Zero Energy Home” in Demark. Following these practices, some

ZEBs were built for demonstration, from low-rise houses (Tommerup, 2007; Paker, 2009; Wang, 2009; Mahdavi, 2010; Bojic, 2011; Fong, 2012), gradually to multi-story residential (Marszal, 2011; Morelli, 2012; Dong-Wo, 2013) and office buildings (Garde, 2012; Marta, 2011; Pena, 2013). The feasibility of ZEB has been proved in various climate zones and countries. Basically, the application of passive strategies has shown better energy saving potential and payback performance than active technologies (Sun, 2018). Despite the ZEBs caused greater use of non-renewable resources input, they were still more sustainable compared to conventional practices (Yi, 2017).

After that, the projects of ZEB have been popularized all over the world and the number of completed buildings has been kept rising continuously. Musall (2013) analyzed 282 ZEBs from various countries, and found that German, the U.S. and Canada have the most ZEBs while the development of ZEBs in China, Korea and Japan is much slower. Furthermore, he found that ZEBs have been widely integrated with both passive and active technologies, among which high-performance insulation, PV system, solar thermal system and heat pump were the most popular and other technologies such as natural lighting, shading, passive ventilation, high efficiency appliance or heating, ventilation and air-conditioning (HVAC) were also widely adopted. Solar PV panels, double glazed windows with aluminum frame, concrete and insulation are the key carbon-intensive construction materials that should be reconsidered (Mehdi, 2019).

Nowadays, as the technical strategies for ZEB become mature, it is of great importance to explore a rational technical route for integrating them. One integration system was proposed by Deng (2014) that mainly involves three kinds of energy-efficient measures: passive design, service system and power generation from renewable energy sources. Lu (2015) proposed three main steps for achieving the ZEB target through the use of passive design strategy (e.g. building envelope, orientation, geometric/ratios), energy efficiency technologies (e.g. HVAC, hot water, lighting, appliances and equipment) and energy production technologies (e.g. combined cooling and/or heat and power, fuel cells, hydroelectric power, PV panel, wind turbine). Although ZEB research and practice have made great progress, comparative ZEB experiments based on the same climate are still rare. The latest solar technologies need to be tested on ZEB and a comprehensive evaluation system that includes architecture, comfort and energy remains to be explored.

As one of the most important representative ZESH experiment, the Solar Decathlon (SD) organized by U.S. DOE since 2002 first established the experimental objective of satisfying people's daily life through ZESH and set up a test bed which reflected the leading trend of ZEB (U.S. DOE, 2017). Till now, the SD has been held for 12 times. In general, the history of SD can be divided into 4 phases: start-up period 2002-2005, transition period 2007-2009, mature period 2010-2012 and promotion period after 2013 (Table 1).

Table 1 Evaluation system evolution of SD & SDE (data source: www.solardecathlon.gov)

Start-up Period		Transition Period		Mature Period				Promotion Period		
SD2002	SD2005	SD2007	SD2009	SDE2010		SD2011	SD2011	SD2013	SD2015	SD2017
Design & Livability 200	Architecture 200	Architecture 200	Architecture 100	Architecture	Architecture 130	Architecture 100	Architecture	Architecture 120	Architecture 100	Architecture 100
Presentation & Simulation 100	Dwelling 100	Engineering 150	Market Viability 100		Engineering & Construction 80	Engineering 100		Engineering & Construction 80	Engineering 100	Engineering 100
Graphics & Communication 100	Documentation 100	Market Viability 150	Engineering 100	Solar	Solar Systems 80	Energy Balance 100	Energy	Energy Efficiency 100	Energy Balance 100	Energy Balance 100
Comfort Zone 100	Communications 100	Communications 100	Lighting Design 75		Electrical Energy Balance 130	Hot Water 100		Electrical Energy Balance 120	Hot Water 100	Commuting 100
Refrigeration 100	Comfort Zone 100	Comfort Zone 100	Communications 75	Comfort	Comfort Conditions 130	Comfort Zone 100	Comfort	Comfort Conditions 120	Comfort Zone 100	Comfort Zone 100
Hot Water 100	Appliances 100	Appliances 100	Comfort Zone 100		Appliances 80	Appliances 100		House Functioning 120	Appliances 100	Appliances 100
Energy Balance 100	Hot Water 100	Hot Water 100	Hot Water 100	Social & Economic	Communications & Social Awareness 80	Home Entertainment 100	Social & Economic	Communications & Social Awareness 80	Home Entertainment 100	Home Life 100
Lighting 100	Lighting 100	Lighting 100	Appliances 100		Industrialization & Market Viability 80	Communications 100		Industrialization & Market Viability 80	Communications 100	Communications 100
Home Business 100	Energy Balance 100	Energy Balance 100	Home Entertainment 100	Strategic	Innovation 80	Market Appeal 100	Strategic	Innovation 80	Market Appeal 100	Market Appeal 100
Getting Around 100	Getting Around 100	Getting Around 100	Net Metering 150		Sustainability 130	Affordability 100		Sustainability 100	Affordability 100	Affordability 100

The evaluation is evolving accordingly. During the start-up period, the evaluation system emphasized on the conceptual expression of architectural design. In the 2nd phase, market appeal and price were added in the system. In

phase 3, the system started with subjective evaluation (architecture and engineering design), followed by measurement (energy balance, thermal comfort and house equipment), and finally promoted with communication and market appeal assessment (Raugei et al., 2007).

In 2010, the SD was first introduced into Europe. Both 2010 and 2012 SDEs (**Fig.1 & Table 2**) were held in Madrid (inland Mediterranean climate, annual average temperature: 23°C -25°C and relative humidity: 40%-55%). Madrid has greater diurnal temperature range, lower humidity and more solar radiation than Washington DC. Therefore, it is harder for thermal comfort control but has greater potential for solar energy. The distinctive climate and updated evaluation system made SDE in Madrid an excellent test bed for ZESH experiment, and also important new achievement integrating the U.S. system. This paper focuses on the two SDEs in Madrid. Through the analysis of the two SDEs' results, an optimized ZESH system combined active and passive strategies from both architecture and technical perspective can be obtained. It is different from the traditional system that separately focuses on passive or active design; it breaks through the edge between architecture and engineering. Furthermore, the SDE experimental technical route for achieving such a system in Madrid can be promoted for exploration in other regions.

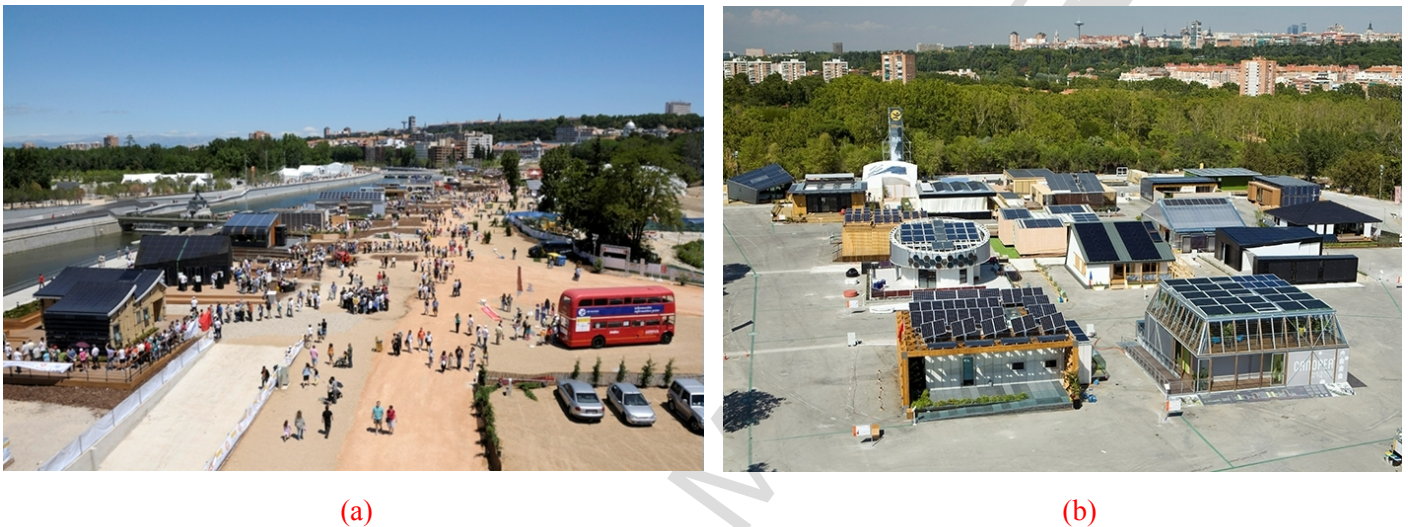


Fig.1. Bird views of SDE2010 (a) and 2012 (b)

Table 2 Regulations and tasks in SDE 2010 and 2012

Year	Site Dimension	Footprint	Insulated Area	Appliances	Solar Capacity	Special
SDE 2010	25m×20m ×5.5m	≤74m ²	≥42m ²	Hot water, cooking, lighting, refrigerator, freezer, washing, dryer, dishwasher, TV, computer, DVD, oven	≤15kWp	-
SDE 2012	20m×20m ×6m	≤150m ²	≥70m ²	Hot water, cooking, lighting, refrigerator, freezer, washing, dryer, dishwasher, TV, computer, DVD, oven	≤10kWp	Energy production-consumption correlation, passive test

As a matter of fact, the solar house competitions and related projects have attracted research attentions. Wang et al.(2009) reported a net-zero-energy modular house, named Element House, which was entered for the 2007 Solar Decathlon competition and discussed a way of effectively designing and building a comfortable and affordable solar house. Navarro et al. (2014), from educational perspective, demonstrated the technical and professional ambitions of the students who participated in SDE 2012 and reported that their knowledge had increased in areas related to technical and multidisciplinary aspects. Cronemberger et al. (2014) highlighted advances, tendencies and solutions through SDE houses and summarized that these houses ran exclusively on solar energy, as part of the requirements of this worldwide competition. Imura et al (2014) and Matallanas et al. (2014) introduced the electrical system development and design of solar houses in SDE 2012. Serra Soriano et al. (2014), from construction point of view, introduced a SML system which was used in SDE for assembling prefabricated and industrialized elements. Brambilla

et al. (2017) using a SD winning prototype examined the relationship between indoor comfort and climatic context. There are also a number of studies that reported projects from China (Lyu et al., 2017; Zhang et al., 2014). The previous studies on SD serial competitions have reported and examined the relevant projects from different perspectives; while an integrative examination is still missing. On the other hand, there is an emerging record of research introducing new solar technologies including active (García-Domingo et al., 2014; Motalleb et al., 2015; Renau et al., 2014) and passive (Ji et al., 2015; Liu et al., 2018) aiming for zero energy solar houses. There is a need for research that can provide strategies to integrate these new technologies for an optimized solar house. This study conducts a critical review of the solar experiments in order to understand how the experiments inform practice. To meet this end, this paper establishes a framework that extends from the current evaluation system to transfer a performance checklist into a series of practical strategies; then, using this framework, this paper examines projects involved in SDE 2010 and 2012 to find out integrative passive and active design strategies that contribute to an optimized zero energy solar house which performs better regarding architecture, comfort condition and electrical energy balance.

2 Method

2.1 Framework

As shown in **Fig.2** (the left part), the SDE evaluation framework is based on five major aspects, covering Architecture, Energy, Comfort, Social Economic and Strategic; under each aspect, there are two sub-aspects to assess the solar house performance (Zaretsky, 2010). The framework and its performance checklist had been successfully used to evaluate competition outcomes. However, the framework does not tell how to capture the knowledge or transfer it into practice. Although the competition claims to generate applicable knowledge for implementation in practice, a commensurate research framework is missing to addresses applicability and generalization of the competition outcomes. One of contributions from the present study is an extended framework that addresses specific passive and active design strategies and their integration and evaluation. **As shown in Fig.2, the relation between SDE evaluation aspects and related design strategies were analyzed (the left part), based on which, 7 key decisions and 24 strategies that lead to an optimized Zero Energy Solar House (ZESH) were identified (the right part).** They key decisions include selecting proper strategies regarding shape, function layout and microclimate organization as passive strategies, adopting solar systems and HVAC systems as the active part, integrating the passive and active with the prefabrication system, and finally evaluating the project with sustainability (mainly EPBT). These 7 key decisions and their related strategies ramified from the original performance checklist but with more technological applicability are examined against performance results. Through multi-criteria linear regression, empirical models integrating both active and passive strategies are established for the architecture, comfort condition and energy balance performance contests, respectively. The aim of using this framework to examine the SDE projects is to extract strategies in an evidence-based approach to achieve an optimized ZESH.

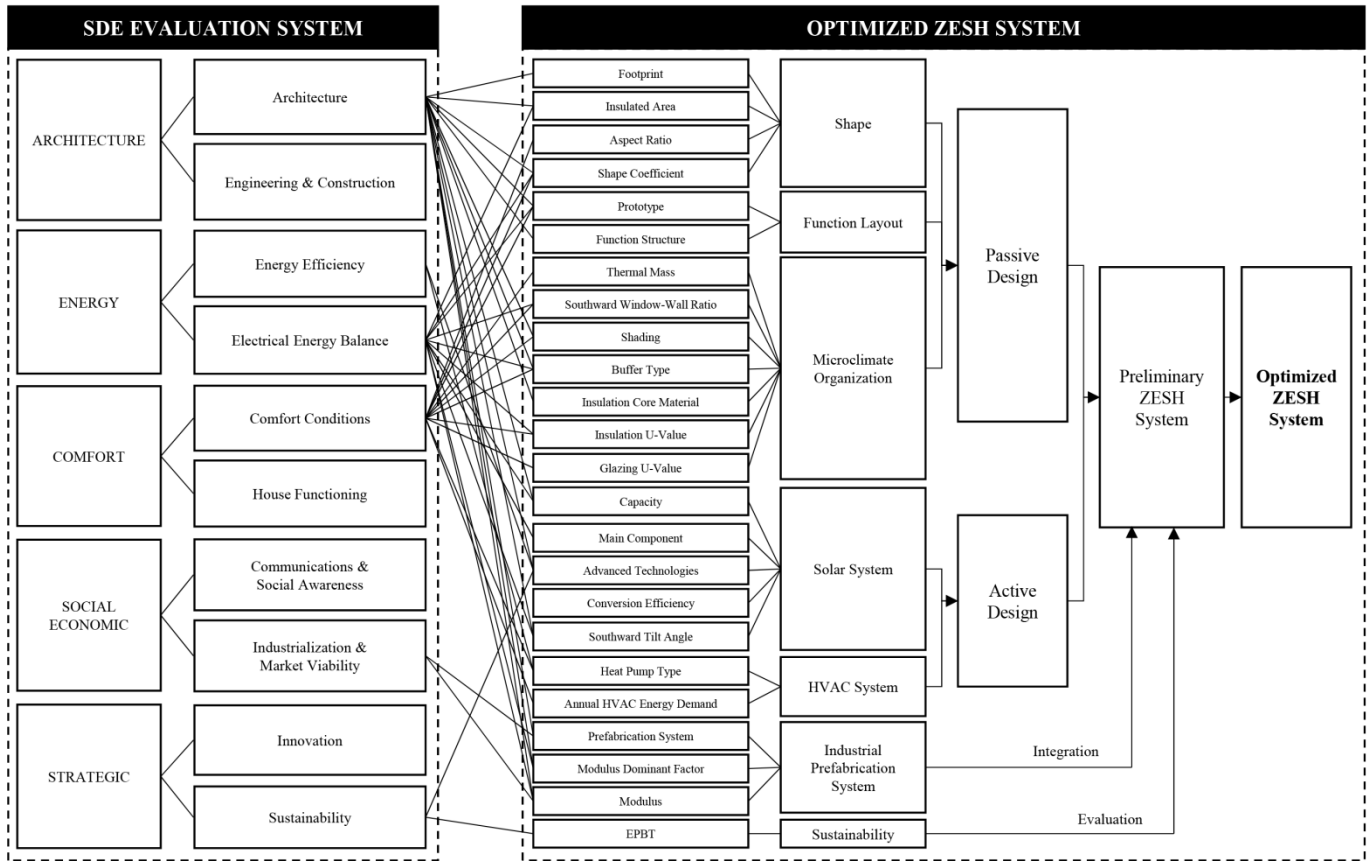


Fig. 2. The framework

2.2 Data source

The data come from 17 houses in SDE 2010 and 16 houses in SDE2012 (Table 3) with the same climatic condition: Madrid, Mediterranean climate. Relevant data are extracted from competition teams' drawings and project manual. The documents are mainly from sources listed below:

- SD history is quoted from <http://www.solardecathlon.gov/> .
- SDE 2010 projects performance and documents are quoted from SDE 2010 official website <http://2010.sdeurope.org/> and official publication Solar Decathlon 2010: Towards Energy Efficient Building.
- SDE 2012 projects performance and documents are downloaded from SDE 2012 official website <http://www.sdeurope.org/> .
- Rules and regulations are issued by the SDE organizer during the competition.
- Part of the photos taken by the author during the competition and others are downloaded from <https://www.flickr.com/photos/sdeurope/albums> .

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Table 3 Teams and their projects included in the data analysis

Competition	No.	Team	Abbreviation
SDE2010	1	Virginia Polytechnic Institute & State University	VPU
	2	University of Applied Sciences Rosenheim	ROS
	3	Stuttgart University of Applied Sciences	HFT
	4	Ecole National Supérieure d'architecture de Grenoble	GRE
	5	Helsinki University of Technology	AAL
	6	Bergische Universität Wuppertal	BUW
	7	Arts et Métiers Paris Tech	AMP
	8	University of Florida	UOF
	9	Universidad CEU Cardenal Herrera	CEU
	10	Fachhochschule für Technik und Wirtschaft Berlin	BER
	11	Tongji University	TJU
	12	Universidad de Sevilla	UDS
	13	Universidad Politécnica de Cataluña	UPC
	14	Universidad de Valladolid	UDV
	15	University of Nottingham	UON
	16	Tianjin University	TUC
	17	Instituto de Arquitectura Avanzada de Cataluña	IAA
SDE2012	1	École Nationale Supérieure d'Architecture de Grenoble	TRA
	2	Universidades de Sevilla, Jaén, Granada, and Málaga	AND
	3	Università Degli Studi di Roma Tre, Sapienza Università di Roma, Free University of Bozen, and Fraunhofer Italy	ROME
	4	University of Applied Sciences Konstanz	HTWG
	5	RWTH Aachen University	RWTH
	6	Budapest University of Technology and Economics	BME
	7	Universidad CEU Cardenal Herrera	CEU
	8	Universitat Politècnica de Catalunya	UPC
	9	"Ion Mincu" University of Architecture and Urbanism, Technical University of Civil Engineering of Bucharest, and Politehnica University of Bucharest	BUC
	10	Tongji University	TJU
	11	Universidad del País Vasco – Euskal Herriko Unibertsitatea	EHU
	12	Bordeaux University	ABC
	13	Universidade Federal de Santa Catarina and Universidade de São Paulo	BRA
	14	Chiba University	CUJ
	15	Universidade do Porto	FAUP
	16	Ecole Nationale Supérieure d'Architecture Paris – Malaquais, Università di Ferrara, Ecole des Ponts Paristech, and Politecnico di Bari	STSH

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153 3 Results and discussion

154 The analysis includes both qualitative and quantitative parts. The qualitative part is a detailed review of the 24
 155 passive and active design strategies used in the solar houses enrolled in the competitions. The review identifies key
 156 factors in these strategies leading to good or bad performance in the competitions. The quantitative part is a
 157 multi-criteria analysis based on a series of regression modellings to verify the qualitative analysis and to find
 158 influential strategies and their synergistic effects on the performance outcomes.

3.1 Passive design

3.1.1 Shape

Footprint and insulated area

A proper shape is the basic for a high performance solar house. In order to ensure a consistent shape of houses, the three-dimensional boundary and footprint are illustrated in **Fig.3**.

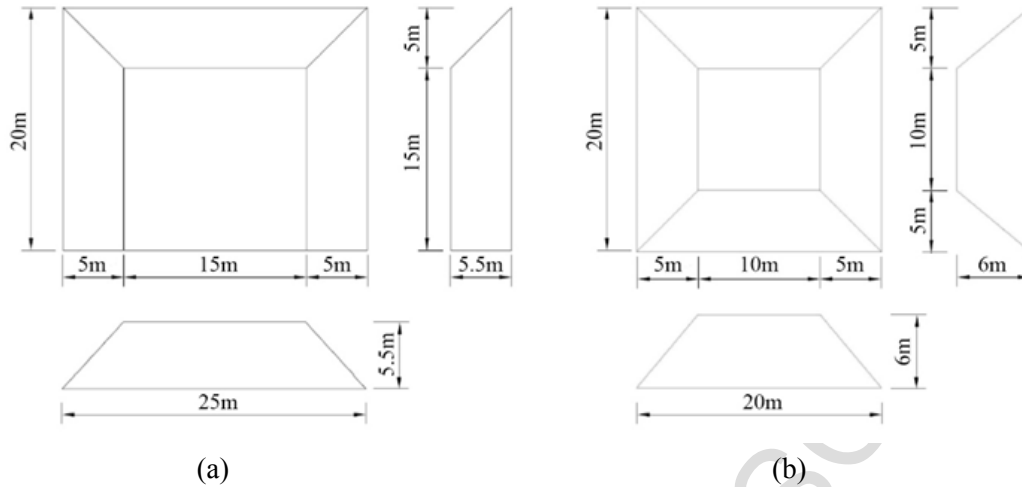


Fig.3. Three-D boundary for SDE2010 (a) and 2012 (b)

In 2010, because of the small scale, most teams adopted large footprint near the upper limit of 74m² for sufficient roofs to collect solar energy, but the architecture (AR) contest did not show preference for bigger insulated area. Regarding to comfort, the best performing projects had big footprint approaching 74m². Their insulated area was mainly 45m²-55m²; projects with the best performance in comfort had slightly bigger insulated area around 50-55m². In 2012, the footprint increased and the footprint of the best project in terms of AR approached the upper limit of 150m². The projects with bigger insulated area close to 70m² also achieved higher scores. In comfort, only one living room and one bedroom were measured, while most teams still chose smaller insulated area. Bigger insulated area strategy can still be observed from the best project for lowering the energy consumption per square meter in the comfort condition (CC) contest.

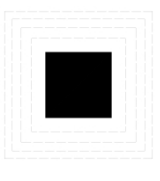





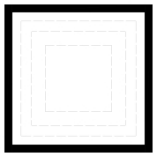
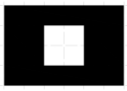


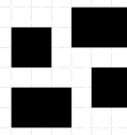

Aspect ratio and shape coefficient

Most projects' shape coefficients were between 1.0-1.4, and the best performing projects were confined to 1.0-1.1. Lower shape coefficient tended to result in better CC performance, but at the same time, projects with shape coefficient below 1.0 could not guarantee stability of thermal comfort, especially when the low shape coefficient was achieved by curved shape or height. Most teams adopted a square or southward rectangle shape with aspect ratio between 0.8-1.6. Highly scored projects usually had higher aspect ratio between 1.0-1.6 (also recommended by Victor Olgyay (2015)). Some projects with aspect ratio above 2.8 were still among the top.

3.1.2 Function Layout

Prototype

Basically, there are two prototypes for a solar house: pavilion and courtyard, representing two environmental moderation prototypes that perform differently regarding thermal comfort, ventilation and solar energy (Banham, 1969; Hawkes and Owers, 1980). Twenty-five teams chose the prototype of pavilion, and the other eight chose courtyard. The pavilion group can be further divided into 5 sub-groups: south-north rectangle, east-west rectangle, square, L shape and curved shape. The courtyard group can be further divided into central courtyard, concaved, cross courtyard, module enclosure and hybrid courtyard (**Table 4**). In the AR contest, the 3 highly ranked teams chose the pavilion type while bottom three teams also chose pavilion. Projects with courtyard had medium performance; the module enclosure type could benefit from the semi-outdoor space, which led to good performance close to those pavilion groups. In the comfort performance contest, the pavilion type occupied 8 positions among top 10 of SDE 2010 and 2012. The east-west rectangle type still was chosen most by top teams. Among the courtyard group, only two teams had good CC performance because of their narrow courtyard and greenhouse strategy.

Prototype	Sub-types				
Pavilion	East-west rectangle	South-north rectangle	Square	L shape	Curved shape
					
Courtyard	Central courtyard	Concaved	Cross courtyard	Module enclosure	Hybrid courtyard
					

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Function structure

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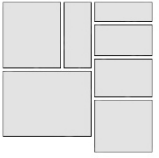
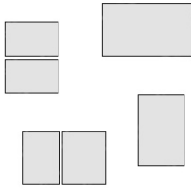
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Base on the prototypes, SDE projects layout can be divided into 3 groups: linear, compact and dispersed (**Table 5**). The linear type is better for free-flowing space; all 6 teams with this type adopted unified space integrating living room and dining room. However, its disadvantage is that the uniform width could not fit into the variety of functions and the flow line is longer. In compact type, either the functions are arranged around the service core, or the north service bar provides support for the south side function unit. For dispersed type, all teams adopted combinations: dining+kitchen, bedroom+restroom and living room. In architecture and comfort, top teams adopted compact most, followed by the linear group.

Table 5 Function structure

Layout	Linear	Compact	Dispersed
Diagram			
Teams	2010: VPU, HFT, BUW, CEU 2012: BME, TJU, EHU	2010: ROS, GER, AAL, AMP, CEU, BER, TJU, UDS, UPC, UDV, UON, TUC, IAA 2012: TRA, ROME, HTWG, RWTH, BUC, ABC, BRA, CUJ, FAUP, STSH	2010: HFT, UOF 2012: AND, CEU, UPC
Remark	2010HFT combined linear and dispersed types, 2010CEU combined linear and compact types.		

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3.1.3 Microclimate

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Thermal mass

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About half teams had clear thermal mass strategy. In general, teams with thermal mass achieved better CC scores. The thermal mass material not only influences the efficiency of energy collection, but also relates to the convenience of storing and using energy. Four types of thermal mass were used in SDE: interior traditional thermal mass, exterior traditional thermal mass, interior phase change material (PCM) thermal mass and exterior PCM thermal mass.

Interior traditional thermal mass can passively collect solar energy, store in dark ground or wall material (such as clay board and sand tube), and release the energy after the nightfall. This type collects and stores energy in low efficiency, and is hard to control the energy release. But it collaborates with southward rectangle shape well. Thermal storage tank can be added to improve the efficiency.

Exterior traditional thermal mass can avoid heat influence on the interior comfort. Four teams in 2012 chose this type. Exterior gravel tank storage and water tank storage are two examples of exterior thermal mass that helped the teams to achieve good performance.

PCM was used most frequently in SDE as a thermal mass. It can be divided into interior circulation (AAL, TJU, EHU & ABC in 2010 and AND in 2012) and exterior circulation system (ROS, HFT, AMP & UDS in 2010 and RWTH & CUJ in 2012). During the competition, since the indoor temperature requirement (23-25 °C) is close to PCM transition temperature, interior circulation hardly had positive effect. But the teams who adopted exterior circulation in 2010 achieved excellent performance.

Southward window-wall ratio and buffer type

Madrid is hot in summer and cold in winter; thus passive solar heating is needed. Southward openings are not only beneficial to the passive solar energy collection, but also engender better ventilation. In SDE projects, the ratio of southward opening to wall was between 0% - 70%. In general, projects with higher ratio between 40%-70% got slightly better comfort performance.

In response to the hot climate of Madrid during the competition, 12 teams adopted the buffer zone strategy. Three teams chose to use green house as the buffer zone; five chose double skin as the buffer zone and four used courtyard. Among them, green house performed the best with the 2 teams' comfort scores higher than 100, followed by the 3 teams' double skin with comfort scores around 100.

Shading

Most teams in SDE adopted shading elements, including exterior roller blind/curtain/louver with greenhouse, exterior visor blind, exterior curtain/roller blind, exterior louver, horizontal shading and interior curtain. Due to the strong solar radiation in the summer, Madrid local residential buildings often use metal roller blinds that almost shade light completely. In the competition, tighter sunshade also achieved better AR contest performance, not only reflecting the functional advantage of sunshade, but also showing the attractive architectural expression.

Insulation and glazing

High performance insulation wall was required in SDE. Two main insulation systems appeared as structural insulated panel (SIPs) and vacuum insulation panel (VIP) system. In SIPs system, various core materials were used. Considering fire proofing, insulation, sustainability, pollution and acoustic, the core materials were mainly aerogel, wood fiber/cellulose/hemp fiber, wool, mineral wool/rock wool, glass wool and expanded polystyrene (EPS). Among these insulation material, wood fiber/cellulose/hemp fiber have a weakness on fireproof; VIP is vulnerable and aerogel is expensive (Abuseif and Gou, 2018; Sun et al., 2018). Regarding acoustic performance, VIP and aerogel can block some high-frequency sound but they are too thin to absorb low-frequency noise; hemp fiber and mineral wool have certain sound absorption ability due to their porous characteristics.

It can be observed that the U-values of SDE projects were mainly under 0.18W/m²·K. Some top projects had U-value around 0.1W/m²·K. Top teams in the CC contest had accordingly lower u-value. Most of top teams used VIP, hemp fiber or wood fiber insulation. Considering the features of insulation materials, the strategy that combined VIP and hemp fiber was chosen by top teams in SDE2010 and 2012. For the opening, most teams adopted triple glazing with U-value mainly between 0.5-1.0 W/m²·K. Most top teams had U-value under 0.7 W/m²·K.

3.2 Active design

3.2.1 Solar system

Capacity and main component

The solar energy technologies selected by SDE teams includes monocrystalline silicon PV, polycrystalline silicon PV and solar film. Some special cutting-edge technologies such as concentrating system, photovoltaic/thermal system (PV/T) system, tracking system and new material were also applied.

The energy performance scoring in 2010 was evaluated by total amount of energy output at the end of test week. Team with most output got full score, and the remaining teams' scores were determined based on their output percentage. Therefore, under the limitation of total footprint, greater capacity and higher conversion efficiency of the solar system can bring advantages in electrical energy balance (EEB). But in 2012, certain energy calculated from the

263 system conversion efficiency and orientation was subtracted before the score was given, and a score for system
264 economic input-output ratio was added into the evaluation system.

265 Thus, the 2010 top teams in energy balance (ROS, UOF, GRE, VPU) adopted capacity higher than 10kWp; GRE
266 and UOF even exceeded 14kWp. In order to reach this capacity, the efficiency of components they used was up to
267 19.3%. In 2012, because of the new evaluation criteria, there was no longer sole pursuit for capacity; most teams
268 chose medium capacity around 11kWp, and more polysilicon and film were chosen by the top teams.

269 A positive correlation can be observed between the EEB ranking and capacity. In 2010, teams with capacity more
270 than 14kWp (covering 74m² roofs with 19% PV) achieved the best performance. In 2012, the correlation was not so
271 clear. However, there was a positive correlation between capacity per square meter and EEB ranking. Capacity density
272 up to 190Wp/m² was a guarantee for good performance in EEB. From the distribution of different technology types,
273 high efficiency monocrystalline silicon PV had great advantages and took the top EEB positions in both SDE and the
274 second is polycrystalline silicon PV.

275 *Southward tilt angle*

276 Two types roofs can be identified in terms of the solar array pattern: slope and flat roofs. More than half of teams
277 (19 out of 33) adopted southward slope roofs with an over 5° angle. To capture solar radiation of low incidence angle,
278 10 teams adopted east or west façade solar systems. Through the simulation of solar radiation from different angles in
279 Madrid, it can be found that the total annual direct radiation reached the highest at around 35° and that the total diffuse
280 solar radiation reached peak at 25°. The best option for capture diffuse radiation is flat roofs. Based on the solar
281 energy simulation data of each project, the annual energy generation per unit capacity (1kWp) was normally between
282 1200kWh-1300kWh with 1400kWh as the extreme case. In 2010, the energy generation capacity per unit reached its
283 peak at around 25°, but in 2012, because of more films were adopted, the peak reduced to 15°. Nevertheless, the final
284 score in EEB did not increase when solar panel approaching the best angle. On the contrary, teams with angle between
285 0°-5° performed the best. At the same time, teams with 19% conversion efficiency performed best, and the second
286 group was polysilicon module with efficiency of about 15.4%.

287 *Advanced technologies*

288 Four types of special solar technologies: PV/T, concentrate system, tracking system and new material were used
289 in SDE. PV/T systems consist of PV modules and heat extraction units, which can simultaneously provide electrical
290 and thermal energy (Kalogirou and Tripanagnostopoulos, 2007). The concentrate system can be further divided into
291 trough concentrator (Tao et al., 2011) and Fresnel concentrator (Xie et al., 2011). Altitude tracking and azimuth
292 tracking were individually or collectively used in solar tracking. New material refers to high efficiency solar film;
293 some team (VPU in 2010) used dual-side PV panel as the new material.

294 From the perspective of EEB and sustainability, flat PV/T panels performed well in both competitions. AMP in
295 2010 who adopted trough concentrator and teams with multi-junction solar film achieved high performance in
296 sustainability by applying innovative technologies; however, they could not ensure adequate and stable energy supply
297 for houses and turned out poorly ranked in EEB. At the same time, teams with azimuth tracking or concentrator did
298 not achieve expected performance due to the complexity of their technologies. It also can be observed that the teams
299 with the PV/T system had the best performance in energy efficiency; new solar material performed averagely;
300 regarding the tracking system, only altitude tracking achieved good ranking (**Table 6**).

Team	Technology				Detail	Electrical Energy Balance Ranking	Energy Efficiency Ranking	Sustainability Ranking
	PV/T	CPV	Solar Tracking	New Material				
2010AMP	√	√	√	×	Altitude tracking, trough concentrator	11	3	1
2012TJU	√	×	√	×	Azimuth tracking, flat PV/T	10	12	14
2012ABC	√	√	√	×	Altitude and azimuth tracking, Fresnel concentrator	7	13	9
2010VPU	×	×	√	√	Altitude tracking, dual-side PV	4	4	16
2010HFT	√	×	×	×	Flat PV/T, Radiative cooling	5	1	3
2012TRA	√	×	×	×	Flat PV/T	6	5	5
2012AND	√	×	×	×	Flat PV/T	1	1	2
2012FAUP	×	×	√	×	Azimuth tracking	8	16	18
2012STSH	×	√	√	×	Altitude and azimuth tracking, trough concentrator	17	16	16
2010UON	×	×	×	√	CIS film	16	16	2
2012RWTH	×	×	×	√	Multi-junction solar film	13	5	3
2012BME	×	×	×	√	Multi-junction solar film	16	3	6
2012CEU	×	×	×	√	CIGS film	2	8	8

3.2.2 HVAC design

Annual HVAC energy demand

Among all active design strategies, HVAC system is relevant to the CC score which involves temperature, humidity and CO₂, especially the temperature because of the dry weather in Madrid. The performance was evaluated by continuous measurements in two main insulated spaces (living room and bedroom).

The on-site outdoor temperature was between 16.1°C and 28.2°C in July, and in September it was between 15.4-26.4°C. The outdoor humidity was between 44% and 50%, which is close to SDE requirement. Thus, the HVAC energy demand was for cooling at noon and heating at night. All projects' annual energy demand for cooling and heating in 2010 was 290-2953kWh/a; in 2012, because of the greater insulated area, the total energy demand was higher, which was 736-2223kWh/a.

In 2010, with the increase of energy consumption per square meter, the CC ranking gradually decreased, indicating that higher energy consumption also increased the difficulty of indoor environment control. In 2012, due to the lack of data, this trend was not so clear. At the same time, in both competitions, top teams' energy consumptions per square meter were around 10kWh/a, and secondary teams' consumptions were around 25kWh/a.

Heat pump

The energy resource is rich in Madrid. Therefore, various types of HP were used in SDE, including water source heat pump (HP), air source HP and water-air dual source HP (Table 7). The most stable among the three types was the water-air dual source HP, which was not only highly ranked in CC but also won top positions in general. It is mainly because it combines the advantage of the two: the air source HP had stable cold/heat source while the water source HP could capture cooling energy at night in cooperation with radiator/solar system.

HP	Teams	Comfort Condition Ranking
Water source HP	2010: ROS, BER, 2012: ROME, HTWG	1, 15, 9, 10
Air source HP	2010: GRE, AMP, BUW, TJU, 2012: BME, BUC, EHU, ABC	4, 2, 10, 11, 2, 6, 13, 11
Water-air dual source HP	2010: VPU, TJU, UDS, 2012: TRA, CUJ	3, 3, 7, 1, 8
Passive	2010: HFT, 2012: UPC	8, 4
Other	2012: RWTH	15

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System design

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Efficiently capturing, storing and using the passive energy resource for maintaining comfortable indoor environment conditions is the main challenge in SDE; also, it is the starting point for looking for innovative system design. For teams who used air source HP, the exhausted heat recovery unit became standard choice where innovative system design was embodied in the end and auxiliary energy resources. The VP 18 Compact from German is a typical system in this type; based on this system, ABC in 2010 added a PCM tank as the energy storage and GRE in 2010 stored energy in hot water tank and moderated indoor temperature with clay walls with radiators.

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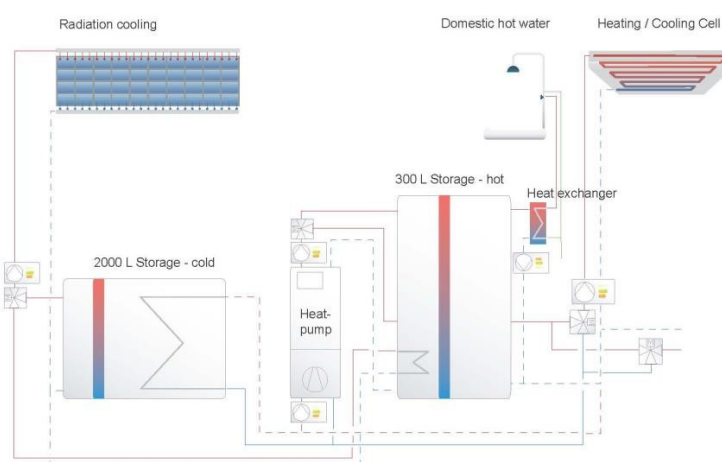


Fig.4. Water source HP of ROS in 2010

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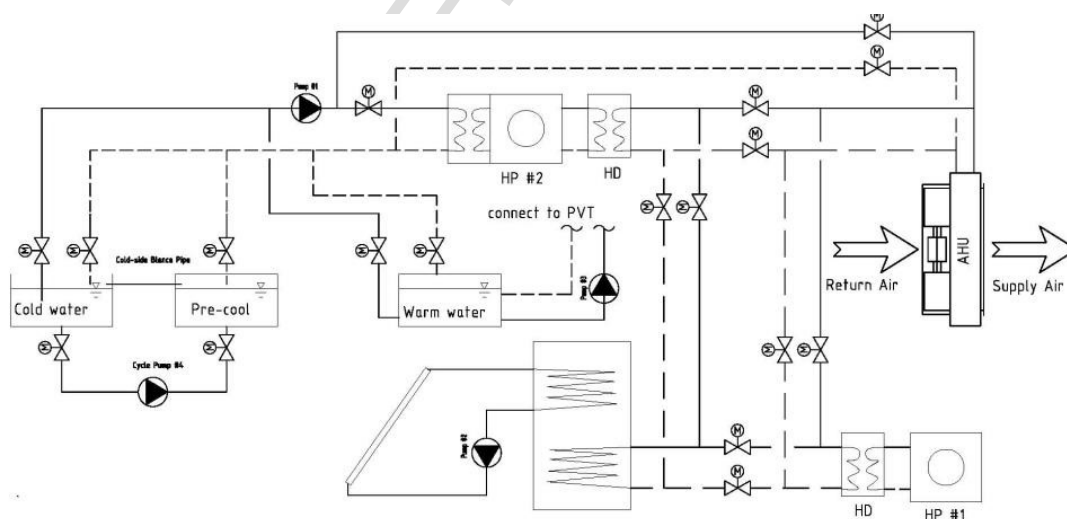


Fig.5. Water-air dual source HP of TJU in 2012

ROS in 2010 used an innovative system for water source HP, which is representative (Figs. 4). The cold resource was collected at night by solar radiator and exterior PCM ducts and was stored in 2 water tanks. Indoor temperature was adjusted by radiation ceiling. This system took full advantage of the solar system and eliminated the air HP system, which was efficient and simple. In the actual performance, this team achieved the 1st in the CC contest. TRA

in 2012 used an innovative system of air-water dual source HP; based on the air source HP system developed by GRE in 2010, a water source HP developed by ROS in 2010 was added to collect heat from the PV/T system, and then the heat together with exhausted heat from air HP were stored in storage tank. TJU in 2012 used similar dual HP system, and the team added supplementary open cold storage water tanks under south deck, which helped to collect passive cold source and to reduce the overall energy consumption of HVAC system (**Fig. 5**).

In terms of HVAC end selection (**Table 8**), half of top teams used air diffusers and the others used radiators. Among them, all teams who used air diffusers chose mixed ventilation. According to various radiation positions, teams with radiators can be divided into 4 groups: radiation ceiling (for cooling & heating), radiation ceiling (for cooling) and floor (for heating), radiation wall (for cooling & heating), radiation floor (for heating). In general, the radiation mode was more energy efficient and had more stable temperature conditions; while mixed ventilation had the advantages of rapid temperature regulation and low CO₂ concentration. The radiation ceiling (for cooling & heating) made full use of local climate characteristics, and the only need was setting up one water HP system; thus it was the most suitable type. With the lower initial investment, it gained the top position in comfort in both SDEs. The type of cooling ceiling and heating floor complied with the comfort requirement of head and foot. The wall radiator also performed well, but required long solid wall.

Table 8 HVAC end selection

End type	Sub type	Features	Top 5 Teams in Comfort Condition Contest
Air diffuser	Mixed ventilation	Rapid temperature regulation, low CO ₂ percentage, low temperature gradient	2010 AMP, AAL 2012 TJU, UPC, BRA
	Ceiling for cooling & heating	Energy saving, stable temperature, only one system needed, space saving, slow temperature regulation	2010 ROS 2012 TRA
Radiation	Ceiling for cooling & floor for heating	Energy saving, stable temperature, large initial investment	2012 BME
	Wall for cooling & heating	Energy saving, stable temperature, long solid wall needed	2010 GRE
	Floor for heating	Stable heating, 2 systems with large initial investment	2010 VPU

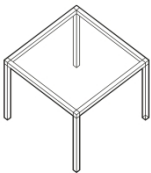
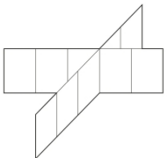
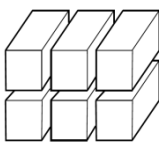
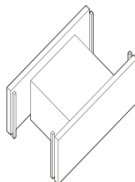
3.3 Industrial prefabrication system

3.3.1 Prefabrication system

Due to the strict limitation of 7-10 days' assembly time, most teams adopted industrial prefabrication (**Table 9**). The assembly system in two SDE competitions can be divided into four categories: frame, panel, module, and hybrid (Smith, 2010). Few teams used the frame-type while most of teams adopted the panel and module type because of time restriction.

The assembly system mainly affects the rankings of AR and industrialization & market viability (IMV). In AR, both panel system and hybrid system performed well. UPC in 2010 and TRA in 2012 who adopted the hybrid system had the best result in architecture. The main reason is that both teams adopted the ecological system consisting of well insulated boxes and buffer zones. The frame structure was applied to buffer zones for pretreating thermal environments while boxes integrated with module system. This shows a good collaboration between the hybrid type and multi-layer ecological space.

Regarding IMV, the performance of panel type was poor. The panel structure could not be standardized due to the various dimensions of interior space and openings on the exterior wall. It is not easy to achieve dense seam at the joint between roof and floor. The performance of module type was outstanding for its good integration of solar energy facilities, space, and interior elements.

Type	Diagram	Teams	Industrialization & Market	
			Architecture Ranking	Viability Ranking
Frame		2010: TJU, 2012: HTWG;	2010: 12, 2012: 4;	2010: 10, 2012: 1;
Panel		2010: AAL, BUW, AMP, BER, UON, TUC, 2012: ROME, BRA, BUC, CUJ, STSH;	2010: 1, 4, 12, 10, 12, 17, 2012: 3, 12, 14, 14, 16;	2010: 15, 5, 17, 10, 6, 16, 2012: 7, 12, 9, 16, 17;
Module		2010: VPU, ROS, HFT, UOF, CEU, UDS, IAA, 2012: AND, RWTH, BME, CEU, TJU, EHU, FAUP;	2010: 1, 6, 8, 12, 6, 8, 10, 2012: 4, 2, 8, 4, 8, 8, 16;	2010: 3, 2, 6, 8, 1, 13, 13, 2012: 6, 4, 11, 14, 15, 8, 13;
Hybrid		2010: GRE, UPC, UDV, 2012: TRA, UPC, ABC;	2010: 4, 1, 16, 2012: 1, 4, 8;	2010: 4, 9, 12, 2012: 2, 3, 10;

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3.3.2 Modulus

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The modulus of a building is usually determined by a combination of factors; the dominant factors have a decisive influence. In SDEs the factors were the following five: solar panel, space, transportation, material and furniture. The four major prefabrication types mentioned above had their own dominant factors of modulus. The modulus of the panel type was mostly dominated by indoor space. The module type was usually determined by transportation with consideration of assembly on site. In hybrid system, because of integration of buffer zones and solar facilities, the modulus was normally determined by solar panels.

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The different choices of modulus mainly affected the performances of AR and IMV. Most teams selected modulus which was between 455mm and 4200mm and concentrated in the range of 1500mm to 3000mm. The ranking of AR and IMV increased with the increase of modulus. The positive correlation proved that larger modulus had a better performance than the piecemeal one. For AR, the best modulus choice was between 2000mm and 2500mm, which were adopted by the hybrid type and module type. The top 4 teams used solar panels as a dominant factor for adaptation to their special dimension to achieve good building-integrated photovoltaic (BIPV) effect. Following the solar panel, transportation was another dominant factor among winning teams; in order to perform well with this factor, modulus needed to exceed 3500mm, which required special traffic control during transportation. For example, VPU in 2012 used warship for transportation. This faced restrictions in practice. In terms of IMV, the hybrid and panel types also achieved best performance. Teams who used solar panels as a dominant factor occupied top positions in the ranking; the second was transportation factor. Teams who adopted smaller modulus with consideration of material and furniture did not perform well.

3.4 Sustainability

3.4.1 Solar system sustainability

In the SDE competition, sustainability of the solar system was mainly reflected in EPBT (energy payback period time); 19 team out of 33 teams had a clear conclusion about this in their project manual. In general, the EPBT ranged from 1 to 21 years, most of which were between 1.5 and 7 years. Teams with special high-efficiency solar technologies had shorter EPBT (such as VPU in 2010 and ABC in 2012). VPU in 2010 used dual-side PV panels with single-axis altitude tracking system; ABC in 2012 used high-efficiency monocrystalline silicon (Mono-Si) concentrating photovoltaic (CPV) components.

The overall EPBT of polycrystalline silicon (Poly-Si) solar systems were around 2.2 years, which had more advantages than Mono-Si. In terms of efficiency, higher efficiency was not equal to a better performance in EPBT. The efficiency of top teams in terms of payback periods was only around 15%, which indicates that there should be a balance of the two (Table 9). There are two calculation methods for EPBT: energy recovery and electricity bill. The energy recovery period was usually shorter than the electricity bill payback period. Three teams based on the electricity bill had obtained payback time more than 10 years, showing that the economic recovery period for the solar system was even longer than the energy recovery. Two out of these three teams used solar film system. Particularly, CUJ in 2012 integrated solar film into the tiles of sloped roof; the manufactured small components resulted in a huge disadvantage of sustainability (longest payback period).

Table 10 Solar system EPBT

Solar System Type	Team	Efficiency	EPBT (year)
Mono-Si	2010 VPU	15.7%	0.9375
	2010 ROS	19.3%	12.2 (Bill)
	2010 UOF	18.5%	2.68
	2010 AND	20.4%	4.0
	2012 TJU	16.84%	5.9
	2012 TRA	-	6.8
Poly- Si	2010 GRE	15.4%	2.16
	2010 BUW	-	2.4
	2010 TUC	15.7%	2.2
	2010 UPC	13.4%	10.85
Film	2012 ROME	13.75%	2.2
	2010 UON	-	11.6 (Bill)
Mono +Poly-Si	2012 CUJ	-	21.6 (Bill)
	2010 HFT	13-17%	1.36
Mono-Si+Film	2010 AAL	15.4%	2.2
	2010 BER	13.77%	3.3
Poly-Si+Film	2012 BME	9.1-15%	2.91
	2012 HTWG	-	4
Concentrated	2012 ABC	-	1.93

3.4.2 Insulation material sustainability

The material in SDE competitions could be classified as thermal insulation materials, decorative materials and PCM materials. **Table 11** lists out the material choices for top teams.

Regarding the sustainability of conventional insulation material, based on the life cycle comparison of functional unit with $1\text{W}/\text{m}^2 \cdot \text{K}$ (U-value), the EPS insulation wasted most energy and resources, and also caused severe acidification effect. The best energy saving material was rock wool and mineral wool, followed by hemp fiber and glass wool. Hemp fiber is easy to recycle and growing fast, which is superior to glass wool (Ardenete et al., 2008).

As a new special material emerging in the competition, the VIP had an advantage in thermal insulation performance; however, considering sustainability, it was not so good as traditional mineral wool insulation. For example, in a small Swedish house, when using mineral wool and VIP to achieve the same thermal insulation effect, the energy consumption was respectively 33% and 39%, lower than the Swedish standard; VIP performed worse than mineral wool insulation in most life cycle criteria.

Table 11 Material choice of top teams

Ranking		1	2	3	4	5
SDE2010	Team	ROS	AMP	VPU	GRE	AAL
Comfort Top 5	Insulation	Vip+hemp	Mineral wool	Aerogel+EPS	Wood fiber	Cellulose
SDE2010	Team	AMP	UON	HFT	GRE, BER, IAA	
Sustainability Top 5	Insulation	Mineral wool	Glass wool	VIP+wool	Wood fiber or wool	
SDE2012	Team	TRA	BME	TJU	UPC	BRA
Comfort Top 5	Insulation	VIP+cellulose	cellulose	VIP	Wood fiber	Glass wool
SDE2012	Team	ROME	AND	RWTH	BRA	TRA
Sustainability Top 5	Insulation	Wood fiber	Mineral wool	VIP+wood fiber	Glass wool	VIP+cellulose

Thus, regarding sustainability, mineral wool was a good choice in general, followed by glass wool. When it did not require strict fire proof quality, hemp fiber became a better choice. VIP board was not the best choice, although it had a positive influence on stable thermal performance. The selection of insulation materials also proved this. In the competitions, the mineral wool insulation won the best sustainability performance; glass wool or cellulose was also a good choice. The insulation system with VIP core achieved the best performance in thermal comfort, but it did not perform well in sustainability.

3.5 Multi-criteria analysis

3.5.1 Dependent and independent variables

The performance of the solar contest was determined by combination of different passive and active strategies introduced above. In order to reveal the dynamic relation between these strategies and performance outcomes, a comprehensive multi-criteria analysis (MCA) was conducted. Three key performance contests consist of architecture (AR), comfort condition (CC) and electrical energy balance (EEB) that evaluate the output of ZESH, were chosen as dependent variables. Among them, AR was subjective contest evaluated by juries. CC and EEB were objective measurement contests. In the CC contest, temperature (23°C - 25°C , 70 points), humidity (40%-55%, 10 points), CO_2 (<800ppm, 5 points), work station lighting (>5000lux, 20 points) and acoustic (15 points) were measured; main differences between teams' performance were temperature and acoustic. In the EEB contest, SDE 2010 evaluated the positive accumulated balance (for example, the team with biggest surplus over 40kWh achieved the maximum points) and temporary generation-consumption correlation; SDE 2012 modified the accumulated balance rule (specifically, full points are endorsed when the accumulated electricity is more than certain value calculated from the tilt angle) and added electricity use per measurable area. The 24 strategies mentioned above are selected as independent variables for

the MCA, as shown in Table 12. Among them, 13 strategies' values are numerical and retrieved from official submitted documents (projects drawings and manual) while 11 strategies are categorized and assigned value according to their thermal performance from low to high.

Table 12 Independent variable selection and value assignment

Decision	Independent Variable	Strategy	Type	Value range	Criteria for value assignment
Shape	X ₁	Footprint	Numerical	55.0-149.9	Retrieved from project drawings
	X ₂	Insulated area	Numerical	42.0-75.1	Retrieved from project drawings
	X ₃	Aspect ratio	Numerical	0.46-3.10	Retrieved from project drawings
	X ₄	Shape coefficient	Numerical	0.92-1.65	Retrieved from project drawings
Function layout	X ₅	Prototype	Categorized	1-10	From courtyard to pavilion
	X ₆	Function structure	Categorized	1-3	From dispersed to compact
Microclimate organization	X ₇	Thermal mass	Categorized	0-4	From low energy storage capacity to high
	X ₈	Southward window-wall ratio	Numerical	0.0-69.6	Retrieved from Project Drawings
	X ₉	Shading	Categorized	0-6	From no sunshade to completely shaded
	X ₁₀	Buffer type	Categorized	0-3	From no buffer to greenhouse
	X ₁₁	Insulation core material	Categorized	1-7	From low U-value material to high
	X ₁₂	Insulation U-value	Numerical	0.080-0.450	Retrieved from Project Manual
	X ₁₃	Glazing U-value	Numerical	0.118-2.100	Retrieved from Project Manual
Solar system	X ₁₄	Capacity	Numerical	2.750-15.850	Retrieved from Project Manual
	X ₁₅	Main component	Categorized	1-6	From low conversion efficiency to high
	X ₁₆	Advanced technologies	Categorized	0-2	From no advanced technology to mature PV/T
	X ₁₇	Conversion efficiency	Numerical	9.1-20.4	Retrieved from Project Manual
HVAC system	X ₁₈	Southward tilt angle	Numerical	0.0-30.0	Retrieved from Project Drawings
	X ₁₉	Heat pump type	Categorized	0-3	From no heat pump to dual source heat pump
Industrial prefabrication system	X ₂₀	Annual HVAC energy demand	Numerical	290-2953	Retrieved from Project Manual
	X ₂₁	Prefabrication system	Categorized	1-4	From frame to Hybrid
	X ₂₂	Modulus dominant factor	Categorized	1-5	From furniture to solar panel
sustainability	X ₂₃	Modulus	Numerical	300-4200	Retrieved from Project Drawings
	X ₂₄	EPBT	Numerical	0.94-6.8	Retrieved from Project Manual

3.5.2 MCA results

With regression analysis using IBM SPSS 20, empirical models were established in Table 13-15.

Architecture

Table 13 shows the regression model for AR contest. Significant correlation can be observed on strategies such as shape coefficient, shading, insulation core material, advanced technologies and modulus. In 2010, modulus, insulation core material and shape coefficient most significantly influenced the result, and in 2012, most important independent variables were shading, shape coefficient and insulation core material. From the linear regression result, some preferable strategies can be identified. For passive strategies, greater insulated area, higher shape coefficient and tighter shading were preferred; a tight curved or square shape with small shape coefficient was not a good choice for AR. Basic insulation core material instead of most advanced material performed better in the AR contest. For active strategies, basic mature solar technologies with better BIPV performance were preferred. For industrial prefabrication system, frame and board types were preferred, and greater modulus can help to achieve higher scores. Significant correlations can also be observed for prototype, function structure, buffer type, southward tilt angle, footprint and modulus dominant factor. However, due to changes in scale and juries, the correlation strength between these strategies and AR scores also changed. In 2010 when the area was limited, compact industrial layout without buffer was preferred; while in 2012 more relaxed space with buffer space performed better.

Table 13 Regression analysis for the AR scores in SDE 2010 and 2012

Independent variables	2010 Architecture			2012 Architecture		
	<i>B</i>	β	<i>p</i>	<i>B</i>	β	<i>p</i>
Footprint	2.158	0.609	0.016	-0.172	-0.178	0.018
Insulated area	0.160	0.063	0.453	3.147	1.080	0.003
Shape coefficient	185.923	1.865	0.004	105.920	1.090	0.003
Prototype	-20.935	-2.932	0.004	5.188	0.538	0.009
Function structure	47.957	1.336	0.004	-14.302	-0.464	0.019
Shading	14.786	1.515	0.004	9.122	0.736	0.008
Buffer type	-41.829	-1.947	0.004	2.593	0.121	0.037
Insulation core material	-25.446	-2.679	0.003	-13.386	-1.039	0.004
Capacity	-1.522	-0.275	0.079	2.217	0.251	0.012
Advanced technologies	-21.283	-0.909	0.007	-3.020	-0.135	0.019
Southward tilt angle	-1.962	-0.934	0.008	1.686	0.671	0.008
Prefabrication system	-18.154	-0.764	0.011	-1.860	-0.063	0.085
Modulus dominant factor	18.881	0.995	0.010	-10.748	-0.308	0.013
Modulus	0.084	3.782	0.003	0.004	0.181	0.023
	$R^2=0.978$; $p=0.019$			$R^2=0.998$; $p=0.006$		

Comfort Condition

Table 14 shows the regression model for CC contest. Different from the AR where some of strategies strongly influenced the score, the good CC performance required an overall good outcome of these strategies. In both SDEs, positive correlation can be observed between CC and aspect ratio/thermal mass/buffer type, showing that greater aspect ratio, better thermal mass and buffer are preferred. Negative correlations were observed between CC and shape coefficient/insulation u-value/annual HVAC energy demand. Regarding southward window-wall ratio, greater opening was preferred in 2012 SDE but lower ratio performed better in 2010 SDE, showing that the influence of southward opening depended on the scale of the house; when the area was small, high southward window-wall ratio might cause lower stability of interior comfort condition.

Table 14 Regression analysis for the CC scores in SDE 2010 and 2012

Independent variables	2010 Comfort condition			2012 Comfort condition		
	<i>B</i>	β	<i>p</i>	<i>B</i>	β	<i>p</i>
Aspect ratio	10.154	0.409	0.015	5.085	0.180	0.399
Shape coefficient	-13.751	-0.152	0.510	-38.560	-0.736	0.140
Prototype	3.036	0.469	0.054	-3.435	-0.661	0.211
Thermal mass	10.948	0.789	0.064	7.096	0.582	0.077
Southward window-wall ratio	-0.180	-0.206	0.518	0.254	0.445	0.202
Shading	0.187	0.021	0.895	-0.511	-0.076	0.722
Buffer type	7.422	0.381	0.076	6.329	0.546	0.046
Insulation u-value	-106.903	-0.468	0.079	-23.334	-0.193	0.379
Glazing u-value	23.491	0.481	0.111	-19.520	-0.604	0.012
Heat pump type	0.293	0.018	0.929	-5.119	-0.434	0.153
Annual HVAC energy demand	-0.002	-0.077	0.746	-0.010	-0.327	0.132
	$R^2=0.886$, $p=0.006$			$R^2=0.802$, $p=0.042$		

Electrical Energy Balance

Table 15 shows the regression model for EEB contest. In SDE 2010, due to its linear scoring system where more energy achieved higher scores, the EEB performance was significantly influenced by the capacity, southward tilt angle, modulus dominant factor, modulus and shape coefficient. Positive correlations were observed between EEB and

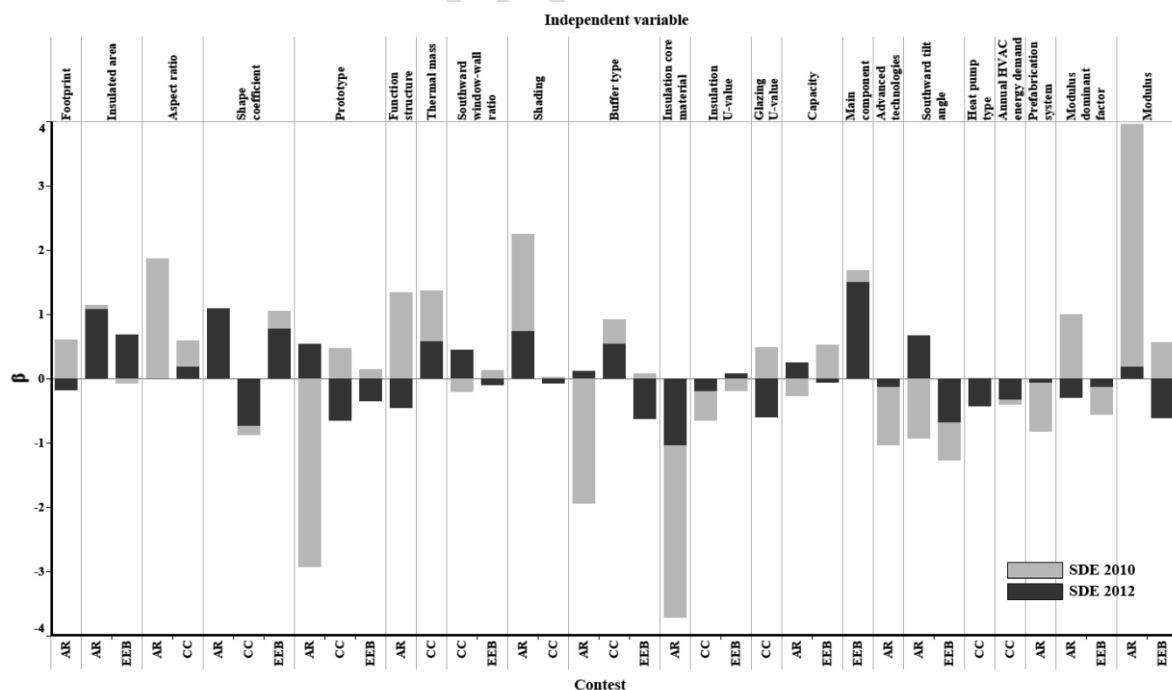
481 the shape coefficient, capacity and modulus; negative correlations existed between EEB and the southward tilt angle,
 482 modulus dominant factor and insulation u-value. Significant positive correlations were observed for main component
 483 and southward window-wall ratio. In SDE 2012, since the embedded energy of solar panels was firstly subtracted
 484 from the cumulative energy before scores were endorsed, capacity did not show significant impact on the
 485 performance. Significant positive correlations were observed between EEB score and the shape coefficient and main
 486 component. Negative correlations were found for modulus. Because energy consumption per unit area was counted in
 487 SDE 2012, greater insulated area also contributed to higher scores.

488 **Table 15** Regression analysis for the EEB scores in SDE 2010 and 2012

Independent variables	2010 Electrical energy balance			2012 Electrical energy balance		
	<i>B</i>	β	<i>p</i>	<i>B</i>	β	<i>p</i>
Insulated area	-0.039	-0.077	0.112	1.329	0.687	0.026
Shape coefficient	5.479	0.275	0.003	50.875	0.775	0.025
Prototype	0.227	0.159	0.045	-2.333	-0.359	0.278
Southward window-wall ratio	0.026	0.137	0.022	-0.073	-0.102	0.760
Buffer type	0.361	0.084	0.129	-9.212	-0.635	0.035
Insulation u-value	-9.775	-0.194	0.009	11.206	0.074	0.813
Capacity	0.575	0.520	0.000	-0.392	-0.066	0.783
Southward tilt angle	-0.248	-0.590	0.000	-1.169	-0.689	0.089
Main component	0.648	0.190	0.024	14.927	1.499	0.030
Modulus dominant factor	-1.669	-0.441	0.000	-3.039	-0.129	0.596
Modulus	0.003	0.565	0.000	-0.010	-0.621	0.020
	$R^2=0.987, p=0.000$			$R^2=0.830, p=0.032$		

489 *Cross-comparison*

490 **Figure 6** shows a cross-comparison among AR, CC and EEB. Some strategies could benefit one performance
 491 contest without compromising others. Mature insulation and solar technologies could contribute to AR; better thermal
 492 mass (exterior PCM) could benefit CC; mono-si solar panel could achieve better EEB performance. Some passive
 493 strategies could benefit more than one performance outcome. Greater insulated area could lead to better AR and EEB
 494 scores; greater aspect ratio could contribute to better AR and CC results because of the passive solar heating.



495
496

Fig. 6. Cross-comparison between AR, CC and EEB

At the same time, some contests had opposite requirements for a specific strategy; for example, AR and EEB required greater shape coefficient, while CC required smaller one. Although greater modulus benefited AR in both SDEs, smaller modulus was preferred in 2012 EEB. Because of different building scale, such opposite requirements also existed between 2010 and 2012 regarding the function structure and southward window-wall ratio.

4 Summary: an optimized ZESH

In the two SDEs, teams proposed various design strategies with their own understanding of climate and ZESH, which contributed to a mature system based on the Madrid climate, and set up foundation for a successful exhibition and widely promotion. Although the winning team already proved the possibility to satisfy daily life with ZESH, even the top teams have weakness in some respects. As revealed in this research, the comprehensive evaluation system requires a series of dynamic and strategic decisions. This paper identified 7 key decisions and discussed 24 strategies. **Table 16** summarizes the decisions and related strategies for an optimized ZESH. Generally speaking, a compact east-west rectangle box with passive solar system with buffer zone and hyper insulation (slightly better than passive house) is proper for Madrid; high efficiency PV and dual source heat pump can provide enough energy; hybrid prefabrication system with modular around 2250mm can integrate them well. These suggestions summarized from the two SDEs should not be directly used in other regions; they are also subject to changes because of rapidly evolving technologies. The framework and analyses proposed by this research can be used as a reference for the practice of pursuing a locally optimized ZESH system through experiments.

Table 16 Optimized ZESH strategies

Design	Decision	Optimized Strategy	
		SDE2010	SDE2012
Shape	Footprint & Insulated Area	74m ² & 50m ²	150m ² & 70m ²
	Shape Coefficient	1.0-1.1	
	Aspect Ratio	1.0-1.6	
Function	Prototype	Pavilion, east-west rectangle	
Layout	Function Structure	Compact	
Passive Design	Thermal Mass	Interior: Passive thermal mass, Exterior: Water or PCM storage	
	Southward Window-Wall Ratio	40%-70%	
Microclimate	Shading	Exterior Roller Blind/Curtain/Louver with Greenhouse	
	Buffer type	Greenhouse	
Organization	Insulation Material	VIP+hemp fiber, mineral wool or wood fiber	
	Insulation U-value	$U \leq 0.1 \text{ w/m}^2 \cdot \text{K}$	
	Glazing U-value	$U \leq 0.7 \text{ w/m}^2 \cdot \text{K}$, triple glazing	
Active Design	Solar System	Capacity & Main Component	14kWp, Mono-Si, Capacity density $\geq 190 \text{ Wp/m}^2$
		Advanced Technologies	Flat PV/T, Trough CPV
	Conversion Efficiency	>19%	
	Southward Tilt Angle	0° -5°	
HVAC System	Annual HVAC Energy Demand	<700kWh/a	<900kWh/a
	Heat Pump Type	water-air dual source heat pump	
Industrial Prefabrication System	Prefabrication System	Hybrid system	
	Modulus Dominant Factor	Consistent with Space and PV panels	
	Modulus	2000mm-2500mm	
Sustainability	Solar System Sustainability	Trough CPV have very good sustainability, Poly-Si with efficiency around 15% is slightly better than Mono-Si	
	Insulation Material Sustainability	Mineral wool, glass wool or cellulose have better sustainability	

5 Conclusion

515 This paper conducted a critical review of the SDE 2010 and 2012 projects to demonstrate the technical route
516 through experimental competition towards an optimized ZESH. Based on the existing SDE comprehensive evaluation
517 framework, this paper analyzed passive design, active system, industrial prefabrication system and sustainability
518 respectively, and identified key predictors and proposed empirical models for AR, CC and EEB contests with MCA.
519 The SDE evaluation framework was further extended to 7 key decisions and 24 detailed strategies after
520 cross-comparison, and finally formed an optimized ZESH system to transfer the technologies and strategies employed
521 in the SDE. Key related findings are as follows:

- 522 • Five strategies (shape coefficient, shading, insulation core material, advanced technologies, modulus)
523 significantly correlated to AR performance. Five strategies (bigger aspect ratio, better thermal mass, better
524 buffer, smaller shape coefficient, lower insulation u-value, lower annual HVAC energy demand) played
525 important roles in CC performance. Seven strategies (shape coefficient, southward window-wall ratio,
526 capacity, southward tilt angle, PV component, modulus dominant factor and modulus) significantly correlated
527 to EEB performance.
- 528 • Synergistic effects in SDE between various strategies have been revealed. Mature insulation core material,
529 mono-si solar panel, exterior PCM can benefit one performance without compromising the others; greater
530 insulated area and aspect ratio can benefit more than one performance contests. There is still great potential
531 for mutually beneficial integration between strategies, such as greenhouse and active system in 2010 UPC and
532 2012 TRA, PV/T technology in 2010 HFT, and highly integrated positive façade in 2012 TJU.
- 533 • Advanced technologies (aerogel, solar tracking system and CPV) still need better integrative design to
534 improve their AR performance and be presented as an elegant system; stylistic architectural strategies (curved
535 roof, light gaps, nonlinear shape) may have negative impact on CC and EEB performance contests, and should
536 be carefully evaluated against engineering performance.

537 This research has some limitations regarding the climate and test bed. Although the framework of evaluation can
538 be introduced to other climate regions, the optimized strategies might be confined to the special climate of Madrid
539 which is hot and dry in summer. The SDE projects analysed were designed according to strict regulations of the
540 competition with specific scale and function, and were only tested with contests during hot season; their performance
541 in winter are yet to be verified. Finally, in order to understand the physical principles behind the empirical models,
542 further work such as parametric thermal comfort and energy simulations will be conducted as a supplement to this
543 research.

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ACCEPTED MANUSCRIPT

A framework with 7 key decisions and 24 strategies for an optimized ZESH is established;

Thirty-three solar houses involved in Solar Decathlon Europe (SDE) in Madrid are examined;

Passive-active integrated empirical models for an optimized ZESH are generated;

Five important lessons for integrating passive and active solar technologies are extracted;

The research helps to transfer the experimental technologies and knowledge into design practices.