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Abstract

Innovations in Heating, Ventilation, and Air Conditioning (HVAC) systems are continuously required to provide a better, healthier and more productive and sustainable built environment for building occupants with minimized energy or cost consumption. This paper provides an overview of the HVAC technologies and systems used in 212 solar-powered houses developed through 13 U.S. Department of Energy Solar Decathlon (SD) competitions. Some comments and discussions on the HVAC technologies and systems used in the SD competitions were also provided. The review was carried out based on the information available from the organizer's project reports and equipment summary, team project manuals, and construction drawings available on the SD official websites as well as the published research papers and textbooks. It was found that 84.9% and 89.6% of the competition teams used heat pumps for space heating and space cooling, respectively, among which air-to-air heat pumps were used by approximately 50% of the competition teams. A wide range of energy technologies such as phase change materials, night-time radiative cooling, evaporative cooling, desiccant dehumidification, and energy/heat recovery ventilators have been used to reduce the electricity consumption of the HVAC systems. Energy/heat recovery ventilators were used by more than 55% of the teams in each competition held after 2005. Phase change materials were also frequently used in the competitions held in Europe. The SD competitions provided an excellent platform to showcase innovations of the HVAC technologies in residential buildings.

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A review of Heating, Ventilation and Air Conditioning technologies and innovations used in solar-powered net zero energy Solar Decathlon houses

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Abstract: Innovations in Heating, Ventilation, and Air Conditioning (HVAC) systems are continuously required to provide a better, healthier and more productive and sustainable built environment for building occupants with minimized energy or cost consumption. This paper provides an overview of the HVAC technologies and systems used in 212 solar-powered houses developed through 13 U.S. Department of Energy Solar Decathlon (SD) competitions. Some comments and discussions on the HVAC technologies and systems used in the SD competitions were also provided. The review was carried out based on the information available from the organizer's project reports and equipment summary, team project manuals, and construction drawings available on the SD official websites as well as the published research papers and textbooks. It was found that 84.9% and 89.6% of the competition teams used heat pumps for space heating and space cooling, respectively, among which air-to-air heat pumps were used by approximately 50% of the competition teams. A wide range of energy technologies such as phase change materials, night-time radiative cooling, evaporative cooling, desiccant dehumidification, and energy/heat recovery ventilators have been used to reduce the electricity consumption of the HVAC systems. Energy/heat recovery ventilators were used by more than 55% of the teams in each competition held after 2005. Phase change materials were also frequently used in the competitions held in Europe. The SD competitions provided an excellent platform to showcase innovations of the HVAC technologies in residential buildings.

Keywords: Net zero energy; HVAC; Solar Decathlon; Innovations; Renewable energy

Abbreviations

DW	desiccant wheel
ERV	energy recovery ventilator
GSHP	ground source heat pump
HRV	heat recovery ventilator
HTF	heat transfer fluid
HVAC	heating, ventilation and air conditioning
LAC	Latin America and Caribbean
LD	liquid desiccant
ME	Middle East
PCM	phase change material
PVT	photovoltaic-thermal
SD	Solar Decathlon
TES	thermal energy storage

1. Introduction

Heating, Ventilation, and Air Conditioning (HVAC) systems are among the major energy consumers in buildings and responsible for about 50% of total building energy consumption (Chua et al., 2013; Pérez-Lombard et al., 2008). HVAC systems are one of the main contributors to the peak demand of electric grids (Desideri, 2009) and are becoming increasingly important in the maintenance of the quality of life for a large fraction of the world's population. The number of HVAC systems installed is expected to dramatically increase in the coming decades, largely driven by economic growth, global warming and improvement in the living standards (Isaac and van Vuuren, 2009; Pérez-Lombard et al., 2008). It is estimated that the world electricity consumption of the HVAC systems will increase by a factor of 33 by the end of the century (Axell, 2015). On the other hand, there is long-standing and comprehensive evidence that HVAC systems have a direct effect on health, wellbeing, and productivity of building occupants. Low carbon and healthy HVAC systems are therefore essential to reducing global energy usage and greenhouse gas emissions, mitigating climate change, and maintaining satisfied indoor environment.

Over the last several decades, numerous innovations have been made on the development of innovative HVAC technologies. For instance, desiccant cooling has gained significant scientific attention due to its potential to achieve energy savings in tropical and subtropical regions (Ren et al., 2019a; Sahlot and Riffat, 2016). Thermal energy storage (TES) using phase change materials (PCMs) as an integrated component of HVAC systems has been investigated for effective peak demand control and load shifting (Cui et al., 2015; Sun et al., 2013). There has been a great initiative to take HVAC off the gird by developing solar thermal driven HVAC technologies and stand-alone solar-powered HVAC systems (Al-Alili et al., 2014; Huang et al., 2016). Solar assisted ground source heat pump (GSHP) systems and deep borehole GSHP systems are being examined, aiming to improve long-term heat transfer performance of ground heat exchangers and provide energy efficient heating and cooling (Wang et al., 2017; Xia et al., 2018). Heat and energy recovery ventilators were also extensively studied to assist in achieving energy savings (Mardiana-Idayu and Riffat, 2012).

Great efforts have also been made on the development of advanced design and control strategies for building HVAC systems to achieve enhanced energy or cost savings (Huang et al., 2015; Wang and Ma, 2008). The optimal solutions were generally determined based on one or multiple objectives such as energy performance, thermal performance, environmental performance and economic performance (Huang et al., 2015). Both the model-based approach and model-free approach have been used to formulate design and control optimization problems for HVAC systems. For instance, a model-based strategy using genetic algorithms was developed to optimally design active cooling energy storage units integrated with the HVAC systems for demand-side management of commercial buildings (Cui et al., 2017). A multi-objective design optimization strategy for vertical ground heat exchangers was developed to minimize the system upfront cost and entropy generation number (Huang et al., 2015). Adhikari et al. (2018) presented an optimal control method that uses a combination of a greedy algorithm and a binary search algorithm for a population of HVAC units to optimize the aggregated power demand. A self-optimization strategy with extremum seeking control was employed to achieve energy efficient control of a hybrid GSHP system (Hu et al., 2016). The model-based control strategies with and without learning and predictive functions have been extensively studied and used to search for the most energy efficient control settings for HVAC systems under ever-changing working conditions (Afram and Janabi-Sharifi, 2014; Ma and Wang, 2011). The results from these studies showed that optimization can play an essential role in ensuring that HVAC systems can deliver a healthy and productive built environment with minimized energy or cost consumption.

Innovations and breakthroughs in HVAC systems are continuously required. The U.S. Department of Energy Solar Decathlon (SD) is a great initiative and a live demonstration of the latest innovations in technologies, materials, and solutions developed for sustainable buildings (Solar Decathlon US, 2017). The buildings developed by the SD teams are generally single-family detached houses. More than 200 solar-power houses which aimed to achieve comfortable indoor environment and net-zero energy consumption have been developed and built through the SD competitions and a wide range of innovative HVAC technologies have been used in these houses. However, the HVAC technologies and HVAC innovations used in these SD houses have not been reviewed in the previous studies.

This paper aims to provide an overview of main HVAC technologies and systems developed and used in the previous Solar Decathlon competitions to demonstrate evidence-based HVAC innovations. The organization of this paper is as follows. Section 2 provides a brief introduction to the Solar Decathlon competition and thermal comfort contest. Section 3 presents a statistical analysis of major HVAC technologies used in the previous SD competitions. In Section 4, the major HVAC technologies and systems used in the previous SD competitions are reviewed, discussed and summarized. Some conclusive remarks are provided in Section 5.

2. Introduction to the Solar Decathlon competition

Solar Decathlon is an international competition initiated by the U.S. Department of Energy in 2002 that challenges collegiate teams to develop and operate efficient solar-powered houses that blend design excellence, smart energy production, and market potential (Solar Decathlon US, 2017). Fig. 1 presents an example of the Solar Decathlon competition held in the SD China 2013 competition. Like the Olympic decathlon, the Solar Decathlon competition consists of ten contests. The ten contests used in the Solar Decathlon Middle East 2018 consisted of architecture, engineering and construction, energy efficiency, sustainability, communication, innovation, energy management, comfort conditions, house functioning, and sustainable transportation (Solar Decathlon Middle East, 2018).

Fig. 1. An example of the competition in the Solar Decathlon China 2013 competition.

Fig. 2 presents the locations of the universities participated in the previous SD competitions and the countries and locations where the competitions were held, as well as the number of the teams participated in each competition (see the number in the bracket). It is noted that some competition teams were formed with more than one university. To date, there were eight competitions in the US, two competitions in China, three competitions in Europe, one competition in Latin America and Caribbean (LAC) and one competition in the Middle East (ME). The number of the teams participated in each competition varied from 13 to 22.

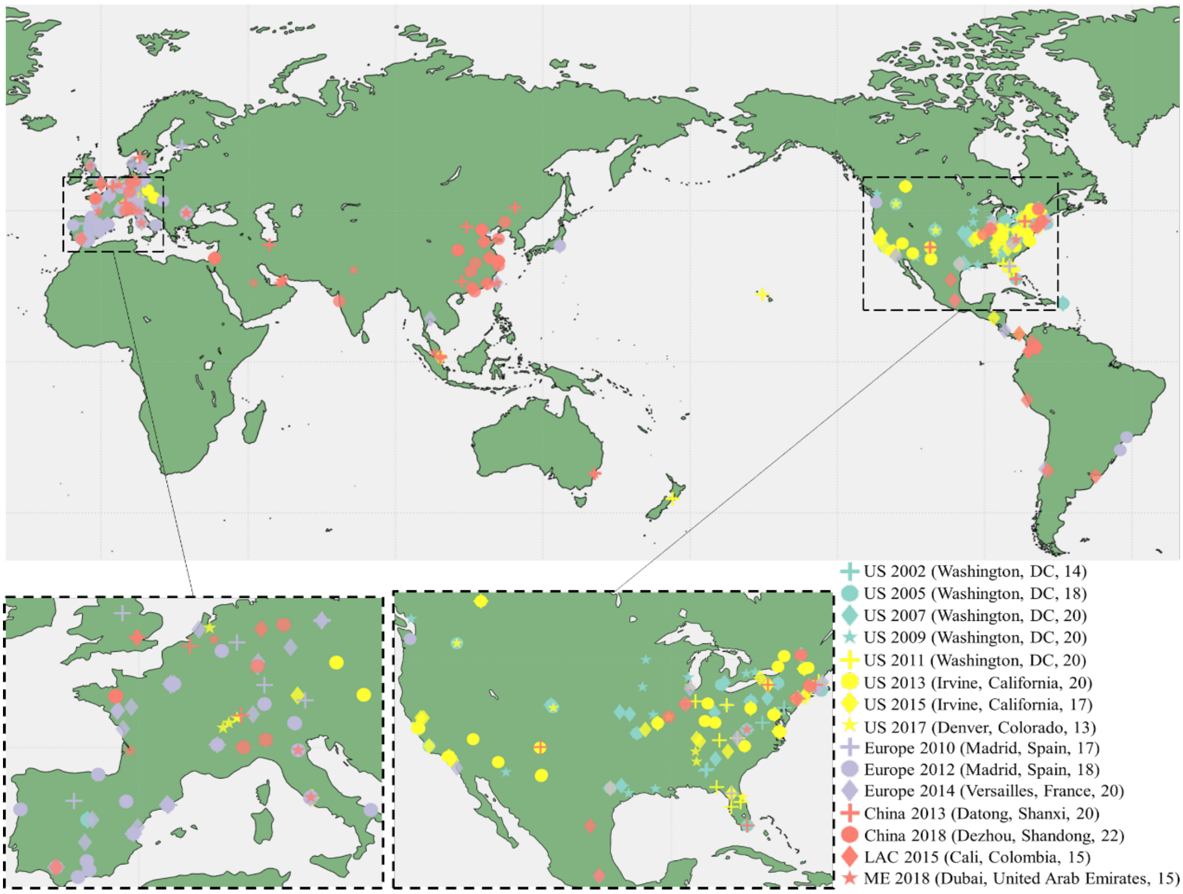


Fig. 2. Illustration of the locations of the universities participated in the previous SD competitions (Solar Decathlon China, 2018; Solar Decathlon Europe, 2014; Solar Decathlon Europe, 2012; Solar Decathlon Latin America & Caribbean, 2015; Solar Decathlon Middle East, 2018; Solar Decathlon US, 2017; Xiao et al., 2015).

The HVAC systems used in the SD competitions directly affect the comfort conditions contest, energy management contest, and energy efficiency contest. They may also influence other contests such as the innovation contest and sustainability contest. Using the competition in the SD Middle East 2018 competition as an example, the comfort conditions contest consisted of six sub-contests including temperature, humidity, air quality, lighting, façade airborne sound insulation, and HVAC noise (Solar Decathlon Middle East, 2018). According to the competitions rules, full points can be obtained if the teams can maintain their indoor conditions within the required ranges, and no point will be awarded if the indoor conditions were above or below certain values. Otherwise, a reduced point can be obtained.

3. Statistical analysis of the HVAC technologies used in the previous SD competitions

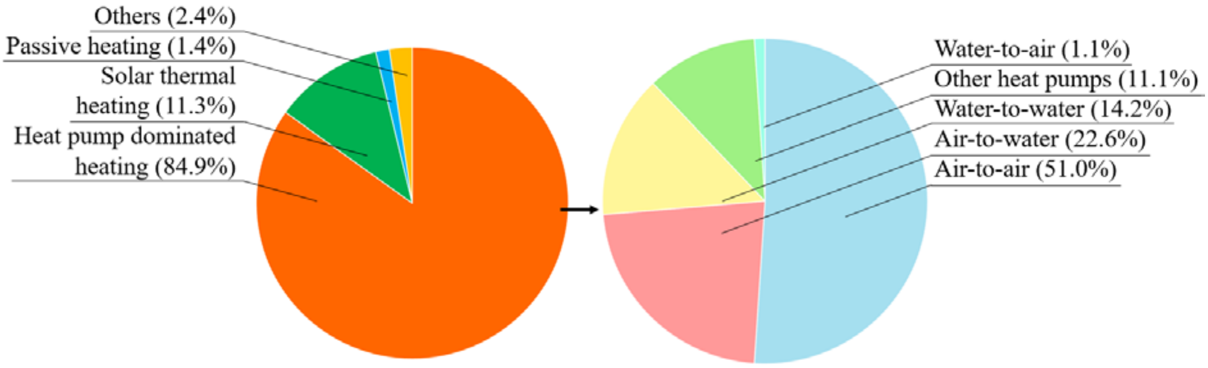
3.1 Methodology of the review

In this section, the HVAC systems and technologies used in the teams participated in the previous SD competitions were analyzed. The analysis was performed based on the information available from the organizer's project reports and equipment summary, team project manuals, and construction drawings available on the SD official websites as well as the published research papers and textbooks. It is noteworthy that the HVAC systems used in 13 competition teams were not reviewed due to lack of the information available and it is not our intention to miss the HVAC system used by a particular team. It is also worthwhile to note that the team names used referred to the names provided on the SD official websites.

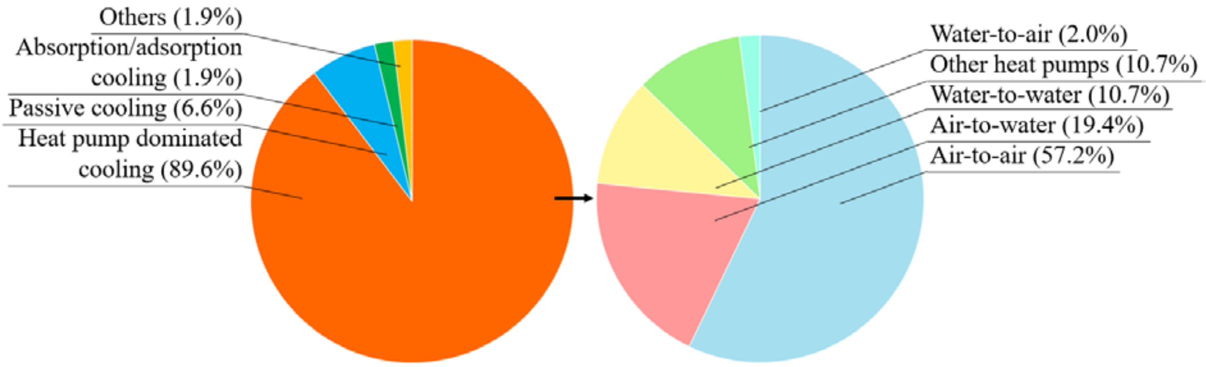
Due to lack of the information from some competitions and some teams, the HVAC systems used by 212 teams were analyzed herein, including 134 teams from the SD US competitions, 55 teams from the SD Europe competitions, 10 teams from the SD China 2013 competition, and 13 teams from the SD ME 2018 competition. It is noteworthy that this analysis was developed based on our best understanding of the information provided in the aforementioned literature and the actual systems from some teams built on-site may be slightly different due to various reasons. In addition, the teams that withdrew from the competitions and failed to build the house on-site were not analyzed.

3.2 HVAC systems used in 212 competition teams

Fig. 3 presents a statistical analysis of the HVAC technologies used for space heating and space cooling in the 212 teams reviewed. The HVAC technologies used for space heating were mainly categorized into three groups including passive heating, solar thermal heating and heat pump dominated heating. Passive heating represents that the space heating was achieved using passive technologies such as daylight control and thermal mass with integrated ventilation systems and did not rely on any active heating devices ((e)co Team, 2012; Team Mexico UNAM, 2014). It is noted that simple passive solar designs such as south-oriented windows and using low-emissivity glasses were not considered as passive technologies in this statistical analysis. Solar thermal heating represents that space heating was achieved by using solar thermal collectors only (Team FENIX, 2014; Team Iowa State, 2009). Heat pump dominated heating represents that space heating was either provided by heat pumps only or jointly provided by heat pumps and solar thermal collectors (Team Ohio State, 2011; Team Prêt-à-Loger, 2014). The HVAC technologies used for space cooling were categorized into passive cooling, absorption/adsorption cooling, and heat pump dominated cooling. Similarly, passive cooling means that space cooling was achieved using passive technologies such as night-time ventilation and natural ventilation ((e)co Team, 2012; Sánchez et al., 2010). Absorption/adsorption cooling means that only absorption or adsorption cooling technologies were used for space cooling (Team Cincinnati, 2007; Team Santa Clara, 2007). Heat pump dominated cooling represents that space cooling was provided by heat pumps only or jointly provided by heat pumps and other cooling technologies such as evaporative cooling, night-time radiative cooling, desiccant dehumidification, and thermoelectric cooling (Team Alabama, 2017; Team TDIS 2018; Fiorentini et al., 2015). It can be seen that heat pumps were used by the majority of the competition teams for both space heating and space cooling. Passive heating and solar thermal heating were used by 3 teams (1.4%) and 24 teams (11.3%), respectively. 14 teams (6.6%) and 4 teams (1.9%) used passive cooling and absorption/adsorption cooling for space cooling, respectively.



a) Space heating



b) Space cooling

Fig. 3. HAVC technologies used in 212 SD competition teams for space heating and space cooling.

A further analysis was carried out for the heat pumps used in the previous SD competitions and the results are also presented in Fig. 3. According to the heat transfer fluids used in the evaporator and condenser, the heat pumps used were categorized into five groups including air-to-air heat pumps, air-to-water heat pumps, water-to-water heat pumps, water-to-air heat pumps, and other heat pumps. The heat pumps were mainly categorized based on the heat sink/source used for space cooling and the heat source/sink used for space heating. Other heat pumps mainly included compact heat pumps for both air and water heating at the same time; heat pump water heaters using solar panels as the evaporator; and thermodynamic heat pumps in which the compressor was operated by a thermally driven turbine.

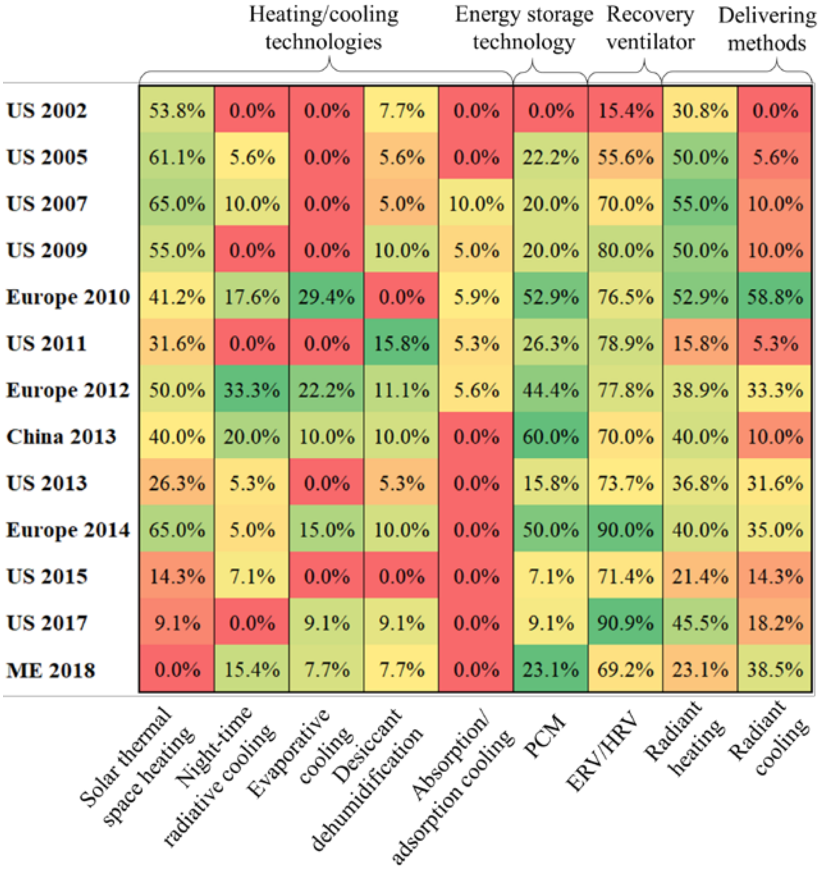
From Fig. 3, it can be observed that air-to-air heat pumps were the most popular type of heat pumps used in the SD houses, followed by air-to-water heat pumps, water-to-water heat pumps, other heat pumps, and water-to-air heat pumps for both space heating and space cooling. 51.0% and 57.2% of the heat pumps used for space heating and space cooling were the air-to-air heat pumps, respectively. The percentages of using air-to-water heat pumps and water-to-water heat pumps for space heating were slightly higher than those for space cooling. Only a few teams used water-to-air heat pumps for space heating and space cooling. It is worthwhile to note that water-to-water heat pumps and water-to-air heat pumps used by some teams were developed based on the concept of ground source heat pumps, in which ground heat exchangers were emulated by using a water tank (Team Penn State, 2007; Team Virginia Tech, 2009; Team WASH U – ST. LOUIS, 2017) or a phase change material (PCM) thermal energy storage (TES) unit (Sánchez et al., 2010).

For the delivering method of the HVAC systems used by the 212 SD houses reviewed, 54.3% of the teams used air to condition the indoor space through either ducted systems or ductless systems for space heating, and 71.2% of the teams used air to deliver cooling energy. 15.1% and 6.6% of the competition teams used radiant panels such as radiant floor, radiant ceiling and hot water radiator for space heating and cooling, respectively. A number of teams used both air and radiant panels for space heating (24.1%) and cooling (14.6%), respectively.

Heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) as energy recovery solutions have been frequently used to improve the energy performance of HVAC systems. The HRV and ERV were used to recover the sensible heat and total heat, i.e. sensible heat and latent heat, between the two air flows, respectively. Among the teams used HRVs and ERVs, 63.3% of the teams used ERVs and the rest used HRVs. HRVs were mostly used in the SD competitions held in Madrid (Spain) and Versailles (France) where weather conditions are moderate, and humidity control was not the major focus in the HVAC system design.

3.3 HVAC technologies used in each competition

To examine the technology transformation and innovations, the HVAC technologies used in each competition were also analyzed. In this section, the HVAC technologies were analyzed based on the technologies used including solar thermal space heating, night-time radiative cooling, evaporative cooling, desiccant dehumidification, and absorption/adsorption cooling as heating/cooling technologies, PCM as energy storage technology, ERV/HRV as recovery ventilators, and radiant heating and radiant cooling as delivering methods. It is noted that the focus of this review was on the technologies used to provide and/or assist space heating, cooling, and ventilation, and domestic hot water was not included in the statistical analysis. The analysis was carried out by determining the percentage of the teams using these technologies to the total number of the teams participated in each competition. The results of the statistical analysis are summarized in Fig. 4.



	Heating/cooling technologies					Energy storage technology	Recovery ventilator	Delivering methods	
	Solar thermal space heating	Night-time radiative cooling	Evaporative cooling	Desiccant dehumidification	Absorption/ adsorption cooling	PCM	ERV/HRV	Radiant heating	Radiant cooling
US 2002	53.8%	0.0%	0.0%	7.7%	0.0%	0.0%	15.4%	30.8%	0.0%
US 2005	61.1%	5.6%	0.0%	5.6%	0.0%	22.2%	55.6%	50.0%	5.6%
US 2007	65.0%	10.0%	0.0%	5.0%	10.0%	20.0%	70.0%	55.0%	10.0%
US 2009	55.0%	0.0%	0.0%	10.0%	5.0%	20.0%	80.0%	50.0%	10.0%
Europe 2010	41.2%	17.6%	29.4%	0.0%	5.9%	52.9%	76.5%	52.9%	58.8%
US 2011	31.6%	0.0%	0.0%	15.8%	5.3%	26.3%	78.9%	15.8%	5.3%
Europe 2012	50.0%	33.3%	22.2%	11.1%	5.6%	44.4%	77.8%	38.9%	33.3%
China 2013	40.0%	20.0%	10.0%	10.0%	0.0%	60.0%	70.0%	40.0%	10.0%
US 2013	26.3%	5.3%	0.0%	5.3%	0.0%	15.8%	73.7%	36.8%	31.6%
Europe 2014	65.0%	5.0%	15.0%	10.0%	0.0%	50.0%	90.0%	40.0%	35.0%
US 2015	14.3%	7.1%	0.0%	0.0%	0.0%	7.1%	71.4%	21.4%	14.3%
US 2017	9.1%	0.0%	9.1%	9.1%	0.0%	9.1%	90.9%	45.5%	18.2%
ME 2018	0.0%	15.4%	7.7%	7.7%	0.0%	23.1%	69.2%	23.1%	38.5%

Fig. 4. Statistical analysis of the HVAC technologies used in each SD competition.

The percentage of the teams using solar thermal for space heating in the SD US competitions increased from 53.8% in 2002 to 65.0% in 2007 and then decreased to 9.1% in 2017. For the competitions held in Europe, the percentage of the competition teams using solar thermal for space heating increased from 41.2% in 2010 to 65.0% in 2014. No team used solar thermal for space heating in the SD ME 2018 competition. The night-time radiative cooling was first used in the US 2005 competition and only a few teams used this technology in the SD US competitions. However, one-third of the teams used night-time radiative cooling in the SD Europe 2012 competition. The data from the more recent competitions (i.e. US 2015 and US 2017) showed that the application of night-time radiative cooling in the SD houses was still limited, although there were two teams used night-time radiative cooling in the SD ME 2018 competition. Evaporative cooling in Fig. 4 refers to the use of direct evaporative coolers and indirect evaporative coolers. Evaporative cooling was first used in the SD Europe 2010 competition and this technology was more preferred in the competitions held in Europe as the percentages of the teams used evaporative cooling were always not less than 15% in the SD Europe competitions, while evaporative cooling was only used in the most recent competition held in the US with a relatively low percentage (i.e. 9.1% in the SD US 2017 competition). The percentage of the teams using desiccant dehumidification was always less than 16% in the previous SD competitions. The absorption/adsorption cooling was first used in the SD US 2007 competition and the application of this technology was quite limited probably due to its high initial cost and high temperature (e.g. above 80 ^{o}C) (Gomri, 2013; Shirazi et al., 2018) thermal energy generally required which cannot be continuously provided by solar thermal systems.

It can be seen that the application of PCMs in the US competitions first increased to the peak of 26.3% in 2011 and then decreased to less than 10% in recent competitions. The percentage of the teams using PCMs in the SD Europe competitions remained at a relatively high level of approximately 50%. The highest percentage of 60.0% resulted in the SD China 2013 competition however it should be noted that only 10 teams were reviewed for this competition. It is also worthwhile to note that the above data included both active and passive applications of PCMs such as using PCM as separate TES units and using PCMs in building structure to enhance thermal mass. It can be observed that ERV/HRV is becoming more and more popular in the SD competitions. In the SD US 2002 competition, the ERV/HRV was only used in 15.4% of the competition teams and it increased to 55.6% in the SD US 2005 competition. After that, more than 69% of the competition teams used this technology in the following competitions. The radiant heating was frequently used in the SD competitions. Compared to radiant heating, radiant cooling was much less frequently used in the SD competitions held in the SD US and China competitions while it was still a preferred option in the SD Europe and ME competitions.

From the above results, it can be seen that some technologies were preferred in some competitions. For instance, using solar thermal for space heating was not used in the SD ME 2018 competition due to its hot and humid weather conditions and was less frequently used in the SD US 2013 (Irvine, California) and 2015 (Irvine, California) competitions due to the relatively warm weather conditions in Irvine. The evaporative cooling was frequently used in the SD Europe 2010 (Madrid, Spain) and 2012 (Madrid, Spain) as the average maximum daily temperature and the average relative humidity of Madrid in July were 25.6 ºC and 38%, respectively (La Agencia Estatal de Meteorología, 2019). However, it seems that some technologies such as heat pumps, ERV/HRV, and radiant cooling, were not obviously influenced by the location of the competition.

The above analysis showed that heat pumps were the preferred technology that has been used by the majority of the competition teams for space heating and space cooling probably due to their reasonable prices and robustness to provide heating and cooling, easy to install, and easy to control. The frequent use of air-to-air heat pumps may be due to the fact that their installation was easier than that of heat pumps using liquids as the heat transfer fluid.

Solar thermal, night-time radiative cooling, and desiccant dehumidification were also frequently used by the competition teams to showcase innovations and reduce the electricity consumption of the HVAC systems. The solar thermal space heating was the most frequently used renewable energy technology, as solar collectors are the mature technology and have been widely used in many residential buildings (Huang et al. 2019). However, the use of solar collectors will reduce the availability of the roof area for PV installations. Therefore, the size of solar collectors to be used should be optimized in order to maximize the utilization of the available roof area and solar energy in SD houses. As solar energy is intermittent, the HVAC system needs to be grid-connected or integrated with thermal and/or electrical storage systems in order to continuously provide services.

4. Overview of energy efficient HVAC solutions used in the Solar Decathlon competitions

Fig. 5 shows the major HVAC technologies used in the previous SD competitions, in which the technologies that were not covered in this section were presented in grey boxes while those reviewed in this section were presented in boxes with different colors. Some of them such as heat pumps, radiant panels, and ERV/HRV have been widely used by many competition teams while some of them such as absorption cooling and adsorption cooling were only used in a few houses. In this section, the HVAC technologies reviewed mainly included thermal energy storage using PCMs, solar thermal energy for space heating, night-time radiative cooling, desiccant dehumidification, evaporative cooling, and advanced control strategies. It is noted that passive applications of PCMs, which integrated PCMs into building structures to increase building thermal mass only, thereby reducing heating and cooling demand of HVAC systems and improving indoor thermal comfort (Lin et al., 2016), were not reviewed. The review of the passive application of PCMs by a number of the competition teams participated in the early SD US competitions and the SD Europe 2012 competition can be found in Rodríguez-Ubiñas et al. (2011) and Rodriguez-Ubinas et al. (2014), respectively.

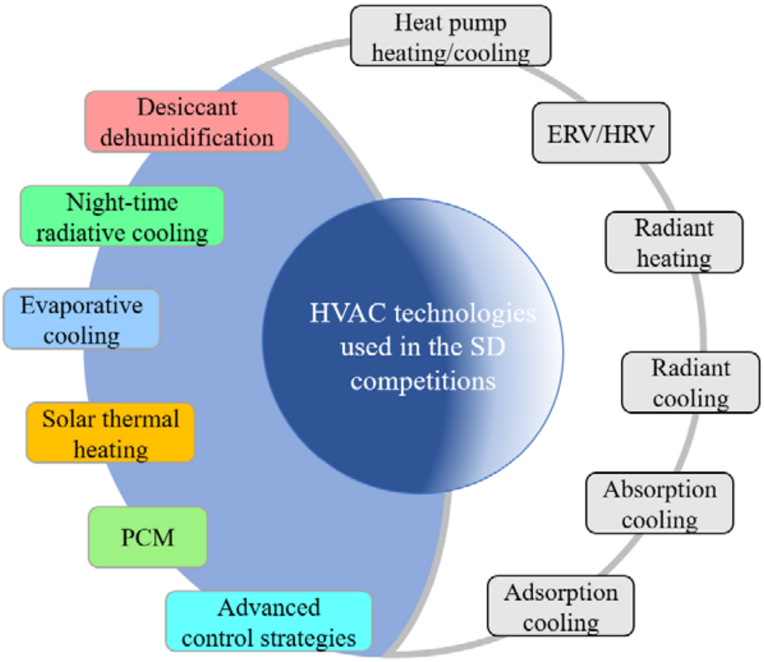


Fig. 5. Summary of main HVAC technologies used in the SD houses.

4.1 Thermal energy storage using PCMs

PCMs which have large energy storage densities and are available with different melting temperatures have been widely considered as an energy efficient solution to enhance building energy efficiency (Ma et al., 2016; Rehman et al., 2019). A number of the competition teams that used PCM TES as stand-alone systems, and integrated PCM TES with building HVAC systems, as well as integrated PCMs into building structures but a heat transfer fluid was used to actively charge/discharge the PCM are reviewed hereafter. The details of the competition teams used PCM TES as stand-alone systems, and integrated PCM TES with building HVAC systems are summarized in Table 1. It is worthwhile to note that the PCM TES units used by a few teams were not included in Table 1 due to lack of the information.

It can be seen that PCMs were generally used as centralized TES units for storage of renewable and non-renewable thermal energy, such as solar thermal energy, ambient coolness/heat, night-time radiative cooling, evaporative cooling, and heating and cooling energy generated by heat pumps. A TES unit, for instance, which consisted of spheres filled with water and placed in a water tank, was used by Team Colorado (2007a, 2007b) in the US 2007 competition. The TES unit enabled the ice thermal storage to shift the peak load of space cooling in summer, and it was also served as a TES system to store solar thermal energy from water-based photovoltaic-thermal (PVT) collectors and operated as the heat source of a water-to-water heat pump in winter. In the SD US 2011 competition, a PCM TES tank with three coil heat exchangers inside was developed by Team New York (2011). The PCM used was an organic PCM of RT82 (Rubitherm GmbH, 2019). The PCM was charged by solar thermal energy generated from evacuated tube solar collectors and the thermal energy was used to power an adsorption chiller or drive radiant floor heating, and also used for domestic hot water. The tank was designed by considering the volume change of the PCM during the phase change process and the heat transfer performance between the PCM and the heat transfer fluid. A water-based PCM thermal storage tank was developed by Team UOW (2018) in the recent SD ME

2018 competition, as shown in Fig. 6. The PCM TES unit was used in the HVAC system for load shifting and demand-side management. The PCM used was an inorganic PCM (i.e. TubeICE S10) (PCM products Ltd., 2019) with a nominal phase change temperature of 10 ^{o}C, which was pre-encapsulated in high-density polyethylene (HDPE) tubular containers. These tubes were arranged in a triangular array and encased in a stainless-steel cylindrical tank. The PCM tubes were constrained in the tank using two stainless-steel plates with openings, and a large number of perforated holes were fabricated to ensure an even water flow distribution through the PCM tube array.

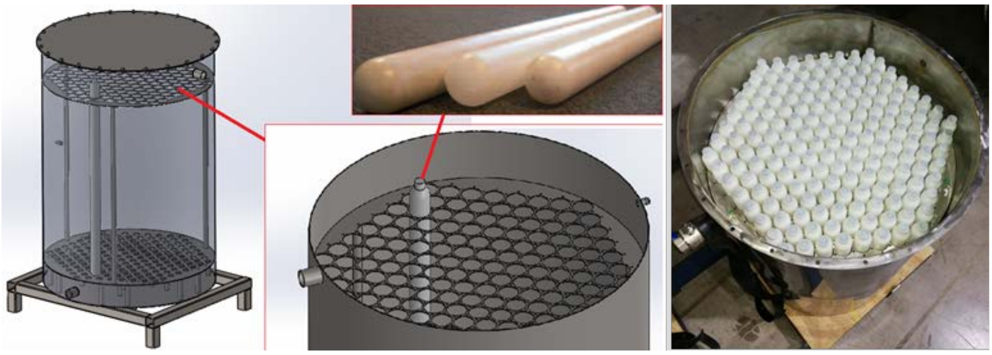
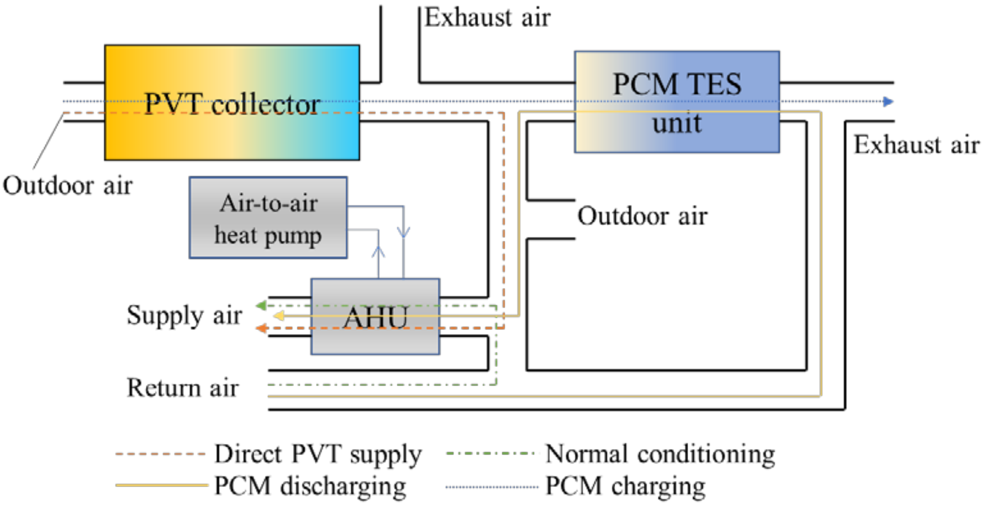


Fig. 6. PCM TES used in the HVAC system of Team UOW Desert Rose house for load shifting in the SDME 2018 competition.

In the SD Europe 2010 competition, Team Napevomo (Sánchez et al., 2010) installed four air-based PCM TES units under the floor for space cooling. The PCM was cooled by the ambient air during night-time and the indoor air temperature was regulated by circulating the air between the TES units and the indoor environment during daytime. An air-based PCM TES unit, as shown in Fig. 7a), was used in a solar-assisted HVAC system (Fig. 7b) in the SD China

2013 competition. The PCM used was an inorganic PCM product (i.e. PlusICE S21) (Fiorentini et al., 2015; PCM products Ltd., 2019), with a phase change temperature of around 22 °C. In this system, the air-based PCM TES unit was used to store the heating and cooling energy generated by the air-based PVT collectors via solar radiation and night-time radiative cooling, respectively. The stored thermal energy was then used for space heating and cooling by circulating the air between the PCM TES unit and the indoor environment, or for pre-heating or pre-cooling the air for the air handling unit of the HVAC system.

a) Air-based PCM TES system



b) HVAC system with integrated PCM TES unit

Fig. 7. Illustration of the PCM TES and HVAC system developed by Team UOW for the SD China 2013 competition, modified from Fiorentini et al. (2015).

An innovative PCM emulsion was used by Team RWTH Aachen University (2012) in the SD Europe 2012 competition as the heat transfer fluid and TES material for space cooling. The PCM emulsion used was essentially a mixture of water and paraffin wax, whose heat capacity was 1.59 times higher than water in the temperature range of 16-22 °C (Team RWTH Aachen University, 2012). The PCM emulsion was regenerated using the coolness collected from a rooftop night-time sky radiative cooling and water evaporation system.

A number of the competition teams implemented PCMs in the building structures but charging/discharging of the PCM was actively controlled by circulating the heat transfer fluid through the PCM. These PCM systems increased the local thermal mass of the building structures and at the same time served as TES units for building thermal energy management. The details of these systems are summarized in Table 2. Again, the PCM used in some competition teams were not included due to lack of the details.

Team Madrid developed a hybrid PCM system in their SD house in the SD US 2005 competition (Moon et al., 2005). Three layers of macro-encapsulated PCM with a phase change temperature of 22-24 ºC were integrated into the raised floor (Hernández-Martínez, 2011). During the winter daytime, the PCM was passively charged by the solar radiation transmitted through the window on the south façade, and actively charged using the indoor air heated by the greenhouse double skin façade. During night-time, the thermal energy stored in the PCM can be discharged passively, or can be discharged actively by circulating the air between the PCM and the indoor environment via a fan. In summer, the night-time coolness was stored in the PCM and it was released during the daytime for space cooling. A surface activated radiant cooling system enhanced by PCMs was adopted by Team Darmstadt (2007) in the SD US 2007 competition. The micro-encapsulated PCM was embedded into plasterboards, and then integrated onto the east and west walls, and ceilings. The PCM enhanced plasterboard on the ceiling was coupled with capillary-tube mats for space cooling. It was charged using the chilled water generated by a passive ceiling cooling system with water evaporation and sky radiative cooling on the rooftop during the night-time. In the SD US 2011 competition, Team Appalachian State (2011) developed a PCM-enhanced Trombe wall which consisted of rotatable Trombe fins filled with oil-based PCM. The PCM was charged by the solar radiation on the Trombe wall during daytime and the thermal energy could be passively released during night-time for space heating. The Trombe fins could also be used to assist daylight control.

The above review showed that PCMs have been frequently used by the SD competition teams to reduce energy consumption of the HVAC systems mainly through load shifting and load reduction. The use of PCM TES could also facilitate the application of renewable heating and/or cooling systems by solving the mismatch between the energy demand and solar thermal energy generation, which could further reduce the energy consumption of HVAC systems or even take air conditioning off the grid. However, the real performance of the SD houses due to the use of PCMs was not reported. As PCMs are generally expensive in comparison with building construction materials, detailed performance optimization and cost benefit analysis should be carried out during the decision-making process.

Table 1. Summary of stand-alone PCM TES units and PCM TES units integrated with HVAC systems.

Team	HTF	Details of the TES units	PCM used			Reference
			Name/type	Melting temp. (^{o}C)	Latent heat (kJ/kg)	
RISD	Liquid	PCM bricks were placed in a container under the house and used as separate heat and cold sinks.	Salt hydrates	-	-	Moon et al. (2005), U.S. DOE (2005)
Colorado	Liquid	An ice TES system was integrated with a water-to-water heat pump.	Ice	0	334	Team Colorado (2007a, 2007b)
Germany	Air	A TES was placed above the ceiling and charged through night-time ventilation for space cooling.	Delta-COOL23	20-25	185	Team Germany (2009)
Ohio State	Air	PCM was filled in HDPE containers and placed in an air-based TES unit; PCM was charged by wall-integrated solar air heaters.	PCM29P (mainly $CaCl_2$ hexahydrate)	29	-	RGEES (2019), Team Ohio State (2011)
New York	Liquid	PCM was filled in a TES tank with three coil heat exchangers inside; PCM was charged by solar water heaters, and used for space heating via radiant floor and for space cooling via an adsorption chiller.	RT82 (Paraffin)	77-82	170	Team New York (2011), Rubitherm GmbH (2019)
AZ State / New Mexico	Liquid	An ice TES unit was integrated with a chiller.	Ice	0	334	Team AZ State / New Mexico (2013)
Solar Cal Poly	Air	PCM was filled in the aluminum tubes and placed in the air duct.	BioPCM (palm oil)	-	-	Team Solar Cal Poly (2015)
Las Vegas	Air	PCM was encapsulated into foil packets and installed in a fresh air plenum; PCM was charged by ambient heat or coolness.	Eutectic salt	25.6	-	Team Las Vegas (2017)

Napevomo	Air	PCM was filled in the tubes and placed in a TES unit; PCM was charged by night-time ventilation and used for space cooling.	-	-	-	Sánchez et al. (2010)
Bamboo House	Air	Four rectangular ventilation ducts with PCM bricks were used to regulate indoor air temperature for both space heating and cooling.	-	-	-	Sánchez et al. (2010)
URCOMANTE	Liquid	PCM was used to emulate thermal inertia of the earth for a geothermal heat pump.	-	-	-	Sánchez et al. (2010)
Rhône-Alpes	Liquid	PCMs with different phase change temperatures were filled in a water tank and charged by PVT collectors via solar thermal energy and night-time radiative cooling, respectively, or by a heat pump, and used for indoor radiant heating and cooling.	-	35/10	-	Team Rhône-Alpes (2012)
RWTH Aachen University	Liquid	PCM emulsion was used as the working fluid for space cooling, and was cooled by night-time radiative cooling and water evaporation.	PCM emulsion (RT20 based)	16-22	40	Team RWTH Aachen University (2012), Hanu et al. (2012)
CEU Team Valencia	Liquid	Two PCM tanks were integrated with a heat pump for space cooling; One was used as the heat sink while the other was used as cold storage.	-	-	-	CEU Team Valencia (2012), Real et al. (2014)
Aquitaine Bordeaux Campus	Air	Three PCM heat exchangers were used for space cooling by using the coolness generated via night-time ventilation.	Paraffin	21	-	Team Aquitaine Bordeaux Campus (2012)
équipe VIA-UJI	Air	PCM was charged by the heated air from a greenhouse and discharged during night-time for space heating.	S25	25	180	Team équipe VIA-UJI (2014)

FENIX	Air	PCM was charged by the heated air from the solar air heater and discharged during night-time for space heating.	-	25-28	-	Team FENIX (2014)
Réciprocité	Air	The system used was similar to that used by Team FENIX (2014).	-	46	-	Team Réciprocité (2014)
UOW	Air	PCM was filled in the plastic containers and placed in a TES unit; PCM was heated and cooled via solar thermal energy and night-time radiative cooling, as well as a heat pump.	PlusICE S21	22	170	Fiorentini et al. (2015), PCM products Ltd. (2019)
UOW	Liquid	A TES unit with a number of HDPE tubes filled with PCM was used to store cooling energy for load shifting and demand side management.	TubeICE S10	10	155	Team UOW (2018), PCM products Ltd. (2019)
ORA	Air	A PCM TES unit was charged by night-time ventilation and used for space cooling.	PlusICE S32	32	200	Team ORA (2018), PCM products Ltd. (2019)

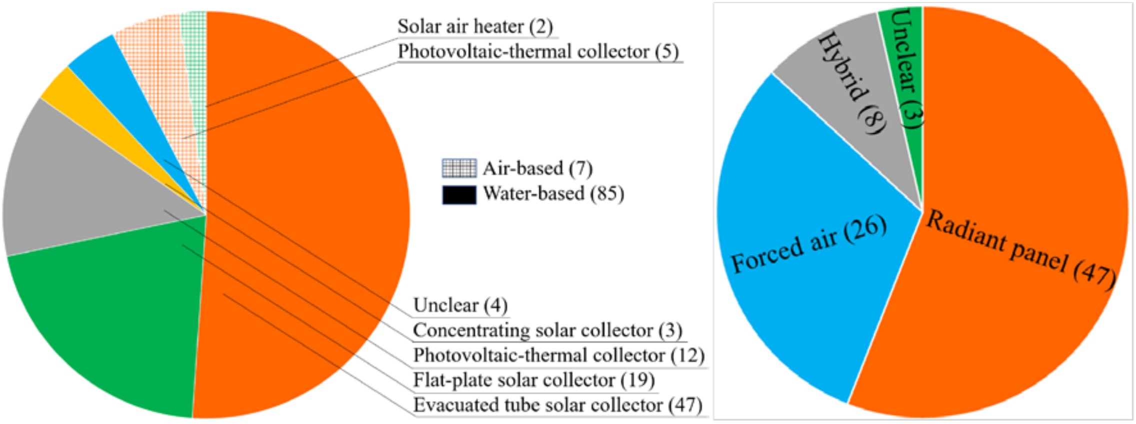
428 **Table 2.** Summary of the PCMs actively used in building structure of the SD houses.

Team	HTF	Details of the TES systems	PCM used			Reference
			Name/type	Melting temp. (^{o}C)	Latent heat (kJ/kg)	
Madrid	Air	PCM was placed under the floor and used for intake air preheating and precooling; PCM was charged through greenhouse double-skin façade.	-	22-24	-	Moon et al. (2005), Hernández-Martínez (2011)
Canadian	Air	PCM-soaked bricks were placed beneath the floor; PCM was charged by PVT collectors and used for space heating.	Organic mixture	-	-	Moon et al. (2005), U.S. DOE (2005)
Darmstadt	Liquid	PCM was integrated with a chilled ceiling and charged by the water which was cooled via evaporative cooling.	Micronal plaster board	-	-	Team Darmstadt (2007)
Appalachian State	Air	PCM was integrated with rotatable fins of a Trombe wall and was charged by solar radiation for space heating.	BioPCM - 27M	27	165-200	Team Appalachian State (2011)
home^{+}	Liquid/ Air	PCM was integrated with a chilled ceiling and charged by a PVT collector via night-time radiative cooling, or a heat pump, or evaporative cooling.	-	21-23	-	Sánchez et al. (2010)
IKAROS Bavaria	Liquid	PCM was integrated with a radiant ceiling for both space heating and cooling, which was integrated with a heat pump.	-	-	-	Sánchez et al. (2010)
ECOLAR	Liquid	PCM was integrated with a chilled ceiling and charged by a PVT collector via night-time radiative cooling or a heat pump.	-	-	-	Team ECOLAR (2012)
Chiba University	Air	PCM was filled in the containers and placed under the floor, which was integrated with a raised floor air conditioning system for both space heating and cooling.	Paraffin	21	100	Team Chiba University (2014)

Rooftop	Liquid	PCM was integrated with a chilled ceiling, and charged by a heat pump or night-time natural ventilation or evaporative cooling via a constructed wet-land.	-	23	-	Team Rooftop (2014)
Virginia Tech	Air	PCM was mounted on the ceiling for demand-side management. It was charged by the HVAC system and used for space cooling at non-solar production period.	-	22	-	Team Virginia Tech (2018)

4.2 Solar thermal space heating

A number of the SD houses used solar thermal energy for space heating. The types of solar collectors and delivering methods used as well as the number of the teams which used different solar thermal technologies for space heating are summarized in Fig. 8. Solar collectors could be generally categorized into water-based collectors and air-based collectors dependent on the heat transfer fluid used. The water-based solar collectors used for space heating could be further categorized into evacuated tube solar collectors, flat-plate solar collectors, photovoltaic-thermal (PVT) collectors, and concentrating solar collectors. The delivering methods were required when water-based solar collectors are used, which could be categorized into three types including radiant panels, forcing air, and hybrid method which used both radiant panels and forcing air. The air-based solar collectors could be categorized into solar air heaters and air-based PVT collectors, and thermal energy collected could be directly delivered into the indoor space via air flow. It can be clearly seen that water-based collectors were used by many competition teams for space heating. Among different water-based collectors, evacuated tube collectors were used by 47 teams, which was the most popular type of solar collectors. The flat-plate solar collectors and PVT collectors were also used by a number of the competition teams, while concentrating solar collectors were only used by 3 teams. The air-based solar collector was used by only 7 teams. The number of the teams used radiant panels was almost doubled than that used forced air to deliver thermal energy generated by water-based collectors, and a few teams used both delivering methods. ‘Unclear’ in Fig. 8 indicated that the type of solar collectors and the delivering methods were not clearly stated.



a) Types of solar collectors b) Delivering methods for water-based collectors

Fig. 8. Summary of solar collectors and delivering methods used in solar thermal space heating systems of the SD houses.

Some solar thermal space heating technologies used in the SD houses are briefly introduced herein. In the SD US 2007 competition, Team Texas (2007) developed a solar thermal space heating system by using evacuated tube solar collectors and a radiant floor heating system to generate hot water and deliver thermal energy to the indoor space, respectively. A similar design was also adopted by a number of the competition teams. Team Cincinnati (2007) also utilized the evacuated tube solar collectors for space heating while the thermal energy was delivered by using both a radiant floor heating system and a water-to-air heat exchanger in the SD US 2007 competition. Team Ontario/BC (2009) developed a solar thermal space heating system by integrating a heat pump with evacuated tube solar collectors in the SD US 2009 competition. The hot water generated by the solar collectors can be directly used for space heating via an air handling unit or used as the heat source of a water-to-water heat pump to enhance its performance for water heating. Using solar thermal energy as the heat source of heat pumps was also adopted by 10 teams and 11 teams from the SD competitions held in the US and Europe, respectively. A solar thermal space heating system assisted by solar air heaters, an air-based PCM TES unit, and flat-plate solar water heaters was developed by Team Ohio State (2011) in the SD US 2011 competition. The air-based solar thermal collectors were installed on the south-facing wall of the house and used to provide hot air for space heating. The flat-plate solar water heaters were used to generate hot water for both domestic hot water and space heating. When space heating was required, the thermal energy generated by the flat-plate solar water heater was used to provide hot water for a hydronic heating coil in an air handling unit. The hot air generated by the solar air heaters first passed through the TES unit for PCM charging and then supplied to the air handling unit as pre-heated air for space heating. The thermal energy stored in the PCM can be used for space heating when the solar radiation was low.

The above review showed that solar thermal space heating was mainly used for pre-heating and/or as a supplementary heating system of HVAC systems. Water-based solar thermal space heating was more frequently used in the previous SD competitions, as compared to air-based solar thermal space heating. Radiant panels were the most frequently used delivering method for solar thermal space heating.

4.3 Night-time radiative cooling

Night-time radiative cooling utilizes heat loss through long-wave radiation to the sky to provide cooling (Eicker and Dalibard, 2011). This technology has attracted increasing interest as it requires negligible energy consumption when comparing to conventional vapor compression systems. The details of the major night-time radiative cooling technologies used in the SD houses are summarized in Table 3.

The night-time radiative cooling technologies can be categorized into water-based technologies and air-based technologies according to the heat transfer fluid used. Team RWTH Aachen University (2012) adopted a water-based PVT system for night-time radiative cooling in the SD Europe 2012 competition. Rainwater was collected and spread onto the PV panel during the night-time to cool the water via the heat loss to the sky. The chilled rainwater was then used to cool a PCM emulsion in a radiant ceiling for space cooling. Team Odooproject (2012) also used a similar water-based night-time radiative cooling PV panel in the SD Europe 2012 competition, while the chilled water was directly used for space cooling. Team UC Davis used sprinklers to spray water onto the roof surface to achieve night-time radiative cooling in the SD US 2015 competition (Alemi and Loge, 2017; Team UC Davis, 2015).

Water cooling via night-time radiative cooling effect could also be achieved by attaching a heat exchanger to the back of a surface that was chilled by the heat loss to the sky. In the SD Europe 2010 competition, Team home$^+$ developed a water-based night-time radiative PVT system (see Fig. 9) which consisted of PV cells covered and supported by glass and water tubes with absorber plates attached to the bottom of the lower glass (Eicker and Dalibard, 2011; Sánchez et al., 2010). The night-time radiative PVT was used to provide chilled water for a PCM ceiling, a radiant floor, and a heat sink tank. Similar devices were also used by Team Rhône-Alpes (2012) and Team ECOLAR (2012) in the SD Europe 2012 competition. Water-based solar collectors were also used for night-time radiative cooling by Team DTU in the SD Europe 2014 competition (Gennari and Péan, 2014; Team DTU, 2014), Team Israel (2013) in the SD China 2013 competition, and Team North Carolina (2013) in the SD US 2013 competition.

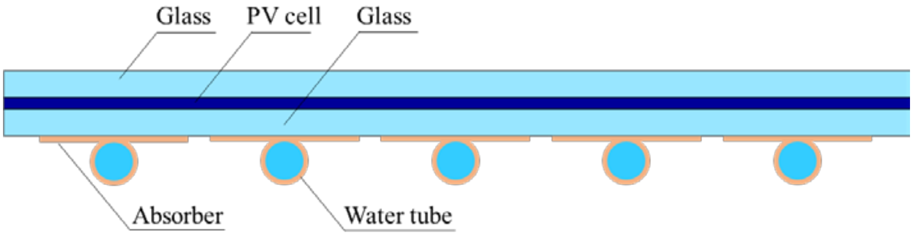


Fig. 9. Night-time radiative PVT system used by Team home$^+$, modified from Eicker and Dalibard (2011).

An air-based night-time radiative cooling system was used by Team UOW in the SD China 2013 competition (Fiorentini et al., 2015; Fiorentini et al., 2017). Air-based PVT collectors were used in the HVAC system which integrated with a PCM TES unit, as presented in Fig. 7, to generate electricity during daytime and cooling energy via night-time radiative cooling during night time. The cooled air could be used for space cooling directly or used to charge the air-based PCM TES unit.

Based on the systems reviewed above, it can be seen that the cooling provided by the night-time radiative cooling effect was mainly delivered via radiant panels. Only two teams used air-based night-time radiative cooling. Night-time radiative cooling alone may not be able to maintain indoor thermal comfort. It can be used to assist in improving the performance of the HVAC systems. The night-time radiative cooling could provide nearly free cooling during night with minimized energy consumption. This technology has attracted increasing attention in recent years (Zeyghami et al., 2018; Zhao et al., 2019), and the emerging day-time radiative cooling may provide alternative solutions for the SD houses (Raman et al., 2014; Goldstein et al., 2017).

533 **Table 3.** Summary of night-time radiative cooling technologies used in the SD competitions.

Team	Radiative surface	HTF	Details	Reference
Crowder	PVT collector	Liquid	PVT collectors were used to chill water for air conditioning.	Moon et al. 2005
Colorado	PVT collector	Liquid	HTF was chilled by the PVT collector and stored in a tank which was used as the heat sink of a water-to-water heat pump.	Team Colorado (2007a, 2008b)
Darmstadt	Roof surface	Liquid	Overnight, water was sprayed onto the roof of the house and chilled by a passive cooling system; The chilled water was used for space cooling via radiant panels.	Team Darmstadt (2007), Eicker and Dalibard (2011)
North Carolina	Rooftop heat exchanger	Liquid	HTF was pumped into flat-plate heat exchangers on the rooftop, and used for space cooling via radiant walls and ceiling.	Team North Carolina (2013)
UC Davis	Roof surface	Liquid	HTF was sprayed onto the roof surface by lawn sprinklers to achieve night-time radiative cooling, and used for space cooling via radiant floor.	Alemi and Loge (2017), Team UC Davis (2015)
home$^+$	PVT collector	Liquid	Water was chilled by the night-time radiative cooling system on the roof, and supplied to a PCM ceiling, radiant floor and a heat sink tank.	Eicker and Dalibard (2011), Sánchez et al. (2010)
Rhône-Alpes	PVT collector	Liquid	Water was chilled by a heat exchanger beneath the PV panel, and used as the heat sink of a water-to-water heat pump, or stored in a thermal storage tank.	Team Rhône-Alpes (2012)
ECOLAR	PVT collector	Liquid	HTF was chilled by a flat plastic absorber beneath the PV panel, and used for space cooling via radiant ceiling with embedded PCM and two water-to-air heat exchangers.	Team ECOLAR (2012)
RWTH Aachen University	PV panel	Liquid	Water was sprayed onto the PV panel by a sprinkler system and chilled by night-time radiative cooling, and used to cool the PCM emulsion in the radiant ceiling.	Team RWTH Aachen University (2012)
Odooproject	PV panel	Liquid	Water was sprayed onto the PV panel by sprinkler heads and chilled by night-time radiative cooling, and used for space cooling via the radiant ceiling.	Team Odooproject (2012)
(e)co	-	Air	A tank filled with gravel was opened during night-time to achieve radiative	(e)co Team (2012)

			cooling, which served as a sensible TES unit and was discharged during daytime for space cooling.	
Tongji	-	Liquid	Water was chilled by night-time radiative cooling, and was used for space cooling directly or used as the heat sink of a heat pump for space cooling.	Team Tongji (2012)
DTU	Unglazed solar collector	Liquid	Water was chilled by night-time radiative cooling and used for space cooling via radiant floor	Gennari and Péan (2014), Team DTU (2014)
UOW	PVT collector	Air	Air was cooled by air-based PVT collectors with air channels beneath PV panels, and directly used for space cooling or to charge an air-based PCM TES unit.	Fiorentini et al. (2017), Fiorentini et al. (2015)
BaityKool	Thermal radiator	Liquid	A thermal radiator was installed on the roof of the house and used to chill the water during night-time; The chilled water was used for space cooling via radiant panels.	Team BaityKool (2018)
VIRTUe	PVT collector	Liquid	Water was cooled by water-based PVT collectors and stored in a chilled water thank; The chilled water was used for space cooling via radiant panels.	Team VIRTUe (2018)

4.4 Desiccant dehumidification

Desiccant dehumidification utilizes hygroscopic materials to absorb moisture from the air. The materials usually need to be regenerated with thermal energy to reject the moisture into ambient, and the hygroscopic material was then reused for dehumidification. This regeneration process could be driven by low-grade thermal energy such as solar thermal energy, which opens up opportunities for the SD houses (Giampieri et al., 2018; Ren et al., 2019b). The major desiccant dehumidification systems and devices used in the SD houses are summarized in Table 4. Both liquid desiccant and solid desiccant (i.e. desiccant wheel and DESICA) systems have been used.

Liquid desiccant dehumidification generally consists of a dehumidifier, a regenerator, and heating and cooling systems. The dehumidifier is an air-to-liquid contactor in which air is dehumidified by the liquid desiccant via an absorption process. The regenerator operates in the opposite way and the water is desorbed from the liquid desiccant using scavenging air, in which the liquid desiccant was concentrated and reused for the dehumidification. The heating and cooling systems were respectively used to heat the liquid desiccant and to cool the liquid desiccant in order to facilitate the regeneration and dehumidification processes. Two liquid desiccant waterfall systems were developed by Team Maryland in the SD US 2007 and SD US 2011 competitions (Team Maryland, 2007a, 2007b; Team Maryland, 2011), using $CaCl_2$ and LiCl water solutions as the desiccants, respectively. The indoor units (i.e. dehumidifiers) of both liquid desiccant systems were designed as the waterfall for aesthetic purpose. A schematic of the dehumidification system used in the SD US 2011 competition is presented in Fig. 10

(Team Maryland, 2011). The indoor air was dehumidified by the waterfall (i.e. dehumidifier) via directly contacting with the concentrated liquid desiccant. The diluted liquid desiccant was then pumped to a heat exchanger and heated by glycol from solar collectors, after which the liquid desiccant was re-concentrated by the regenerator. A liquid desiccant waterfall system was also used by Team Florida (2011) in the SD US 2011 competition.

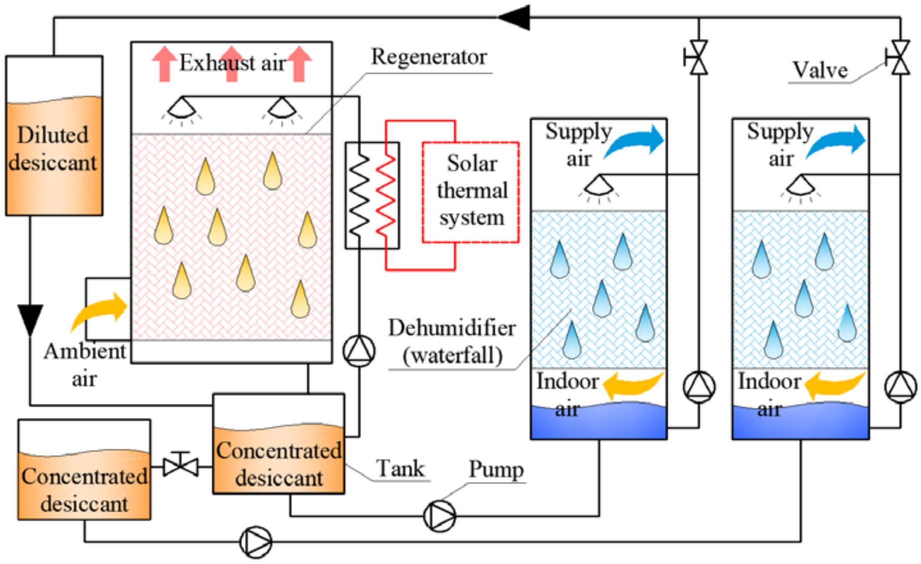


Fig. 10. Schematic of the liquid desiccant waterfall system developed by Team Maryland in the US 2011 competition, modified from Team Maryland (2011).

Team Minnesota (2009) used counter-flow packed-beds with random packing materials as the dehumidifier and regenerator in the SD US 2009 competition. A mixture of LiCl and $CaCl_2$ desiccant solutions was used as the working fluid. The air from the indoor space was delivered to the dehumidifier through ducting and re-supplied to the indoor space after it was dehumidified. A similar design was also used by Team Alabama (2017) in the SD US 2017 competition. An HVAC system with an integrated liquid desiccant dehumidification system using $CaCl_2$ solution was developed by Team Iowa State (2009) in the SD US 2009 competition. The dehumidifier was integrated into the air distribution system of the HVAC system, and a liquid-to-liquid heat exchanger was used to exchange the heat between the liquid desiccant at the outlets of the dehumidifier and regenerator. A liquid desiccant dehumidification system including an indoor unit, a roof unit, and a solution tank was developed by Team Stevens (2013a, 2013b) in the SD US 2013 competition. The indoor unit operated as a dehumidifier and the roof unit worked as the regenerator which used the greenhouse effect as the heat source to evaporate water from the liquid desiccant.

A desiccant wheel with a size of 0.3 m × 0.1 m was used by Team Ohio State in the SD US 2011 competition (O'Kelly et al., 2015; Team Ohio State, 2011) to deal with the latent load with the assistance of an ERV and a hydronic cooling coil. Air-based solar thermal collectors were used to provide thermal energy for the desiccant wheel regeneration. A desiccant wheel regenerated by solar thermal energy was also used by Team Réciprocité (2014) in the SD Europe 2014 competition while evacuated tube solar collectors and a water-to-air heat exchanger were used to provide hot air for the regeneration process. A commercial product which integrated a desiccant wheel with an air-to-air heat pump was used by Team Alberta (2013) in the US 2013 competition and Team TEC (2014) in the SD Europe 2014 competition. The evaporator of the heat pump was used to cool the air before it was dehumidified by the desiccant wheel, and the heated air from the condenser of the heat pump was used to regenerate the desiccant wheel. The supply air can be cooled and dehumidified simultaneously while extra electricity was required to power the heat pump. A commercial product, DESICA, was used by

Team Tongji (2012) and Team UOW (2018) for desiccant dehumidification in the SD Europe 2012 and SD ME 2018 competitions, respectively. The DESICA was essentially an air-to-air heat pump which used desiccant-coated heat exchangers as the evaporator and condenser. During the dehumidification process, the evaporator and condenser were continuously swapped in order to regenerate the desiccants.

Based on the systems reviewed above, it can be concluded that desiccant dehumidification was mainly used as supplementary dehumidification devices to HVAC systems for better humidity control, and the dehumidification systems were mainly driven by solar thermal energy. The liquid desiccant systems used in the SD houses were mainly designed and developed by the team members as there are limited commercial products available. However, liquid desiccant cooling is now close to being viable and its economic proposition is now better than before due to the development of corrosion resistant materials (e.g. plastic) and improvement in heat and mass transfer efficiency (Giampieri et al., 2018; Fu and Liu, 2017).

Table 4. Summary of desiccant dehumidification technologies used in the previous SD competitions.

Team	Types	Desiccant materials	Details	Reference
Maryland	LD	$CaCl_2$	A liquid desiccant waterfall was used as the dehumidifier; The liquid desiccant was regenerated using solar hot water.	Team Maryland (2007a, 2007b)
Iowa State	LD	$CaCl_2$	A flat-plate dehumidifier was integrated into the ducting of the HVAC system; The liquid desiccant was regenerated using an internally-heated regenerator with solar hot water.	Team Iowa State (2009)
Minnesota	LD	LiCl and $CaCl_2$	Pack-bed dehumidifier/regenerator with random packing was used; The liquid desiccant was heated by a heat exchanger using solar thermal energy, before supplied to the regenerator.	Team Minnesota (2009)
Team Florida	LD	$CaCl_2$	A liquid desiccant waterfall was used as the dehumidifier; The liquid desiccant was regenerated in a solution tank.	Team Florida (2011)
Maryland	LD	LiCl	Two liquid desiccant waterfalls were used as the dehumidifiers; The liquid desiccant was regenerated using solar hot water.	Team Maryland (2011)
Stevens	LD	$CaCl_2$	A packed-bed column with trays filled with 76 mm Heilex Rings was used as the dehumidifier; The liquid desiccant was regenerated by an outside unit on the roof via the greenhouse effect.	Team Stevens (2013a, 2013b)
Team Alabama	LD	$CaCl_2$	Pack-bed dehumidifier/regenerator with structured packing was used.	Team Alabama (2017)
RWTH Aachen University	LD	LiCl	The liquid desiccant was regenerated using solar thermal energy from solar water heaters.	Team RWTH Aachen University (2012)
Ohio State	DW	-	A desiccant wheel was used to dehumidify the supply air and it was regenerated using the heated air from solar air heaters.	O’Kelly et al. (2015), Team Ohio State (2011)
Alberta*	DW	-	A commercial product, which was an integration of a desiccant wheel and an air-to-air heat pump, was used; The condensing heat of the heat pump was used	Team Alberta (2013)

			for desiccant wheel regeneration and the evaporator was used for air cooling.	
Réciprocité	DW	-	A desiccant wheel was used to dehumidify the supply air; The regeneration air was heated by a water-to-air heat exchanger mainly using solar hot water.	Team Réciprocité (2014)
TEC	DW	-	The same product as that used by Team Alberta (US 2013).	Team TEC (2014)
Tongji	DESICA	-	DESICA which was an air-to-air heat pump with desiccant material coated on both the evaporator and condenser was used to dehumidify the fresh air.	Team Tongji (2012)
UOW	DESICA	-	DESICA was used as a dehumidifier and integrated with the HVAC system.	Team UOW (2018)

[*] The product was listed in the take-off list of the project manual.

4.5 Evaporative cooling

Evaporative cooling is a technology that conditions the air by increasing its vapor content (Cuce and Riffat, 2016). It has been used for indoor space cooling by a number of teams in the SD competitions. It is noted that passive technologies such as using a green wall or a water pond for evaporative cooling were not considered as evaporative cooling herein. The evaporative cooling devices used in the SD competitions can be categorized into two types including direct evaporative cooling and indirect evaporative cooling. In the direct ones, the air to be supplied to the house directly contacts with water and was cooled by the evaporation of the water. However, in indirect evaporative cooling systems, secondary air flow was cooled using the same way as that used in direct evaporative cooling. The air to be supplied to the house was cooled in the dry channel by sensible heat transfer through the plate which separates the dry and wet channels.

Direct and indirect evaporative cooling systems were used by a few teams as part of their space cooling systems. In the SD Europe 2010 competition, Team Wuppertal (Sánchez et al., 2010) used an indirect evaporative cooler to condition the supply air. Team Nottingham H.O.U.S.E. (Sánchez et al., 2010; Ford et al., 2012) developed a direct evaporative cooling system by deploying nozzles at the top of the double height space of the house to generate a mist of water in the SD Europe 2010 competition. The warm ambient air was drawn into the house and cooled by the water evaporation, and the air distribution was achieved passively via the downdraught effect. Team Unicode (2014) developed a water wall which was developed using packing materials of Raschig rings in the SD Europe 2014 competition. The water was distributed from the top of the wall, and the outdoor air was cooled to reduce the air temperature around the terrace of the house, which further decreased the heat gain of the living space from ambient. A desiccant cooling system using an indirect evaporative cooler and a direct evaporative cooler was developed by the RWTH Aachen University (2012) in the SD Europe 2012 competition, as presented in Fig. 11. In this system, the outdoor air was first dehumidified by a liquid desiccant dehumidifier and then cooled by an indirect evaporative cooler in which the return air from the indoor space was used as the secondary air. A hydronic coil was used to condition the supply air and a direct evaporative cooler was used to cool and humidify the supply air. A similar indirect evaporative cooler to that used by the RWTH Aachen University was also used by Team VIRTUe (2018) in the SD ME 2018 competition for conditioning the fresh air, in which the return air was used as the secondary air and exhausted to the ambient.

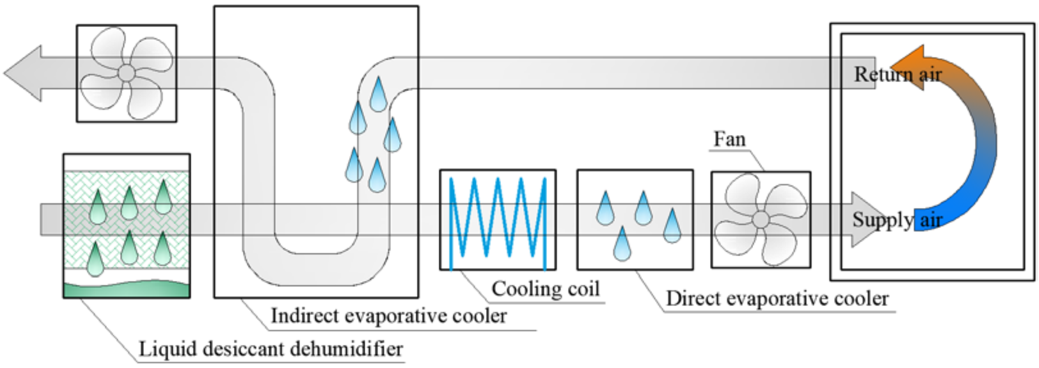


Fig. 11. A desiccant cooling system integrated with an indirect evaporative cooler and a direct evaporative cooler, modified from Team RWTH Aachen University (2012).

A portable evaporative cooler named as a robot cooler was developed by Team Alabama (2017) in the SD US 2017 competition. The robot cooler was essentially a direct evaporative cooler integrated with a motorized base with wheels, which means that the robot cooler could move in the SD house via the motorized base. The direct evaporative cooler was powered by a lithium-ion battery which could power the whole device for up to three hours. The robot cooler was designed to provide occupants with localized cooling in different places of the house.

It can be clearly seen that the application of evaporative cooling is still limited. In general, direct evaporative cooling could introduce extra moisture into the supply air, which is generally not favorable to the comfort conditions contest in the SD competitions. The indirect evaporative cooling could cool the supply air without increasing its humidity level while the configuration and structure of such coolers was more complex than that of the direct evaporative cooler. The evaporative cooling technology is more applicable for the SD competitions held under arid and moderate weather conditions.

4.6 Advanced control strategies

Control of HVAC systems is another critical issue to ensure that the HVAC systems are operated in an energy-efficient and cost-effective manner (Wang and Ma, 2008; Ma and Wang, 2009). However, the detailed description of the control strategies used for the HVAC systems of the SD houses was generally not provided in the project manuals.

Only a few teams reported the use of advanced control strategies for their HVAC systems. A model-based supervisory control strategy, for instance, was used by Team Maryland (2017) to optimize the use of water, electricity and thermal energy, and carbon-based resources. The mathematical models were developed to predict the solar radiation and the performance of the PV panels, as well as to determine the heating and cooling load, indoor air temperature, and overall net electricity consumption and generation of the household. Based on the modelling results, the sequence of the events that consume or generate significant amounts of energy, water, and other resources was optimized by the control strategy, in order to maximize the sustainability and economic goals of the SD house. Team Las Vegas (2017) used the monitoring results of the indoor and outdoor conditions to forecast the spikes of cooling and heating load. The forecast results allowed the control system to optimize the operation of the mechanical system to maintain indoor thermal comfort.

Team UOW (Fiorentini et al., 2015; Fiorentini et al., 2017) developed a hybrid model predictive control (HMPC) strategy to optimize the operation mode and control settings of the solar-assisted HVAC system with integrated PVT collector and PCM TES unit, as presented in Fig. 7. The HMPC was developed with two hierarchical levels, in which an HMPC controller was used to select the operation mode of the HVAC system, and each operation mode was then optimized at the low level. Team UOW (2018) integrated a model predictive control strategy into the building management system. The strategy could forecast various factors over the next 24 hours, e.g. weather conditions, power output of the PV panels, occupant’s energy usage habit. The forecast results could be used to optimize the operation of the HVAC system.

Advanced control strategies were only used in the SD houses in recent competitions. Such technologies may play an important role in future SD competitions to optimize the operation of the HVAC system through reliable load prediction, demand side management, rational use of solar energy, and dynamic optimization of control settings.

5. Conclusions and discussions

This paper provided an overview of the HVAC technologies and systems used in the previous Solar Decathlon (SD) net-zero energy houses. Statistical analysis was implemented for 212 SD houses from 13 SD competitions. Some conclusive remarks and recommendations are as follows.

- Heat pumps have been used by the majority of the competition teams for space heating and space cooling probably due to the fact that they have been widely used in residential buildings and showed good robustness in thermal comfort control, high energy efficiency, easy to implement and easy to control. ERVs/HRVs have also been frequently used in the SD houses as they could provide energy savings under a wide range of weather conditions.
- A number of the competition teams have explored the opportunities of using emerging technologies such as phase change materials and desiccant dehumidification to showcase innovations and reduce the electricity consumption for space heating and cooling. However, the real performance of such systems was not reported.
- PCMs have been frequently used in the SD competitions held in Europe. However, it seems that its popularity has been decreased in recent US competitions. When the PCMs are integrated with HVAC systems, advanced control such as model predictive control is generally required to optimize the charging and discharging processes to maximize the benefits of using PCMs.
- Solar thermal space heating has been frequently used in the SD competitions, especially in the competitions held in cold climates, while it was less preferred in the

recent competitions held in the US. This technology was mainly used for pre-heating and/or as a supplementary heating system of conventional HVAC systems to reduce HVAC energy consumption. Recent studies showed that the simple payback period of solar thermal space heating systems could be 6.5 years under certain weather conditions (Agathokleous et al., 2019). Photovoltaic/thermal collectors could be a promising technology to generate electricity and thermal energy simultaneously.

- Desiccant dehumidification has been used by a number of the competition teams for better indoor humidity control and such systems in the SD competitions were mainly driven by solar thermal energy.
- The application of evaporative cooling in the SD houses is limited. This technology has been proven to be an effective solution for temperature control when it was integrated with desiccant dehumidification. However, the use of direct evaporative cooling may increase the latent load of the process air. The combination of evaporative cooling and desiccant dehumidification may be a feasible solution in the SD competitions for space cooling as it can be driven by low-grade thermal energy and can provide independent temperature and humidity control.
- Although several competition teams used absorption/adsorption systems for space cooling. However, such systems generally require relatively high-grade thermal energy (e.g. 80 ^{o}C) and high initial investment so they might not be a good technical option for the SD competitions.
- The innovative HVAC technologies used in the SD houses demonstrated the potential

of using solar energy to take air conditioning off the grid. This will make great contribution to cleaner production.

Innovations in HVAC technologies are continuously required. It is expected that renewable heating and cooling with integrated thermal energy storage and dedicated model predictive control will play an essential role in future to provide low carbon emission heating and cooling for buildings and improve the productivity and wellbeing of occupants. It is believed that the SD competitions will continue to be an excellent platform to provide a live demonstration of the latest innovations in HVAC technologies.

Declarations of interest

None.

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