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A review of solar driven absorption cooling with photovoltaic thermal systems

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ABSTRACT

The aim of this investigation is to evaluate the recent advances in the field of solar absorption cooling systems from the viewpoint of solar collector types. A review in the area of photovoltaic thermal (PVT) absorption cooling systems is conducted. This review includes experimental and computational work focusing on collector types and their efficiencies and performance indicators. Compared to vapour compression air conditioning systems, 50% of primary energy was saved by using solar absorption cooling systems and 10–35% maximum electrical efficiency of PVT was achieved.

This review shows that Coefficient of Performance (COP) for solar cooling systems is in the range of 0.1–0.91 while the thermal collector efficiencies are in the range of 0.06–0.64. The average area to produce cooling for single effect absorption chillers for experimental and computational projects is 4.95 m^2/kW_c and 5.61 m^2/kW_c respectively. The specific area for flat plat collector (FPC) is in the range of 2.18–9.4 m^2/kW_c, while for evacuated tube collector (ETC) is in the range of 1.27–12.5 m^2/kW_c. For concentrated photovoltaic thermal collector (CPVT) and PVT, the average area to produce cooling for solar absorption chillers are 2.72 m^2/kW_c and 3.1 m^2/kW_c respectively.

1. Introduction

The demand for energy is increasing around the world due to population growth and industrialisation. Fossil fuels such as oil and natural gas are considered as primary sources of energy. In 2035, more than 80% of the energy consumption will be produced by fossil fuels in some developed countries [1]. Producing energy by traditional methods leads to more gas emissions and accelerated global warming. Alternative renewable sources of energy such as solar energy, wind energy and geothermal energy are required [2].

In response to the need for alternative energy sources, solar cooling technologies have become an important factor especially in hot countries due to the huge amount of solar radiation and the need for cooling. Solar cooling systems are environmentally friendly compared to conventional cooling systems and are an important technology to reduce emissions [3].

Pazheri et al. [4] estimated that a 20 MW solar plant, which would need an area of 1.25 km^2, can generate 200–300 GWh/year and that could save 500,000 barrels of oil per year. The potential for solar energy and the opportunity to utilise it for cooling purposes depend on the location in the world. For example, Europe, North America, most of Latin American and western Asia have a 100–200 W/m^2 average annual rate of solar radiation while in the Middle East, the value reaches up to 250 W/m^2 [4].

In Europe, the residential sector accounts for about 40% of energy consumption and heating purposes represents about 68% of this sector [5,6]. In contrast, cooling systems have been the main energy consumer in the residential sectors in hot climatic conditions. In Saudi Arabia, 72% of residential electricity is consumed by cooling equipment [7].

However, in the last decade, many researchers has focused on solar cooling systems and so different types of solar thermal cooling systems have been reviewed [8,9]. The use of solar collectors such as FPC and ETC for thermally driven solar cooling systems and photovoltaic panels (PV) to provide electricity for vapour compression air conditioning units has been discussed [10–12]. The application of thermally driven systems such as absorption, adsorption, desiccant and ejector systems have been highlighted in the review papers [13–15]. Options for thermal and cold storage have also been discussed [16]. There are limi-

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tations in some of these reviews because they were specified in a particular region or application [13].

Alili et al. [9] reviewed solar thermal air conditioning technologies and reported a number of research outcomes from the point of view of working fluid temperature, collector type, collector area, storage volume and COP values. The authors evaluated research depending on conditions such as the temperature of evaporators, condensers and generators. From this research, evaporator temperature is in the range of −9 °C and 26 °C, condenser temperature in the range of 24 °C and 45 °C and generator temperature between 74.1 °C and 120 °C. The paper analysed six experimental and five simulation studies and reported that the average area of solar collector for a solar absorption cooling system is 4.67 m^2/kW_c. The areas required of evacuated tube collectors ranged between 2.7 and 9.4 m^2/kW_c while these areas were 1.4–3.3 m^2/kW_c for flat plat collector.

Review papers that focus on solar cooling absorption technology are scarce; Zhai et al. [17] provided a literature survey of solar cooling absorption systems but did not mention the use of PVT and only include one project that used CPVT with single absorption chillers. Raja and Shanmugam [18] also reviewed solar absorption systems, aiming to reduce the initial cost of the systems. The authors discussed auxiliary components that are typically used in the systems such as backup heating and some solar collector types. The paper did not report any existing PVT collectors and only one CPVT project was mentioned. Different types of absorption solar cooling systems which include single effect, double effect and half effect absorption cycle have been also reported in the review papers [19–21]. The required heat source temperature, refrigeration output, capacity range, COPs and fluid pairs have been reported for single-effect absorption refrigeration cooling technologies in Table 1. Table 2 illustrates small capacity absorption chillers in market which is in the range of 4.5–17.6 kW. Table 2 also show that COP is in the range of 0.63–0.77 and the driving temperature for absorption chillers is in the range of 75 °C to 90 °C.

The incorporation of solar collectors such as ETC and FPC with absorption chillers have been highlighted but there is a lack of data in the use of photovoltaic thermal collectors (PVT) with absorption chillers [22].

Based on the performance and the initial cost of solar cooling systems, single effect absorption systems were estimated to be more efficient with lower costs. The majority of this research analysed the incorporation of solar collectors such as ETC and FPC with absorption chillers, but most did not report the cost of solar collectors, their efficiencies and the overall system cost. From previous review papers, there is a lack of data on the combination of photovoltaic thermal collectors (PVT) with absorption chillers [18]. In these studies, absorption systems shows an opportunity to achieve a relatively high COP (0.5 − 0.8) for generation temperature in the range of 70 °C and 90 °C [8,18].

The aim of this review is to establish the current developments in the field of photovoltaic thermal collectors (PVT) for cooling purposes and to identify the opportunity of using PVT for absorption cooling system. The review also includes the current developments in the field of solar absorption cooling systems from the point of view of solar collecting options. The review includes experimental and computational studies and focuses on collectors' types and their efficiencies. Heat source, refrigeration output, capacity range, performance indicators and economic viability for the overall solar absorption systems are discussed. In Section 2, previous work relating to thermal absorption cooling systems including experimental and simulation studies are reported. In Section 3, the use of photovoltaic thermal collector for cooling system are highlighted with focussing on thermal and electrical efficiency for the collector. In Section 4, the economic viability of PVT are discussed with focusing on performance and economic indicators. Finally, in Section 5, the solar thermal and photovoltaic cooling systems are discussed and summarised in Tables 5–7 with a focus on collector types, thermal and electrical efficiency, COP and the capacity of the projects.

2. Thermal collectors' absorption cooling systems

The dominant driving power in solar absorption cooling systems is the thermal power from solar energy collectors. Solar radiation is absorbed by solar collectors then delivered to the storage tank through a

Table 1
Single-effect Absorption refrigeration cooling technologies [8,14].

Capacity KW	Working fluid pairs	Driving temperature °C	Chilled water Temperature °C	COP	Cooling applications
5–7000	$LiBr–H_2O$	70–90	5–10	0.5–0.8	Industry, large-scale building, and small units for residential use
10–6500	$H_2O–NH_3$	100–200	−60 − 0	0.25–0.6	Large capacity for industrial refrigeration, and small size for light commercial use
10–90	$H_2O–NH_3$	80–200	5–10	0.5–0.6	Residential and small commercial building cooling

Table 2
Small capacity absorption chillers available in the market [15].

Manufacturer	Capacity (KW)	Working fluid pairs	Driving temperature (°C)	Cooling temperature (°C)	Chilled water Temperature °C	COP
Rotartica (Spain)	4.5	H2O–LiBr	90/85	30/35	13/10	0.67
Climatewell (Sweden)	10	H2O–LiCl	83/--	30/--	--/15	0.68
Pink (Austria)	10	NH3–H2O	85/78	24/29	12/6	0.63
Sonnenklima (Germany)	10	H2O–LiBr	75/65	27/35	18/15	0.77
EAW (Germany)	15	H2O–LiBr	90/80	30/35	17/11	0.71
Yazaki (Japan)	17.6	H2O–LiBr	88/83	31/35	12.5/7	0.7

Table 3
Different solar cooling alternative technologies based on Noro and Lazarin [26].

System	Description
FPC_SilGel	Flat plate collectors coupled to silica-gel adsorption chiller
FPC_LiBr_SE	Flat plate collectors coupled to single effect water-LiBr absorption chiller
ETC_LiBr_SE	Evacuated tube collectors coupled to single effect water-LiBr absorption chiller
ETC_LiBr_DE	Evacuated tube collectors coupled to double effect water-LiBr absorption chiller
ETC_NH3_Air	Evacuated tube collectors coupled to GAX ammonia-water absorption chiller
PTC_LiBr_SE	Parabolic trough collectors coupled to single effect water-LiBr absorption chiller
PTC_LiBr_DE	Parabolic trough collectors coupled to double effect water-LiBr absorption chiller
PTC_NH3_Air	Parabolic trough collectors coupled to GAX ammonia-water absorption chiller
PV mSi_VC_w	Mono-crystalline silicon PV modules coupled to water cooled vapour compression chiller
PV mSi_VC_a	Mono-crystalline silicon PV modules coupled to air cooled vapour compression chiller
PV aSi_VC_w	Amorphous silicon PV modules coupled to water cooled vapour compression chiller
PV aSi_VC_a	Amorphous silicon PV modules coupled to air cooled vapour compression chiller

Table 4
Initial cost for some component in solar cooling systems.

Component	**Price Euro/m^2**	**References**
CPV cell,Cell packaging, primary concentrator, housing, …)	129.8, 43.3, 132	
Inverter, Thermal system, Battery	52, 226.1, 230.4 Euro/kWh	[40]
FPC, ETC, PTC	350, 650,450	
PV mSi, PV aSi	330, 130	
Adsorption chiller H2O silica jel	600 Euro/kWc	
Absorption LiBr H2O single effect,	400 Euro/kWc	[26]
Absorption LiBr H2O double effect	700 Euro/kWc	
Emission penalty cost	0.023 (Euro/kgCO2)	
PVT (2015), PVT (2012)	400, 700–1000	
PV module (c-Si), FPC Solar collector	450, 500	[37]

hydraulic pump. A backup heater is fixed with the storage tank and the temperatures in the system should be managed to meet the required temperature for the absorption chiller. The most common working fluid in absorption systems are H_2O/LiBr (Water is refrigerant) and NH_3/H_2O (Ammonia is refrigerant) [12]. Fig. 1 shows a schematic diagram of the solar cooling system which consists of a thermal solar absorption system, made up of solar collector, storage tank and absorption chiller.

Fong et al. [23] carried out a comparison study of different solar cooling systems which included solar electric compression refrigeration, solar mechanical compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration and solar solid desiccant cooling based on their performance throughout the year. The study was based on the simulation program TRNSYS to calculate the performance indicators which include solar fraction (SF), coefficient of performance (COP), solar thermal gain (G_{solar}) and primary energy consumption in order to meet the cooling load of 29 kW$_c$. The driving temperature, which is the water temperature supplied to the generator, was in the range of 67–90 °C. The work provided good performance indicators and the findings from the study indicated that solar absorption refrigeration and solar electric compression refrigeration had the highest energy saving. The work further found that the solar absorption system achieved a solar factor of 50% throughout the year and the COP was 0.769, total global solar radiation (G_{solar}) was 37,234 kWh and the primary energy consumption (Ep) was 72,797 kWh. Fig. 2 details the schematic of the solar absorption refrigeration system.

Hartmann et al. [24] also carried out a comparison between a solar electric compression refrigeration system and a solar adsorption refrigeration system to evaluate the primary energy savings and the cost to meet the demand for heating and cooling of a typical building in Germany and Spain. The cooling and heating load throughout the year, the performance of photovoltaic PV system and the performance of a FPC system were simulated in TRNSYS for varying solar collector areas. The study highlighted that the annual cost of a solar cooling system was 128% higher than a conventional compression chiller in Spain and 134% in Germany whilst the annual cost for solar electric cooling varied between 102–127% in Spain and 102–125% in Germany. They concluded that for the same energy saving in the PV cooling systems with a defined of PV field area, six times this area would need to be covered by FPC solar collectors. Fig. 3 shows the investment cost for a solar thermal system ST and a solar electric system PV, achieving a primary energy saving of 36% in Germany, Freiburg by comparison.

Ayompe et al. [25] carried out work on a forced circulation solar water heating system with FPC and heat pipe ETC. They considered meteorological weather data in Dublin in summer 02/06/2009, autumn 25/11/2009 and winter 20/01/2010. The model was simulated in TRNSYS and the results were validated with the experimental set-up. This included two flat plate collectors and evacuated tube collector, a storage tank, pumps, controllers and other accessories as shown in Fig. 4. The useful energy was calculated by measuring the inlet and outlet temperature of the solar collector.

The work showed good correlation between the simulation and experimental results and the output fluid temperature from the FPC and ETC showed percentage mean absolute errors (PMAE) of 16.9% and 18.4% respectively, whilst the useful and delivered energy showed 14.1% and 6.9% for the FPC and 16.9% and 7.6% for the ETC respectively [25].

Fumo et al. [1] carried out a theoretical comparative analysis of solar thermal cooling systems based on the reduction of the primary energy need and its cost. The two setups included an evacuated tube collectors, absorption chiller, and a solar electrical system, which included photovoltaic panels and a vapour compression system. The reference system was an air cooled vapour compression system that consumed electricity from the grid as displayed in Fig. 5.

The authors highlighted that 12 m^2 of evacuated tube solar collector were required to produce 1 t of refrigeration (3.517 kW$_c$) for solar absorption cooling system and 7 m^2 of PV panels were required for solar electric cooling system. They also established energy saving, for both the PV and thermal system based on specific parameters and conditions such as electric rate of $0.1/kWh as shown in Fig. 6.

These findings can be used as an initial assessment for solar cooling systems. However, they are preliminary results and further investigation is needed to validate these results [1].

Eicker et al. [2] carried out an economic evaluation of photovoltaic (PV) and thermal cooling systems based on primary energy savings in a case study building with 309.9 m^2 floor area. This study included a reference system, which included a 30–50 kW$_c$ vapour compression chiller derived by grid electricity and 1500 L cold storage tank. The study included a PV cooling system which was composed of a vapour compression chiller and PV modules, thermal solar cooling system, which included a flat plat collector FPC or compound paraphilic collector (CPC), 5000 L solar storage tank, 1000 L cold storage tank and 25 kW$_c$ absorption chiller.

The solar cooling system required a specific collector area of 2.5 m^2/kW$_c$, and a 130–170 m^3/h air volume cooling tower per kW$_c$.

Table 5
Summary of the solar absorption cooling system, experimental studies.

Collector type	A_c (m^2)	Solar collector Efficiency	Chiller Type	Cooling Capacity (kW)	COP	Experimental Type	References
	42.2		LiBrH2O	4.5		Outdoor	[47]
FPC	90	0.24–0.55	Single effect	30	0.30 −0.8	Outdoor	[48]
	90		Double-effect	30		Outdoor	[49]
	500			100		Outdoor	[50]
	500		LiBrH2O	100		Outdoor	[50]
ETC	72	0.35–0.64	double effect	35	0.31–0.7	Laboratory	[51]
	220	–	Single effect	55	1.43–1.91	Outdoor	[52]
	12		LiBrH2O	4.5	0.42–0.69	Outdoor	[53]
	72		Hybrid	35.2		Outdoor	[54]
	260		absorption	738		Outdoor	[55]
	42		Double effect NH3-H2O	10.1		Outdoor	[56]
	27	0.37–0.46	LiBrH2O	Na		NA	[57]
CPC	105	0.50	Double effect	15	0.19–0.45	Outdoor	[58]
	96	0.45–0.43	LiBrH2O	8	0.8	Outdoor	[59]
	42	0.32	Double effect NH3-H2O	10			[60]
PTC	39	NA	LiBrH2O double effect	16	0.8 − 0.91	Outdoor	[61]
	56	0.35–0.45	Single effect LiBrH2O	23	0.11 to 0.27	Outdoor	[62]
LCC	352	0.35	LiBrH2O Double-effect	174	1.1–1.25	Outdoor	[63]

A_c: Collector Area (m^2)
ETC Evacuated solar collector tubes
PTC parabolic trough solar collectors
CPC: Compound Parabolic Concentrator
LCC: Linear concentrating collector

The PV cooling system was simulated in INSEL and FORTRAN whilst the thermal cooling system was simulated using TRANSOL 3.0 and TRNSYS. The findings in the study in Palermo indicated that the solar collector efficiencies were 31% and 23% for CPC and FPC respectively. The primary energy consumptions for each cooling system is shown in Fig. 7.

The annual COP values were calculated as 3.19, 0.79 and 0.77 for the compression chiller, CPC-Absorption chiller and FPC-absorption chiller respectively. The work concluded that the reduction of the initial cost of solar cooling system is a key factor for the system to be a competitor in the market and reported valuable specific cost parameters for the initial assessment for the solar cooling system. They also suggested parametric studies for the system to reduce the energy demand [2]. Fig. 8 describes the thermal solar cooling absorption system with cold and hot storage tank.

Noro and Lazarin [26] carried out a comparative study of different solar cooling systems in order to meet the cooling demand in a typical office building with floor surface of 230 m^2 in two different climates in Italy during the summer season. Alternative technologies have been used in this study as shown in Table 3 and TRNSYS dynamic simulation has been used to evaluate the systems based on the performance and economic analysis.

In the thermal cooling system, FPC, PTC and ETC were the alternatives to single and double absorption chillers. In the PV cooling system, Mano-crystalline (m-si) and Amorphous-crystalline (a-si) photovoltaic panels were the alternatives to supply electricity to air or water cooled chillers. The findings in the study indicated that the use of PV panels were generally better than the use of solar collectors for cooling purposes in the working conditions and 50% overall system efficiencies (OSE) were reported for PV-msi and PTC double effect absorption system as shown in Fig. 9.

The authors also reported that seasonal thermal efficiency for ETC was the highest among the solar collectors by 54% and 57% in Milan (MI) and Trapani (TR) respectively while the highest seasonal electrical efficiency was approximately 11% for PV-msi as in Fig. 10.

The work concluded valuable economic analysis and more investigation are recommended such as considering the study of solar cooling and heating throughout the year.

3. Photovoltaic/thermal cooling systems (PVT)

Photovoltaic thermal collectors or hybrid PV/T systems utilise solar radiation to produce electricity and thermal energy. These systems have a combination of solar cells with solar thermal collector. Water is the most common fluid used to remove the heat from the panel but there are many options such as air or nano-fluid. Sheet and tube PVT is the most common configuration where PV cells are fixed with flat plat collector. An experimental study showed that a reduction in PV temperature by 20% led to an increase in the electrical efficiency by 9% [27]. The main components of a PVT system are the PV cells to produce electricity, channels for the fluid, absorber plate and thermal insulation to minimize the heat loses as shown in Fig. 11.

Aste et al. [29] reviewed the water flat plate PVT system in the market with an emphasis on the elements that compose PVTs such as photovoltaic cells (PV), covers and insulation material. The authors reported that PV technologies have different features such as efficiency, which is in the range of 13–22% for crystalline and 7–13% for amorphous silicon. Another feature is the temperature coefficient which represents the effect of the cell's operating temperature on the efficiency of the PV module. For crystalline silicon, the temperature coefficient is in the range of 0.3–0.5(%/k) while it is 0.2–0.3(%/k) for amorphous silicon. The study also highlighted that cell thickness is in the range of

Table 6
Summary of the solar absorption cooling system, computational studies.

Collector type	$A_c(m^2)$	Solar collector Efficiency	Chiller Type	Cooling Capacity (KW)	COP	Method	Reference
	5–220		LiBr/H2O Single effect	2.7–3 (m^2/kW_c)		TRANSYS	[64]
FPC	37.5	0.29 – 0.50	NH3/H2O		0.46–0.82	Analytical	[48]
	38.4	NA	NA	4.5	0.1–0.65	method	[65]
	100	0.27–0.44	LiBr/H2O Single effect	17.6	0.12–0.33	Transol	[66]
	NA			26	NA	TRNSYS	[67]
	25			10			[68]
	38.4			10			[69]
				17.6 kW			
	5–220		LiBr/H2O	1.7–12.5 (m^2/kW_c)		TRNSYS	[64]
ETC	–	0.06 – 0.50	Single effect	35.17	0.82–1.2	TRNSYS	[70]
	45		NH3/H2O Single effect	10		Theoretical	[71]
	60					–	[72]
PTC	52	0.634	LiBr/H2O Double effect	16	NA	TRNSYS	[73]
CPC	96	0.45–0.43	LiBr/H2O	8	0.25 to 0.38	Experimental Matlab	[59]
			Single effect				
NA	65–145		Double-effect	23	NA	TRNSYS	[74]
			LiBr-H2O	121	NA	TRNSYS	[75]
	200–500	NA	LiBr/H2O	15	1.2–2.5	Simulation models	[76]
	NA		Single effect				

A_c: Collector Area (m^2)
ETC Evacuated solar collector tubes
PTC parabolic trough solar collectors
CPC Compound Parabolic Concentrator

0.2–0.5 mm for crystalline silicon whereas it is in the range of 0.0002–0.0006 mm for amorphous silicon. Crystalline silicon costs 0.55–0.85 (Euro/w_p) whereas amorphous silicon ranges between 0.35 and 0.45 (Euro/w_p). Crystalline silicon (c-Si) delivers higher electrical efficiency than the thin film technology and the most used group are monocrystalline silicon cells (mono-sc-Si) and polycrystalline silicone cells (pc-Si) which have slightly lower efficiency. Researchers reviewed PVT systems focussing on environmental impact and design parameters that affect PVT performance [30–33]. However, few studies relate to the use of PVT for cooling purposes. The following research in this section discussed these studies.

Guo et al. [34] reviewed the utilisation of PVT for desiccant cooling and dehumidification that required a temperature in the range of 50 °C to 60 °C. The study concluded that the design factor's that achieve high outlet PVT temperature include mass flowrate, addition of glazed cover and hydraulic channel geometry.

Mittelman et al. [35] studied the performance and the economic viability of using triple junction cell concentrating photovoltaic thermal collectors (CPVT) for cooling and power generation. The plant consisted of 2660 m^2 of CPVT and a water lithium bromide (LiBr-H2O) chiller with cooling capacity of 1 MW and natural gas backup heater. The thermal model of the CPVT was analysed theoretically using heat transfer mechanics to calculate the incident power by considering thermal loses to the environment through back and front insulation. The global solar radiation was considered to be 900 W/m^2 and the nominal electrical efficiency was consider as 37%. The mass and energy balance were applied for each component in the chiller for varying generation temperature from 65 to 120 °C. The findings of the study indicated that electrical efficiency has a significant effect on coolant outlet temperature and decreased from 23% to 20% with the increase in coolant outlet temperature from 50 °C to 150 °C while the thermal efficiency was about 60% in the same range of the coolant temperature.

The authors reported that the PV cell temperature was 10–30 °C higher than the outlet coolant temperature and the rated electric power and cooling power were 0.518 MW_e and 1.0 MW_c respectively, while the annual electric and cooling energy were 1244MWh_e and 4380MWh_c. In this system, the thermal energy was considered to be used directly to the absorption chiller without use of a storage tank which is expected to increase the overall efficiency of the system and decrease the backup heater capacity. Fig. 12 describe the photovoltaic thermal (PVT) module.

Vokas et al. [36] investigated the use of hybrid PVT instead of FPC along with absorption chiller, in order to meet the cooling and heating domestic load throughout the year. The performance for the collectors was analysed for different geographical region using the approximation method F-chart. The study highlighted that the performance was highly effected by the geographical region and electrical efficiency of the PVT was improved due to the reduction of its operation temperature but the thermal efficiency was lower than the FPC by 9%. The study also revealed that FPC can cover 54.26% of the heating load and 31.87% of the cooling load while these percentages decreased by 11.9% and 21.4% in the case of PVT for heating and cooling respectively. Electrical performance for PVT and parameters for FPC were not reported, the results were not validated and further justification is needed to explain the decrease in thermal efficiency of PVT.

Calise et al. [37] investigated the performance of a solar cooling and heating system based on energy saving and economic analysis by considering a specific case study of a university building in Italy. PVT collectors of 1000 m^2 were simulated in TRNSYS to produce both electrical and heat energy to supply a 325 kW_c single lithium bromide ab-

Table 7
Summary of the use combination of PVT with solar cooling system, computational and experimental studies.

Collector type	Area (m^2)	Thermal Efficiency	PV Efficiency	Cooling System	Cooling Capacity (KW)	COP	Method	References
	2660				1000		Theoretical analysis.	[35]
CPVT	18	0.32–0.63	0.08	LiBr/H2O	NA	0.6–0.8	Trnsys&Experiment.	[77]
	130		−0.40	Single effect	61–72		TRNSYS & Matlap	[39]
	12+ (Geothermal)			NA	700		TRNSYS	[78]
				LiBr/H2O	NA		CFD	[79]
	NA			Double effect.	325		TRNSYS	[38]
	996				NA		Polysun	[80]
	47059 (10 MW)			Adsorption system.				
	1000			LiBr/H2O	325		TRNSYS	[81]
PVT	30–70	023 −	0.10	Single effect.	NA	0.6–0.8	Analytical equations	[36]
	NA	0.35	0.10.4	F-chart ooling	2.7		Experimental	[42]
	NA	NA	NA		20 RT	2.88	Experimental	[82]
	70	0.15	0.15–0.17	Method.	16.7	0.3	Mathmatical method	[83]
	70	−0.21		Heat pump.	16	0.13–	Mathmatical method	[84]
	20	0.36–0.39	0.104–0.107	Adsorption chiller.	7	0.47	TRNSYS	[85]
						0.51		
				Adsorption chiller.		0.55		
				Adsorption chiller.				
				Adsorption chiller.				
	40–180	0.789	0.15	Adsorption	50	0.68	Simulation SACE.	[24]
FPC& PV	112.5 (124 PV)	0.35	0.27	chiller.	30	0.7	TRANSOL EDU3.0	[2]
				LiBr/H2O Single effect			INSEL 7.0 for PV.	
ETC & PV	4	0.54	0.18	LiBr/H2O	NA	0.7	Simulation tool	[1]
	0–50			Single effect			NA	

A_c: Collector Area (m^2)
ETC Evacuated solar collector tubes
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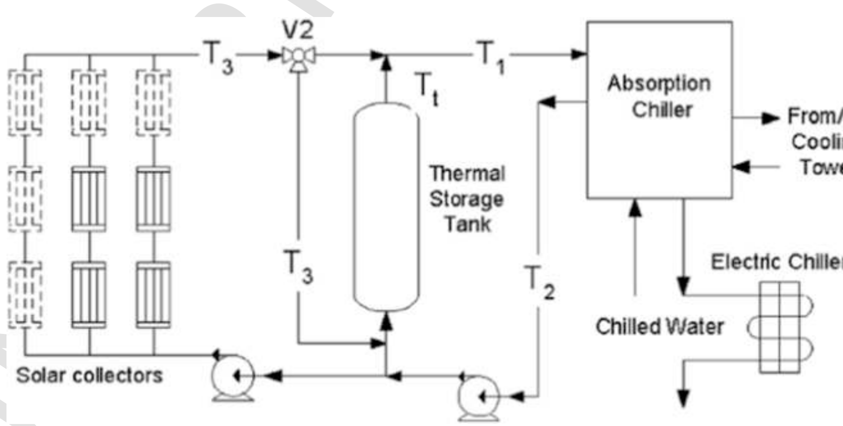

Fig. 1. Schematic diagram of solar cooling system with multi solar collectors [1].

sorption chiller that operates at 80 °C. Other components such as the storage tank, auxiliary heater and cooling tower are shown in Fig. 13.

The findings of this study indicated that PVT performance is significantly affected by ambient and operating temperature. They also found that the PVT system can produce 18% electrical efficiency at an outlet fluid temperature in the range of 60–80 °C. The authors reported that the type of the cover of PVT systems is an important factor that affects the PVT performance and further research is required. They high-

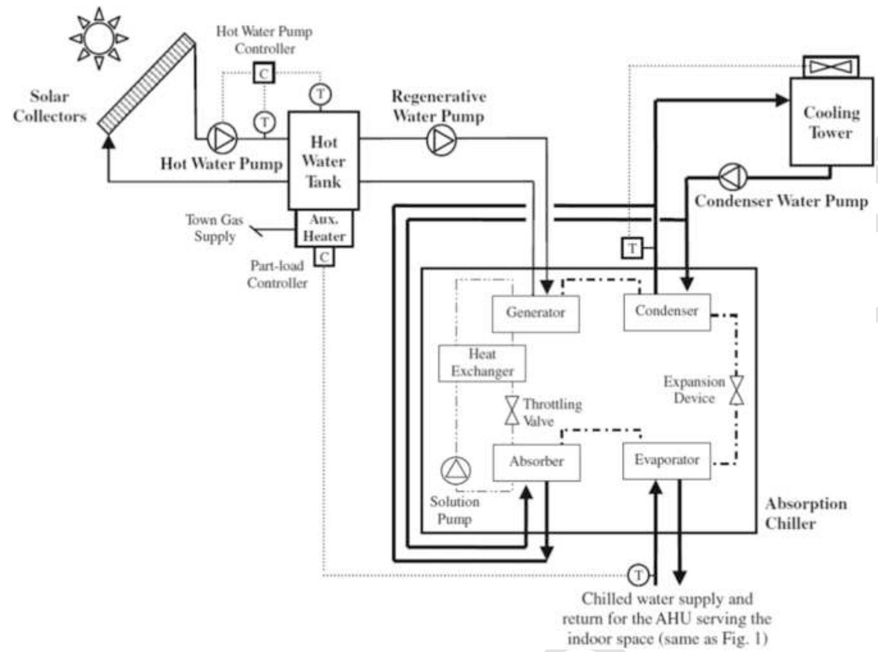

Fig. 2. Solar absorption refrigeration system with cooling tower, air handling unit (AHU) [23].

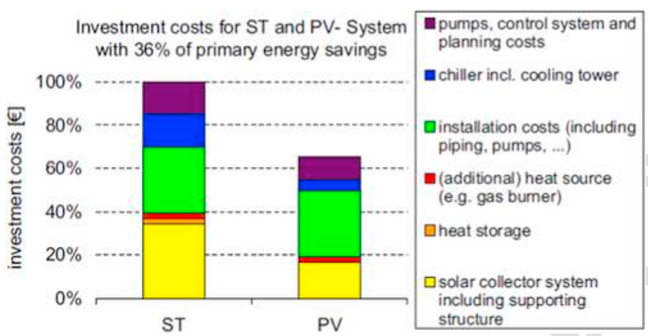

Fig. 3. The investment cost for solar thermal system ST and solar electric system PV to achieve primary energy saving of 36% in Germany, Freiburg [24].

lighted that the tube and sheet c-Si PVT systems show a good ratio of energy production for cooling and heating. In the study it was shown that surplus electricity was produced and was sold to the grid or supplied to the building for other purposes [37].

Calise et al. [38] investigated a dynamic simulation system for cooling, heating and other building demand for electricity in order to find the optimal capacity of a solar collector field. The study considered a case study in Italy that included a 325 kW double stage absorption chiller (LiBr-H2O) and CPVT collector area of 996 m^2 as shown in Fig. 14. TRNSYS was used to simulate the project throughout the year.

The findings of this work highlighted that the research in concentration photovoltaics to drive double effect absorption chillers is very attractive due to the utilisation of the same area to produce both electric and thermal energy and the reduction in the area of PV cells due to the concentration of the solar radiation. 2.64×10^9 kJ/year and 1.09×10^9 kJ/year were the total amount of thermal and electric energy produced by the CPVT while the average thermal and electrical efficiency throughout the year were 32% and 13.3% respectively. The primary energy saving and simple payback period were 84.4% and 15.2 year respectively. Furthermore, the study highlighted the need for a public fund for the CPVT cooling systems in order to become a competitor compared to conventional systems. They reported that no prototype for this system had been tested. Further research is needed to define the optimal value of the capacity and area for solar collectors [38].

Bunomano et al. [39] considered a building of 1200 m^2 in Italy as a case study to developed a MATLAB code for studying the performance

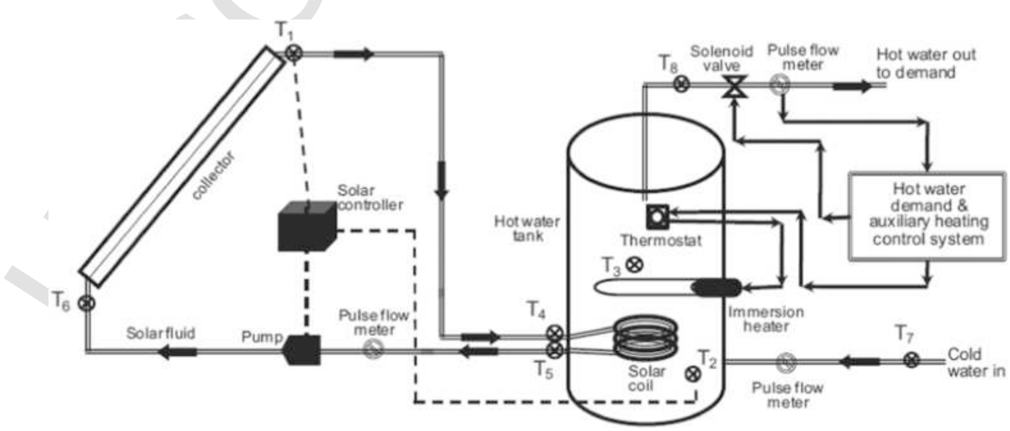

Fig. 4. Schematic diagram of the solar water heating systems with storage tank and backup heater [25].

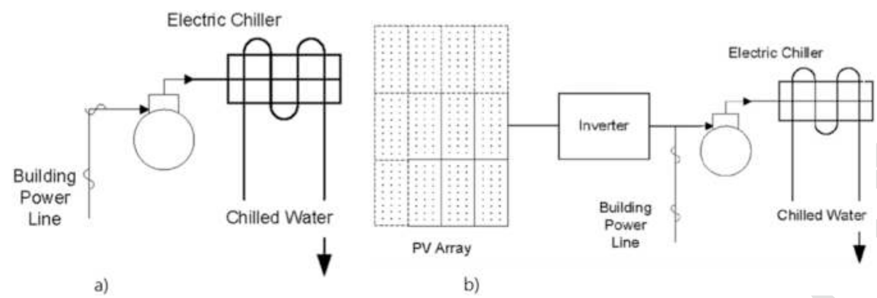

Fig. 5. Schematic diagram of a) Reference system and b) photovoltaic cooling system.
Modified from [1].

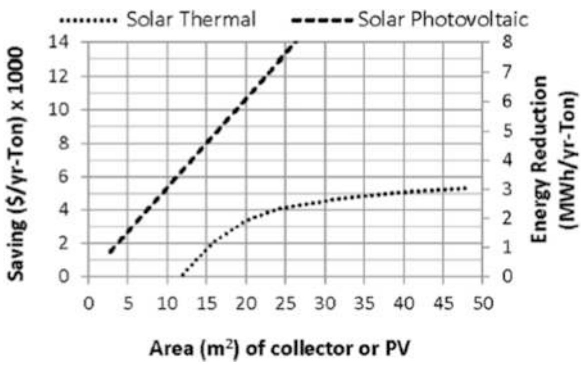

Fig. 6. Cost and energy savings based on electric rate of $0.1/kWh and specific parameters and conditions in the united states [1].

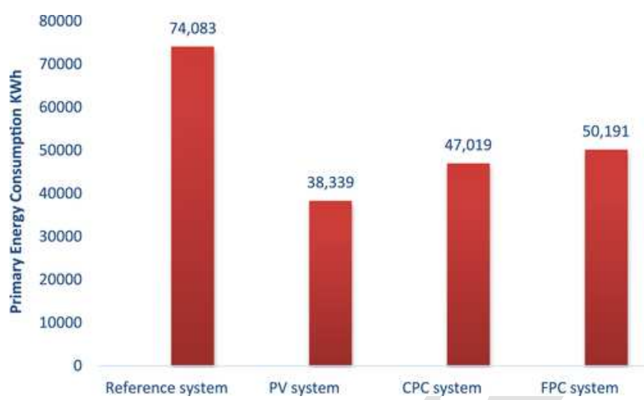

Fig. 7. Primary energy consumptions for reference, PV, CPC and FPC cooling systems.

of solar cooling systems based on energy saving. The roof of this building was covered by 130 m^2 of evacuated tube collectors or concentrating photovoltaic thermal collectors to power a single absorption chiller. The work was validated with literature data using TRNSYS and showed a good correlation. The findings of the study indicated that the primary energy saving can reach 74% and 100% for ET and CPVT respectively. Further research is needed in different countries taking into account gas emission factors and energy prices in these countries [39].

Sanaye and Sarrafi [40] carried out a multi objective optimisation approach for combined solar cooling, heating and power generation system CCHP based on energy, exergy and economic evaluation. The main components in this system were 2 m^2 PV panels, 114×135 mm CPVT (concentrating the light 555 times) collectors and evacuated tube collectors 2 m^2 and a single effect absorption chiller as in Fig. 15.

TRNSYS was used to calculate the cooling and heating load for a 150 m^2 case study building in Tehran. The cooling and heat loads reached 8 kW_c and 3.7 kW_h respectively throughout the year while the LINMABP technique was used to select the optimum value for each component of solar collectors and the size for the storage tank and the battery. The relative annual benefit (RNAB) was defined as the annual profit from the use of solar system instead of the reference system which included heat pump grid electricity dependent to provide cooling and heating for the space and gas fired water heater to provide domestic hot water. The finding in this study reported that the optimum value for a stand-alone system for the CCHP were 9 CPVTs, 5 PVs, 1.97 m^3 water storage tank and 33.99 kWh battery while exergy efficiency and RNAB were 9.1% and 6279$/year respectively. The work concluded a good correlation between the simulation and experimental results that were reported from the CPVT manufacturer.

From the literature, there are limited experimental and simulated projects that used PVT collectors with absorption chillers because the PVT system is more expensive than the conversional collectors and may produce electricity more than is required for the absorption cooling system. Most of the reviewed projects exported electricity to the grid or utilized it for other purposes such as domestic load. In the following research, PVT was used for other cooling systems.

Tsai [41] studied a refrigerant-based PVT system integrated with a heat pump water heating (HPWH) device to evaluate the electrical and thermal performance. Refrigerant R134a was used as the working fluid in a 1 kW_p HPWH system which was simulated by MATLAP/Simulink and validated with an experiment test. The system consisted of a PVT collector, which made of polycrystalline silicon cells and copper pipe arrangement to convert solar radiation to electricity and thermal energy. The PVT module consisted of a copper tube which contained the refrigerant, polystyrene foam as insulation and 48 six inch PV cells of 4.17W_p, arranged in two rows (200W_p), to produce electricity. Fig. 16 illustrates the cross sectional and top views of the PVT module.

The PVT module, as in Fig. 17, represents the evaporator where the refrigerant is heated then the outlet fluid (Point 1: Vapour, 4.146 bar, 25 °C) is compressed through the compressor to the condenser (Vapour, 14.915 bar, 65 °C). The water storage tank is then heated by the condenser coils and the refrigerant is condensed (Point 3: Liquid, 16.822 bar, 60 °C). The pressure and temperature are sharply decreased through the expansion valve (Point4: Liquid/Vapour 4.146 bar, 10 °C).

The work concluded a good agreement between the simulation and experimental results with respect to the electric output power which was in the range of 700–920 W. Further, the water was heated from 20 to 58 °C during an hour and the PVT temperature was in the range of 34–35 °C. The findings of the study also showed that the electricity produced from the PVT met the compressor's electricity requirement. The system was tested during June 2013 for one hour each day and further research is needed to examine it continuously during the day as well as the need for electricity and thermal storage technologies to be conducted in the system. [41].

Fang et al. [42] investigated electrical and thermal performance of a PVT heat pump air-conditioning system. The experiment set up consist of a PVT evaporator, compressor, heat exchanger, four way electro-

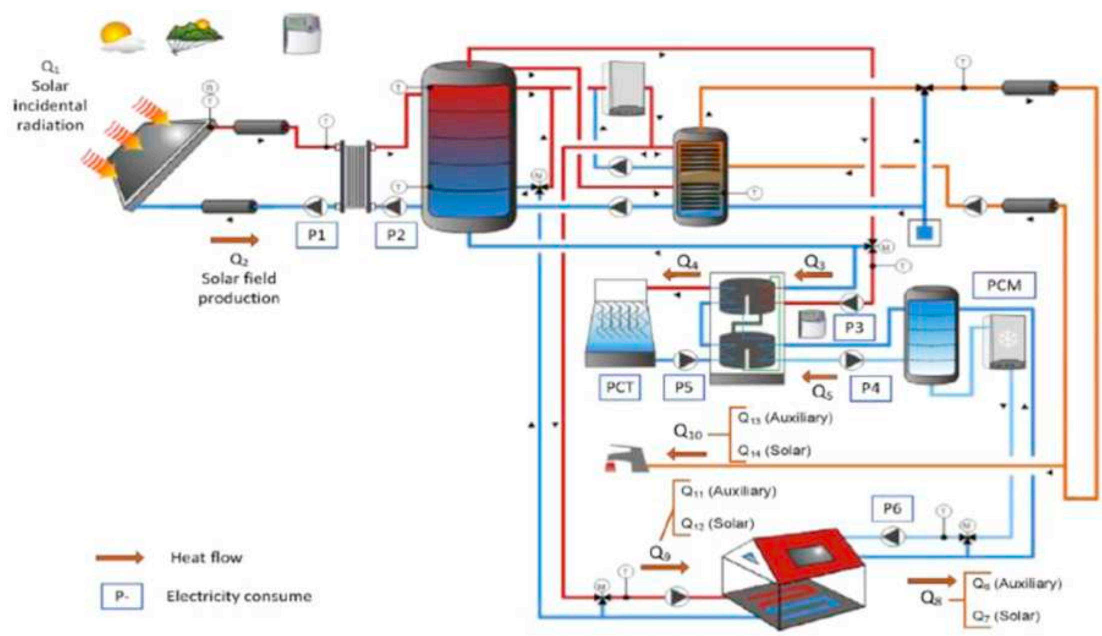

Fig. 8. Thermal solar cooling absorption system with cold and hot storage tank [2].

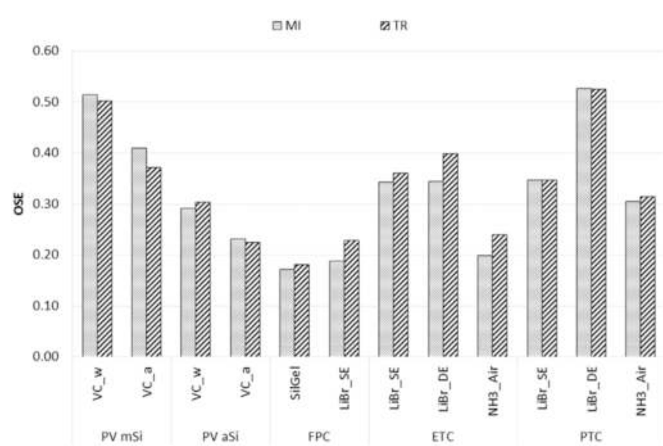

Fig. 9. Seasonal overall system efficiencies (OSE) for different technologies from Noro and Lazarin study [26].

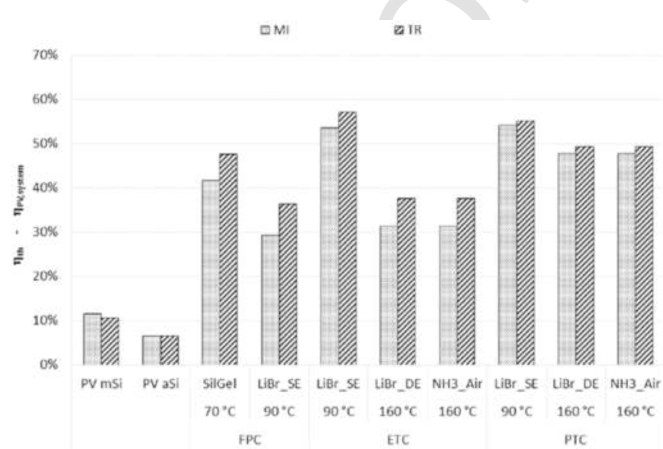

Fig. 10. Seasonal thermal and electrical efficiencies for different technologies from Noro and Lazarin study [26].

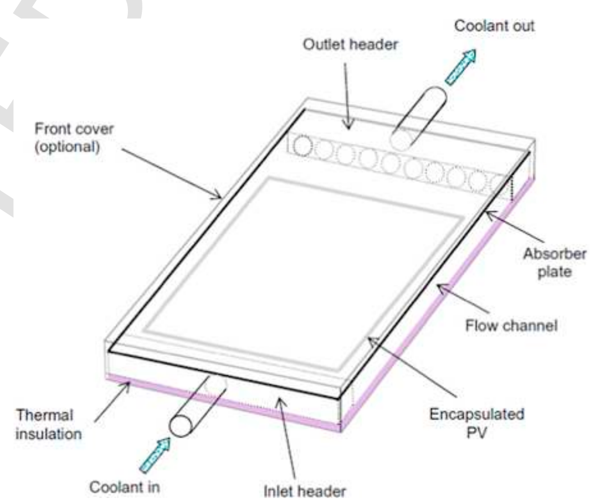

Fig. 11. Flat plate PVT collector which consist front cover, absorber plate and thermal insulation [28].

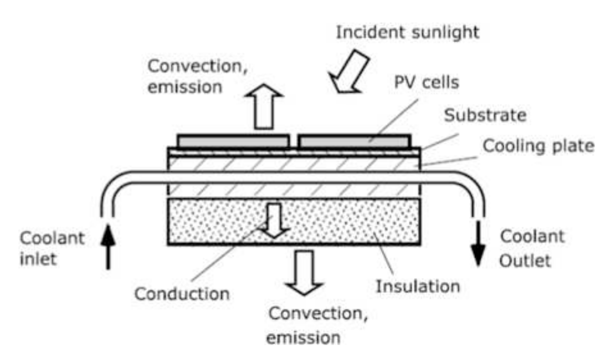

Fig. 12. PVT Module with heat transfer to the coolant and heat losses.

magnetic valves and expansion valve in the outdoor section, and heat exchanger, expansion and electromagnetic valves in the indoor section. The PVT module's geometry was 1500×750 mm and 100 mm in thickness, and consist of photovoltaic cells, aluminum plate, copper tube and insulation material. The study reported that the average photo-

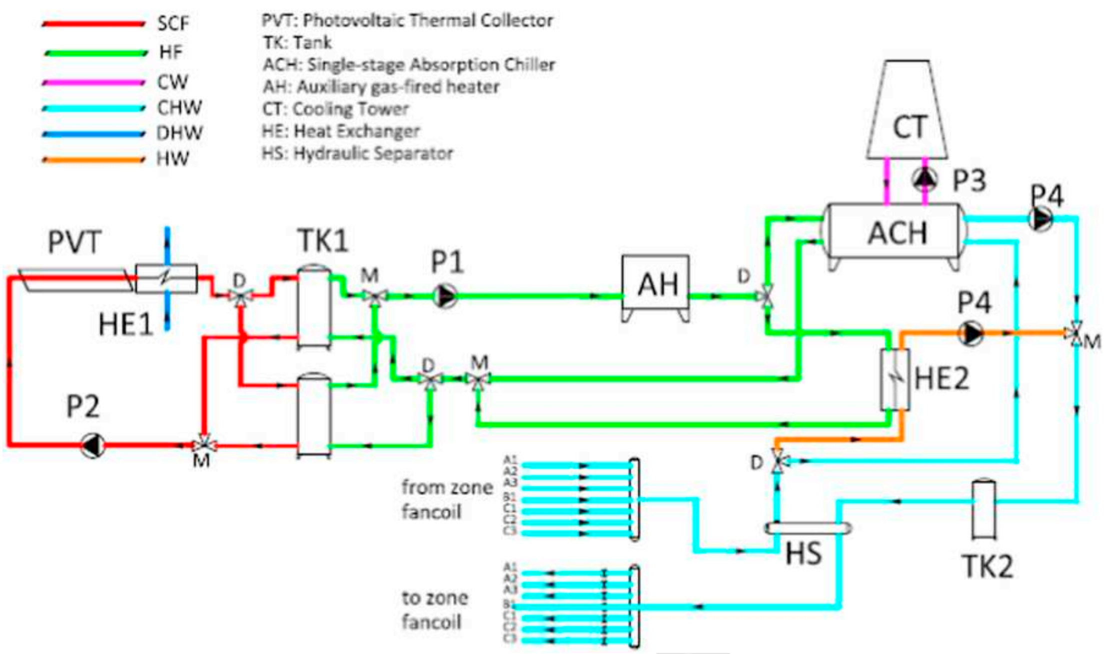

Fig. 13. Schematic diagram of solar absorption cooling system with photovoltaic thermal collector, cooling tower [37].

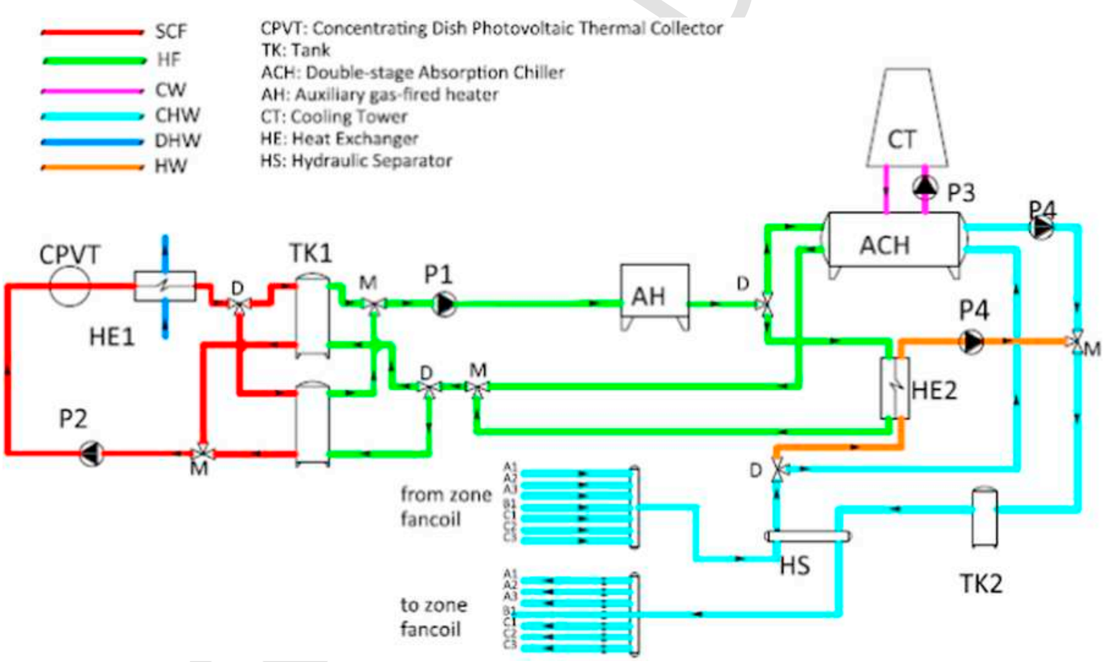

Fig. 14. Schematic diagram of solar absorption cooling system with concentrating photovoltaic thermal collector, cooling tower [38].

voltaic efficiency was improved by 23.8% more than the conventional PV due to the reduction of its temperature. They also highlighted that the average COP was 2.88 and the water temperature in the tank was heated to 42 °C.

Al-Alili et al. [43] investigated a hybrid PVT system to supply thermal energy for solid desiccant and electricity for vapour compression systems. The cooling section included a condition zone, desiccant wheel cycle, 17.5 kW vapour compression unit and heat recovery wheel as in Fig. 18.

The main components of the solar section were solar collector, thermal storage tank, battery and backup heater to maintain the supplied air temperature to desiccant wheel within the acceptable range. The COP was defined for the system by the ratio of the total cooling capacity for both compression and desiccant cycle to the total energy input to the system. The thermal performance of the system was analysed throughout the year using TRNSYS and parametric studies were made by varying the CPVT collector area from 5 m^2 to 80 m^2, storage tank volume from 0.5 m^3 to 4 m^3 and the numbers of batteries from 9 to 16 batteries. The findings of this study indicated that the overall performance was significantly affected by CPVT area and the overall COP for the desiccant with vapour compression system was 0.68. The COP for the system showed better performance at the same condition compared to an evacuated tube with an absorption chiller system and photovoltaic with vapour compression system which achieved 0.34 and 0.29 respectively. They also reported that in a hot and humid climate, the solid desiccant with vapour compression

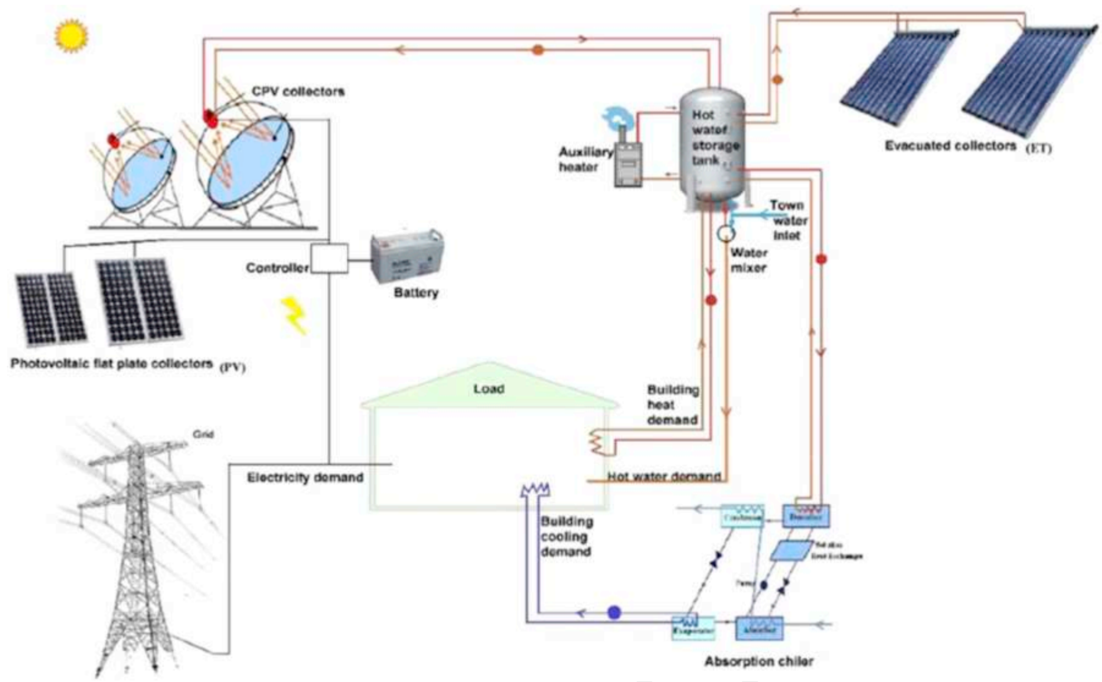

Fig. 15. Combined solar cooling, heating and power generation system [40].

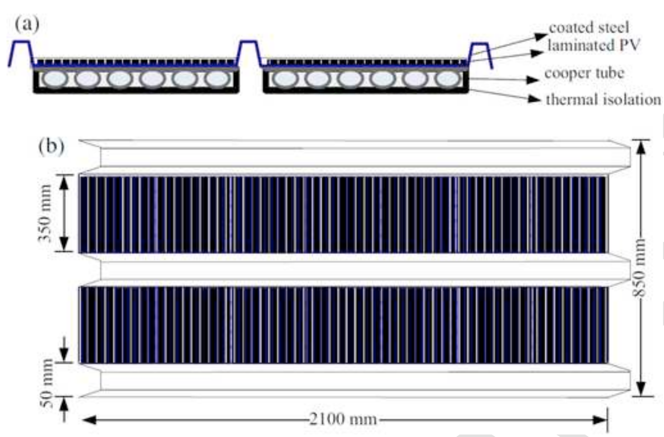

Fig. 16. Cross sectional (a) and top view (b) of polycrystalline silicon cells and copper pipe arrangement (PVT) [41].

system is more effective than a standalone vapour compression system [43].

Lin et al. [44] investigated the use of PVT collectors and phase change materials (PCMs) that were integrated in the ceiling, in order to provide heating and cooling by utilizing solar radiation during winter daytime and radiative cooling during summer night-time in Sydney. The PVT was integrated into the ceiling ventilation system to collect thermal energy and store it in the two layers of PCMs. The performance was evaluated using TRNSYS and MATLAB and the system mainly consisted of a 68 m^2 building model, PCM unit and 40 m^2 of PVT module. They reported that, in the winter case, the average thermal and electrical efficiency were 12.5% and 8.31% while maximum PV cell temperature and electrical power were 44.2 °C and 1.35 kW respectively. In the summer case, the average thermal and electrical efficiencies were 13.6% and 8.26% while the maximum PV temperature and electrical power were 71.7 °C and 1.98 kW respectively. The thermal comfort was improved in the building and further research is needed to optimise the dimensions of the PVT and PCM layers. Fig. 19 illustrates the PVT collectors and PCM integrated with ceiling ventilation system.

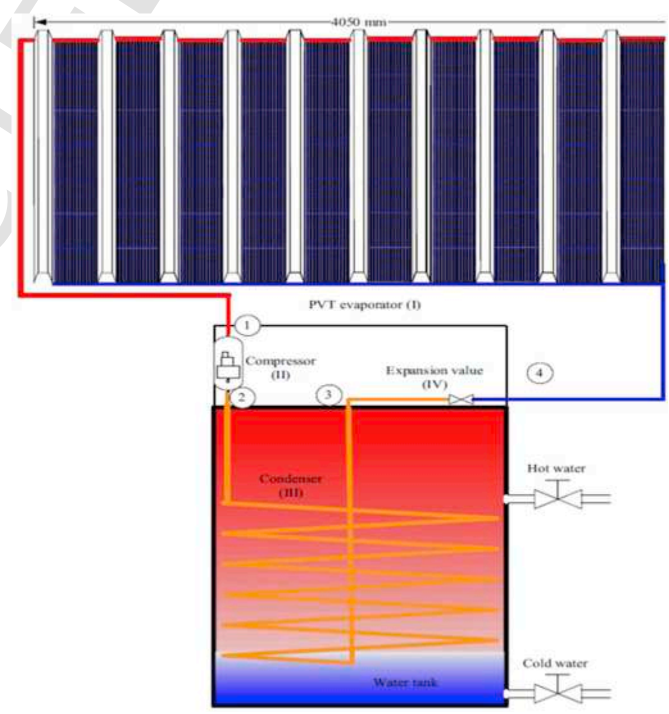

Fig. 17. Schematic diagram of PVT- HPWH system [41].

Beccali et al. [45] investigated the use of single glazed hybrid PVT solar collectors for different desiccant cooling systems without heat storage in hot and humid climate in order to evaluate primary energy saving. TRNSYS was used to evaluate the options to provide cooling for a 107 m^2 floor area building which included standard, desiccant with heat pump and desiccant with an enthalpy wheel. The packing factor which was defined as the percentage of the PV cells that covers the glazed area of PVT was also investigated (100% means that PV covers all the glazed area) as in Fig. 20.

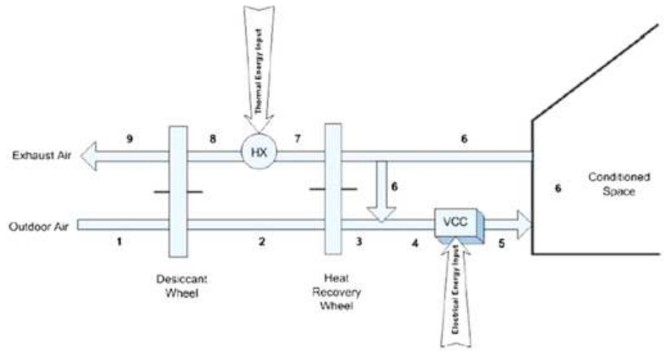

Fig. 18. Solar solid desiccant and vapour compression cycle (VCC) [43].

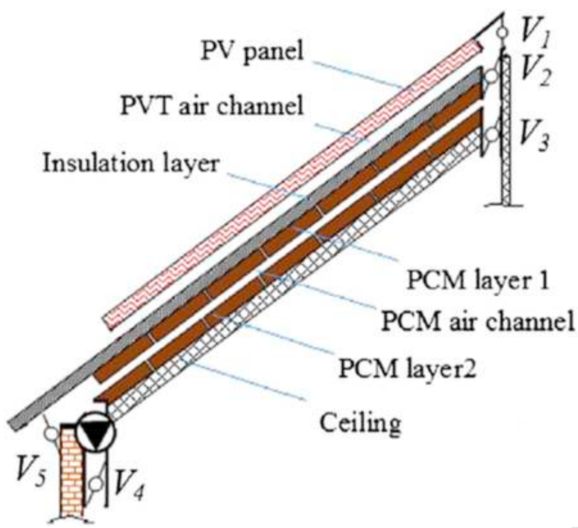

Fig. 19. Schematic diagram of PVT collectors and PCM integrated with ceiling ventilation system [44].

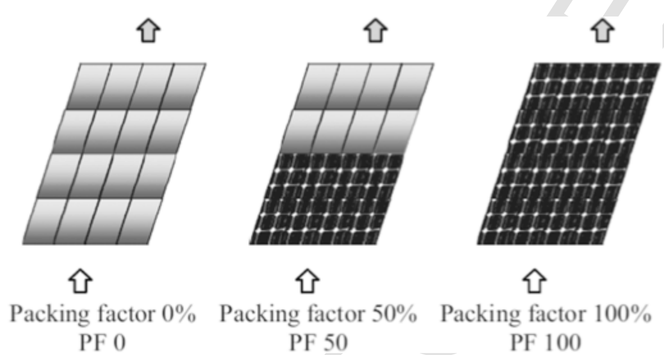

Fig. 20. Photovoltaic thermal solar collector with different packing factors [45].

The findings of the study highlighted that by varying the PVT area from 30 to 50 m^2 for all cases with the desiccant standard system, the simple payback period was in the range of 9.6–13.7 years. They reported that maximum temperature for the outlet PVT was in the range of 62–70 °C and integrated PVT with cooling technologies was more efficient comparing to PV with vapour compression systems. They also reported that integrating a heat pump with solid desiccant technologies showed the best results compared to other systems in the study.

Liang et al. [46] studied the dynamic performance of PVT heating system which consisted of a PVT, to provide electricity and low grade heat energy, hot water storage tank, heat exchanger to transfer the heat to under floor piping system and electric backup heater to maintain the temperature of the under floor system within the design points. TRNSYS was used to calculate the performance of a 32 m^2 PVT system which included inlet and outlet temperature and electrical power. They reported that the indoor temperature fluctuated between 16.3°C and 19.5 °C while the design point in the heating seasons was set at 18 °C (the ambient temperature ranged between −5 °C and −35 °C from October 15th to March 15th). They annually achieved 131 kWh/m^2 electric energy and the solar factor was 31.7%. However, these are preliminary results and further investigations are needed to validate these and provide exact thermal and electrical efficiency for the PVT throughout the year. Fig. 21 shows the schematic diagram of PVT floor heating system.

4. Economic viability

Performance indicators, economic indicators and environmental indicators have been discussed in the literature to evaluate solar cooling systems [12,23]. Solar fractions is an efficiency indicator that measure the ratio of the total energy collected by the solar collectors to the energy required for the system and can be written as:

$$SF = \frac{Q_s}{Q_S + Q_{aux}} \tag{1}$$

where SF is the solar factor of the system, Q_s is the energy absorbed by the solar collector and Q_{aux} is the additional energy from the auxiliary device. Another efficiency indicator is coefficient of performance (COP) which calculates the ratio of the cooling energy need Q_e (usually representing the energy removed from the zone and absorbed by the evaporator) to the energy absorbed by the solar collector Q_s and is written as:

$$COP = \frac{Q_e}{Q_S} \tag{2}$$

Simple payback period (SPP) is an economic indicator that calculate the time required to pay the different between the capital cost of the proposed solar system and the reference system from the operation cost saving. The expression of SPP is written as:

$$SPP = \frac{\Delta C_{inv}}{\Delta C_{op}} \tag{3}$$

ΔC_{inv} is the difference between the capital cost of the proposed and the reference system and ΔC_{op} represents the difference between the operation cost for the reference and proposed solar systems.

Cost of primary energy saved ($C_{PE,Saved}$) is another economic indicator which calculates the ratio of the annual additional cost of the solar system ($\Delta C_{a,c}$) to the primary energy saved (PE_{Saved}) and is written as:

$$C_{PE,Saved} = \frac{\Delta C_{a,c}}{PE_{Saved}} \tag{4}$$

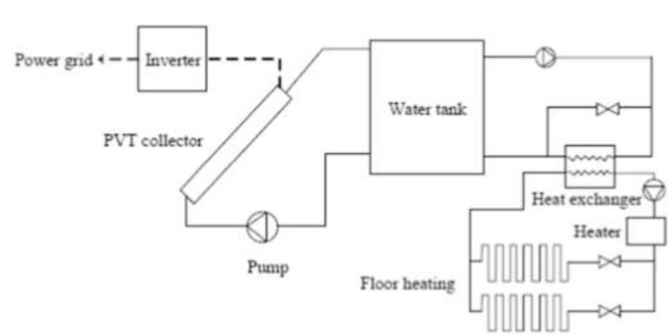

Fig. 21. Schematic diagram of PVT floor heating system [46].

There are other indicators that concern about environment such as global energy requirement (GER), global warming potential (GWP) and Ozone depletion potential (ODP) [12].

Based on a survey of 50 projects on different climatic conditions, the average initial investment cost of solar cooling absorption systems is 267% higher than electric compression chiller (310 Euro/kW_c for absorption chiller) and the average primary energy saving for absorption systems in the range of 25–52% [12]. Table 4 summarises initial costs for the main components and some other prices in solar cooling systems from the literature.

With reference to Table 4, the initial cost of solar absorption systems was mainly based on the solar collector price. From this study, the normalized area of flat plate collectors and evacuated tube collectors to produce cooling ranged between 3 and 9.4 m^2/kW_c and between 2.05 and 5 m^2/kW_c respectively. Based on average expected area for solar collectors in the system, Fig. 22 displays initial cost assessment for solar absorption cooling system.

Based on the price of solar collectors and single absorption chillers, without taking into account the cost of cooling tower and the storage systems, solar collectors represents about 80% of the total investment cost of the system. As a result of that, a reduction of the initial cost of solar collectors is a key factor to reduce the cost of cooling absorption systems. In addition to this, improving the efficiency of solar collectors, developing the design of PVT systems might be another method to reduce the initial investment cost for absorption cooling systems.

5. Results and discussion

Experimental and computational studies for solar cooling systems are discussed and summarised in Sections 5.1 and 5.2 then the use of photovoltaic thermal collector for cooling purposes are also discussed in Section 5.3.

5.1. Experimental studies

Outdoor testing were mainly used in the literature in order to carry out the performance for solar cooling systems. Coefficient of performance for the overall solar cooling system in this research was in the range of 0.19–0.91 whilst solar collector efficiency was in the range of 0.24–0.64. Flat plat collectors (FPC) were used in some of these studies and the normalized area to produced cooling was in the range of 3–9.4 m^2/kW_c. Evacuated tube collectors (ETC) were used for other research and the normalized area was in the range of 2.05–5 m^2/kW_c. For FPC, ETC, compound parabolic concentrator (CPC) and parabolic trough solar collectors (PTC), the average area to produce cooling in the experimental studies for single and double effect absorption chillers were 4.95 m^2/kW_c and 4 m^2/kW_c respectively. These key findings in solar absorption system and other details for each experimental projects are summarised in Table 5.

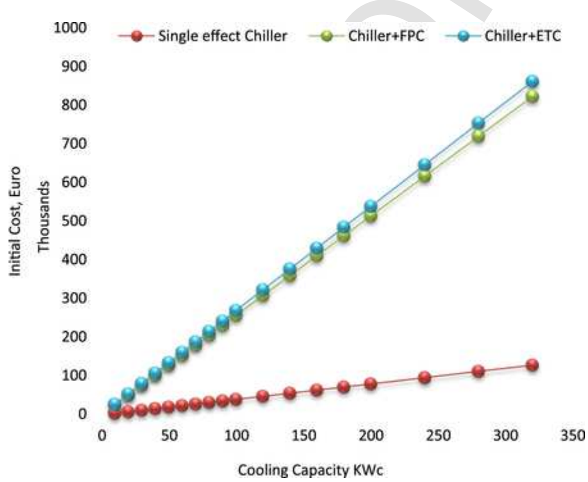

Fig. 22. Initial cost assessment based on prices from the literature as in Table 4 (note: the initial cost assessment doesn't include the cost of storage system and cooling tower).

5.2. Computational studies

Computational studies to evaluate solar cooling absorption system in the literature are reported in this section. TRNSYS which is a widely used software in the field of solar cooling systems were used for about 50% of the simulation studies in this paper. MATLAB and other theoretical model are also examined and validated in the rest of reviewed papers.

COP for the computational systems for solar cooling system in this research was in the range of 0.1–0.82 whilst the solar collector efficiencies in the range of 0.06–0.63. FPCs were used in some of these studies and the normalized area to produced cooling was in the range of 2.18–8 m^2/kW_c. ETCs were used for other research and the normalized area was in the range of 1.27–12.5 m^2/kW_c. For FPC, ETC, CPC and PTC, the average area to produce cooling in the computational studies for single and double effect absorption chillers were 5.61 m^2/kW_c and 3.7 m^2/kW_c respectively. These key findings in solar absorption system and details about collector types, their areas and efficiency, cooling capacity and COPs for each computational projects are summarised in Table 6.

5.3. Photovoltaic solar thermal collectors for cooling systems

Recently, there has been a growing interest to reduce the initial cost and improve the efficiency of solar collectors and this leads to reduced overall investment of the solar cooling system. Photovoltaic thermal collectors have been used for several solar cooling projects in order to produce both electricity and thermal energy and this can improve electric efficiency by 23.8% more than the conventional PV panel [42]. For CPVT and PVT, the average area to produce cooling in the studies for solar absorption chillers was 2.72 m^2/kW_c and 3.1 m^2/kW_c respectively. These key findings in photovoltaic thermal absorption system and more details about collectors' types, their areas and efficiency, cooling capacity and COPs for each photovoltaic thermal projects are summarised in Table 7.

6. Conclusion

The current developments in the field of photovoltaic thermal collectors (PVT) for cooling purposes has been reported. The review also included the current developments in the field of solar absorption cooling systems from the point of view of solar collecting options. Based on the performance and the initial cost of solar cooling systems, single effect absorption systems are estimated to be more efficient with lower costs. Solar absorption cooling systems show an opportunity to be an alternative to conventional cooling technologies. In these studies, absorption systems shows an opportunity to achieve a relatively high COP (0.5–0.8) for generation temperature in the range of 70 °C and 90 °C.

In the review, sufficient efficiency for the PVT was achieved in the range of outlet temperature of 60–80 °C. Despite the fact that there has been an improvement of the electrical efficiency due to reduce the PV temperature by the coolant in the PVT system, there is a good opportunity to utilise the outlet water from PVT to supply absorption chillers. Electrical efficiency, thermal efficiency and overall COP for the PVT solar absorption system are largely affected by ambient temperature and global solar radiation.

Economic evaluation for solar absorption cooling systems is based on the performance of the system, electricity tariff and capital cost of the project. This study determined that solar collectors represents about 80% of the total investment cost of the system (without taking in account the cost of cooling tower, hydraulic and storage systems).

7. Challenges and future work

This review included experimental and computational work focusing on collector types and their efficiency and the performance for solar absorption cooling system. The major challenge in the use of photovoltaic thermal collectors for absorption chillers is to achieve high thermal and electric efficiency with producing sufficiently high outlet fluid temperature. The economic feasibility for the overall system is also an important factor and further research is suggested as the following:

- Dynamics of the flow and thermal behaviour solar collectors within solar absorption systems need to be studied.
- Control strategies for PVT absorption cooling system and operating scenarios need to be instigated.
- Heat transfer, electrical and thermal efficiency of photovoltaic thermal collectors that coupled with absorption cooling systems need to be analysed.
- Outlet fluid temperature for PVT need to be optimised in order to supply absorption chiller.
- Industrial production including prices and performance of photovoltaic thermal collectors should be addressed.
- Economic feasibility of solar absorption system including capital and running cost based on electricity prices and the need for cooling need to be investigated.

Acknowledgment

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