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Produced by

Yong Sun (Dr.)
School of Architecture, Tianjin University; APEC Sustainable Energy Center (APSEC)
216 Yifu Building, 92 Weijin Road, Nankai District, Tianjin 300072, P. R. CHINA
Tel: + (86) 022-2740 0847
Email: sunyong-1984@163.com

Yang Yang (phD)
School of Architecture, Tianjin University; APEC Sustainable Energy Center (APSEC)
216 Yifu Building, 92 Weijin Road, Nankai District, Tianjin 300072, P. R. CHINA
Tel: + (86) 022-2740 0847
Email: doublesunrise@126.com

For
Asia-Pacific Economic Cooperation Secretariat
35 Heng Mui Keng Terrace
Singapore 119616
Tel: (65) 68919 600
Fax: (65) 68919 690
Email: info@apec.org
Website: www.apec.org

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Research Report on Innovative Solar Technologies (EWG 03/2016A)

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Executive Summary

As we all known, energy consumption from building sector accounts for a considerable proportion in the total energy consumption of both APEC region and other areas. This APEC project (e.g. EWG 03/2016A) aims to develop recommendations for application of innovative solar technologies in green buildings to Asia Pacific's various climatic regions, share information on relevant technologies, and promote energy efficiency of APEC region. Green building is one of measures been put forward to mitigate significant impacts of the building stock on the environment, society and economy. The theory of green buildings includes a lower environment load, higher energy efficiency and resource saving throughout a building's whole life cycle. At the same time, green buildings should provide comfortable, safe and healthy environments for people. Renewable energy utilization (REU) is one of the most important aspects of green buildings. The innovative applications of renewable energy technologies in green buildings are crucial for realising the sustainability target in APEC region. There is a growing level of public awareness of green building for most of member economies in APEC region. However, there also exists extensive barriers on promoting green building in this region. Indeed, the lack of knowledge of renewable energy and green building creates further challenges for promoting and implementing green buildings. RE is defined as energy that is derived from natural processes and that can be replenished constantly, including energy generated from solar, wind, biomass, geothermal, hydropower and ocean resources, and biofuel and hydrogen derived from renewable resources. Among these renewable energy, the feature and innovative application of solar energy would be systematically introduced and summarized within this report, including solar photovoltaic technology, solar heating & cooling, photovoltaic-thermal (PVT) systems and solar-assisted heat pump (SAHP) system.

From preliminary workshop and research, our team think that there exists an exciting opportunity for the development of cost-effective renewable energy supply solutions based on innovative solar technologies to promote green buildings in APEC region. Our team hope the final recommendations including this research report could make contributions to the sustainability development of all 21 member economies of APEC.

Research Report on Innovative Solar Technologies (EWG 03/2016A)

Project Description and Background

Buildings account for about 40% of global energy consumption; therefore renewable energy-supply solutions for buildings will greatly contribute to energy efficiency and energy security of Asia-Pacific region. Responding to 2015 APEC Energy Ministers' instruction for the EWG to "explore strategies to drive the shift towards green buildings including zero energy buildings", this project seeks to foster APEC members' collaborative efforts in developing cost-effective renewable energy-supply solutions based on innovative solar technologies for green buildings in APEC region.

This project aims to develop recommendations for application of innovative solar technologies in green buildings to Asia Pacific's various climatic regions, share information on relevant technologies, and promote energy efficiency of APEC region. A workshop with experts and attendance from renewable energy and green buildings field will be held in China in April 2017. A final research report on RE solutions for green buildings in APEC Region will be submitted.

Project Objectives

The Project Objectives of EWG 03/2016A are:

- To develop recommendations on technical solutions for promoting advanced solar applications in green buildings to Asia Pacific's various climatic regions.
- To make all partners clear about possible sustainable building energy-supply solutions and to enhance understanding of the innovative solar technologies by sharing results and experiences.
- To build interest of governments, investors, architect, manufacturers of building cladding products and photovoltaic companies in the innovative solar technologies and their applications for green buildings including zero energy buildings.

Aim and Objectives of Research Report on Innovative Solar Technologies (EWG 03/2016A)

This research report aims to provide useful information about the innovative solar technology proposed in the project for experts, producers, consumers and equipment suppliers as well as governments and agencies to better understand the related technologies.

Introduction

The fast depleting conventional energy sources and today's continuously increasing energy demand in the context of environmental issues, have encouraged intensive research for new, more efficient, and green power plants with advanced technology. Since environmental protection concerns are increasing in the whole world today, both new energy and clean fuel technologies are being intensively pursued and investigated. Most of the renewable energy from wind, micro-hydro, tidal, geothermal, biomass, and solar are converted into electrical energy to be delivered either to the utility grid directly or isolated loads [1-4]. Human race has been harnessing solar energy, radiant light and heat from the sun since ancient times using a range of ever-evolving technologies. Solar energy technologies include solar heating, solar photovoltaic, solar thermal electricity and solar architecture, which can make significant contributions towards solving some of the most pressing energy problems now faced by the world [5].

For the generation of electricity in far flung area at reasonable price, sizing of the power supply system plays an important role. Photovoltaic systems and some other renewable energy systems are, therefore, an excellent choices in remote areas for low to medium power levels, because of easy scaling of the input power source [6,7]. The main attraction of the PV systems is that they produce electric power without harming the environment, by directly transforming a free in exhaustive source of energy, the solar energy into electricity. Also, the continuing decrease in cost of PV arrays and the increase in their efficiency imply a promising role for PV generating systems in the near future [8,9]. Unfortunately, the technologies associated with photovoltaic (PV) power systems are not yet fully established, and therefore, the price of an energy unit generated from a PV system is an order of magnitude higher than conventional energy supplied to city areas, by means of the grid supply.

The efficiency of energy conversion depends mainly on the PV panels that generate power. The practical systems have low overall efficiency. This is the result of the cascaded product of several efficiencies, as the energy is converted from the sun through the PV array, the regulators, the battery, cabling and through an inverter to supply the ac load [10, 11]. Weather conditions also influence the efficiency, which depends non-linearly on the irradiation level and temperature. For example, a cloud passing over a portion of solar cells or a sub-module will reduce the total output power of solar PV arrays. Under certain cloud conditions, the changes can be dramatic and fast. A method is required to assess the cost of such fluctuations and their effect on other systems to which a solar array may be connected e.g. utility [12, 13]. Several methods have been developed to predict the solar PV array output power. An estimation method used in Ref. [14] proposes that the power output of a PV system is proportional to the insolation levels measured for the surface of a solar cell at any angular position. Since power supplied by the solar arrays also depends on temperature and array voltage, it is necessary to draw the maximum power of the solar array. Various techniques have been proposed and developed to maximize the output power [14–19]. The wide acceptance of a PV power generation depends on the cost and on the energy conversion efficiency. Attempts have, however, been constantly made to improve sun tracking system to increase the efficiency to make solar energy attractive. In current technology condition, utilization of tracking PV system is an optimum selection of enhancing system efficiency and reducing cost.

This paper, therefore, deals with a state-of-the art discussion on solar power generation, highlighting the analytical and technical considerations as well as various issues addressed in the literature towards the practical realization of this technology for utilization of solar energy for solar power generation at reduced cost and high efficiency.

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Session I: Building Integrated Photovoltaics (BIPV)

This chapter mainly refers to the relevant literatures published by Akash Kumar Shukla, K. Sudhakar, and Prashant Baredar, we sincerely thank the relevant authors for their efforts in solar photovoltaic technology.

Solar power is divided into light and thermal power generation and photovoltaic power generation. Generally speaking, solar power refers to solar photovoltaic power generation, referred to as "photoelectric". Photovoltaic power is a technology that uses the optical volt effect of the semiconductor interface to convert light energy directly into electrical energy. The key element of this technology is the solar cell. Solar cells are packaged and protected after being connected in series, forming a large area of solar cell modules, and then combining with power controller and other components, a photovoltaic power generation device is formed.

1. Introduction of BIPV

Solar energy is radiant energy and heat from the Sun is harnessed using a range of ever-evolving technologies such as building integrated photovoltaic, solar heating, solar architecture, solar thermal energy and artificial photosynthesis. Photovoltaic power generation employs solar PV module composed of a number of cells containing photovoltaic material. Materials presently used for solar PV cell include crystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide [1]. Due to the growing demand for renewable energy sources, the manufacturing of solar PV cells and photovoltaic module has advanced considerably in recent years [2–5]. Building integrated photovoltaics are solar PV materials that replace conventional building materials in parts of the building envelopes, such as the rooftops or walls. Furthermore, BIPV are considered as a functional part of the building structure, or they are integrated into the building's design [6]. The BIPV system serves as building envelope material and power generator simultaneously [7]. BIPVs have a great advantage compared to non-integrated PV systems because there is neither need for allocation of land nor facilitation of the photovoltaic system. Illustrating its importance, BIPVs are considered as one of four key factors essential for future success of photovoltaics [8]. The on-site electricity producing BIPV modules can reduce the total building material costs and achieve compelling savings in terms of the mounting costs, especially since BIPV system do not require additional assembly components such as brackets and rails [9]. The BIPV system simply makes non polluted electricity out of sunlight. All these advantages have caused a worldwide growing interest in BIPV products [7].

2. BIPV history

Solar photovoltaic module uses for building began appearing in the 1970s. Aluminium-framed solar PV modules were connected to, or mounted on, buildings skin that were usually in remote areas without access to an electric power grid. In the 1980s Solar PV module add-on to roofs began being demonstrated. These PV systems were usually installed on utility grid connected buildings in areas with centralized power stations. In the 1990s BIPV products specially designed to be integrated into a building envelope became commercially available [10]. An 1998 doctoral thesis by Patrina Eiffert, entitled "An Economic Assessment of BIPV", considered that one day there would be an economic value for trading Renewable Energy Credits (RECs) [11]. A 2011 economic assessment and brief overview of the history of BIPV by the U.S. National Renewable Energy Laboratory (NREL) suggests that there may be significant technical challenges to overcome before the installation cost of BIPV is competitive with photovoltaic panels [12] .However, there is a growing consensus that through their widespread commercialization, BIPV systems will become the backbone of the zero emission energy building European target for 2020 [13]. Despite technical promise, social barriers to widespread use have also been identified, such as the conservative culture of the building and integration with high-density urban design.

3. Architectural Functions of PV Modules

BIPVs foil products (Shown in Fig. 1) are lightweight and flexible, which is beneficial with respect to easy installation and prevailing weight constraints for roofs of building. The solar PV cells are often made from flexible thin-film solar cells to maintain the flexibility in the foil and the efficiency regarding high temperatures for use on non-ventilated roof building solutions. Unfortunately, currently there are many manufacturers on the market that provide weather tight solutions. However, it is possible to vary the degree of inclination of the foil product to a great extent providing flexible solutions.

Fig. 1. Classification of BIPVs Product.

For architects, the application of PV systems must be part of a whole (holistic) approach. A high-quality PV system can provide a substantial part of the building′s energy needs if the building has been designed in the right way. However, the energy consumption for heating, ventilation, and air conditioning (HVAC), lighting, and occupant-related activities in an average house exceeds largely the possible energy production of a BIPV system. Therefore, the building should be designed and engineered in such a way that the building-related energy consumption will be substantially lower than in a conventionally designed building.

A distinction can be made between literally integration of PV in the building skin (PV as a cladding element or integrated into the roof) and integration of PV in building components (awnings, shading devices, etc.) (see examples in Fig. 2).

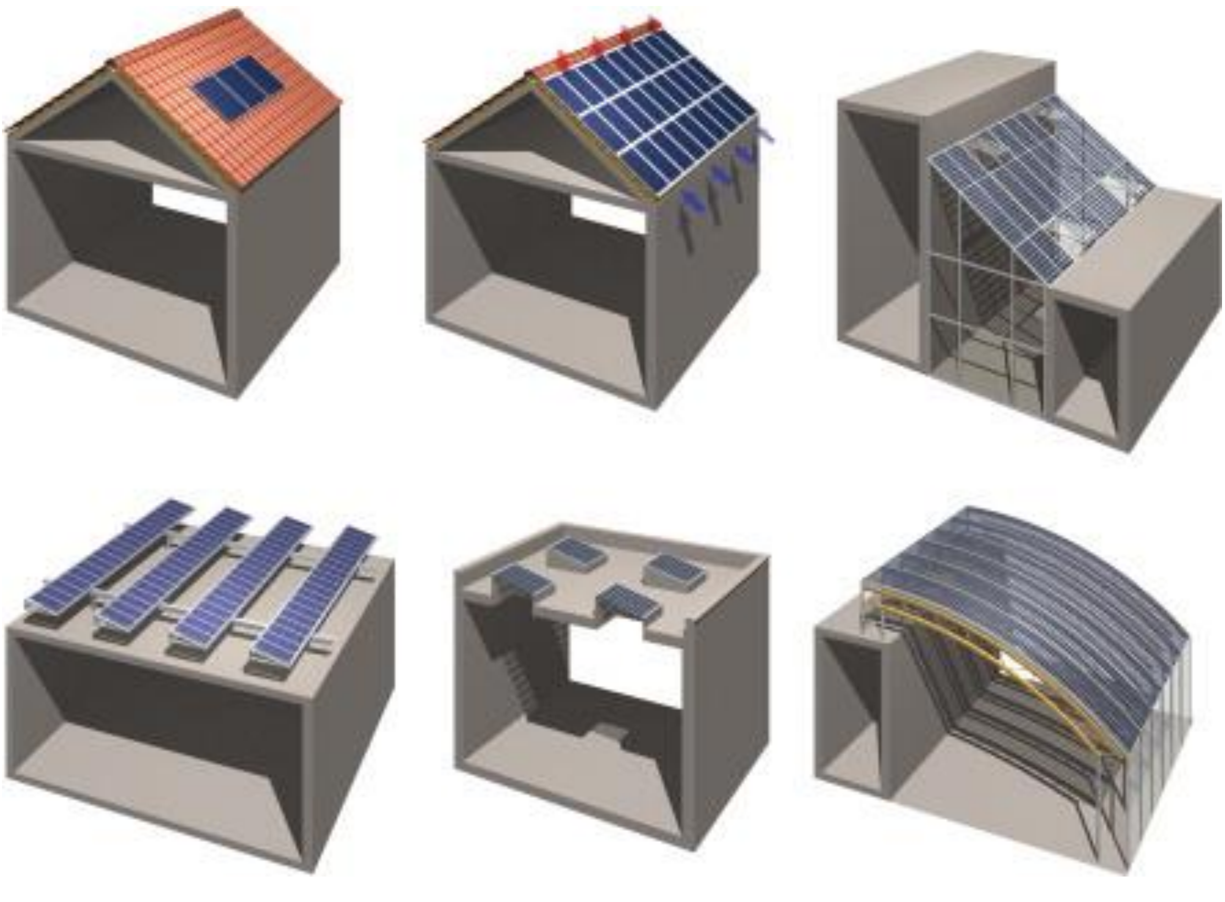

Fig. 2. Pictures of different BIPV applications.

Pictures from the training CD for IEA PVPS Task 7 [3]. Figure © Mart van der Laan.

- **Roof-integrated PV**

A PV system can be integrated into the roof in several ways. One choice is for the integrated system to be part of the external skin and therefore be part of an impermeable layer in the construction. In the early days of BIPV (1990s), several building projects were constructed on the basis of this principle. The other choice for roof mounting the PV system is above the impermeable layer. This is a more secure option but also not without some risk, as the impermeable layer has to be pierced in order to mount the system on the roof. Using PV modules as roof covering reduces the amount of building materials needed, which is very favourable for a sustainable building and can help reduce costs.

In addition to covering the complete roof with modules, there are also many products for small-scale use, for example, PV shingles and tiles. The small scale of these products (from 2 cells on a tile to around 20 cells on a look-alike tile) makes them very convenient for use in existing buildings or as do-it-yourself products.

(Semi)Transparent PV modules used as roofing materials serve as water and sun barriers and also transmit daylight. In glass-covered areas, such as sunrooms and atriums, sun protection on the roof is necessary in order to avoid overheating in summer. Transparent PV modules have the solar cells mounted between two transparent layers (mostly glass), while a certain distance has been kept between the different cells. The PV cells absorb 70–80% of the sun radiation. The space between the cells transmits enough diffused daylight to achieve a pleasant lighting level in the area. In order to increase the usage of daylight in the workplaces, transparent PV modules have been used instead of glass.

Of course, PV cells convert sunlight into electricity (with typical efficiencies of 6–20%) with the remainder of the solar energy being converted into heat. This residual heat can also be used to warm the building, for example, by designing an air cavity underneath the PV modules, through which warm air (heated by PV modules) is flowing. This hybrid collector provides warm air to the heating system in the home, which in this case, makes it a cost-effective use of the collector.

A relatively new application of PV combined with a thermal system is PVT: a PV module mounted on a solar thermal module. The residual heat is used to heat the water (or other liquid) in the thermal system. A demonstration project, which was financially supported by the European Commission, can be seen at the head offices of RES UK in Kings Langley, north of London (UK) (see Fig. 3).

Fig. 3. PVT façade at RES UK in Kings Langley (UK). Photograph © Henk Kaan.

At the Netherlands Energy Research Foundation (ECN) in Petten (NL), Building 42 has a conservatory with 43 kWp BP solar roof-integrated transparent laminates that reduce light and sun transmission by around 70% as compared to glass. The conservatory therefore acts as a big parasol over the offices, protecting them from the sun while still providing enough daylight.

- **Façade-integrated PV**

Façades are basically constructed using in situ bricklaying or concrete constructions, prefab elements, or structural metal façades that are mounted in place. Concrete constructions form the structural layer and are covered with insulation and a protective cladding. This cladding can be wood, metal sheets, panels, glass, or PV modules. For luxury office buildings, which often have expensive cladding, cladding with PV modules is not more expensive than other commonly used materials, for example, natural stone and expensive special glass. This cladding costs around \$ 1500 m^{-2}, which is considerably larger than the cost of the PV module today.

Structural glazing or structural façades are constructed using highly developed profile systems, which can be filled with all types of sheeting, such as glass or frameless PV modules.

The development of transparent modules has gone further in the last 10 years. In the semi-transparent modules from the 1990s, the space between cells and the light transmission through the tedlar back foil stipulated the amount of light that came through. Starting with the Sunways cells, a complete new generation of light-through cells have been developed like Schott ASI Glass and Suntech MSK′s light-thru and see-thru cells that can be used in roofs and structural façades.

- **PV in building components**

Façades are very suitable for all types of sun shading devices, louvers and canopies. There is a logical combination between shading a building in summer and producing electricity at the same time. Architects recognize this and many examples of PV shading systems can be seen around the world. A terrace with a roof on the sunny side of a building is a good place for BIPV systems thus providing shade, protection from rain, as well as electricity.

- **PV art in structures**

Freestanding applications of PV power systems have been constructed in a variety of more or less creative designs. Well known are solar sails that are landmarks for companies and show their green involvement. Many other types of freestanding construction designs to support PV power systems have been constructed. Remarkable are the constructions that show PV as a flower and in some cases track the sun.

On the small scale, there are many artistic modules both in cell colour and pattern and in module form. Artists like Jürgen Claus (Germany) and Sarah Hall (Canada) became famous as PV artists, and also many architects use PV systems in an artistic way. The façade of the JingYa hotel in Beijing is huge (designed by Simone Giostra and ARUP for Greenpix). It is in fact a gigantic 2200 m2 billboard with 2292 modules that collect the energy to light the light-emitting diode (LED) billboard at night.

4. Challenges and advantages of BIPVs

- **BIPVs challenges**

The barriers to BIPV integration include lack of public awareness, policy and building codes. Since building products (foil, tile, etc.) prices are variable by application depending on the specifics of the system structure, calculating the cost of electrical energy as measured in dollars per kilowatt hour can be a challenge.

However, the value of offsetting existing building materials costs, including the materials itself, transportation, installation and maintenance must be known, in order to truly assess the lifetime cost of BIPV energy generation. The cost of electrical energy is calculated by summing all the costs incurred during the lifetime of the generating technology, divided by the kilowatt hours of energy generated during the lifetime of the project. It goes beyond just the cost of production to enable a comparison of different energy generating technologies of unequal life times and differing capacities and permit grid competiveness comparisons for different geographies.

In different countries, the need to test every sized product no longer exists. While the ultimate goal for technology developers is to make BIPV cost competitive with the building materials it replaces (e.g. foil, tile, glass facade, stainless steel, granite, etc.), this can only happen when the energy cost recovery over the lifetime of the building solar product exceeds the lifetime cost of the solar photovoltaic component of the building product.

- **Advantages of BIPVs system**

In new construction of BIPV system, building costs are attributed to facades and glazing solar products. These BIPV products (foils, tiles, module etc.) must be purchased from the suppliers, transported to the site and installed into the building structure. Since these costs are already included in the cost of the building materials, the added cost of enabling the products photovoltaic capability is reduced to the cost of the technology itself, electrical connectivity and inversion. The advantages and disadvantages of BIPV over solar module is given as fellow.

Advantage:

- Aesthetically pleasing
- Saves building materials and labour Costs
- Can be used on weaker building structures and roofs where Solar Panels cannot be installed.
- Can be used on structures such as facades. And skylights where solar modules cannot be installed

Disadvantage:

- Higher cost is the biggest disadvantage of BIPV over normal crystalline PV Modules
- BIPV Efficiency is lower as BIPV modules normally are made of thin film which have lower efficiency.
- More complex and requires high labour charges than normal PV mod ules installation.
- Difficult and expensive to retrofit older buildings.

The original cost of the substrates, transportation, installation and maintenance are already included in the cost of the building and BIPV products often offer a higher insulation value, which also contributes to energy saving. In essence, BIPV will not only generate power, but also reduce energy consumption i.e. zero energy building. Additionally, enabling traditional building materials with high embodied energy costs help to offset the manufacturing carbon footprint.

BIPV system can be integrated into the building envelope which appeals to architects, designers, builders and property owners. Building integrated photovoltaic system enabling technologies include crystalline silicon, thin film, organic solar cells, which can be processed from solution and offer the potential for inexpensive, large-scale electricity production; and dye-sensitized solar cells (DSSC), which are made of low-cost materials that do not require elaborate or high energy consuming manufacturing equipment. These third generation solar photovoltaic technologies can be used in a variety of building integration and applications, including roofing, facade, and glazing.

5. Future scope for BIPVs

Building integrated photovoltaic system poses an opportunity to play an essential part in a new era of distributed power generation. While some critical challenges (economic and policy) exist, the value of generating power directly where it is used, aesthetic designs and flexible thin film solar PV module form factors is just starting to be understood, which may help to mitigate the barriers posed for current building integrated photovoltaic applications.

6. Conclusion of BIPV

BIPV is a replacement of conventional construction material with PV material which can perform dual functions; providing building envelop and generating electric power for buildings. Thin film and organic solar cells are suitable for BIPV products but organic solar cell technology is still under research. The conventional building roof, façade & window shading systems are replaced with BIPV products. The construction cost of BIPV system is marginally higher as compared to conventional construction with approximately the same life span as conventional PV rack versions. This system also reduces HVAC load of buildings. BIPV/T system simultaneously produces electric power and hot water for variety of needs. The power generation efficiency of the BIPV system is less compared to stand alone and BIPV/T system but it eliminates the additional space requirement for power generation. BIPV products are now globally available in the market though the domestic suppliers in India are limited. Overall this technology has a very bright future in the coming time due to its functional features.

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Session II: Solar heating and cooling

Solar energy is widely recognized as one of the most important renewable energy resources due to its even distribution, safety and serving as sources for others. In past decades, global solar thermal capacity increases rapidly and now it has been widely used worldwide to provide heating and cooling. This chapter mainly refers to the relevant literatures published by T.S. Ge et al[1], and we sincerely thank the relevant authors for their efforts in solar heating and cooling research.

Solar heating and cooling technologies include solar water heating, solar space heating and cooling, using active technologies and passive system designs, day-lighting, and agricultural and industrial process heating. The use of solar energy in housing presents remarkable advantages as follows: requires less energy; causes less adverse environmental impacts, for example, CO2; provides open sunlight; improves building aesthetics; and provides a new medium for architectural expression.

1. Solar heating

Hot water and space heating consumes a great proportion of energy consumption in buildings. Non-renewable sources including electricity or natural gas are significant supply. Due to the roaring concerns on energy conservation and environmental protection, using electricity or fossil fuel driven heating devices in buildings is limited in many countries, solar energy are proposed instead to meet the legislation. Converting solar radiation into heat is the most simple and direct application of solar energy, with greater potential than other forms of renewable sources.

While solar water heating and solar space heating have been in the market for decades, new approaches for solar thermal applications (e.g., for cooling and process heating) are now emerging in the market. Solar-assisted cooling is an extremely promising technology as peak cooling requirement coincides with peak solar radiation. Small-scale solar cooling systems are now commercially available. Fig.4 illustrates the market development from solar thermal technologies.

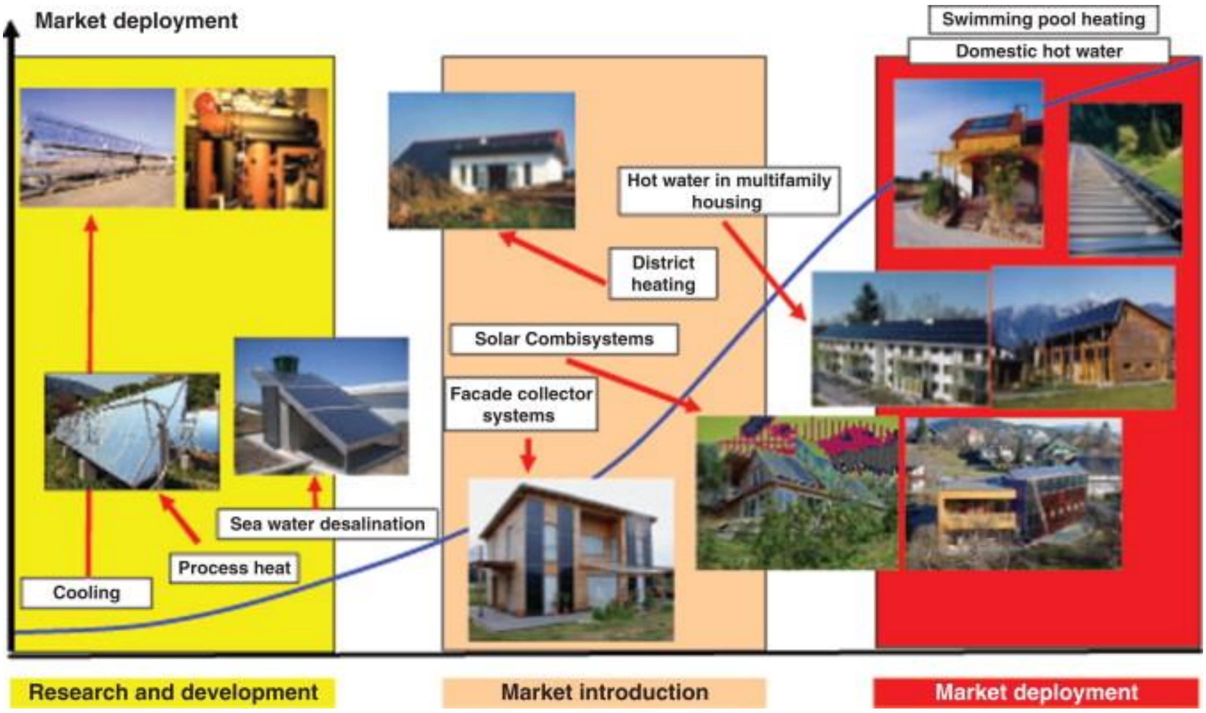

Fig. 4. Illustrates the market development from solar thermal technologies.

- **Solar water heating**

Solar water heating is one of the most widely used water heating system worldwide. The solar water heater can convert solar energy into concentrated heat efficiently, with advantages of mature technology based, low risk on global warming and low life cycle cost. China is also the primary driver of demand for new solar thermal capacity, especially the market segment in multi-floor residences keeps increasing in past 3 years.

Solar hot water preparation in high-performance houses is sensible. In such houses, the energy needed to heat domestic water can equal or even exceed the energy needed for space heating, since the latter has been so far reduced by insulation and heat recovery. In Europe, about 50% of the new detached and row houses and about 15% of apartment houses are designed on this concept.

Further, demand for heating domestic water is a 12-month energy demand, including the high insulation during the summer months. Using a solar system is therefore an effective way to reduce the total primary energy demand. Increasingly, the market for solar water heating systems also includes systems that provide, in addition to hot water preparation, space heating in winter, called “Solar Comb systems”.

For hot water heating in transition countries, such as China and India, and also in countries without space heating systems, direct electricity is used. Large amount of electricity is necessary to meet the hot water requirements in domestic, institutional, and commercial sectors resulting in peak load and load shedding to the shortage of power supply. With solar hot water systems, the electricity demand as well as the peak load can be reduced remarkably (Fig. 5).

Fig. 5. Solar hot water systems to replace electricity demand and to reduce peak load.

(1) Passive water heating system

Solar water heating system usually consists of solar collector, water tank, work fluid and circulation pipelines. Based on the driven forces to realize the circulation of working fluid within the system, solar water heating systems are divided into two categories: passive and active systems. For passive system, the circulation of working fluid is realized by density difference and it is named as thermosyphon system. In such systems, working fluid is heated in the solar collector with increasing temperature and decreasing density, and then hotter working fluid automatically goes into the storage tank.

In order to solve the problems of high heat losses on back side of solar collector and to reduce required space for many components, integrated collector storage solar water heating system is developed. In such systems, a single unit functions as both absorber and storage, both collector and storage tank are utilized to collect solar radiation. However it suffers from heavy heat losses, especially during cloudy hours.

(2) Active water heating system

Contrarily, active system adopts a pump to drive the operation of working fluid from tank to solar collector, and direct system which adopts water as working fluid in solar collector is the conventional type. All-glass vacuum tube collectors are widely adopted in direct circulation system. Meanwhile in the past few decades, majority of vacuum tube collectors were used for domestic water heating purposes. Investigations on direct active water heating system mainly concentrate on improving collecting efficiency by optimal solar collector design and testing practical system performance under different climatic conditions [2, 3].

Indirect active water heating system utilizes two loops to realize heating, one is collector loop and another is water tank loop. Water, refrigerants, and anti-freeze mixtures can be adopted in closed loop. Solar heat collected by these working fluids is transferred to water by a heat exchanger.

- **Solar space heating**

(1) Passive solar space heating system

Passive solar space heating is realized primarily based on building or component design with no solar collector. This concept has been proposed since 1986s and Trombe wall is widely recognized as the first example. Chan et al. [4] concluded the development of passive solar space heating including solar wall, solar chemistry, solar façade and solar roof are the main types of such systems. It can be seen that pass solar space heating system is realized by cooperating with civil design. Meanwhile the heating effect is still limited.

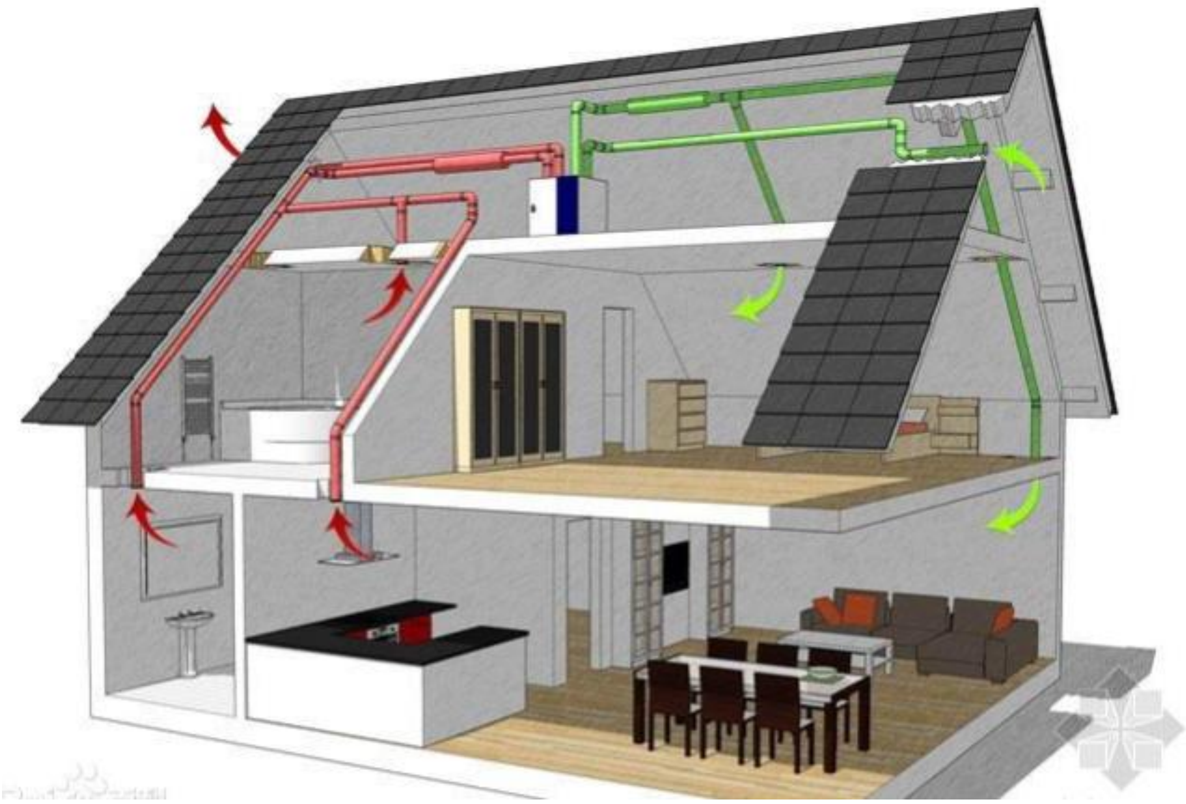

Fig. 6. Passive solar space heating system

(2) Active solar space heating system

Active solar space heating system uses solar air collector to produce hot air or solar water collector to heat up indoor air indirectly. Compared with solar water heating system for domestic hot water alone, the thermal demand of space heating requires significantly larger area of solar collector. Consequently, how to integrate large areas of solar collectors into the building envelop becomes the major research work.

Roof integration is the most common way of solar collector integration, as shown in Fig.4. Roof always has an inclination angle which naturally provides the required installation angel for solar collector. However, for roof-integrated collector, the wind force has to be taken into account when designing and installing the supporting structure, and distance between two rows of collectors on flat-roof needs to be calculated to prevent one row of collectors shading against another. Balcony integration is another usual way, especially for high-rise residential buildings without enough roof space. Existing examples already prove the satisfied performance and significant economic benefit. For buildings with awnings, since the structure of the solar collector is water-proofing, it is also an alternative to the conventional awning, as shown in Fig.7. Besides, façade collector mounted directly to the wall is also a potential way of solar collector integration. Taken as s part of the outer shell of the building, the solar collector can improve heat insulation and weather protection for the facade.

Fig. 7. (a) Roof (b) Balcony (c) Awning (d) Wall [4] integration of solar collectors.

2. Solar cooling

Solar energy can not only be directly adopted in heating but also utilized to produce cooling power. Compared with solar heating system, the solar irradiation energy has better fit with the required cooling power in cooling system. For instance more cooling power is required when solar energy is abundant at outdoor. Both solar thermal energy and electricity produced by solar PV can be used to power different cooling system. It should be noted during the season when air condition is not required, heat or electricity produced by the collector or PV can be adopted to supply hot water or to power other electric equipment.

- **Solar thermal cooling**

Solar thermal energy is transferred to cooling power operating on adsorption/absorption principle with use of different adsorption/sorption working pair. Cooling power is produced by evaporation refrigeration of working substance under relatively low pressure, and solar thermal energy is adopted to realize regeneration of adsorbent/sorbent. Schematic figure of solar thermal cooling technology is plotted in Fig. 8.

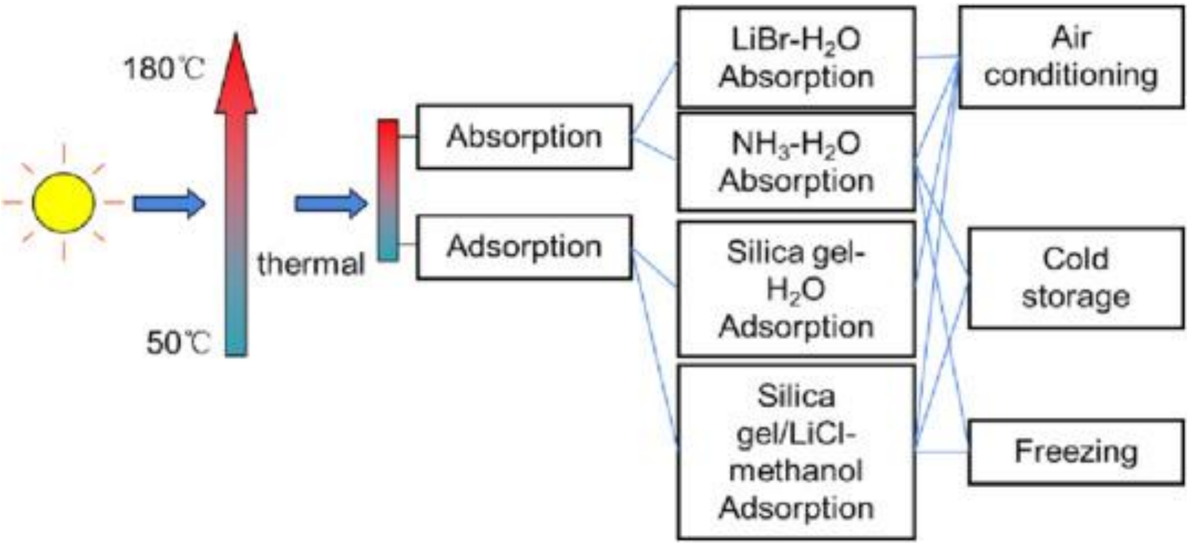

Fig. 8. Schematic figure of solar thermal cooling technology

- **Solar PV cooling**

It is called solar PV cooling when electricity produced by photovoltaic (PV) system is used to power a conventional vapour compression refrigeration cycle, which has been proposed for several decades. Solar PV cooling was limited by low PV efficiency and high initial investment and its application has been ignored until recent years. Because of the sharp fall down of PV module price, the initial investment of PV air conditioner (PVAC) decreased as well, advantages of PVAC stand out among different kinds of solar cooling and more attention has been paid to PVAC. Some experimental results and practical data proved that PVAC has the merits of high performance, electricity saving, stable and reliable operation. Considering both the massive cooling market and the potential PV market, PVAC is likely to attract more and more attention in future.

Fig. 9. PV air conditioner

In theory, all vapor compression air conditioners powered by electricity can be modified into PVACs, and there exist several different criteria to categorize PVAC. For example, according to different categories of air conditioners, PVAC can be divided into different types to meet different demands including small PVAC for room (e.g., split room PVAC), small central PVAC (e.g., variable refrigerant flow PVAC), and large central PVAC for commercial use (e.g., centrifugal PV chiller). However if based on PV connection with the grid, the PVAC can be divided into two types: the stand-alone (or off-grid) and the grid-connected PVAC. The stand-alone PVAC is powered only by PV system with a set of batteries. It is very suitable for remote villages where the grid is not available. The grid-connected PVAC is connected with the grid and powered by both the PV system and the grid. For grid-connected PVAC, the grid acts as backup. The residual power from PV system can be sent to the grid when the PV power is more than what unit needs, and also the power can be drawn from the grid to meet the gap when the PV power is less than. Also according to the direct current (DC) or alternating current (AC) which is used to power the air conditioner, the PVAC can be divided into two types: DC driven PVAC and AC driven PVAC. AC driven PVAC can be built based on the common air conditioner by adding the PV system, control system and an inverter [5]. However, DC driven PVAC is designed to utilize the DC electricity directly generated by PV system without the converting process from DC to AC. Thus the system is simplified and energy efficiency is improved.

The DC driven PVAC is commercialized recently by some companies in China and has been applied in many cases. The Gree PV direct-driven inverter centrifugal chiller as shown in Fig. 7[6] is used as example. During the cooling season from May to October, the monthly energy generation and power consumption are tested. It is found that the total energy generation is 179MWh, which is 26.95% higher than the total energy consumption (141MWh), meaning the system provides “free” cooling for the building.

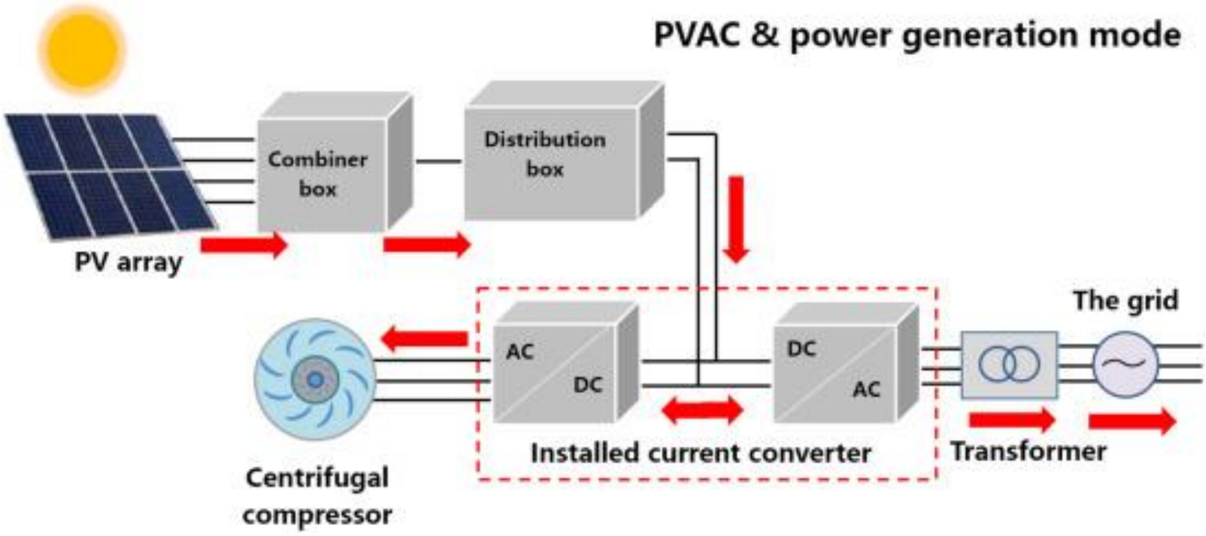

Fig. 10. PVAC works in the PVAC & power consumption mode [6].

Since the electricity price of large scale commercial building is much higher than domestic one, it is relatively more economically beneficial to install PV panel in commercial building with better future. It is suggested that following developments are necessary to complete. First the stable and efficient energy control strategies for PVAC are essential to realize its complex functions and improve energy efficiency. The PV power generation is changing fast due to the transient characteristics of solar radiation, and the power drawing from the grid or feeding in to the grid varies greatly. The corresponding control strategy is required to manage this process and to keep the energy in dynamic balance. Besides to obtain the maximum economic benefit, the control strategy is needed to determine that the PV power is consumed only by PVAC or is sent to the grid according to the electricity price variation. Also air conditioner is the main energy-consuming equipment in buildings. Smart control strategy should be able to record and analyze the energy consumption in buildings and then helps make more energy-saving decisions. Then subsidy policy for PVAC should be carried out. Most part of the PV power is directly utilized within the PVAC and thus cannot be sold to the grid at a high price, which is different from PV power station. So the subsidy policy for PVAC should be designed to make sure that the PV system in PVAC can get the same subsidy as PV power station. Last but not least, software to design and optimize PVAC is important for its widespread applications. It should also be able to demonstrate the power generation and consumption conditions, the PV pay-back time and system efficiency.

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Session III: photovoltaic–thermal (PV/T) systems

This chapter mainly refers to the relevant literatures published by Tripanagnostopoulos Y, Tyagi V V,Hasan M A,Battisti R, etc., and we sincerely thank the relevant authors for their efforts in PV/T systems research.

1. Introduction on photovoltaic–thermal (PV/T) systems

A PV–thermal (PV/T) collector is a module in which the PV is not only producing electricity but also serves as a thermal absorber. In this way both heat and power are produced simultaneously [1]. The dual functions of the PV/T result in a higher overall solar conversion rate than that of solely PV or solar collector, and thus enable a more effective use of solar energy. Since the demand for solar heat and solar electricity are often supplementary, it seems to be a logical idea to develop a device that can comply with both demands. Photovoltaic (PV) cells utilize a fraction of the incident solar radiation to produce electricity and the remaining is turned mainly into waste heat in the cells and substrate raising the temperature of PV as a result, the efficiency of the module decreased. The photovoltaic thermal (PV/T) technology recovers part of this heat and uses it for practical applications.

The simultaneous cooling of the PV module maintains electrical efficiency at satisfactory level and thus the PV/T collector offers a better way of utilizing solar energy with higher overall efficiency. There are alternative approaches in PV/T integration. Among many others, there can be selections among air, water or evaporative collectors, monocrystalline/polycrystalline/amorphous silicon (c-Si/pc-Si/a-Si) or thin-film solar cells, flat-plate or concentrator types, glazed or unglazed panels, natural or forced fluid flow, standalone or building-integrated features, etc. A major research and development work on the PV/T technology has been conducted in the past few years with a gradual increase in the level of activities.

The attractive features of the PV/T system are [2]:

- It is dual-purpose: the same system can be used to produce electricity and heat output.
- It is efficient and flexible: the combined efficiency is always higher than using two independent systems and is especially attractive in building integrated PV (BIPV) when roof-panel spacing is limited.
- It has a wide application: the heat output can be used both for heating and cooling (desiccant cooling) applications depending on the season and practically being suitable for domestic applications.

2. Categorization of PV/T Collectors

PV/T solar energy systems can be divided into three systems according to their operating temperature: low- (up to about 50 °C), medium- (up to about 80 °C), and high-temperature (>80 °C) systems. The hybrid PV/T systems that are referred to applications of very low temperatures (30−40°C) are associated with air or water preheating and are considered the most promising PV/T category.

The PV/T systems that use typical PV modules and provide heat above 80 °C have lamination problems due to the high operating temperatures and need further development. In PV/T systems, although electrical and thermal output is high if operated at low temperatures, the main aim is to provide heat at a considerable fluid temperature to be useful for practical applications, also keeping the electrical output at a satisfactory level. The electrical and thermal output, although is of different value, could be added in order to give a figure of the hybrid system total (electrical and thermal) energy output, and new devices are in development toward cost-effective and of low environmental impact solar energy conversion systems. The flat-type PV/T solar systems can be effectively used in the domestic and in the industrial sectors, mainly for preheating water or air. Hybrid PV/T systems can be applied mainly in buildings for the production of electricity and heat and are suitable for PV applications under high values of solar radiation and ambient temperature. In Figure 11[3], the two basic forms of PV/T collectors, with and without additional glazing, are shown. In these devices, water or air is circulated in thermal contact with the PV, exchanging heat. When air is used, the contact with PV panels is direct, while in the case of using liquids, the contact is made through a heat exchanger. The water-cooled PV modules (PV/T-water systems) are suitable for water heating, space heating, and other applications (Figures 11(a) and 11(b)). Air-cooled PV modules (PV/T-air systems) can be integrated on building roofs and facades, and apart from the electrical load, they can cover building heating and air ventilation needs (Figures 11(c) and 11(d)). PV/T solar collectors integrated on building roofs and facades can replace separate installation of thermal collectors and PVs, resulting in cost-effective application of solar energy systems. To increase system operating temperature, an additional glazing is used (Figures 11(b) and 11(d)), but this results in a decrease of the PV module electrical output because an amount of the incoming solar radiation is absorbed and another part is reflected away, depending on the angle of incidence. These new solar devices can be mainly used for residential buildings, hotels, hospitals, and other buildings; to cover agricultural and industrial energy demand; and also to simultaneously provide electricity and heat in several other sectors.

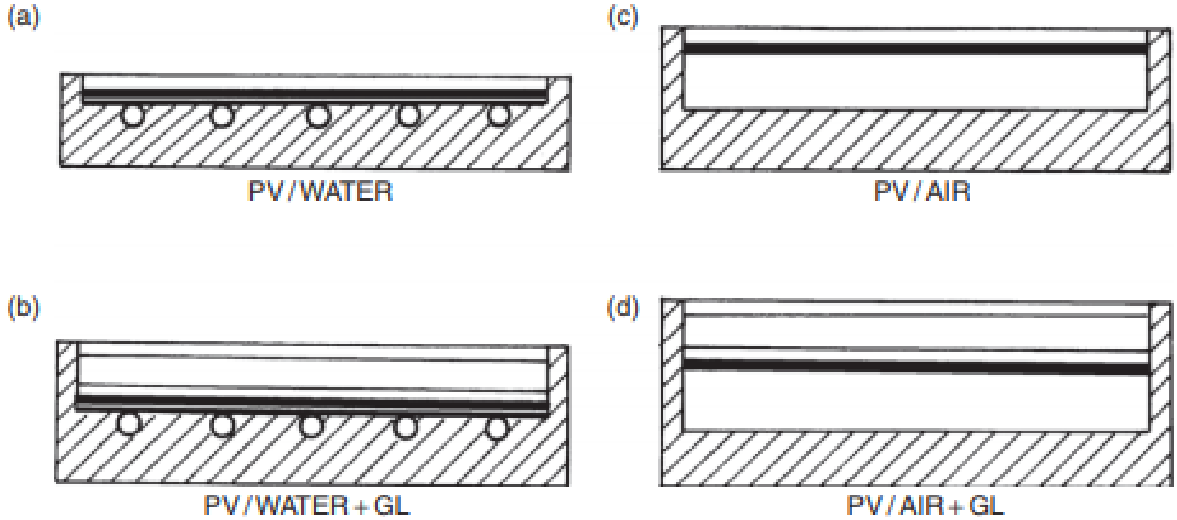

Fig. 11 Cross-section of PV/T experimental models for water and air heating

In PV/T system applications, the production of electricity is of priority; therefore, it is necessary to operate the PV modules at low temperatures in order to keep PV cell electrical efficiency at a sufficient level. This requirement limits the effective operation range of the PV/T unit to low temperatures; thus, the extracted heat can be used mainly for low-temperature applications such as space heating, water or air preheating, and natural ventilation in buildings. Water-cooled PV/T systems are practical systems for water heating in domestic buildings but their application is limited up to now. Air-cooled PV modules have been applied to buildings, integrated usually on their southern inclined roofs or facades. In PV/T systems, the electrical output from PV modules can be increased contributing to building space heating during winter and ventilation during summer, thus avoiding building overheating. PV/T-water systems are promising solar energy systems and they are under development to become cost-effective for commercial applications. Some new systems have been introduced in the market, but with limited use so far.

Natural or forced air circulation is a simple and low-cost way to remove heat from PV modules, but it is less effective at low latitudes where ambient air temperature is over 20 °C for many months during the year. In BIPV applications, unless special precautions are taken, the increase of PV module temperature can result in the reduction of PV efficiency and the increase of undesirable heat transfer to the building, mainly during summer. In air-cooled hybrid PV/T systems, the air channel is usually mounted at the rear of the PV module. Air of lower temperature than that of the PV modules, usually ambient air, is circulating in the channel, and PV cooling as well as thermal energy collection can be achieved. In this way, the PV electrical efficiency is kept at a sufficient level and the collected thermal energy can be used for the building′s thermal needs. Regarding water heat extraction, the water can circulate through pipes in contact with a flat sheet placed in thermal contact with the PV module′s rear surface. In PV/T systems, the thermal unit for air or water heat extraction, the necessary fan or pump, and the external ducts or pipes for fluid circulation constitute the complete system.

Hybrid PV/T systems can be applied, apart from the building sector, to the industrial and agricultural sectors, as high quantities of electricity and heat are needed to cover the energy demand of production procedures. In most industrial processes, electricity for the operation of motors and other machines and heat for water, air, or other fluid heating and for physical or chemical processes is necessary; this makes hybrid PV/T systems promising devices for an extended use in this field adapting several industrial applications (such as washing, cleaning, pasteurizing, sterilizing, drying, boiling, distillation, polymerization, etc.). In the agricultural sector, typical forms or new designs of PV/T collectors can be used as transparent cover of greenhouses and applied for drying and desalination processes, providing the required heat and electricity. The combination of solar radiation concentration devices with PV modules is a viable method to reduce system cost, replacing the expensive cells with a cheaper solar radiation concentrating system. Besides, concentrating photovoltaics (CPVs) present higher efficiency than the typical ones, but this can be achieved in an effective way by keeping PV module temperature as low as possible. The concentrating solar systems use reflective (mirrors) and refractive (lenses) optical devices and are characterized by their concentration ratio C or CR. The CPVT solar system consists of a simple reflector, properly combined with the PV/T collectors; tracking flat reflectors; parabolic trough reflectors; Fresnel lenses; and dish-type reflectors. In CPVT systems with medium or high CR values, the system operation at higher temperatures makes the application field wider, but requires PV modules that suffer temperatures up to about 150 °C, as it is possible to produce steam or achieve higher temperatures by the heat extraction fluid.

Apart from the individual use of hybrid PV/T systems, they can also be applied to buildings combined with other renewable energy sources, such as geothermal, biomass, or wind energy. When geothermal energy is used for space heating and cooling of residential, office, and industrial buildings, shallow ground installations of heat exchangers are applied combined with heat pumps (HPs). In these installations, the PVs can provide the necessary electricity for the operation of the HPs, while the thermal units of the PV/T system can boost the extracted heat from the ground. In the case of using biomass, PV/T collectors can be used to preheat the water and store it in a hot water storage tank, while the main heating is performed by the biomass boiler. In combination with PVs, small wind turbines can provide electricity. PV/T systems can effectively replace typical PV modules and new concepts are rising, with the supplementary operation, in some applications, of solar energy and wind energy subsystems.

Life-cycle assessment (LCA) methodology and cost analysis for typical PV and PV/T systems can give an idea for the environmental impact and the practical use of these systems. These analyses should consider the materials used and the application aspects, and as PV/T collectors substitute both electricity and heat, calculations confirm their environmental advantage compared with standard PV modules. Regarding PV/T system applications, modeling tools (such as TRNSYS methodology and others) can be used to get a clear idea about practical aspects, including their cost-effectiveness.

3. Application Aspects of PV/T Collectors

The operating temperature of a PV/T collector affects the electrical power output of the PV module, and for maximum electrical production, the PV/T collector should operate at low temperature as much as possible under the prevailing weather conditions of solar radiation, ambient temperature, and wind speed. This can be achieved by circulating a fluid much colder than the PV module with proper flow rate, but this would result in a low temperature rise of the fluid, hence low thermal output. Thus, a PV/T system desired for electrical power production results in lower outlet temperatures of the fluid that are useful for low-temperature applications such as space heating (air) or water preheating for domestic or industrial use and swimming pool heating. The operation at higher temperatures is more useful for thermal applications requiring medium temperatures around 55 °C such as the solar domestic hot water (SDHW) systems. The use of PV/T systems with additional glazing is interesting mainly for the increase of system thermal output, because the PV electrical efficiency is reduced.

The intensity of solar radiation on PV module surface affects the rise of PV temperature. Considering the integration of PV/T systems on building facades, the modules are usually in a vertical position and the incoming solar radiation is reduced, mainly in low latitude countries, as the angle of incidence is large in most days of the year. During summer the sun′s altitude is high, resulting in lower intensity on the module plane, also mainly in low latitude countries. In tilted installed PV/T collectors on buildings or in parallel rows on the horizontal building roof, the solar input is higher and this results in higher PV module temperature. The performance of PV/T-air systems depends on air channel depth, system tilt, airflow mode, and flow rate. The air channel depth affects the air heat extraction and the thermal efficiency is increased for smaller depth, but the pressure drop must also be taken into consideration for the determination of the additional electrical power input from the fan.

The reduction of temperature has a positive effect on the electricity output but it affects the practical value of cells to be used as thermal absorbers because the low temperature is of lower value for the thermal applications. PV/T collectors are efficient and therefore useful, mainly for lower-temperature applications, such as for water or air preheating in low temperatures (30-40 °C). In other applications, the building integration of PV/T collectors is practical when the available external surface area of building facade and roof is not enough for the installation of a considerable number of solar thermal collectors and PV modules (in number or in square meter). This requirement is obvious often in multiflat residential buildings, in hotels, athletic centers, and so on, where the thermal and electrical demand is high and the available installation surface area is small. In these cases, the PV/T collectors are more useful than separate thermal collectors and PV modules and it is the main application that could be considered as cost-effective. Another useful application of PV/T collectors, considering mainly PV/T-air collectors, is their use for space heating during winter and space cooling (by enhancing the air ventilation) during summer. In these applications, when these solar devices (the PV/T collectors) are directly mounted on a building facade or inclined roof, the building overheating from the transmitted heat by PV modules can also be avoided.

Industry is the sector responsible for the consumption of about one-third of total energy demand in most developed countries. PV/T collectors can significantly contribute to this load, as both electricity and heat are necessary in most industrial processes. Industrial buildings usually have large available surfaces suitable for the installation of solar thermal collectors of PVs and hybrid PV/T collectors. The application of solar energy systems in industry is still at low installation level, because the cost of conventional energy sources (e.g., oil, gas, electricity) is still kept low. The technological improvements and the rise of conventional energy cost would result in a wider application of solar energy systems, assisted also by other renewable energies such as geothermal and biomass and this penetration will contribute to the saving of conventional energy sources and environmental protection. PV/T collectors could play an important role to this as industry has a high ratio of low-temperature heat demand, and even if the collectors provide preheated fluid, it is very useful for the final energy contribution of solar energy systems. Flat-type PV/T collectors can contribute to warm water and air, while in the case of CPVT collectors, the demand in higher temperatures (such as cooling, steam for heating, or other processes) can also be covered. A similar situation is also in the use of PV/T collectors in agricultural applications. Solar drying and desalination processes can be adapted well with PV/T collectors and is a promising technology for the future. The first work on industrial applications of PV/T collectors refers to the application for water and air heating [4]. Later, a study using TRNSYS calculations [5] shows the interesting results from the use of PV/T collectors in the industrial processes.

4. Application of PV/T Collectors

● PV/T collectors in the built environment

In new buildings or retrofitting, the emphasis is addressed to the effective use of passive and active solar energy systems to partial or entire adaptation of the demand for natural lighting, space heating and cooling, air ventilating, domestic hot water, and electricity. The facades and the horizontal or inclined roofs of buildings constitute appropriate surfaces for an expanded use of solar thermal collectors (STC) and PVs, and their effective integration should be adapted in a harmonic way to the building architecture. The several types and forms of STC and PV constitute new and interesting systems, which can be easily integrated to the buildings, giving new shapes and a symbol of the ecological concept. It is also a new material in the architect′s hands, ready to be shaped and create alternative buildings. The emerging concerns for environmental protection and global energy saving have introduced new architectural design rules, aiming at buildings of reduced energy consumption with effective integration of solar energy systems in combination with satisfactory esthetics. Solar energy systems are installed on the roof or the facade of buildings to cover hot water and space heating/cooling needs and provide electricity for lighting, operation of electric devices, and so on. The application of STC and PV is actually useful and efficient, considering the total energy consumption of buildings. Apart from the typical form of solar energy conversion systems, the new devices, the hybrid PV/T collectors, can play a significant role.

In PV/T collectors, the reduction of temperature has a positive effect to the electricity output but it affects the practical value of cells to be used as thermal absorbers because the low temperature is of less value for thermal applications. PV/T collectors are efficient mainly for lower-temperature applications such as water or air preheating (30-40 °C). Building integration of PV/T collectors is considered practical when the available external surface area of building facade and roof is not enough for the installation of a considerable number of solar thermal collectors and PV modules. In multiclass residential buildings, hotels, athletic centres, and other buildings, the thermal and electrical demand is high and the available installation surface area is small; thus, PV/T collectors are more practical than separate thermal collectors and PV modules. Another useful application of PV/T collectors, mainly of the PV/T-air collectors, is for space heating during winter and space cooling (by enhancing the air ventilation), during summer. In these applications, when these solar devices are directly mounted on a building facade or inclined roof, the building overheating from the heat that is provided by PV modules can also be avoided.

In BIPV applications on facade and inclined roof, the rear surface of PV modules is thermally protected from back thermal losses and cell temperature rise resulting in electrical efficiency reduction. In addition, heat from PV modules is transmitted to the building, mainly during summer. In this case, the building temperature rises above the acceptable comfort level and more electrical energy is needed to cover the increased load of the air-conditioning system to reject this undesirable heat out to the ambient and to cool the building. In higher latitude applications, this effect is less significant, as building needs for space heating is almost all year and ambient air temperature is not high enough during summer to demand building cooling. To avoid overheating, apart from increased wall thermal insulation, another mode is to use hybrid PV/T solar systems, which can extract the surplus heat and contribute to building energy needs. PV/T systems are appropriate for installation in buildings with both thermal and electricity needs. They can be placed on their facade and roof, and one type of solar module (in form and color) can be used instead of separate PV panels and solar thermal collectors, in side-by-side installation, aiming to a practical utilization of the available surface of the building.

Horizontal and tilted roof installations are more practical at low latitudes, while building facade and high tilted roof installations are more effective for medium and high latitude applications because of the lower sun altitude angles. In facade and tilted roof-integrated PV/T systems, the additional back thermal protection increases the thermal efficiency of the system, but the lower thermal losses keep PV temperature at a higher level, therefore they are operating with reduced electrical efficiency.

Considering the BIPV and PV/T systems, there are some operational and architectural aspects. In PV/T systems, the cost of the thermal unit is the same, irrespective of the PV module construction, whether with c-Si, pc-Si, or a-Si type of cells. Thus, the ratio of the additional cost of the mounted thermal unit per PV module area cost is different and is almost double in case of using a-Si compared with c-Si or pc-Si PV modules. The complete PV/T systems include the necessary additional components (BOS for the electricity and the BOS hydraulic system for the heat) and therefore the final energy output is reduced due to the electrical and thermal losses from one part to the other. Considering the installation of solar energy systems on building roofs or facades, the combination of PV/T collectors with solar thermal systems have some esthetic problems due to the different size and appearance. The problem can be overcome if there is a harmony in size and if the color of solar thermal collector absorber adapts esthetically with the color of PV cells.

A combined system suitable for application on building atria is the Fresnel lenses with linear PV/T absorbers, which apart from electricity and heat production, the system can operate as transparent material that controls the lighting and temperature of building interior spaces [6, 7]. In addition, stationary symmetric or asymmetric CPC reflectors can be effectively combined with linear strip-type PV modules and flat thermal absorbers, resulting in novel PV/T systems [6, 8]. Low-concentration solar energy configurations have been investigated and studied regarding the effect of the concentrator geometry to the PV electrical output. Flat diffuse reflectors provide an almost uniform distribution of the solar radiation on PV surface, linear Fresnel lenses additionally achieve solar control of interior spaces, and CPC reflectors effectively combine PV strips with flat solar thermal absorbers. These new concentrating collectors can be integrated on buildings being adapted with their architecture and contributing to their energy and esthetic requirements. Based on the investigated CPV and CPVT systems, some new architectural designs have been suggested [8], giving a better idea about their esthetic integration in the building structure.

- **PV/T Collectors in Industry and Agriculture**

Hybrid PV/T systems can be applied, apart from the built sector, to the industrial and agricultural sectors, as high quantities of electricity and heat are also needed to cover the energy demand of production processes. In most industrial processes, electricity for the operation of motors and other machines and heat for water, air, or other fluid temperature rise and for physical or chemical processes is necessary; this makes hybrid PV/T systems promising devices for extended use in this field adapting several industrial applications (such as washing, cleaning, pasteurizing, sterilizing, drying, boiling, distillation, polymerization, etc.). The most suitable use of PV/T systems is the application that needs heat in medium (60–80 °C) and mainly in low (< 50 °C) temperatures, as both the electrical and the thermal efficiency of the PV/T system can be kept at an acceptable level. The fraction of heat demand at low temperatures is high, especially in food, wine, beer, beverage, paper, and textile industries. In these industrial processes, the heat demand could be up to 80% of the overall thermal energy needs in these sectors. Although solar energy can adapt to the energy requirements of the industrial processes, the penetration of solar thermal systems in industry is very low considering the total industrial heat demand. In many industries, the thermal load is so high that there is no need for storage of solar energy; thus, the PV/T systems are of lower cost. Most solar applications for industrial processes that use thermal collectors have been on a relatively small scale, are mostly experimental in nature, and only a few large systems are in use worldwide. The PV/T plants could be installed on the ground or on either flat or sawtooth roofs or on facades. PV/T-water systems could heat up water for washing or cleaning processes and PV/T-air systems could provide hot air for drying processes in food, beverage, or textile industries. Regarding electricity, PV modules are also applied to few industrial buildings, although large surfaces are available for their installation. Among the few publications for the industrial applications of PV/T collectors, a study on the possible use of PV/T collectors is given by Battisti and Tripanagnostopoulos [4] and a TRNSYS analysis for the application to three different locations by Kalogirou and Tripanagnostopoulos [5]. Referring to the agricultural sector, PV/T collectors can be applied to greenhouses, for drying, and also for desalination processes, providing the required heat and electricity.

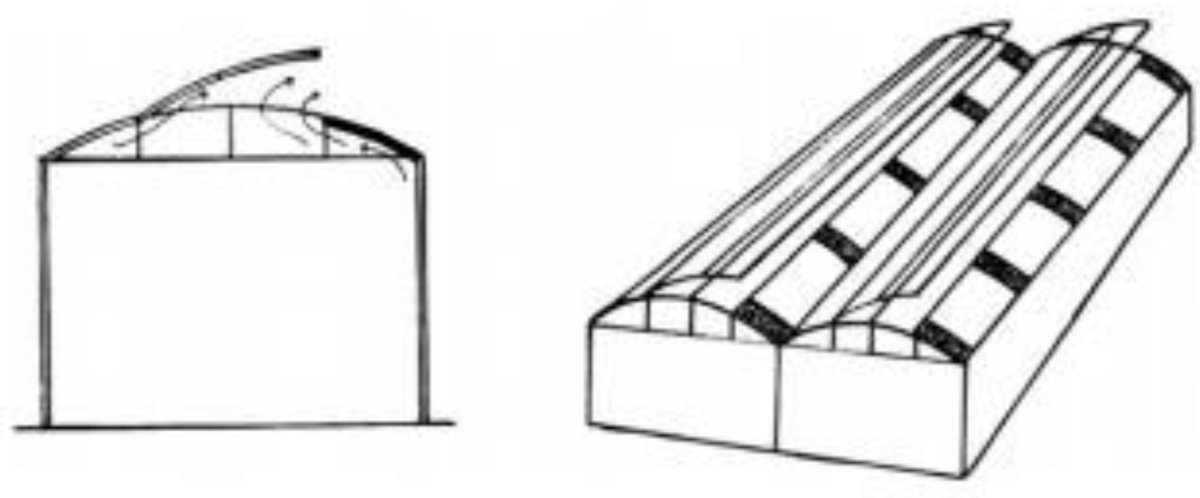

Fig. 12 Integration of PV/T collectors on greenhouse roof [9]

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Session IV: Solar-assisted heat pump (SAHP) system

The solar-assisted heat pump (SAHP) system which is an integration of heat pump and solar collector, can utilize solar energy as heat source to achieve high coefficient of performance (COP) [1]. According to the connecting mode of solar collector and evaporator, solar-assisted heat pump can be classified as: the indirect expansion solar-assisted heat pump and the direct expansion solar-assisted heat pump [2]. The concept of SAHP was first proposed by Sporn et al. [3]. Since then, numerous theoretical and experimental studies on the SAHP systems have been conducted by various investigators. Utilisation of solar energy as a free and renewable energy source is the way forward in research and development of SAHP. It has various advantages including low carbon emission, utilisation of waste heat, raising the temperature significantly by compression and versatility for variety of applications.

Having a look into the future trends of SAHP technologies, it is likely to recognise growing demands for improved energy efficiency, reduced impact on environment and better utilisation of renewable energy sources at lower total cost.

This chapter mainly refers to the relevant literatures published by PeterOmojaro,S.J.Sterling , Mahmut SamiBuker,JingyongCai et al, and we sincerely thank the relevant authors for their efforts in solar heating and cooling research.

1. Direct expansion solar assisted heat pumps

Direct expansion solar assisted heat pump systems have widely been used in solar drying, water heating, space heating, space air conditioning and cold storage applications. With the high potentials of its efficient heat retrieving unit to effectively use low temperature solar energy, the investigation of the heating and cooling applications of the system has advanced within the past decade. Also, large numbers of refrigerants with high potentials for use in direct expansion solar assisted heat pump have been explored. Investigation results have shown ways of evaluation and various factors determining the performance of the system. These investigations are necessary in order to extend design and performance knowledge and to improve the technology in general.

A direct expansion solar-assisted heat pump (DX-SAHP) sys- tem is a technique of particular interest because it converts and transport heat energy from the sun (source) to water or absorbers (sinks). In comparison with other solar assisted heat pump systems, it has the ability to transfer heat for storage purposes. Direct use of high and low solar intensity efficiently for heating and cooling is also possible. This is achieved through the direct heating and expansion of the flowing refrigerant in the integrated solar collector–evaporator. Through the collector–evaporator modification, a reduction in the number of system units, reduced collector set up cost requirements and higher collector efficiencies have been achieved.

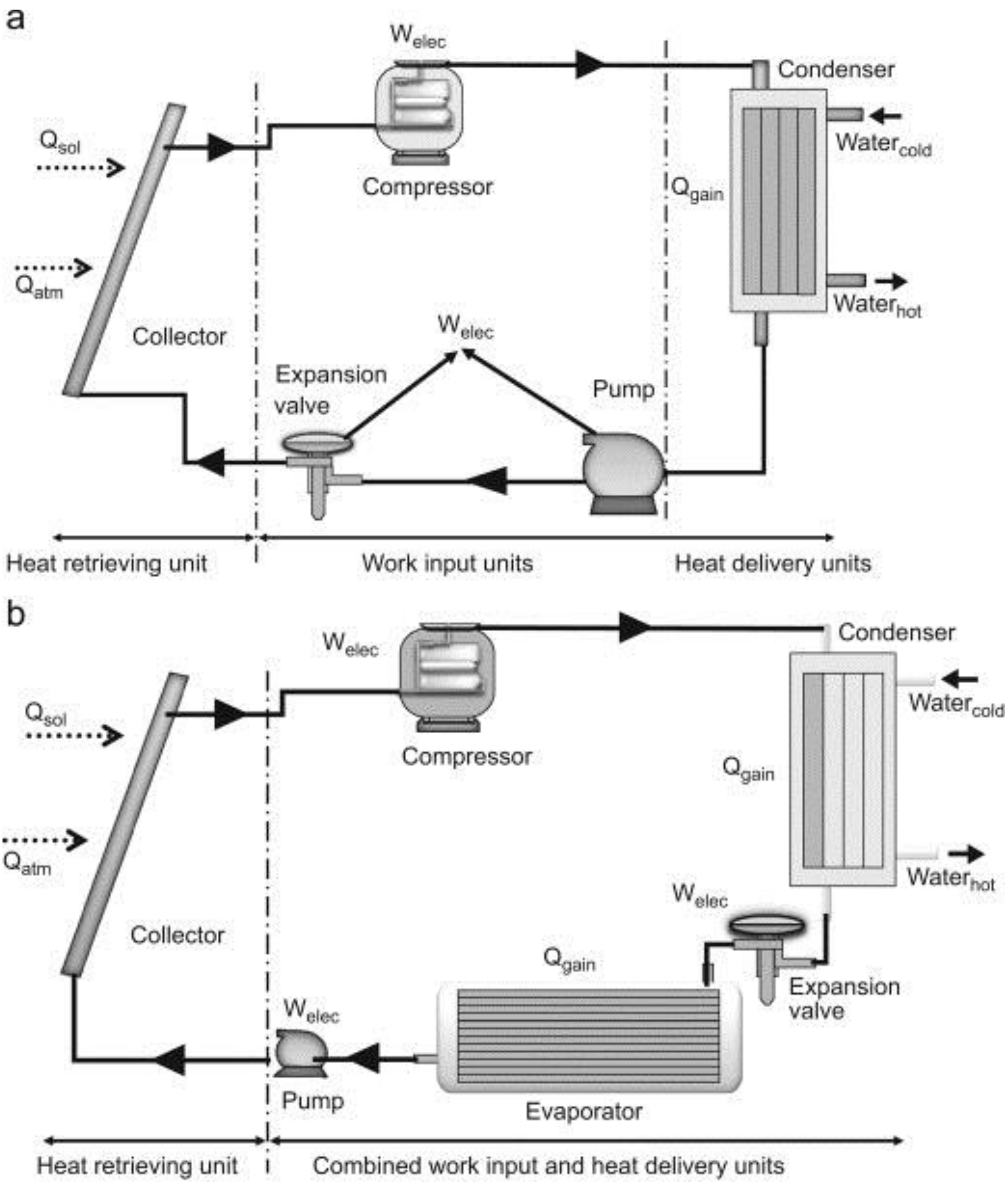


Fig. 13. Schematic view of a direct expansion solar assisted heat pump system, (a) heating and (b) cooling.

A schematic view of a direct expansion solar assisted heat pump is shown in Fig. 13(a) and (b). Fig. 13(a) depicts a DX-SAHP heating system comprising of three operation units namely, the heat retrieving unit, the work input unit and the heat delivery unit. It can be seen that both atmospheric heat and solar-radiated heat are harnessed by the collector–evaporator (heat retrieving unit). The compressor, the pump and the expansion valves are power consumption or work input units while, the heat gain is delivered at the conventional condenser side for heat exchange. Fig. 13(b) depicts the operation units of a DX-SAHP cooling system which includes the heat retrieving units and the combined work– heat delivery units. The heat retrieving unit remains as in Fig. 13(a) while, the work input and heat delivery units are interlocked because of the application objective. This makes it slightly different from the conventional set up as the operational units do not follow the same order as in Fig. 13(a). The cooling application set up is similar to the vapor compression cooling set up with the inclusion of the collector– evaporator. The advantage is the ability to use the ambient and available solar heat to replace or reduce the work input for heat retrieving and generation to and from the system.

- **Application of DX – SAHP system**

Day and Karayiannis [4] presented a comprehensive classification of solar assisted heat pump in their review of its research and development. They categorised DX-SAHP systems together with multi-source solar-assisted heat pump systems. They pointed out that its ability to source for heat used to expand flowing refrigerants from available ambient temperature together with/or in the absence of direct solar radiation allows it to be referred to as a dual source solar assisted heat pump system. The two major classification of DX-SAHP application is namely heating and cooling.

The potential of the system is shown in the operation pattern over the time of solar energy availability. During the consumption of the available solar energy through direct usage, a measured amount of storage can still be achieved. The heating and cooling demand could be met directly when the available energy is highest and the stored energy could be used to assist or provide for small consumption at low solar energy availability.

Most studies on DX-SAHP description have mainly focused on the benefit for all kinds of heating applications. Comparison of the application areas is depicted in Fig. 14 and shows that 75% of the literatures reviewed in this study have been attributed to DX-SAHP heating applications. It goes on to show it commercial viability for water, space and floor radiant heating. Thus, many heating demands are been met in domestic or household, hospitals, production industries and service establishment like hotels and restaurant. In this mode of application, it is obvious that DX-SAHP systems have recorded a high technical and commercial performance when compared with other forms of solar assisted heat pump systems.

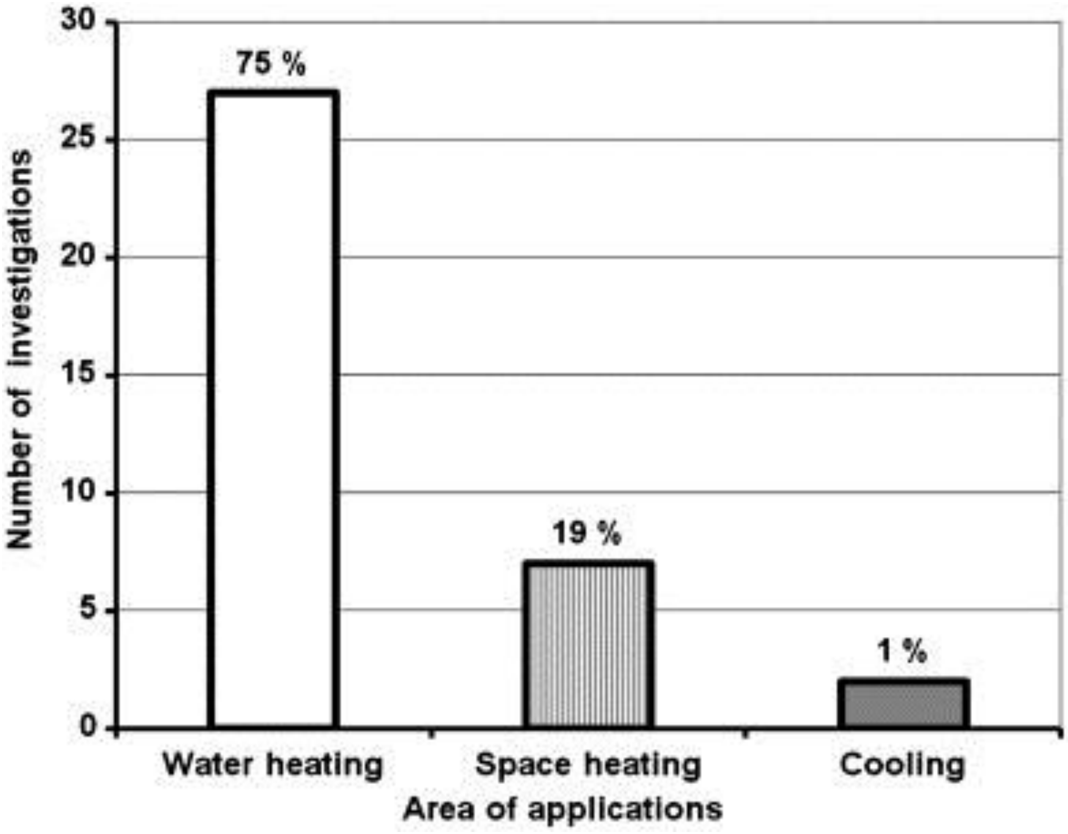


Fig. 14. Comparison distribution of DX-SAHP system application are a from literatures review.

- **Configurations of DX-SAHP systems**

Presently, there is no specified number of configuration modes agreed upon for DX-SAHP systems configurations because they all follow similar pattern of operations based on the application demand. For convenience and based on reported research works, this review divided the configurations into two main categories namely 'basic models' and 'advance models'.

- **Basic configuration models**

The basic model which is the most investigated model involves the heating and expanding of the liquid refrigerant to vapour in the collector–evaporator. It is further heated up and given off as a high pressured hot vapour by the compressor. The hot vapour refrigerant at high pressure is then transferred into the storage- heat exchanger medium for water heating purposes as well as space and floor heating purpose. This has been reported by a lot of researchers and is characterized by low cost and simple set up because of the less number of components needed for the set up. It is of importance to point out that heating purpose has been the major area of application for this mode of configuration. Figs. 1 is example of typical schematic views for many basic configurations.

- **Advance configuration models**

The advance model configurations follow the same operation pattern as the basic model but involve extra components or combining the system as a whole with other system. An experiment was performed by Kun and Wang [5] to investigate the performance of a multi-functional direct-expansion solar assisted heat pump system. It was set to operate at different operation mode for various weather conditions. The refrigerant-filled solar collector function was varied by reversing the refrigerant flow direction at the four-way valve to serve the different purposes. Gang et al. [6], integration involves combining the photovoltaic evaporator to a conventional air source evaporator such that, at low solar radiation and consequently low photovoltaic performance, the ambient air was maximized. Figs. 15 and 16 depict a two-stage direct expansion solar-assisted heat pump for high temperature applications using low and high pressure stage compressors [7] and a performance analysis of a proposed integrated solar-assisted heat pump water heater by [8].

Direct expansion solar-assisted heat pump (DX-SAHP) systems have been used for instance consumption and storage of solar energy during heating and cooling applications. The DX-SAHP heating application commercial viability was shown to be high and accounts for 75% of the research papers reviewed in this study. The collector–evaporator accounts for 31%, compressor for 29%, while, 21% and 19% represent the condenser and expansion valves, respectively from research studies. Also, large numbers of refrigerants with good usage potentials in direct expansion solar- assisted heat pump have been shown to exist.

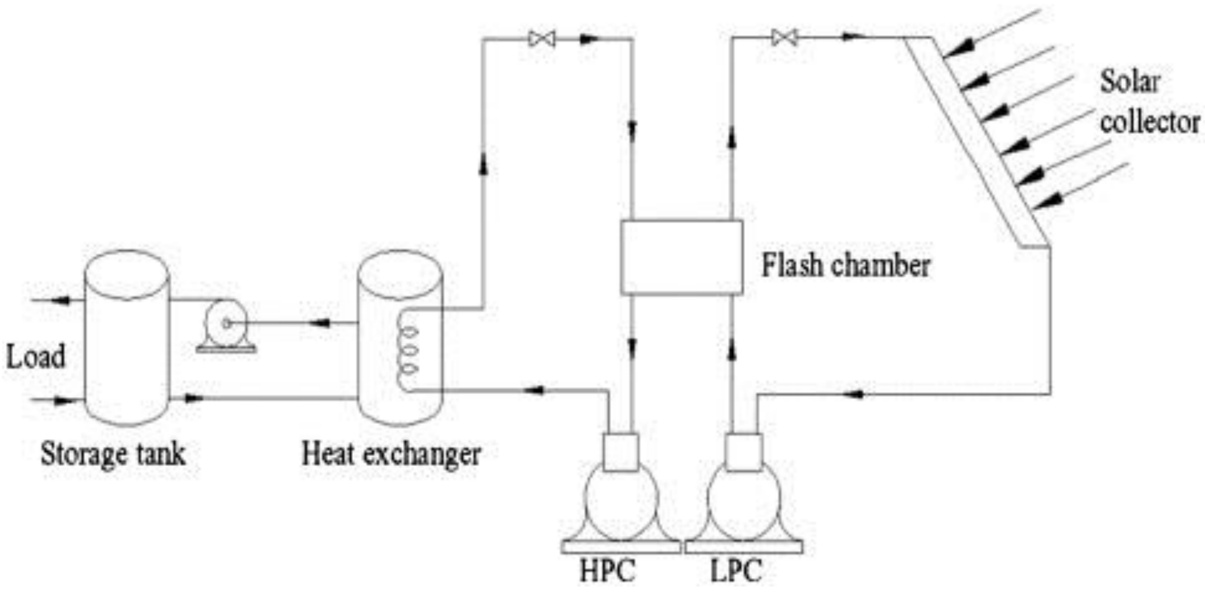


Fig. 15. Schematic view of the two-stage DX-SAHP system by Chaturvedietal [7]

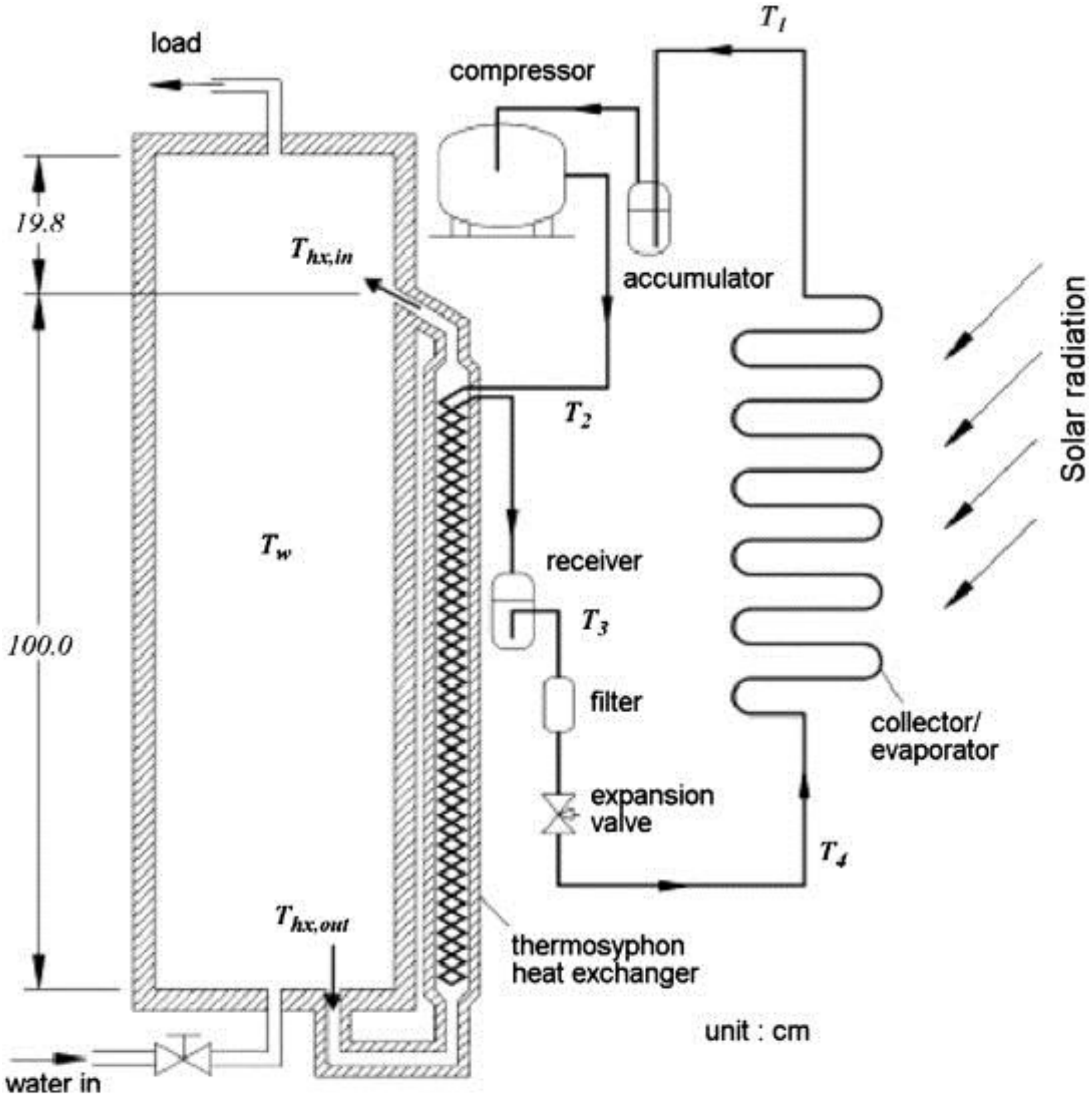


Fig. 16. Schematic view of the integral type DX-SAHP system by Chyng et al. [8]

2. Indirect expansion solar-assisted heat pump (IDX-SAHP)

Indirect expansion solar-assisted heat pump (IDX-SAHP) can be divided into series type, such as parallel type, parallel-series type, and dual heat source type according to the different combinations between solar energy and heat pump systems.

Izquierdo et al. [9] designed a parallel-type solar PV/T system that was directly heated by radiant floor, and heat pump would operate when solar irradiance was insufficient. Meanwhile, Kaygusuz and Ayhan [10] established an experimental set up of a parallel-series-type solar-heat pump system for residential heating, and they concluded that solar-only system was insufficient for heating whereas dual source system was optimal.

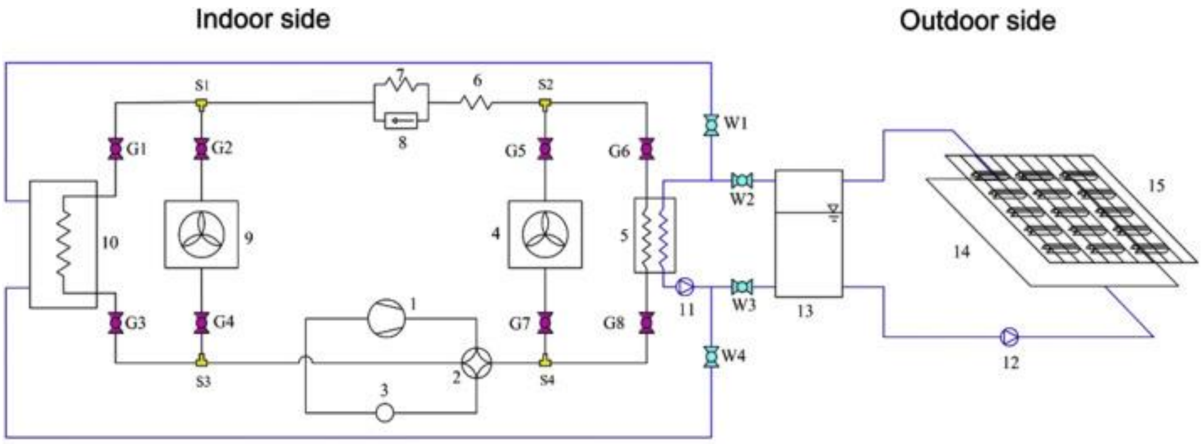
For parallel types IDX-SAHP systems, the solar energy system cannot improve the COP of the heat pump system because they are two independent systems. For series types IDX-SAHP systems, the heat pump system is heavily dependent on the solar energy system. For dual heat source types IDX-SAHP systems, it is difficult to design and fabricate the appropriate heat exchangers.

- **Indirect expansion solar-assisted multi-functional heat pump**

A novel indirect expansion solar-assisted multi-functional heat pump (IDX-SAMHP) system which composes of the multi-functional heat pump system and solar thermal collecting system is proposed and studied in this chapter. This system can fulfil space heating, space cooling and water heating with high energy efficiency by utilizing solar energy.

- **IDX-SAMHP experimental system**

The experimental system of IDX-SAMHP is shown in Fig. 17. The IDX-SAMHP system includes the solar thermal collecting system and multi-functional heat pump system. The solar thermal collecting system consists of two solar flat-plate collectors with an aperture area of 3.2 m^2, a solar water tank (300L), and a water pump. The multi-functional heat pump system is modified from a double effect air conditioner. And it composes of a compressor, a reversing valve, an outdoor air heat exchanger, an indoor air heat exchanger, a plate-type heat exchanger, a domestic water tank (200L), a capillary, a one-way valve, a liquid accumulator and a water pump. Compared with the traditional heat pump, the indoor and outdoor air heat exchangers of the IDX-SAMHP system are connected in parallel with the domestic water tank and the plate-type heat exchanger respectively. Six working modes can be realized by different combinations of the evaporator and condenser. The flow diagram of the different working modes of the IDX-SAMHP system is shown in our previous work. In solar water heating mode, the solar water tank acts as the heat source and exchanges heat with the refrigerant via the plate type heat exchanger. The domestic water tank working as the condenser absorbs heat from the refrigerant. In solar space heating mode, the indoor air heat exchanger serves as the condenser, and the plate-type heat exchanger works as the evaporator which is similar to the solar water heating mode.



(a)

(b)

1.compressor 2.reversing valve 3.liquid accumulator 4.outdoor air heat exchanger 5.plate-type heat exchanger

6~7.capillary tube 8.one-way valve 9.indoor air heat exchanger 10.domestic water tank 11~12.water pump 13.solar

water tank 14.solar flat-plate collector 15.solar simulator

G1~G8 refrigeration valve S1~S4.three-way valve W1~W4.water valve

Fig. 17. Configuration diagram of the experimental setup of the IDX-SAMHP (a) schematic (b) photo.

- **Solar water heating mode**

In solar water heating mode, the initial water temperatures in solar water tank and domestic water tank are identical. Then the system starts to operate to heat the water in domestic water tank to 50 °C. Numerical study is conducted to study the influence of the initial water temperature on the performance of the IDX-SAMHP system. The initial conditions are set as follows: the environment temperature is 20 °C, and solar irradiation is 0 W/m^2.

- **Solar space heating mode**

In solar space heating mode, the indoor environment temperature relates to the indoor thermal comfort. Numerical study is conducted to study the influence of the indoor environment temperature on the performance of the IDX-SAMHP system. The boundary conditions are set as follows: the initial water temperature in solar water tank is 30 °C, the outdoor environment temperature is 7 °C, the mass flow rate of water in evaporator is 0.05 kg/ s, and solar irradiation is 0 W/m^2 .

In this paper, a novel indirect-expansion solar-assisted multifunctional heat pump (IDX-SAMHP) is proposed. The IDX-SAMHP system can work in different modes with high energy efficiency. The dynamic model for solar space heating mode and solar water heating mode is presented and validated by experiment.

- **Dual tank IDX-SAHP system**

To attempt to further improve the performance of the traditional SDHW system, a heat pump was implemented into the design and the performance was investigated. The configuration that was investigated here was a dual tank IDX-SAHP system. The schematic and TRNSYS layout are shown in Fig. 18.

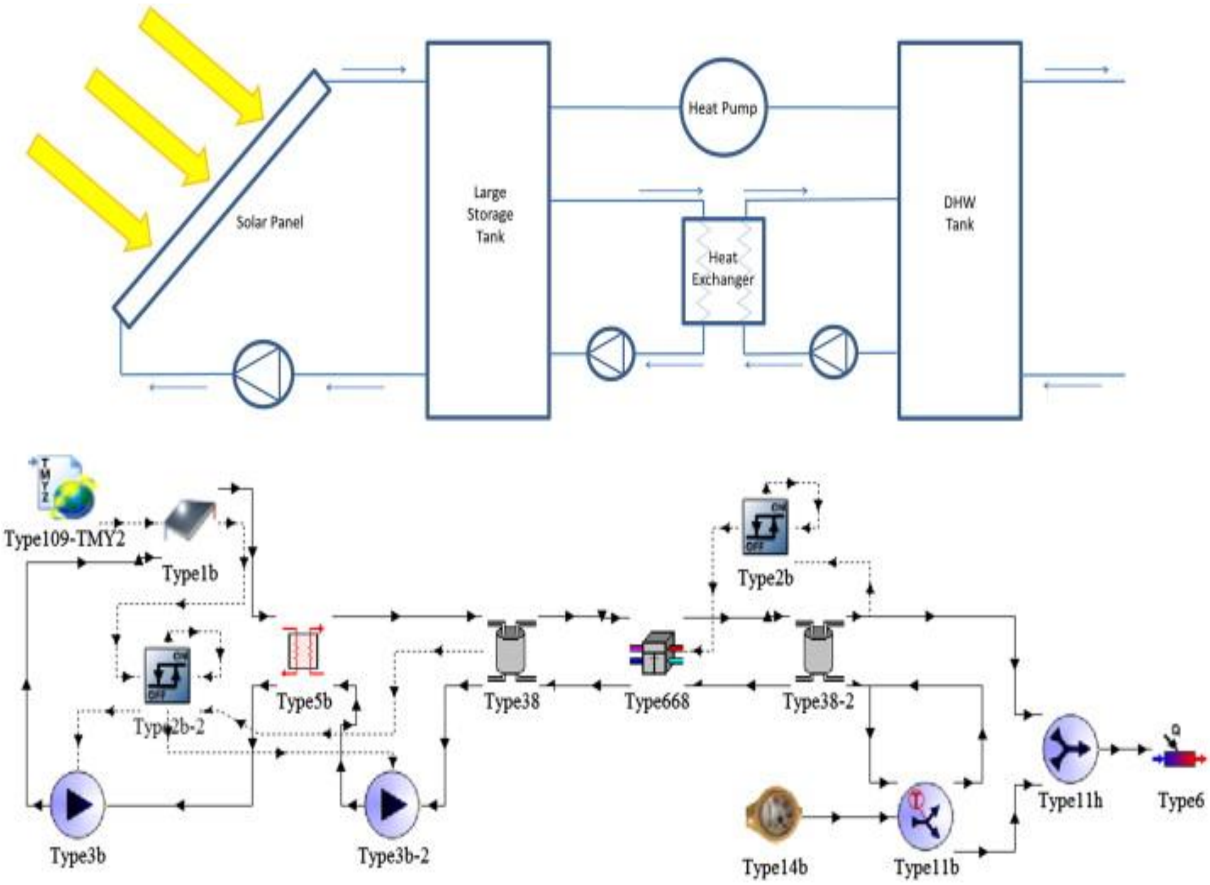


Fig. 18. Dual tank IDX-SAHP domestic water heater

The dual tank IDX-SAHP system was intended to operate in the following way. The collector side operated in much the same manner as the traditional SDHW system, with two notable exceptions.

First, the storage tank was determined to need relatively large thermal capacity, and was therefore sized to contain 500 L of collector fluid. This tank was called the float tank because its temperature was allowed to fluctuate. Secondly, the entire loop was assumed to contain a 50%:50% glycol–water mixture. For simplicity, the schematic shown in Fig. 8 contains an internal heat exchanger in the float tank for the glycol loop. The domestic water side was designed to operate in much the same way that the electric DHW system operated. In this case, however, when the domestic tank needed heat input, the energy was either supplied via a heat pump or heat exchanger loop connected to the float tank instead of from back-up electric heaters inside the tank.

The large float tank in the dual tank IDX-SAHP system increased the overall thermal mass and in conjunction with the heat pump, the system was able to collect and store more solar energy. Fluctuations in the float tank temperatures occurred gradually and the temperature peaks decreased because of the huge amount of thermal mass. The larger the volume of the tank present, the more time it will take for the system to heat or cool the fluid. If the float tank was too small, the temperature fluctuations would be drastic and the system would not be able to meet as high of demands when there was no solar energy to be collected without the use of more electrical input. The low temperature peaks experienced by the float tank due to the lower auxiliary set-point temperatures and larger volume actually caused it to gain more energy from the surroundings than it lost during the entire simulation period. Therefore, the surrounding room temperature air was actually, on average, warmer than the float tank and helped to heat the fluid inside of the tank.

The dual tank IDX-SAHP system proved to be the most energy efficient and had the lowest annual operating cost of the three models analysed. Therefore, the simulation results of this system agreed with previous studies that there is potential for the use of heat pumps to assist solar domestic water heating systems to increase their performance. It should be noted that natural gas water heating systems were not considered for comparison here. There are many places in the system that the heat pump can be introduced and deciding where to put it and what size of heat pump to use are not trivial decisions. Depending on the geographical location, the weather that the system will experience will have a huge impact on the way that the system will function and what is required. There are also many other factors that will influence the performance of these systems. Therefore, computer simulation will be very important in the continuing development of implementing these IDX-SAHP systems. The next step of this project will be to examine more IDX -SAHP configurations and compare their performance to the two base systems and the dual tank IDX -SAHP system presented here.

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