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Review Article

A scoping review on recent advancements in domestic applications of solar thermal systems

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ABSTRACT

The rapid growth in smart technology and green energy contributing crucial role in taking our homes into next level. Meanwhile the solar powered thermal systems (STS) are much desired for energy conservation and management of houses. Domestic application of STS will not only reduce electricity consumption but also reduce carbon emission. This paper gives a scoping review on role of various types of STS namely, solar water heating, solar active and passive space heating and cooling, solar thermal water pumping, solar cooking, solar drying, solar distillation, solar green house, solar photovoltaic thermal systems (PVT) and solar thermal energy storage systems in domestic applications. The recent advancements with respect to each type of STS is outlined. Starting from various collectors and materials for STS, each system's working principle and technological advancements in the view of adopting it to domestic applications are discussed in detail. Also, performance evaluation and role of each different STS in home application is elucidated. The research gaps and potential barriers for adopting STS for domestic homes are explored.

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INTRODUCTION

Most dominating solar energy conversion is solar Photovoltaic energy conversion system (SPV). Besides this solar energy to heat energy conversion is also a predominant, such systems are known as Solar Thermal Systems (STS). STS converts solar energy into heat which is further utilized for multipurpose heating and cooling. The earliest known use of solar radiation for heating of materials and equipment bodies dates back to B.C. millennium. Of course, exposing wet clothes to sunshine to make it dry also comes under solar drying. The day-to-day domestic heating requirements such as water heating, Heating, ventilation and air conditioning (HVAC) systems, air conditioning needs the use of electricity. Which is still a debut source of energy. The compensation for this case is STS. Eco friendly, carbon emission free features of STS is making it as most promising alternative. The use of solar thermal

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energy for domestic applications results in the reduction of electricity consumption and requirement. In 21st century, STS plays a vital role alongside with solar photovoltaics in the making of smart Homes and green buildings. This review sophistically focuses on various applications of STS and its importance in smart homes and green buildings. Unlike electric energy utilities, the construction of STS is simple. Most of the STS materials are easily available. The advancement of nano technology makes a way for development of more productive and efficient STS. In solar STS, the solar radiation is directly absorbed by thermal conductive plates which results in raising temperature of system. This absorbed heat is either transported by heat exchangers or utilized in it to increase the temperature of matter. In cold countries the Seasonal Thermal Energy Storage(STES) integrated with STS are serving as thermal management system for homes and commercial builds [1]. Integrating STS with continuous STES are a much needed and most reliable option in thermal management of indoors. The Leadership in Energy and Environmental Design (LEED) certification for green buildings signifies importance of STS [2]. Impact of solar energy and its correlation between inter-building effect and building energy estimation states the need of solar thermal energy for urbanized cities [3]. Despite of strong research in this area the systems implementation to domestic homes are limited. Many developing and under developed countries still can’t be able to put higher initial investment for domestic STS. Also, in developed countries urbanized living environments where individual homes are replaced by gigantic apartments making the application of STS impossible to all home unit. Here in high population density cities roof space is also a matter of concern. Apart from this variation of climatic conditions across world needs different operating temperatures of STS for respective indoors thermal management. This results in development of suitable Thermal energy storage systems (STES) for particular climatic conditions.

Hence the optimized systems for particular location may not be a well performed system for another location [4]. This paper point outs the potential barriers for STS penetration in domestic application while simultaneously exploring the potential choices for performance enhancement. The working principles of each type STS are briefly explained below followed by findings of scholars in particular systems and each systems significance in domestic use. A detailed outline is given about collectors for STS and materials of it. Importance of material and choice of collectors in performance optimization of STS is also mentioned. The review starts with introducing collectors for STS and materials for of it. Which is followed by the in-detail explanation of each and every STS used in homes. In that the system description has given by stating the working principle. And major advancements in concerned STS and its contribution and importance in domestic application is discussed. Meanwhile, the research gaps with respect to thermal management and temperature control explored. The solar systems advancements explained below are namely, solar water heating system which is used to heat water, solar space heating which can control indoor temperature with the regulation of thermal management system in home, solar refrigeration which is used for food preservation, solar cooking whose main purpose is to serve as alternate to conventional cooking stoves, solar distillation which is used in homes for water purification or separating saline water and pure water., solar water pumping which can serve in water storage purpose of homes, solar greenhouse whose prime role is in plants gardening and solar drying used for blowers heat and drying of nuts and cloths. The mentioned topics has its share in building the green house. Each systems performance evolution is outlined and major research gaps in integrating these systems with buildings are explored. Finally, the need of energy for night times is satisfied by solar thermal energy storage systems(STES). Whose advancements and importance in domestic application are discussed and also stated its research gaps like thermal management and climate-based operation limitations. Along with these solar Photovoltaic thermal systems (SPVT) significance also outlined. SPVT systems draws electricity and heat from a single solar panel. This integration is already proved as a performance enhancement method of solar energy conversion.

MATERIALS

Choice of materials governs the performance and overall efficiency of STS. Most of the thermal systems materials are classified as heat absorbing materials which are highly thermal conductive in nature. Research on phase change materials (PCMs) for Thermal Energy Storage (TES) is showing rapid growth [5]. Other governing properties for choosing materials including corrosion resistance, compressive strength and tensile load withstanding capability. The conductive materials in STS have a property of very high thermal conductivity, durability and robust. The heat trapping glass has a high Refractive index (RI). Crystal glass, Acrylate, Plexiglass, Polycarbonate and Polyester are most suitable materials for absorber plate. Tempered glasses have proven to be durable and most suitable as glass cover [6]. This also highly resistance to mechanical impacts. The percentage of iron content in glass is the predominate factor in amount of light moves in to the cover. Most of the cover materials have RI of 1.5. it means that, almost 92% incident radiation is transmitted into STS. This glass cover transmits solar energy to heat absorber. This heat is insulated with in system by insulating covers. This further reduces heat losses. Insulating materials are responsible for insulating the collected heat with in the system. The low thermal conductivity property is the key factor in deciding

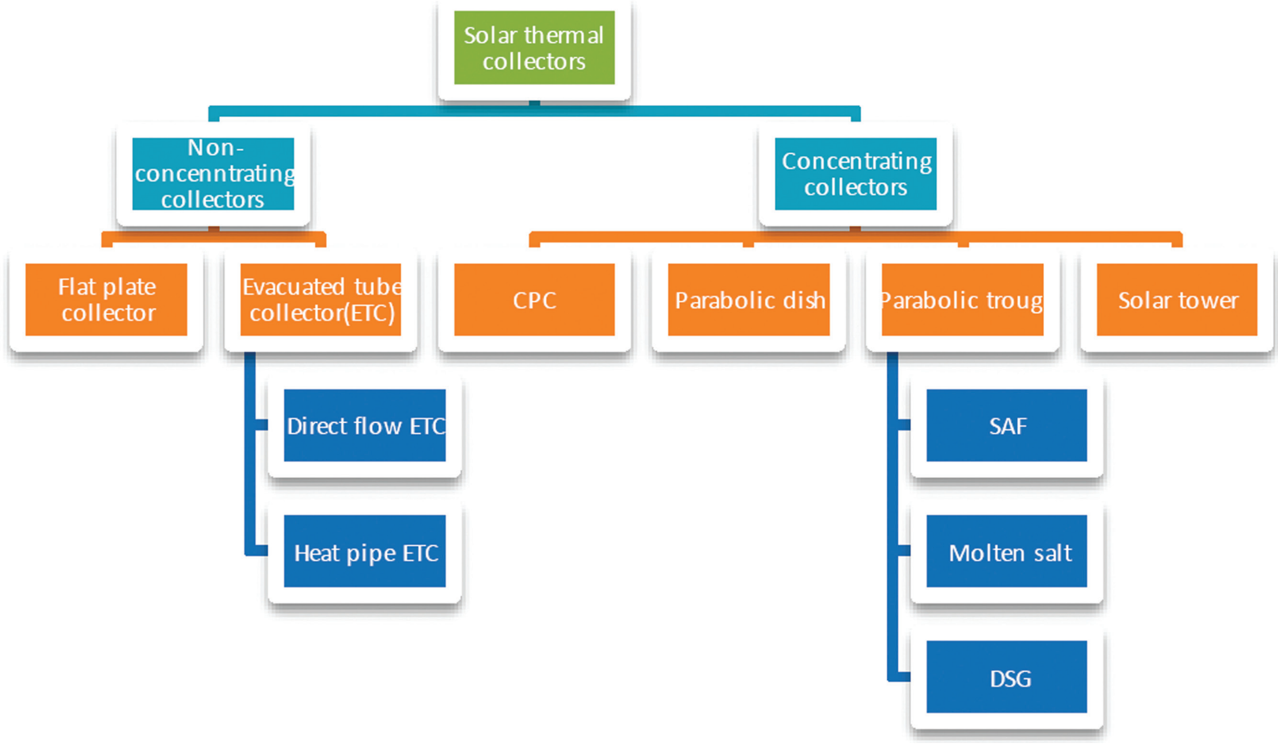


Figure 1. Various types of solar thermal collectors.

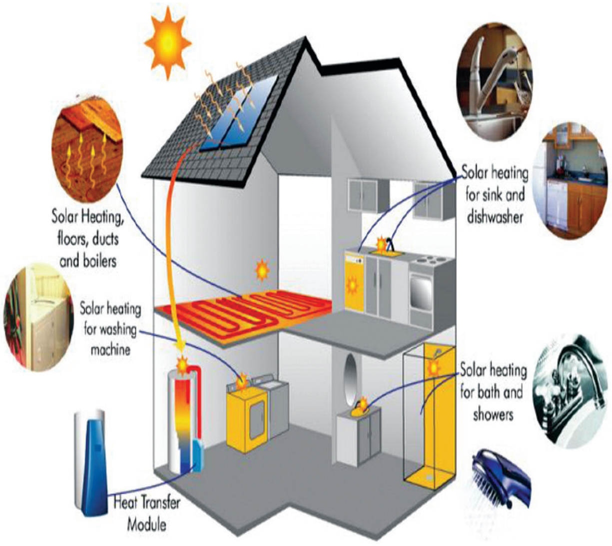


Figure 2. Typical smart home utilizing the solar thermal system.

the insulating materials. Remaining properties including working temperature, no out gassing up to 200°C. And also, insulation acts as a shield for outgoing radiation of the absorber plate. Incoming solar energy transmission rate is the bench marking property in choosing insulating materials [7]. The mechanical properties of materials such as density, melting point, tensile strength, moisture penetration and degradation due to exposure to atmosphere, etc. decides durability of STS.

DOMESTIC APPLICATIONS OF SOLAR THERMAL SYSTEMS

The application of STS to domestic purposes results in high initial investment with reduced electricity consumption and moderate payback period. These systems make building as eco-friendly and pollution free. The utilization free solar energy along with STES bring a solution for reduction in domestic energy demand in cold countries. It is also evident that energy management with solar energy integration gives reliable output and reduction of energy consumption [8]. The advancements in technology are building the bridge between research development and consumer utilization. A typical smart home with STS is shown in figure 2. STS use can replace the high fuel consumption generator sets and air conditioners. Already SPV gains a dominant role in domestic applications. But daily thermal management applications of homes need thermal energy. For this direct use of solar radiation as heat source is a better, easy and efficient way rather than using electrical heaters operated by solar PV panels. In this article a complete description and recent progress about these systems are discussed along with its merits, demerits.

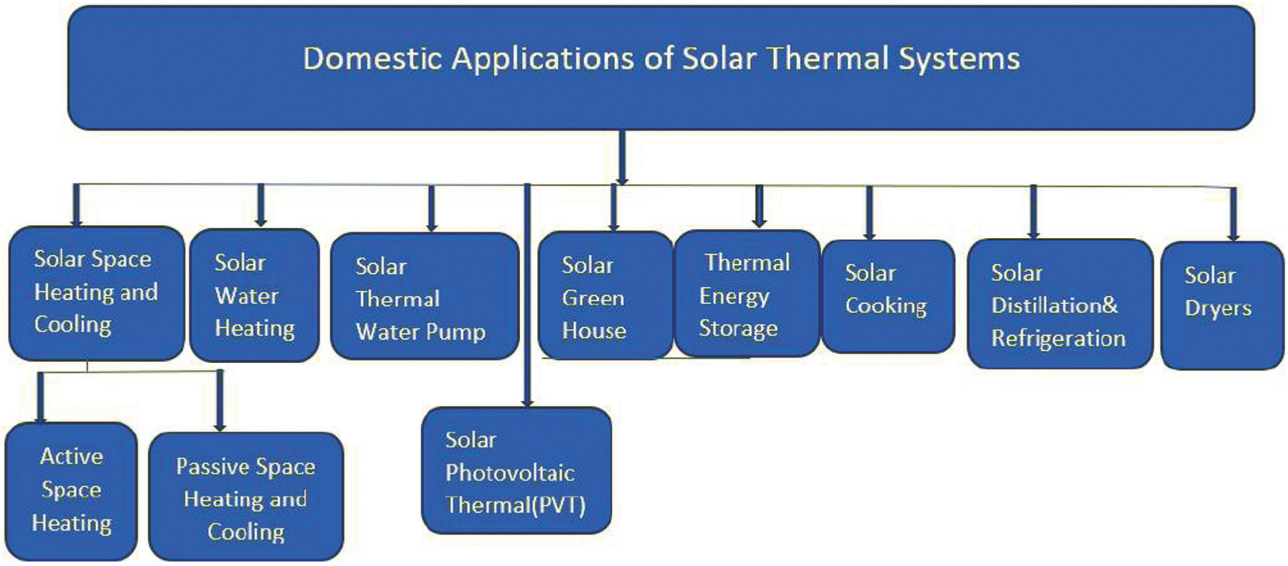


Figure 3. Various domestic applications of solar thermal systems.

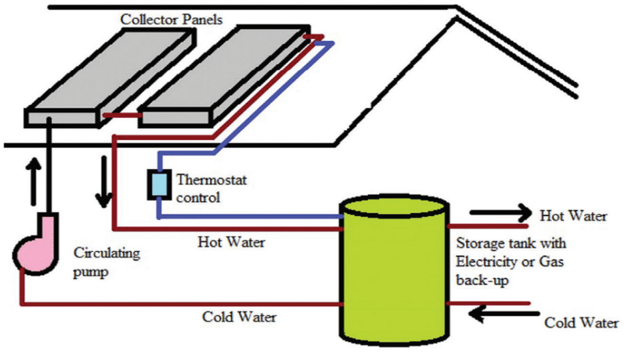


Figure 4. Roof mounted solar water heating collector system.

Solar Water Heating

A typical solar water heating system consists of a flat plate tilted solar collector with internal copper pipes for water circulation. This set upon is thermally insulated by backside, while fronts and top end is covered by glass casing to allow maximum radiation. A water tank is mounted on top of it where the hot water is stored. When the radiation falls on top side of tilted collector, the water in copper tube gets heated, this makes top water in copper tube to be a low density. While the bottom water pushes up due to density difference and hot water is collected in tank. Again, this process repeats due to hot water at top side of collector. Different type of solar collectors for solar water heating are used along with thermal energy storages. A study on solar parabolic trough collector with latent heat thermal energy storage system (TESS) is investigated. By using RT-45 as phase change material (PCM) the hot water temperature of maximum 85°C attained [9]. Efficient and sustainable domestic hot water (DHW) production is a key factor in energy conservation [10]. In order to ensure the optimal performance of system heat loss must be minimized. By setting up tracking for concentrating collectors, the parabolic dish reflectors can collect optimum radiation. The use nanofluids for heat transportation also makes the system optimum [11]. In a study of domestic solar water heating systems using thermosyphon principle (DSWHS-TP) in Mexico, DRC found that an annual energy supply of 5.27giga joules, annual saving of 428USD is reported. And also a CO_2 emissions reduced to 0.006tons [12]. This economic and ecofriendly feature are providing the way towards sustainable growth. By estimating the solar potential and analyzing its capability to be a potential source of clean energy, a study reported 71% energy saving with a payback period of around 8 years [12]. Constructive characters optimization of thermosiphon systems of 28 different types with Standard ISO 9459-5:2007 found that reduced volume values greater than 0.8 has good influence on system performance. This also recommends location and utility based system optimization [13], the thermal stratification of solar heating systems using algorithm based on off control achieved 5 to 28% rise in solar fraction [14].

Solar Space Heating Systems (HVAC)

The consumption of electricity for space heating and cooling accounts for 10 percent of total demand and around 20 percent of domestic electricity consumption. Hence the application of clean energy for air conditioning is much deserved in order to reduce the carbon emissions and electricity consumption. Domestic solar space heating is broadly classified as active and passive solar systems based on use of integrated auxiliary supply to the unit. In active solar space heating system collector is used to collect and absorb radiation combined along with electric pumps for the transfer of heat. It also consists of thermal energy storage systems to deliver heat in the absence of sun. meanwhile passive solar systems use natural draught produced due to pressure difference for heat and cooling circulations. The use of solar chimneys for producing natural draught and using for space temperature management is tested with improved performance and reduced greenhouse emissions [15]. The integrated geo thermal air tube with solar chimney is proven to be raised the temperature by 6.4°C [16]. In low temperature dominate regions room heating by warm water circulation through pipes is investigated. This study finds optimum utilization of warm water for space heating. In this investigation by using a FORTAN program parametric optimization has done [14]. By compared with regular central heating system the floor heating using solar ground water heat pump (SGHP) demonstrated overall energy savings of 30.55% [17].

Principle of Operation

A solar passive space heating system is shown in figure 5. in this a thick Trombe wall made of concrete, stone, or composites of sand and brick with painted black color coating of rear end is located facing south. This entire wall is covered by multilayer glassing with 0.1 to 0.2cm distance. The trapped solar radiation inside of glass allows to heat the thermal storage wall. The air entering in between glass and wall gets heated, rises up and by using upper vent it enters into room. This makes the space inside room hot and cool air leaves the room from lower went to rear end of glass covered wall. This allows cool air to heat at thermal wall and again rises up, enters room through upper vent making the cycle process complete. The room temperature is controlled by adjusting vents inlet and outlets. Similarly, the active space heating follows the same process with the auxiliary circulating system. This makes active system better regulated than passive system.

Trombe Wall

A Trombe wall is usually a south facing solid wall of house. This wall maintains a few millimeters gap with outside wall glassing in order to store and regulate heat in passive and active mode. It is an effective method for utilization of solar energy for heating the buildings. By integrating phase change material to the Trombe wall researchers are able to commence heat transfer from 5cm PCM Trombe wall to building at 23°C temperature [18] using solar energy for thermal comfort reduces the brown energy consumption. Solar thermal systems are found to be useful in Heating [19-21], ventilation [22-23] and air conditioning [24] popularly known as HVAC system. Trombe wall is the cheapest way of thermal management of buildings. It is a passive method of solar HVAC system Abdeen et al. calculated that a Trombe wall with height, channel depth and thickness of 1.7m,0.22m,0.3m respectively reduced 38.19% energy consumption in a week [25] by using Trombe wall 44.14 % of Chillan and 25.35% of coronel heat energy consumption is reduced which eventually increase two cities indoor thermal comfort by 69.35% and 56.29% [19]. Bevilacqua et al. 71.7% heat energy consumption can be reduced by Trombe walls in hot climate zones and 18.2% for cold climate areas [20]. even though solar space heating system is proven to be more efficient in hot climate regions rather than cool climate regions. The HVAC systems are required mostly in cool climates needs better management and efficiency for better thermal comfort. In Lyon an investigation is carried out by agurto et al. calculated that Trombe wall application reduced in 20% of annual energy consumption [21]. The performance of Trombe wall for various climates and different seasons are improved by changing the materials used in construction of wall. It is also known that the wall facing is also different in southern and northern hemispheres. And the cost-effective wall construction is also depending on locally available materials and its performing characteristics. By using Nano black high absorption coating at absorber surface increases energy gain by wall [26]. A high

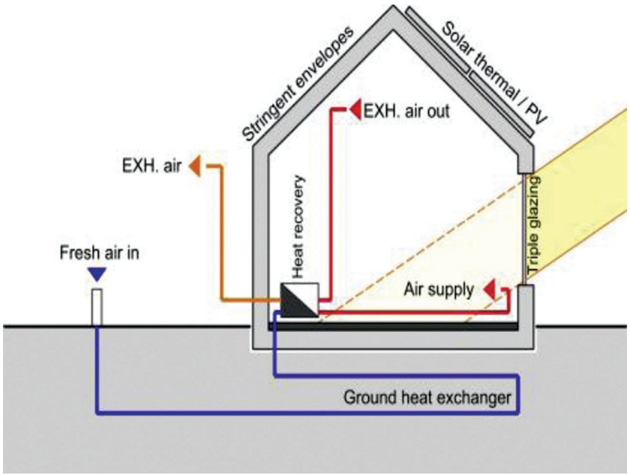


Figure 5. Solar passive thermal comfort system for house.

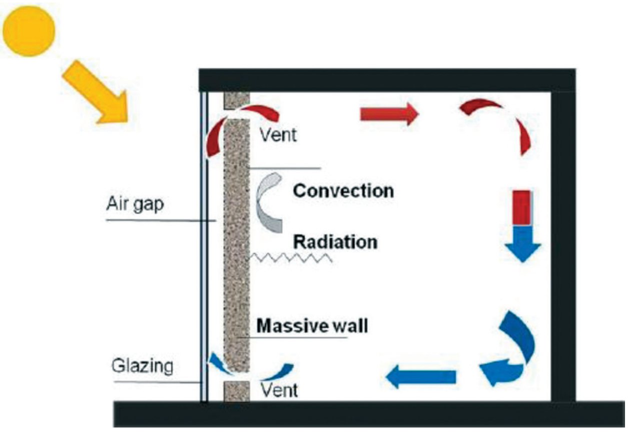


Figure 6. Typical Operation cycle of Trombe wall.

transmittance of glass can improve more intake of solar radiation [25]. For more stable thermal comfort proper thermal insulation is necessary [27]. Mehran R et al. raised the heat transfer rate of Trombe wall by using rectangular thermal fin arrays [28]. Investigation of this systems is emerged as major research scope in this area. The role of nanofluids to rise the performance of systems is gaining attention day by day.

Solar Space Cooling

The increase in solar irradiation of a location results in high temperature, subsequently rise energy spent for cooling of surrounding commercial and residential areas. For that solar space cooling is an emerging system which collects solar power and puts it in a thermal cooling system for temperature control and production of chilled water for building. The collected solar power, if it is a solar photovoltaic is used for driving electrical refrigeration. If the collected energy is solar thermal than it is used for cooling and dehumidification by absorption cooling system, Rankine cycle cooling systems, desiccant cooling systems etc. The figure 7. shows the solar space cooling system. It uses the any one of above cycles for space cooling [29]. Research on various ecofriendly and low temperature evaporating refrigerants as solar cooling system refrigerants is an emerging area. Most of these refrigerants are from manmade halogenated gas such as fluorinated and chlorinated gases. Many of these refrigerants are adding in ASHRAE list, which is popularly known as R-Family. Nanofluid mixtures to modify the performance of this refrigerates for suitability of various climate zones are also an emerging research area.

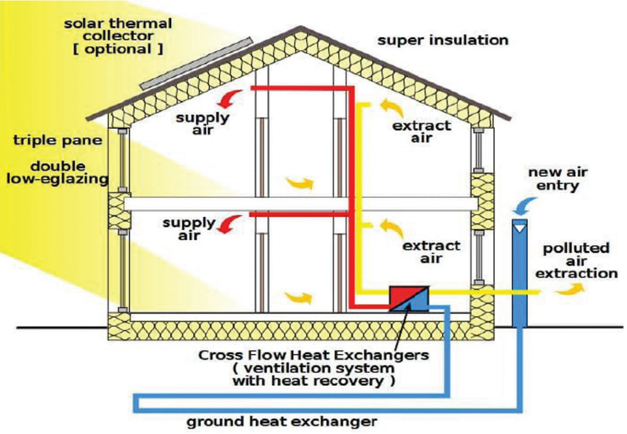


Figure 7. Passive solar cooling for living room.

Solar Thermal Water Pumping

The role of water pumping in domestic houses is for lifting water into top of tank and store in it for cooking and cleaning application. Pumping plays a crucial role in irrigation and heavy lift irrigation systems. Use of solar energy for agricultural water pumping is growing at fast rate. The PV integrated solar pumping emerging as a promising economical system for irrigation water supply. While domestic water pumping is still mostly under grid tied electricity usage. Few systems are tried and developed as solar thermal pumping systems using solar thermal energy as heat input. The collected heat is transfer by a heat transferring fluid preferably water will exchange heat in a heat exchanging chamber with low evaporating fluid of R- family (R-11,R-12), thus results in change of pressure of evaporation fluid. Which is used for running a turbine coupled pump. This system is economical only for either residential buildings or domestic homes with high water consumption.

The performance of pumps is tested by various working fluids namely R-11, R-100, Water glycol solution and pentane. Emerging of solar thermal pumps begins with a limited capacity lift irrigation pump with only one cycle per day is developed as a cost-effective solution [30]. This low-capacity pumps are enough to satisfy domestic water

Table 1. Overview of thermally driven cooling systems with operational parameters

Technology	Absorption	Vapor Compression	Adsorption	Desiccant
Refrigerant	Water	Ammonia	Water	-
Sorbent	Lithium bromide	Water	Silica gel	Silica gel or Lithium chloride
Cooling Medium	Water	Water glycol	Water	Air
Cooling Temperature	6° - 20°C	-20° - +20°C	6° - 20°C	16° - 20°C
Heating Temperature	75° - 100°C	80° - 160°C	55° - 100°C	55° - 100°C
Cooling Water Temperature	30° - 50°C	30° - 50°C	25° - 35°C	Not required
Cooling Capacity Range (per Unit)	5 - 20,500 kW	5 - 1,000 kW	5 - 350 kW	6 - 300 kW
Coefficient of Performance (COP)	0.6 - 0.7	0.5 - 0.6	0.6 - 0.7	0.5 - 1.0

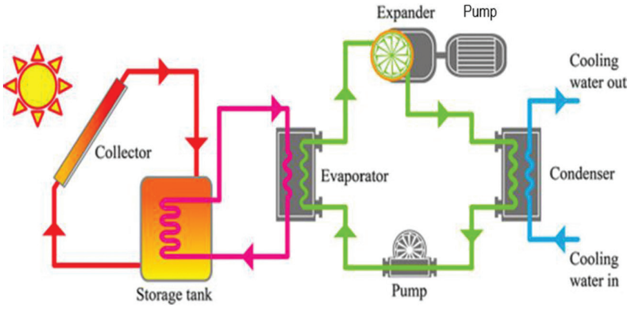
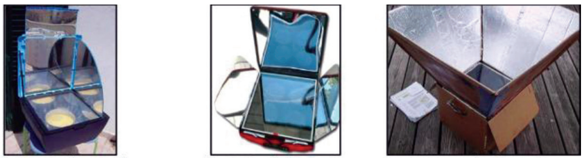


Figure 8. Solar thermal water pumping system for domestic utilization.


(a) Sun Cook two mirror (b) Rohatgi three mirror (c) Heaven's Flame four mirror

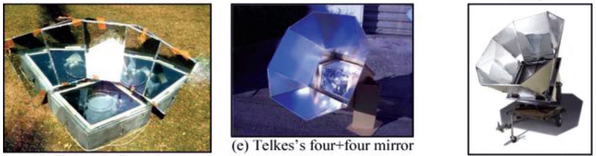

(d) Sharma's five mirror (e) Telkes's four+four mirror (f) Villager model

Figure 9. Real images of different type of solar cookers.

pumping needs. In some designs float and tanks are used to avoid physical contact between water and pump [30,31]. Various designs are demonstrated to improve the vapor capacity and number of cycles in a day. These improvements result in the increase of overall efficiency. The mathematical models and thermodynamic analysis of pumps are carried out by many scholars with different operating cycle [32-35]. To improve efficiency EL-Haron et al. conducted performance analysis of solar pumping with ether and chloroform as working fluid [36]. A similar case study is also done by Hadded et al. [37]. The phase change time period of working fluids and its thermodynamic properties and importance of heating is also experimentally demonstrated [38]. In an experiment the cooling of working fluid during condensation is used to heat the water and the water temperature of greater than 80°C is achieved [39-40]. Despite of all of this improvements still solar PV system is preferred by domestic consumers due to its simple and altering electrical energy advantages. The maintenance of thermal pumps is making the application far lags the conventional pumps. Even in agricultural sector the present operating maximum single pump capacity is less than 5 kilowatt. solar thermal pumps have advantage of high efficiency of around 60% are challenging their photovoltaic counter parts with around 20% average efficiency. The overall performance monitoring, integration of heat and thermal energy comes with a high solar fraction (SF) and improved seasonal performance factor(SPF) of 5 [41].

Solar Cooking

There is huge spent of petroleum gas and LPG for domestic cooking. The usage of cattle dung and domestic waste for cooking is still prevails in developing and under developed countries. This led to environment pollution and increase in carbon emission. For day time cooking solar cooking an alternative option which can simultaneously compensate for both reduced energy consumption and reduced carbon emissions. A typical solar cooker uses cylindrical or concentric solar collector. From collector heat is reflected on cooking pot where cooking takes place. In order to adjust the radiation intensity a movable transparent glass is mounted on it. A box type solar cooker is shown in figure 9. More over solar cooking proved as a potential source for hostels. Mullick et.al [42] has given thermal analyses on solar cooking system and also correlated various parameters with temperature and humidity. Kumar et.al [43] has derived the instantaneous exergy and exergy production with respect to atmospheric temperature for solar cooking. Otte [44] works on the factors influencing domestic applications of solar cooker by compiling economy, environment and technology. Kahsav et al [45] has anticipated the that the cooker with internal reflector is much efficient than cooker without reflectors. Subsequent authors work aids this theory. Later sun tracking for solar cookers is also made. By the use of nano materials, improved heat insulation, higher reflection coefficient for reflector is achieved [46]. Otte [44] has comes with a major breakthrough solution that solar cooking is the one way to address energy shortage in Sahara region of Africa. The heat loss in cooking results in poor performance and increased cooking time this problem is overcomes by heat input distribution pattern throughout the cooker [47]. The efficiency is improved by adding additional mirrors [48]. Cuce et. Al [49] derived time dependent equations for solar cooking by stating that firebox, glass-plate, air and exergy conditions are directly proportional to solar intensity. A typical domestic solar cooker has 1.2 meter^2. area with a capacity to cook 1kg rice in 45minitues at a 900 W/m^2 radiation. Despite of all of these Cooking heat output still depends on number of mirrors. Where the increase in mirrors makes the system bulk. Solar cookers are still thermally inferior to traditional gas stove. High concentration ratio systems are under research for optimizing and performance enhancement of cooking systems. Weldu et. Al [50] achieved 37.24% thermal efficiency. The influence of nano materials for solar cooking construction is also found to be effective. Saxena et. Al [46] conducted an experimental investigation by using three types of materials for thermal energy storge. The use of paraffin wax, carbon powder and a mixture of carbon as a claimed efficiency of 53.81% which the highest ever till date for small size domestic solar cookers. The current studies are much focused on integration of solar cookers with parabolic reflectors, reducing thermal insulation losses. Also, the cooking must take places only in outdoor with sun presence, which is a quite opposite to inside cooking in kitchens.

Solar Distillation

A typical solar distillation system consists of shallow water in basin which is to be treated. This basin is covered with a sloppy transparent glass roof. The solar radiation passing from here is absorbed by the black surface of basin subsequently results in evaporating the water in basin. This evaporated water condenses on sloppy glass cover. The bottom of glass is attached with semi open water collecting pipe. This pipe collects the water to storage tank for drinking and utilization. It is shown in figure 10. Solar distillation is much useful in coastal area salt water desalination and remote sea island for water production. A typical 1 meter^2 distillation unit yields around 5liter/day in summer and 2 liter/day in winter. This output is not even sufficient to single member despite of huge cost. Research in integrating solar distillation with phase change material (PCM) for yield improvement and night time production is show notable results. This method has advantage of to improve latent heat storage for getting constant higher temperatures. While poor efficiency, rusting and regular maintenances are major concerning in this system for adopting into domestic.

T. Rajaseenivasan et al. experimentally investigated the performance analysis of double basin double slope solar still [51]. The performance improvement of passive double slope solar still using Al_2O_3 Nanoparticles is demonstrated by L. sahota et al [52,53]. It is also proved that using tabular solar still output water collection is enhanced [54]. It is also evident that the rate of evaporation is inversely proportional to depth of water in basin and directly proposed to water temperature in basin [55]. N. Rahbar et al. has done performance analysis and numerical simulation using the experimental data with respect to second law of thermodynamics [56]. The distillation stills are made in various shapes and it is also well known that geometry of still has influence on heat and mass transfer [57-58]. The maximum amount of energy can be utilized by the still is investigated by exergy analysis [56]. Exergy of a still can be improve by using efficient and highly conductive heat transfer materials of still. The integration of solar still with other solar and electrical equipment for higher production is also demonstrated by many scholars. Integration of solar still with solar photovoltaics system, solar dish collectors [59], solar water heaters and forced hot air circulation are proven to be efficient. The absence of sun light makes system unoperated. This problem is overcome by using PCM which can store energy during day time, high radiation available period. And returns the heat into the system during night and absence of input radiation [60-61]. This type of PCM integrated solar still are gained importance in generation of continuous water yield irrespective of input energy intensity. The performance and productivity are also improved by integration of thermoelectric modules to solar still is also demonstrated [62-63]. The high difference in glass and undistilled water temperature rises the water output. The glass is cooled and a domestic using solar still is made by using cost-effective low-cost materials for still construction [64-65].

Solar Green House

It is an enclosure provided with artificially regulated ideal environment for production of corps, vegetables and flower plants. The greenhouse is playing vital role in growing biomedical plants in protected environment. its design varies with respect to various environments and crops. A typical solar green house for domestic use can be constructed as an integral part of house. It is called as attached green house while another is free standing greenhouse. A winter green house is shown in figure 11. Here roof and south facing wall is provided with double glazing. North facing roof is made of insulating material with relative inner lining to reflect solar radiation on the plant canopy. Single layer of rigid transparent fiberglass is used for east and west facing walls. in some design's pipes are buries under soil to store surplus heat under soil. Air from this pipe blown out when surplus heat is available. This heat is stored under concrete ground. In night time this heat is recovered by

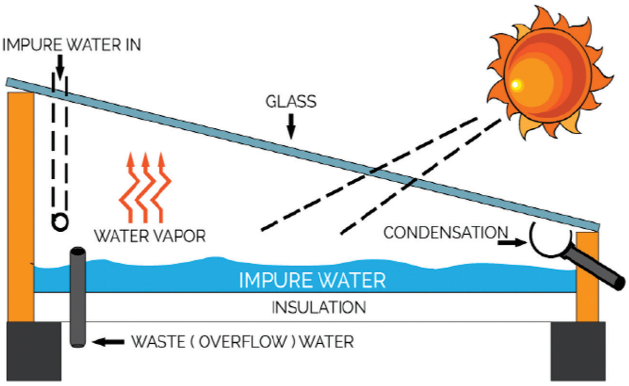


Figure 10. Single slope solar distillation unit.

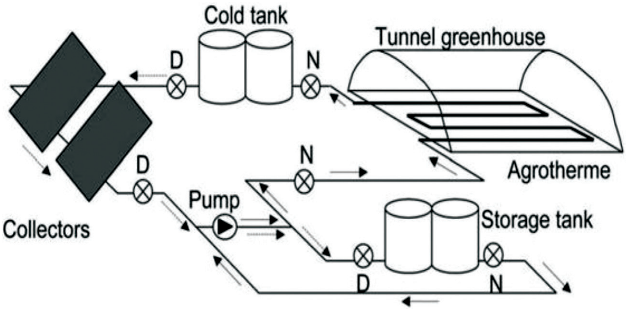


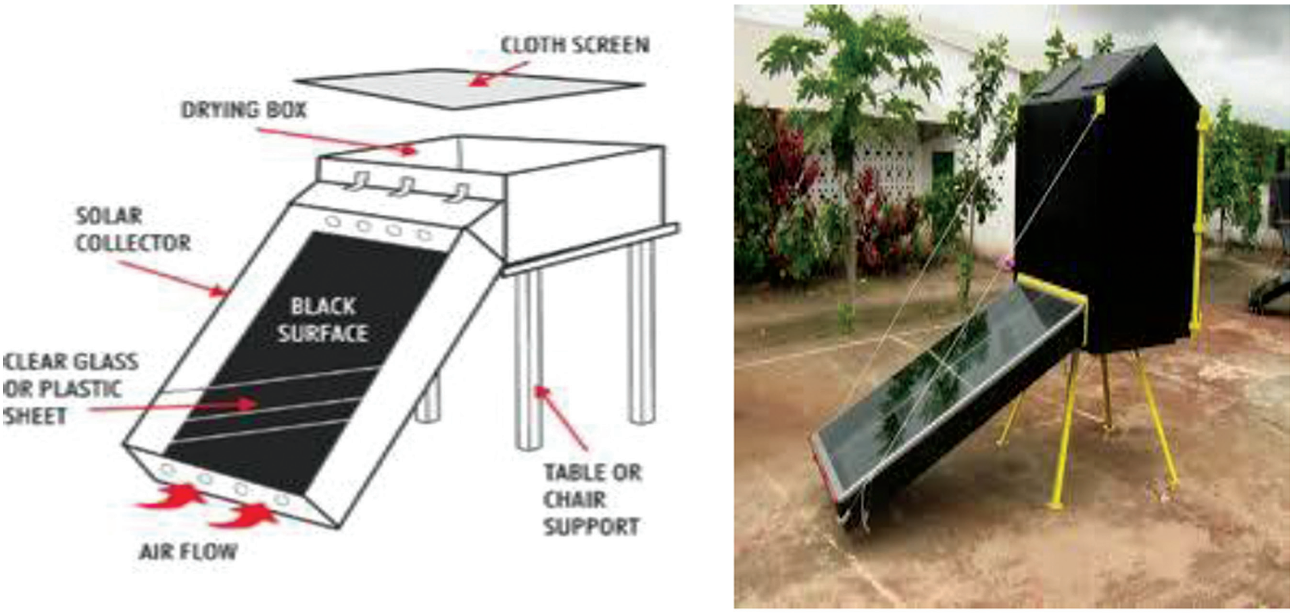
Figure 11. Inhouse attachable greenhouse for crops production.

reversing the air flow. During bitter winter periods especially in cool countries solar greenhouse con sustain due to limited irradiation. This results in mechanical support for temperature control. Unlike solar PV system solar greenhouse sun tracking is unfavorable.

In most of the technological developed countries corps and medicine plants are producing from greenhouses farming rather than conventional forming. Short-wave solar radiation of 0.4–0.7μm is responsible Photosynthesis. Because of this radiation thermal modeling of green house is possible [22] The environmental security in green house results in increased production. Meanwhile the energy consumption of greenhouses can be reduced by using solar green houses. Most dominate greenhouse agricultural product across worldwide is mushrooms. Across worldwide one third of mushrooms are produced by greenhouses [66-68]. The temperature control of green house for the production of mushrooms are examined by Anchez [69]. In this temperature control of greenhouse evaporating cooling method is most easy method for cooling and humidity control inside greenhouse [70]. While for increasing humidity, water is turned into water vapor using solar energy which investigated by Sethi et al [71]. This evaporative cooling system efficiency is depending on ambient temperature [72]. The application of evaporative cooling reduces the overall energy consumption [73-74]. In almost all of the green houses there is at least a temperature control of 2.5°C to 15°C [75]. The domestic green houses are popular in bungalows and enclaves where the garden space is available. Various applications of green houses are crop farming, crop drying, aquaculture, soil solarization, and poultry [76]. In domestic greenhouses apart from aqua and remain are demonstrated. Insufficient solar radiation cannot operate greenhouse alone [77]. It requires an additional heat source [78]. This source may be solar power PV panel are solar dryers. In order to enhance the efficiency, exergy optimization of solar greenhouses equipment is necessary [79]. Hence it evident that integration of various technologies in green house are indeed to improves the performance. Even though this system has demerits, the release of carbon dioxide of plants during night times makes the insulated greenhouse warm. therefore, worms and bugs still digest organic matter.

Solar Drying

Almost all households use solar in drying of cloths by exposing to sun. In a broad view this solar radiation can be used to remove the moisture in drying of some food products like fruits, coconuts and nuts for preserving. This simple mechanical system easily dehydrates the substance with faster drying rate. The use of solar radiation for Crop drying is also an ancient method. A typical drying is shown figure 12. The cool air enters from bottom of the dryer gets heated by trapped sun radiation. This results in hot air drying the items in trays. Which further results in removing the moisture of items. This hot air exhaust from top vents of the dryer due to light density. This process is a bit slow and needs an active/passive circulation system for a large scale drying in agricultural sector. Drying in homes such as drying of chilies, coriander, pepper, banana, papaya amla, carrot, beetroot, potato, turmeric, dehydration of fruits and vegetables like mango, sapota,



(a) **(b)**

Figure 12. (a) diagram depicting parts, (b) Real image of solar dryers.

grapes, bitter guard and many more can be done at faster rate by placing those in solar dryers rather than direct sun exposing.

Study by Motevali et al. on roman chamomile confirmed adding heat pump to PV solar dryer increases the maximum energy efficiency by 17.56% and drying efficiency by 18.12% [80]. A similar case study is also done on mushrooms [81]. These systems achieved a notable coefficient of performance values of around 3.0 and a low energy utilization rate of 0.6. Aktas et al. achieved a high COP value of 3.94 by with a heat recovery of 4.56 kwh energy from heat pump for drying of mint leaves [82]. The performance optimization of solar assisted heat pump drying finds that SMER and COP values are inversely proportional to speed of compressor [83]. Various components for heat pump based drying optimal matching is investigated [84]. Drying chamber parameters and system parameters such as drying temperature, ambient temperature and various materials used in construction of dryers decides the performance of system. The air mass flow rate plays a crucial role in drying time [85] Apart from this minor factor solar radiation, compressor speed and dehumidification capacity of drying chamber has greater impact on drying [86]. The above mentioned aeras still prevailing as wide research scope in these systems. Yahya et al. on drying of cassava chips found that when drying temperature is 40°C the dehumidification per unit energy consumption is 0.38kg/kwh [87]. Since the space on domestic houses tops are limited, the optimization of evaporator and collector area of dryers are necessary because its impact on drying is significant [88]. Research demonstrated that the energy consumption can be reduced with drying due to solar assisted drying and also by its optimization. In a study M. Chandrasekar et al. utilized exhaust heat of AC outdoor condenser unit with the integration of solar dryer and achieved a maximum drying temperature of 43.6°C [89].

Solar Refrigeration

This artificial system maintains temperature below ambient by rejecting heat from it at higher temperature. This energy transfer uses at least one of mechanical, electrical, heat, magnetism or laser to complete work. While the solar refrigeration system uses solar energy as either heat source or electricity source. Energy consumption of refrigerators are as high as air conditioner. These two accounts for 60% in energy consumption of house. Also, there is significant greenhouse effect due to this. The solar refrigeration covers some of these drawbacks by offering free fuel. Most of solar refrigeration system (SRS) works on the electricity produced by solar photovoltaic panels. There also numerous systems which works on vapor absorption cycles and vapor compression cycles using solar thermal energy as input for refrigeration [90]. The figure.13 showing a typical solar powered refrigeration system. The

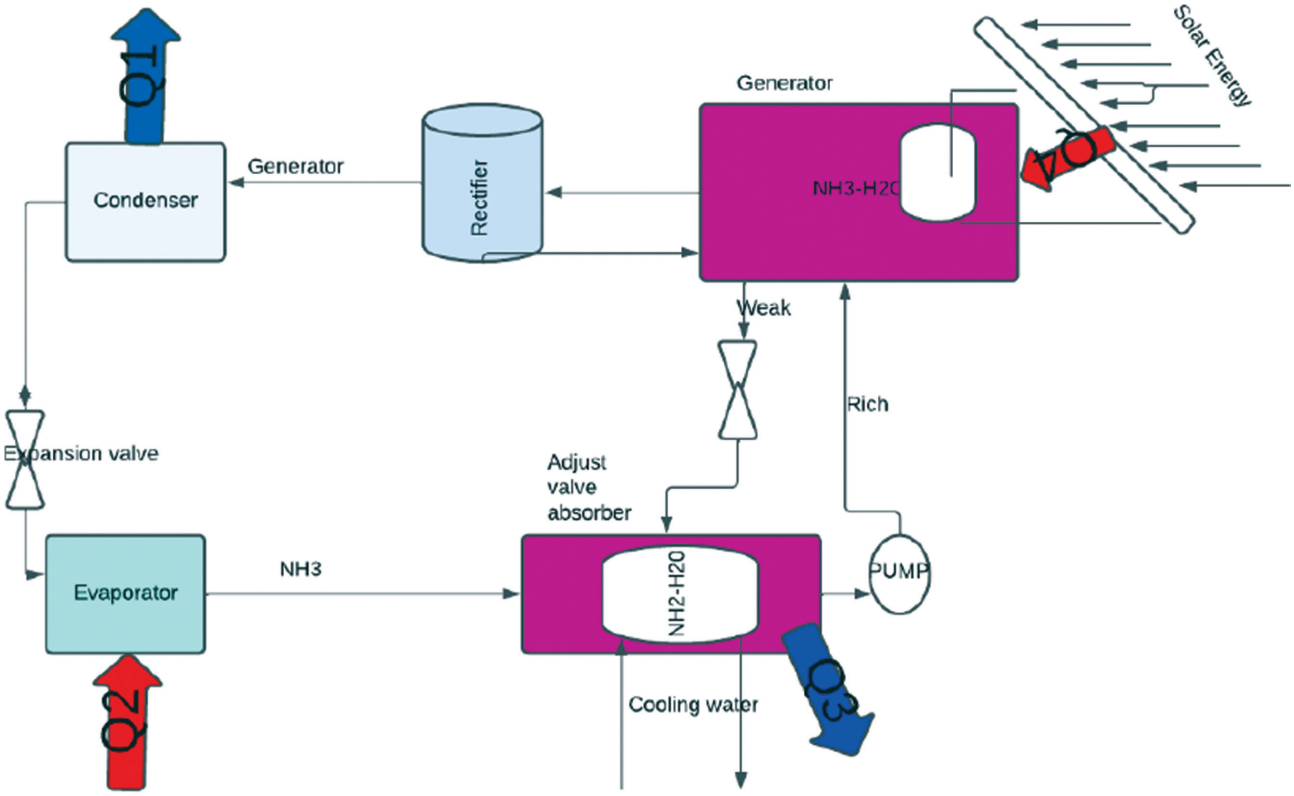


Figure 13. Typical Solar refrigeration system with flat plate collector.

refrigerants namely chlorinated fluorocarbons (CFC) such as R11, R12 are in gaseous state are used as working fluids. Change in pressure at evaporator allows it to undergoes phase change into liquid to vapor form by absorption of heat. This super-heated vapor is cooled by passing through condenser. first of its kind was developed and patented in 1954 by kirpichev and baum with steam as a working fluid and capable producing of 250kg of ice per day. Here steam produced by a cylindrical parabolic concentrator. The most prominent domestic applications of solar refrigerator are food preservation. It also part of domestic energy conservation. Most of the LEED certified buildings uses the solar refrigeration. Said et al. produced a case study on various designs of solar refrigerators in which system saves energy for night operation [91]. Study on optimization of vapor absorption refrigeration is carried by A. Saleh et al. [92] they achieved around 80°C temperature with coefficient of performance of 0.8. also, the air conditioning already mentioned in 3.2 also works on the same vapor compression cycles. He et al. [24] estimated that solar absorption refrigeration system is able to reduce 26.1% total seasonal energy consumption. Many chiller units integrated with parabolic collectors works on solar refrigeration cycle. The combined cooling and heating power(CCHP),combined heat and power (CHP) systems in smart houses uses vapor compression cycle can also performed by integration of solar energy with it [93]. Renato M. et al given thermodynamic and economic analysis of solar refrigeration systems which is a deciding factor in application of SRS to domestic world [94]. His work also covers economic and space occupation comparison between solar thermal and solar PV systems. Despite of all these advances in SRS size optimization, regular maintenance and space availability are perceived as potential barriers. These systems are compatible with other solar systems for CHP and can serve as common unit for most domestic applications. even though refrigerants for SRS are ecofriendly, the toxic and flammability natures are a matter of concern during its domestic application. Researchers are looking in flammability and toxic regulation using prediction and testing methods [95].

Solar Thermal Energy Storage Applications

The diluted form of solar energy with time bounded solar radiation delivery throughout the day makes the solar thermal systems operation instable. In order to keep the thermal systems operation, stable it is necessary to have energy storage. This energy can be utilized for reliable operation in peak loads and in the absence of sun radiation. In domestic space heating solar thermal energy systems plays a vital role. Especially in night the storage heat energy in the form of sensible heat and latent heat storge is utilized by releasing stored energy. From concrete, bed rocks, molten salts to PCMs are used as energy storage materials. The domestic hot water storage for bathing is also possible by thermal energy storge. The latent heat storge is also utilized for buildings inner temperature control.

Various materials are used to store heat energy in different forms namely sensible heat energy [96], thermochemical energy [97] and latent heat energy [98]. The advantage in latent heat system is stored heat is always constant as long as the phase change is maintained. From bed rocks to PCMs there are number of thermal energy storage materials with their respective storage density [99]. An active TES system uses heat transfer fluid with forced convection for thermal control, meanwhile a passive thermal control is provided by either natural convection or convection created due to pressure difference. LEED standard recommends composites namely ceramic, molten salt, graphite use in building

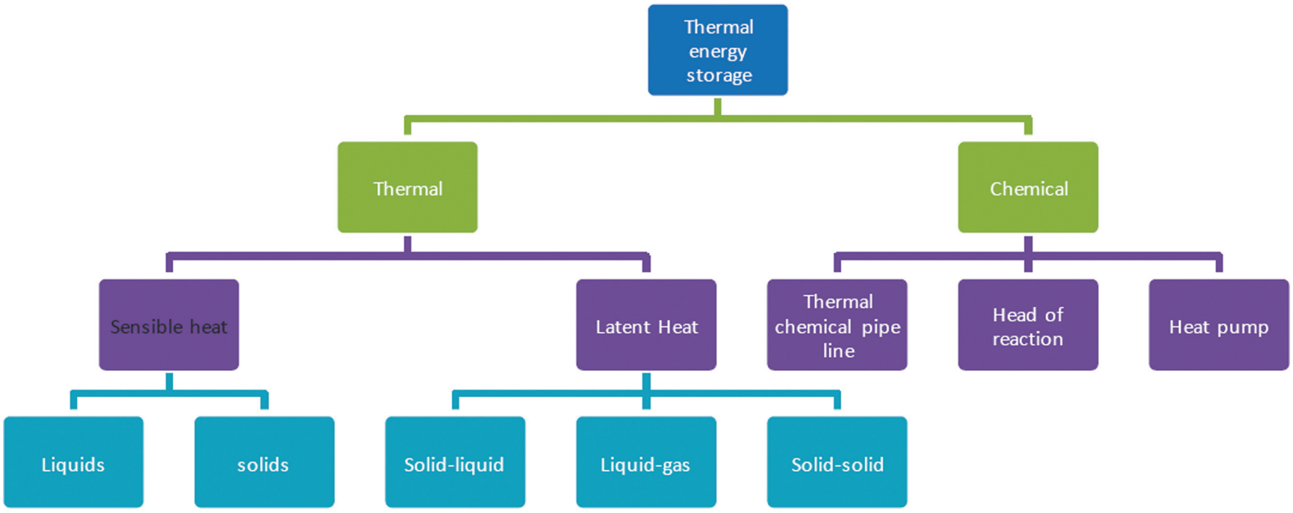


Figure 14. Types of solar thermal energy storage.

Table 2. Heat transfer fluids properties

Medium	Temp. Range for use as HTF (°C)	Heat capacity (J kg−1 K−1)	Density (kg m−3)
Water	0 to 100	4190	1000
Water-ethylene Glycol (50/50% volume mixture)	0 to 150	3470	1050
Ethylene Glycol	0 to 190	2382	1116

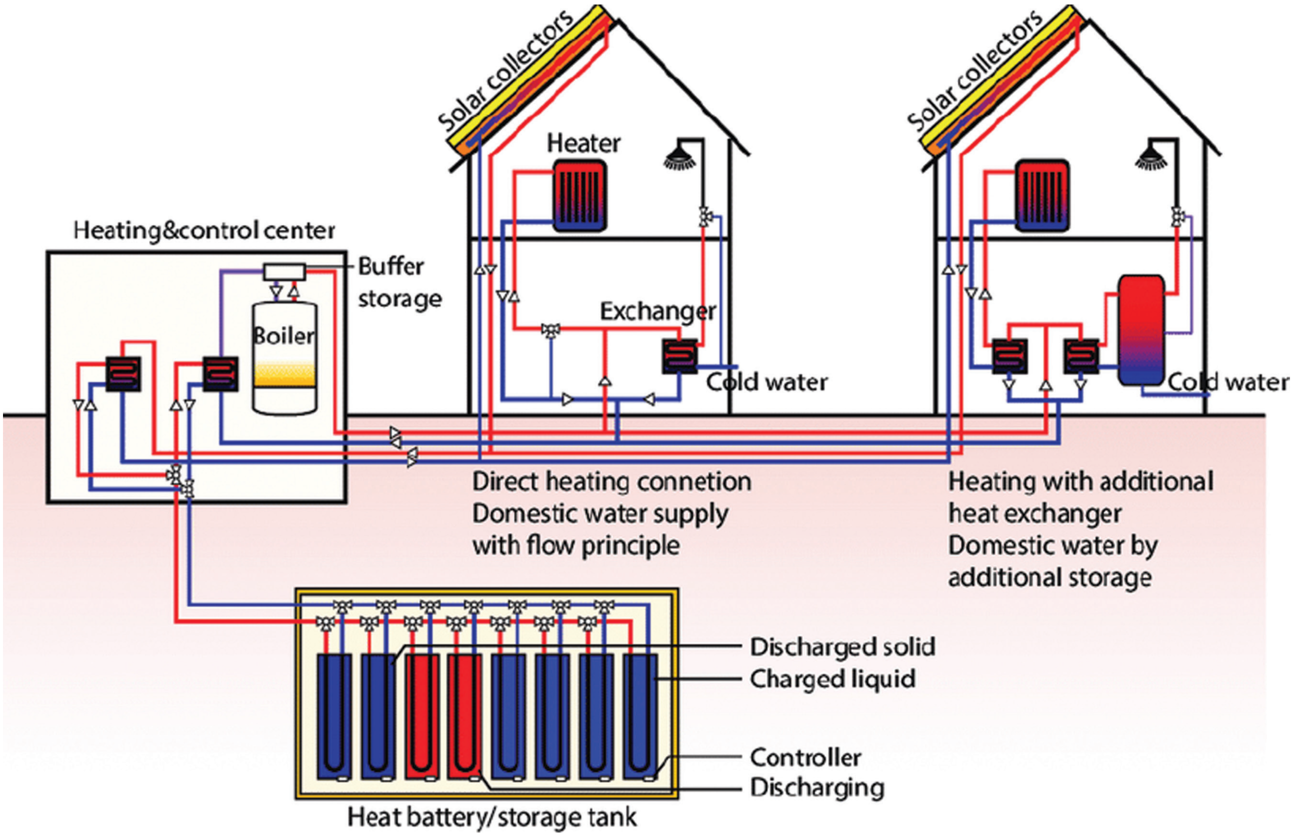


Figure 15. All thermal systems compatible TES for domestic house.

constructions for thermal insulation and storage [100-101]. Even solar slabs for heat storage and water circulation are now becomes a popular in these buildings. it is proved that thermal energy storage is vital in integration of solar thermal resources. The domestic thermal system stability and efficiency are also enhanced with TES. Its applications including use in solar water heating, distillation, cooking, thermal pumping and others. A self-sufficient energy secure houses are integrated with a single TES system for serving all kinds of thermal integration and storge requirements. Recent advancements in nano material with novel 2D nano materials use for TES are proved to be excellent thermal conductivity and photothermal effect which leads in increased energy storage density [102]. Major types of such TES systems are insulated storge tank [103], packed bed storage system [PBSS],moving bed system [104],fluidized bed systems [105]. The advantage of thermal energy storage systems in solar domestic applications are elimination of seasonal dependance, cheap cost and easily available material. Compared with battery energy storge the integration of TES for particular thermal system is cheap. This TES system is the only system in solar thermal systems which is a versatile and can be used for heating, cooling, refrigeration, electricity generation and storage.

Solar Photovoltaic Thermal Systems

Solar PVT are hybrid solar collectors able to generate electricity and collect heat at a time. Hence these systems can also be called as cogeneration systems. While using solar PV around 60% of solar spectrum is converted into

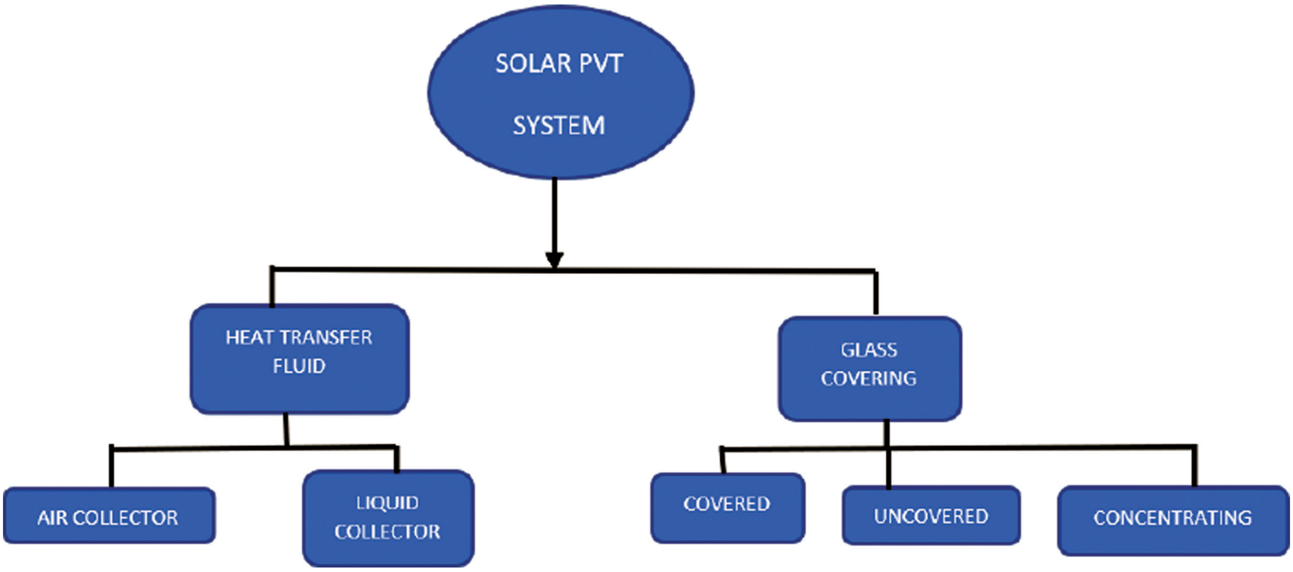


Figure 16. Major types of PVT Collectors.

heat, causing to increase the temperature of panels. The PVT idea is to recover this heat from panels and use for heating application. This has an advantage of both PV panel performance enhancement and also heat recovery. Hence need of separate thermal collectors for heat collection is no longer required. Also, it subsequently saves space utilization in domestic house. These systems are not only limited to domestic but also for industrial applications such as low-grade heat inputs for heat pumps, water heating, air heating [106]. The domestic houses across the world depends on both electricity and heat. This may make PVT system as a vital in domestic applications in future. Based on its design and technology PVT systems can offer a temperature output of 50°C to above 80°C. The building integration of PVT can cover domestic living requirements such as electricity, room heating, water heating [107]. Despite of this systems cogeneration capability, low efficiency and poor thermal management are the major areas of concern. Many scholars are addressed these issues in their capacity to optimize these systems. The hybrid integration of Thermoelectric generators (TEG), coupling of PV and PCM for energy storage are the emerging topics [108,109].The effect of incident angle of solar radiation in concentrated PVT for buildings is validated by shen liang et al. [110].TEG integrated PVT can improve efficiency of up to 60%, PVT with PCM can improve the system performance up to 32%. Ali et al. reviewed the PVT integration with various technologies such as passive cooling approach for efficiency improvement, nano fluids as heat exchangers, water-based hybrid PVT integration and PVT with PCM for energy storage. The use of nano fluids, heat absorbing fins, different shapes and systems optimizations are proposed and yet very few systems are available for building integration. This is due to low-cost effectiveness of system.

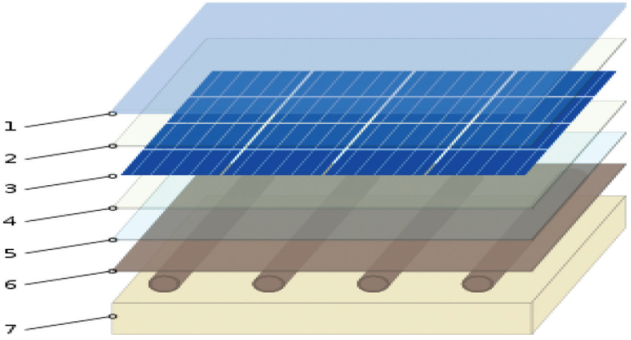


Figure 17. Cross sectional view of PVT (1. Anti reflective glass, 2. Encapsulant, 3. Solar PV cells, 4. Encapsulant, 5. Backsheet, 6. Heat exchanger, 7. Thermal insulation).

Conventional buildings are still impeded to include solar thermal systems due to place management, difficulty in coup up with thermal management systems. Since adding TMS to existing buildings requires separate construction and retrofitting of storage tanks and piping lines for heat transfer. Meanwhile new era buildings like LEED models are designed primarily by keeping solar energy utilization space requirements. Adopting STS to current domestic models requires a great retrofitting effort to update the old blocks into new smart homes. And further this will be a huge cost investment model. Here the discussed merits and demerits are used as validations for the application of solar energy in buildings. Hence this study found that present architecture is not a better option. Meanwhile new design based on LEED model are wise enough to utilize and manage STS with it.

Table 3. Summary of domestic applications of solar thermal systems

S.no	Name of domestic solar thermal systems	Operating temperature (°C)	Major role in domestic application	Heat transfer medium	References
1	Solar water heating	120	Cost effective way to generate hot water	Water	9-14
2	Solar space heating and cooling (HVAC)	32-82	Indoor temperature control	R13/R302	15-29
3.	Solar thermal water pumping	48	Extraction of ground water to water tanks	R113, R410A, R22	30-41
4.	Solar cooking	66 -202	Food cooking	Heat transfer through radiation	42-50
5.	Solar distillation	<60	Production of drinking water from saline water	Evaporation and condensation due to radiation	51-65
6.	Solar green house	25-35	Controlling the process of Germinate seeds and propagate plants	Air	66-79
7.	Solar dryer	65	Humidity control and dehydration of groceries and vegetables	Air	80-89
8.	Solar refrigeration	-10 to 30	Providing comfort cooling, preservation of foods	R11, R12, R13	90-95
9.	Thermal energy storage	Ambient temperature to 100	As energy storage for night time utilization in homes	Either conduction or convection using PCM	96-105
10.	Solar thermo photovoltaic system	50 to >80	Space heating, water heating, electricity	Conduction, convection, radiation	106-110

OPPORTUNITIES AND CHALLENGES

Solar thermal systems play vital role in making the domestic house as a smart house. A self-sufficient and energy secure house is always better choice for sustainable future. The reducing in electrical energy demand aids reduced economic burdens. The absence of utilization of refrigerants for air conditioning and cooling reduces the CO2 emissions. Still the low efficiency and long pay back periods on investments are major constraints in application of solar energy in domestic buildings.

CONCLUSION

The reduction in electrical energy consumption due to lack of necessity of electrical to thermal energy conversion pays the way for energy saving and reduced carbon footprint. The utilization of freely available solar (renewable) energy for domestic thermal comfort will be surely a smart idea. Solar thermal systems are also be able to generate high temperature and can produce steam with water, which is subsequently used for generation of electricity. But this case is a rarely needed in domestic application. This study re insisted that a house in any region with abundant solar energy is able to survive as a standalone smart home which manages its total energy demands by conversion of solar energy into required energy form. And yet the major challenges are

- Managing the Diluted form of solar energy for meeting house energy demand
- The energy storage method and its capacity, efficiency for backup supply in the absence of solar energy
- Development of reliable Thermal management and HVAC techniques.
- Finding effective solutions for Cost and payback analysis which are lagging the utilization of STS.
- Unlike solar PV systems all solar thermal systems occupy individual space on rooftops hence it's a need of the management of space.
- The management of thermal energy according to the seasonal requirements and estimation of energy demand with respect to particular locations
- Optimization, performance enhancement and efficiency improvement of current STS. Since majority of STS efficiencies are less than 30 percent.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

NOMENCLATURE

ASHRAE	American society for heating refrigeration and air conditioning engineers
CFC	Chlorofluorocarbon
CCHP	Combined cooling heating and power
CHP	Combined heat and power
COP	Coefficient of performance
DSWHS-TP	Domestic solar water heating systems using thermosyphon principle
DHW	Domestic hot water
FORTAN	Formula translation
HVAC	Heating ventilation and air conditioning
LEED	Leadership in energy and environmental design
LPG	Liquid petroleum gas
PCM	Phase change materials
PV	Photovoltaic
PVT	Photovoltaic thermal
RI	Reflective index
STS	Solar thermal system
SRS	Solar refrigeration systems
SGHP	Solar ground water heat pump
SMER	Specific moisture extraction rate
STES	Solar thermal energy storage
SPV	Solar photovoltaic
SF	Solar fraction
SPF	Seasonal performance factor
TEG	Thermoelectric generator
TES	Thermal energy storage
TESS	Thermal energy storage systems

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