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Domestic Solar Heating: Historical Development, System Description, Social Aspects, and Future Prospects

Xun Yao, Yuecen Zheng, Jiacheng Zhou

Abstract:
With the advancing technology, there are many well-developed domestic solar systems with two main categories: active heating systems and passive heating systems. This paper focuses on a functional heating system which includes solar water and air heating systems. The main physical principles are solar thermal energy and heat transfer, implemented on solar collectors and heat exchangers. As for the environmental aspect, domestic solar heating systems can reduce greenhouse emissions, alleviating global warming. Moreover, with the increasing demand for renewable energy due to the rising awareness of environmental protection, the marketing size of solar energy has become larger. Solar heating systems have been a fast-growing technology in many countries over the last decade. Compared with other energy, the price of solar energy is considered the cheapest, which can help consumers save around $5,000 with a payback time of 5 years. Therefore, the solar heating market will expand in the future because of carbon emission reduction and increasing efficiency.
Keywords: Domestic heater, Solar technology, System description, Environment, Economy

1. Introduction

Energy, the capacity to do work, has been inseparable throughout human history. People started from fire to electricity--energy has always been an essential part of our lives, such as heating water and living space. For that reason, heating systems are vital for domestic use. As a result, humans have been attempting to use the sun, specifically solar radiation as we often refer to it nowadays, to improve the quality of life since ancient times. Collectors have been invented and improved for centuries since the late 1800s for energy-gathering purposes [1].

A change of events that increased the utilization of solar heating systems is an agreement within the scientific community that climate change and the rising anthropogenic greenhouse gases are disastrous to the ecosystem. If not handled properly, this could become the sixth extinction that will end the human race. Due to this finding, the demand for clean and renewable energy has increased. The domestic solar heating system is one of them. This fast-developing industry does not release any pollution during its operation and is cheaper than the conventional electric heating system. Solar water heating system is expected to have a compound annual growth rate of 8.01% by 2025 [2].

This paper reviews the history, the physical principles, the technology implementation, and the typical domestic solar heating system. Moreover, the system's environmental impact, cost-effectiveness, and future development aspects will also be evaluated.

2. History of Domestic Solar Heating

Life on Earth is only possible because of the sun. Humans have been harnessing and using solar energy domestically in various ways for millennia. Undeniably, solar energy has become an essential part of our everyday life and energy generation. However, the history of domestic solar energy development, various types of domestic solar energy systems, advantages and challenges of those systems are not entirely popularized yet among the general public.

The first licensed solar water heater was created in 1891 by Clarence Kemp for a commercial purpose. Kemp believed solar heat could be collected and stored by exposing metals to the sun. Kemp invented an elliptical cross-sectioned water-containing tube in his water heater system to maximize the water surface exposed to the sum. Small pipes unite the tubes, allowing cold water to enter from one side, heat up along the wired tubes, and come out as warm water on the other. The array of tubes enables the speeding up of the heat transfer and the rejection of the cold water contacting the warm water. Kemp found some

clients for his device and named his heater “CLIMAX” [3].

Unfortunately, Kemp’s “CLIMAX” did not resist winter frost. As a result, it quickly became obsolete, especially after William J. Bailey patented his heater in 1909. He created the first thermosyphon system, which is more ergonomic. The system has an insulated tank placed on the roof with a collector underneath, allowing water to stay hot overnight. Bailey named his business the “Day and Night” solar water heater company. His heater flourished in states with abundant sunlight, such as California and Florida, before cheap natural gas was discovered [4].

3. Physical Principles

3.1. Solar Thermal Energy

The main idea of solar thermal heating is to convert the sun’s energy into heat, which will be used in many fields, such as industry, commercial, and residential areas [5]. As for our project, solar energy transfers heat into home heating systems through hot water and space heating[6]. The application of solar thermal energy focuses on flat-plate collectors, which will be discussed in the technology section, so its energy balance equation is analyzed in the physical principle part. Our calculation is under steady-state conditions. The difference between absorbed solar energy and thermal loss is the actual useful energy, so the equation of energy balance, which is from the PennState College of Earth and Mineral Sciences course website, can be shown as follows [7]:

$$Q_u = A_c[S - U_L(T_{plate} - T_{ambient})] \quad (1)$$

Where Q_u is the actual useful energy, A_c is the area of the collector surface, S is the absorbed solar radiation, U.L. is the total loss, T_{plate} is the temperature of the absorbing plate, and $T_{ambient}$ is the air temperature.

Thermal efficiency is an important parameter to show the collector’s performance and make further modifications. The equation of thermal efficiency (η) is shown below [7]:

$$\eta = Q_u / (A_c G_T) \quad (2)$$

where G.T. is the incident solar radiation flux.

3.2. Heat Transfer

Heat transfer is a process function that describes thermal energy generation, use, exchange, and conversion by energy carriers such as photons and fluid particles. Heat transfer (Q) can be calculated by the product of mass (m), specific heat(c), and temperature difference (ΔT). The equation of heat transfer is illustrated below:

$$Q = mc\Delta T \quad (3)$$

3.2.1 Solar Water Heating System-Heat Transfer Fluid

The working principle of heat transfer fluid (HTF) is collecting heat from the collector and transmitting it to the heat exchanger. The HTF is chosen based on boiling point, freezing point, viscosity, etc. Water or glycol-water mixture (Glycol/water mixtures have a 50/50 or 60/40 glycol-to-water ratio. Non-toxic propylene glycol known as “antifreeze”) can provide good performance on solar water heating systems [8].

3.2.2 Solar Air Heating System-heat Conduction

The physical principle applied to solar air heating is heat conduction. Heat conduction is the heat movement between two objects with different temperatures when they contact each other. As for the micro aspect, conduction is the heat transfer in a solid or a stationary fluid (gas or liquid) due to the random motion of its constituent atoms, molecules, or electrons. The equation of heat conduction is shown below [9]:

$$Q = KA(T_{hot} - T_{cold})t/d \quad (4)$$

where Q is heat transferred, K is thermal conductivity, T_{hot} is hot temperature, T_{cold} is cold temperature, t is time, d is the thickness of the material, and A is the area of surface

4. Technology Implementation

4.1. Solar Water Heating System

Solar water heating system includes three major components: solar collector, heat exchanger, and storage tank.

4.1.1 Solar Collector-Flat Plate Collector

The solar collector concentrates the sun’s radiation and transfers it to the moving liquid. The flat plate collector (FPC), as shown in Figure 1, is a medium-temperature collector usually used for heating water for residential use. FPC includes four parts: the absorber plate, fluid flow network, insulation, and the outer box. The solar thermal energy principle is applied to the absorber plate. The absorber plate is made up of highly selective material with a coating of non-selective material, which can absorb heat from the sun’s radiation [10].

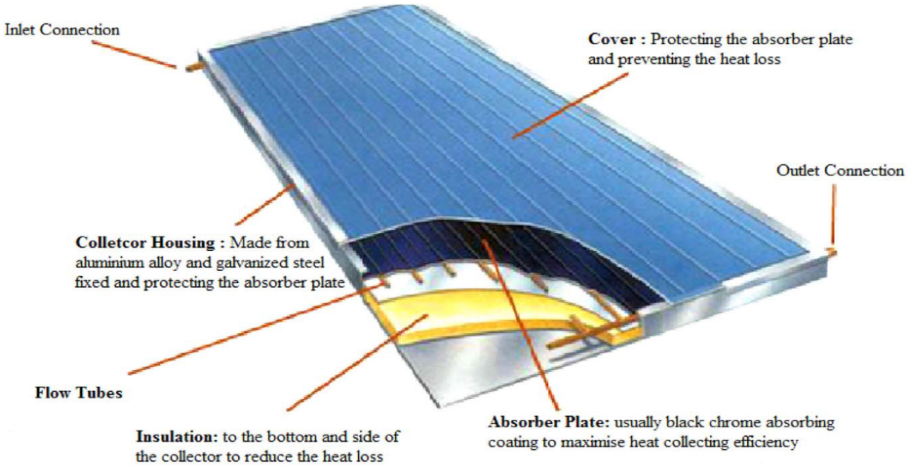

Figure.1. A flat plate collector structure. Adapted from 'A review on technical improvements, economic feasibility and world scenario of solar water heating system,' by A.Gautam, A.Kumar, S.Chamoli and S.Singh, 2017.

4.1.2 Heat Exchanger

The heat transfer principle is applied to heat exchangers. Thermal energy is transmitted from the collectors to the storage tank by indirect circulation in the exchanger. The heat exchanger is made of materials with good thermal conductivity and high corrosion resistance, such as copper, steel, bronze, etc. A mantle heat exchanger with a gap of 10mm used in a solar water heating system with FPC can make the daily efficiency reach up to 50%. Additionally, the heat exchanger with a single row works better than the double-row heat exchanger [10].

4.2 Solar Air Heating System

The outer surface can classify solar air collectors. There are two types of solar air collectors, unglazed and glazed solar collectors. The recirculating types-glazed solar collectors are usually used for space heating. The collector includes an absorber material with a selective surface which can increase operational efficiency. It captures sun radiation, and then this solar thermal energy is transferred to air via conduction heat transfer. Air typically passes along the front or back of the absorber plate while scrubbing heat directly from it. After that, heated air will be transferred to the building space for air heating. A glazed air system only works when the air temperature in a solar collector is higher than the building temperature [11].

5. Typical System Description

As mentioned previously, there are two main categories of domestic solar heating systems: active and passive [12]. The active solar heating system will be discussed in detail in this section.

5.1 Solar Air Space Heating Systems

The solar air space heating system is one of the most typical active heating systems. Using room air heaters directly warms up the living space with an air heater mounted on the roof or the wall. The heater pulls cold air into a solar collector, heating the cold air in the collector and blowing the warmed air back into the room. Ducts and holes are implemented through the walls for the heated air to get pushed into the room for roof-mounted and wall-mounted heaters, respectively. The system has been well-popularized in the U.S., with around 10,000-50,000ft² systems installed on a single wall [12].

5.2 Solar Water Heating Systems

The solar water heating system uses hydronic systems by absorbing solar radiation, converting it into heat, and transferring the heat energy with non-toxic antifreeze. The system can quickly increase the liquid's temperature up to 10 ° –20 ° F (5.6 ° –11 ° C) by passing it through the collector [12]. The warmed fluid then flows to a heat exchanger or a water storage tank. These solar water heating systems are categorized into three more specific types: radiant floor, hot-water baseboard, and central forced air systems [13].

5.2.1 Radiant Floor System

In a radiant heating system, heat is radiated into the room due to warm liquid flowing through a system of pipes implemented under the carefully designed thin concrete floor. There are a variety of advantages to this system. One of the major advantages is that a separate heat storage tank can be eliminated. However, this is only true when the flooring is carefully designed. A conventional boiler or a standard domestic water heater is enough to supply backup heat. Once the system is in operation, consistent

heat is guaranteed throughout the entire space. Of course, there are also some disadvantages to the system. For example, tile is one of the most ideal flooring materials. On the contrary, thick rugs or carpets can hinder the system's efficiency. Moreover, the radiant floor system usually takes longer to heat space from a cold start than other heat distribution systems [12,13].

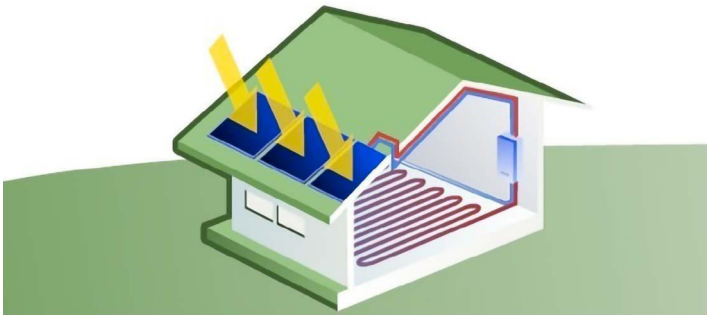

Figure. 2. Conceptual sketch of the radiant floor system. Adapted from 'Solar heating systems and the art of minimizing electricity bills,' by Jagpreet Sandhu, 2020, Solar Reviews.

5.2.2 Hot-Water Baseboards System

The baseboard hot water system gets its name because it is installed at the baseboard of the ground or sometimes close to the ground. This design allows a natural rise of heat and even heat distribution. A system of pipes, which pump hot water, transfer heat from the warm water to the room, and pipe cool water back to the boiler room for reheating, is installed in the baseboard. Typically, these fin-shaped pipes are manufactured with copper. This can ensure faster heat dispersion [12].

5.2.3 Central Forced Air System

Uniquely, a forced-air heating system does not use hot water to heat homes. Instead, fuels, such as propane or electric heaters, are implemented. It is originally converted from a liquid heating system and works best for central heating. This was done by putting a heating coil, a liquid-to-air heat exchanger, in the air-return duct in a space. The solar-heated liquid heats the air in the exchanger as the air is drawn into the duct. These two components--the duct and the coil--work together, which enables the solar-radiation heated water to circulate through the system. However, one of the major drawbacks is the coil size--it must be large for the deposit of an adequate amount of heat into the room at the least operating temperature of the collector [12].

6. Environmental Impact

6.1 Introduction

Ever since the industrial revolution, the surface temperature on Earth has risen about 1 degree Celsius. If the Earth warms up by another 1.5 degrees Celsius, it will be warm enough to melt the ice glaciers and cause rising sea levels [14], leading to a substantial increase in natural disasters. A rising temperature can also cause pollution, lack of food sources, ecosystem disruption, etc. The cause behind climate change is the over-emission of greenhouse gases. These gases are emitted by burning coal, gas, and oil to produce energy. The goal is to limit global warming below 2 degrees Celsius compared to pre-industrial levels. Because of this, the development of renewable, carbon-free energy technologies is urgently needed. Domestic heat has always been the biggest consumption in residential energy use. In the U.S., 51% of household energy consumption was used for domestic heating in 2018 [15]. Due to the staggering increase in rising temperatures, the world urges renewable technologies to protect the environment.

6.2. Detriments of Solar Heating Systems

One way to collect solar energy to heat water is to use solar P.V. panels. Collecting solar radiation, it operates the electrons inside the panels to create electricity. Then, the electricity can be used to operate a heating system. The problem is that there could be environmental pollution during manufacturing, operation, and recycling.

6.3 Pollution During Manufacture

Photovoltaic panels contain a chemical element called silicon, essential in a photovoltaic cell. The problem with silicon is that they require significant energy to manufacture. Due to this reason, the manufacture of silicon could cause CO2 emission. This problem is even worse when developing countries like China have twice as much carbon footprint for solar panels as Europe [16]. Another reason is the recycling issues, which will be discussed later. Even though producing solar cells requires a lot of input energy, they can repay the energy. For most systems, it usually takes two years, some as soon as six months [17]. Manufacturing silicon also includes purifying metallurgical-grade silicon into polysilicon.

However, doing so can produce a by-product called silicon tetrachloride ($SiCl_4$). Which, when mixed with water and moist air, can cause corrosive hydrogen chloride gas(HCl) [18]. HCl in humans can cause coughing, pain, inflammation, edema, and desquamation in the upper respiratory tract [19]. Another step during the manufacture of solar collectors involves the manufacturing of wafers. During this process, manufacturers use hydrofluoric acid to purify the wafers. If it is not taken care of and disposed of properly, it can destroy tissues and decalcify the bones of living organisms [17]. The manufacturing process of solar panels is complicated. If not careful enough, the environmental pollution it will cause is irreversible.

6.4 Pollution During Operation

Another potential environmental pollution for using a solar water heating system is during operation. For a silicon-based solar P.V. panel water heating system, there is a possibility of fast aging and degradation of power generation leading to possible fire due to the panels' environment. Researchers found a 2% chance fire will occur to P.V. panels, 0.6% in residential areas [20]. Although solar heating systems are mostly safe, there could still be dangers if they are not properly manufactured and utilized.

6.5 Recycle Problems

The biggest environmental issue of solar power is during the recycling process. Only the E.U. and a few other countries defined P.V. panels as e-waste. In most countries, they fall under regular waste groups. At the current growth rate, considering the average lifetime of P.V. panels is 25 years, P.V. waste is expected to reach about 4%-14% of total generation capacity by 2030 and over 80% (about 78 million tonnes) by 2050 [21]. This will not only have potential pollution, as listed, but it will also lose a recoverable value of $15 billion by 2050 [22]. Even if recycled as e-waste, 60%-90% of them could be illegally traded and dumped [23], creating even bigger problems. However, the P.V. manufacturers have been working with government institutions to resolve these issues. For instance, to ensure the quality of solar technology, the Environmental Protection Agency (EPA) has introduced regulatory standards that aim to implement technology and financial plans to reduce the possibility of accidents [2]. The pollution caused by the manufacturing, operation, and recycling of domestic solar heaters could significantly impact the environment if for the lack of expertise.

6.6 Environmental Benefits of Solar Heating Systems

Although there might be potential determinants of domestic solar heating systems, the benefits they bring to reduce greenhouse gases should not be ignored. A household uses about 64 gallons of hot water daily and about 235 - 250 therms of natural gas per year. Implementing solar water heaters will save 116 therms of natural gas (50%-80%) in one year. This will save about 1.12 tons of greenhouse gases and $235 - $250 per household annually [24].

6.7 Conventional Electric Heating Systems V.S. Solar Heating Systems

Traditional electric heaters have benefits such as heating and cooling water faster than solar heaters. Still, the environmental impact it creates is why more solar heaters are being implemented. Solar water heating has significantly fewer environmental effects than traditional electric water heaters. First, solar water heaters do not generate greenhouse gases during operation, while electric water heaters, served by Great River Energy (GRE), have an annual emissions rate of 1,607 pounds per MWh [25]. Residential households, with an average of 4 people, can produce about 3 tons of CO2 per household per year [26]. Installing a solar water heater will save at least 3 tons of CO2 during operation.

6.8 Water Saving

Another benefit that solar heating systems bring is saving water used. Solar collectors require a lot of water during manufacturing. Cleaning, cooling, chemical processing, and air pollution control require abundant water to produce photovoltaics. Among them, the largest water-consuming process is during cleaning [17]. Even so, solar panel water usage is significantly smaller than fossil fuel power plants. In 2005, as shown in Figure 3, 41% of U.S. freshwater was withdrawn for thermoelectric. In 2017, thermoelectric power plants in the U.S. used 52.8 trillion gallons of water, with water withdrawn to a kilowatt-hour generated 13 gallons in 2017 [27].

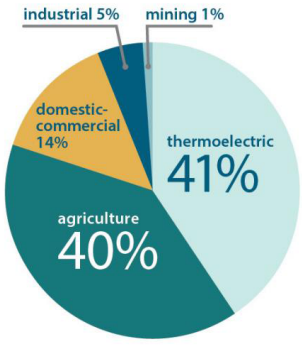

Figure. 3. U.S. freshwater withdrawals in 2005. Adapted from 'Union of Concerned Scientists,' by Kenny et al., 2009, USGS data.

Domestic Solar Heating systems can help reduce

greenhouse gas emissions and a huge amount of water.

6.9 Why Is It Clean?

For an energy source to be clean, it must not release greenhouse gases or pollutants [15]. If the solar heating system is properly produced and recycled, it is considered a clean energy source; because it directly utilizes the sun's energy. They do not produce pollutants or greenhouse gases during their operation.

6.10 Summary

There are potential issues with producing and operating domestic water heaters. But if they are properly manufactured and recycled, they can bring many environmental benefits. Domestic solar heating systems could help reduce the residential emissions of heating significantly. They do not release greenhouse gases during their operation and can help reduce water usage since they do not rely on fossil fuel power plants. Domestic solar heating uses a clean energy source.

7. Economics of Domestic Solar Heating

7.1 Introduction

Due to the global awareness of climate change, the need for renewable energy has increased. As the demand increased, so did the market size. The world's renewable energy market was valued at $928.0 Billion in 2017 [28]. Among the renewable energy sources, solar energy is the fastest-growing electricity source. Generates about 505 GW of electricity in 2018 (2% Global) [29]. One factor that caused the increased demand and supply of solar power is the result of falling prices. The World Energy Outlook 2020, published by the International Energy Agency, confirmed that solar is now the cheapest form of energy. The fast-growing use of solar power has created more opportunities for different solar power technologies. Solar water heaters, for instance, seek an increase due to the greenhouse gas effects caused by electric water heaters, which have an annual emission of 3 tons of carbon dioxide [26]. Because of this significant emission, government institutions demand solar water heaters.

7.2 Annual Growth

Solar water heaters have been a fast-growing heating technology in countries such as China over the last decade. The market size for solar water heaters in 2016 was valued at $2.05 billion in 2016, expected to have a compound annual growth rate of 8.01% by 2025 [2]. One reason that they are growing so fast has to do with the government institutions.

7.3 Government Implementations

To help the reduction of greenhouse gases emission, governments have found ways to take action in renewable energy production. For example, the U.S. federal government presented a corporate tax to help the effective utilization of solar energy products. The credit limit has been ascertained at 30%. This corporate tax has validity until 2022. This tax will help increase production efficiency and decrease production costs, which will help boost the growth of solar technology [2]. Governments' implementations and regulatory standards have helped boost solar technology development.

7.4 Recycling

Just like mentioned in the environmental impact section, recycling solar panels is a huge problem that will limit the growth of solar technologies. If proper infrastructure and management are in place, we can substantially increase solar technology development and economic growth. There are many benefits of P.V. recycling. First will be able to create more jobs creating demands and supplies to help the economy's growth. Second, it will be able to have a recoverable value of $15 billion by 2050. Lastly, recycled materials will be able to produce 2 billion new solar panels, producing about 640 GW [22]. Overall, recycling old solar panels will create more jobs, save money, and reduce spending.

7.5 Competitive Market

To convince people to use renewable energy instead of fossil fuels. Domestic solar heating systems rely on solar power and are considered the cheapest energy [30]. On average, a solar water heating system is about to generate about 1702 kWh per year. Consumers can save around $5,000, with a payback time of 5 years [31]. Solar energy is one of the biggest competitors in replacing fossil fuels.

7.6 Price Reduction

Installing solar heating systems can also help reduce the cost of spending. According to research, it will be able to drop water heating bills by 50%-80%. Not to mention that the possibility of increased prices of fuels would be ignored since solar power will just become cheaper and cheaper [32]. Solar electricity's dropping price was underestimated in 2019. It was 20-50% cheaper than the estimation in their 2019 outlook [33].

7.7 Summary

Due to the demands for renewable and cheap energy, domestic solar heating systems are a fast-growing type of technology in countries such as China and India. They are extremely competitive compared to conventional electric heating systems since solar has become the cheapest form of energy. The market of domestic heating

systems can even seek a larger increase if better recycling infrastructures are in place.

8. Conclusions & Future Prospects

In conclusion, people have been implementing solar energy domestically for many years. Active heating systems (solar water and air heating systems) are investigated in technological, environmental, and economic fields. The conversion of solar energy into thermal energy and heat transfer are the main working principles for solar heating systems. In addition, as for the environmental aspect, global warming is the major and most dangerous environmental issue. Domestic solar heating systems can reduce 1.12 tons of greenhouse gases per household annually, alleviating environmental pollution problems. However, if the heaters are not properly manufactured and recycled, they could still have potential harm to the environment. For instance, corrosive gas will likely be generated during manufacturing. Moreover, among the renewable energy sources, solar energy is the fastest-growing source. Due to the high recycling efficiency, there are significant recycling benefits shown by the huge energy produced and high recoverable value. Solar heating systems are cheaper than conventional heating systems, so installing a solar heating system can decrease the cost and drop water heating bills by 50%-80%. If better recycling infrastructures can be achieved, the market for domestic solar heating will be larger.

Due to global warming, people are encouraged to use renewable energy, so the solar heating system will be more widely used in the future. Factors such as reducing carbon footprint and increasing efficiency are likely to expand the solar heating market and increase the usage of solar heaters. The solar water heater market is expected to grow at a CAGR of more than 5.5% from 2021 to 2026 [34]. The system is a fast-growing technology in many countries, such as China. The price is very competitive compared to fossil fuels since it is currently the cheapest source.

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