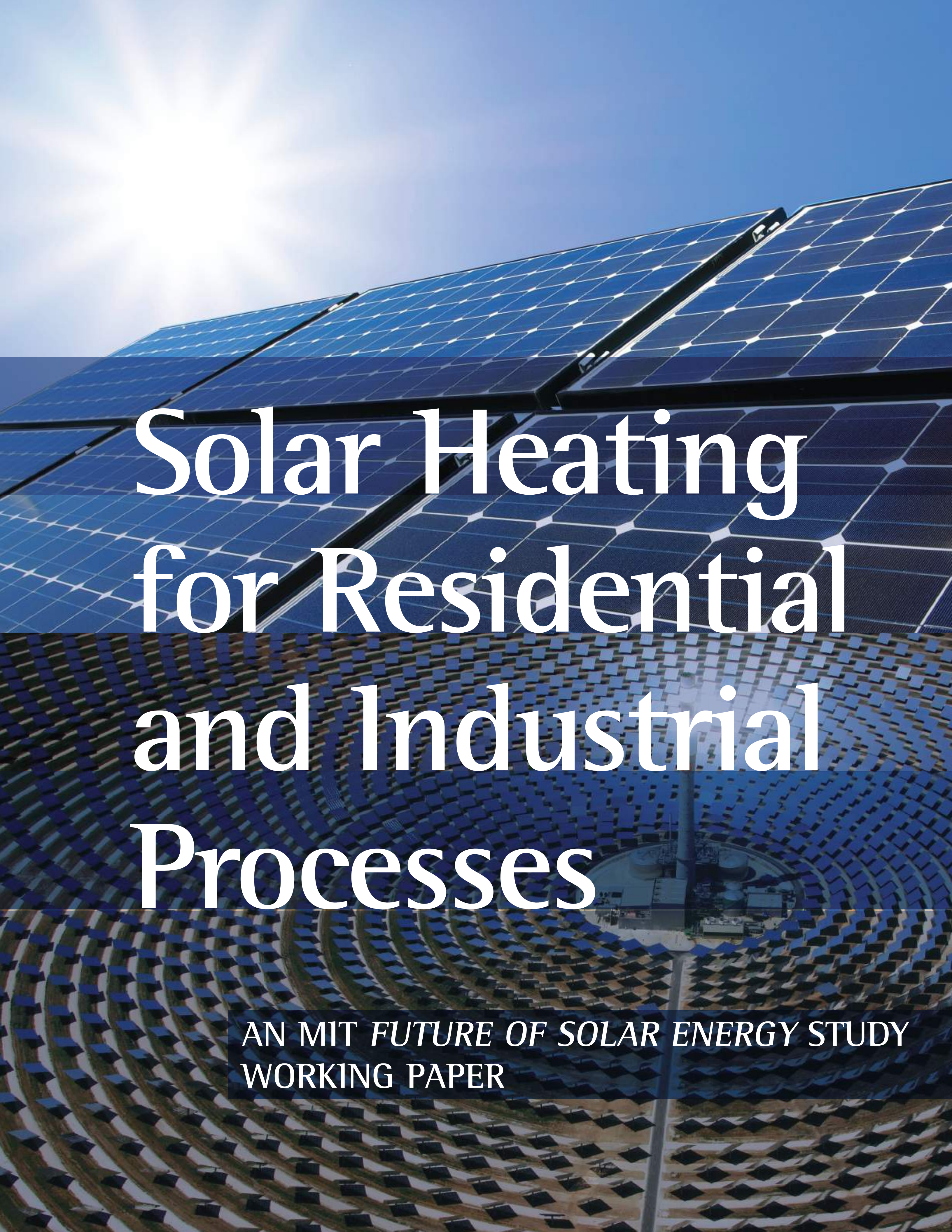

Solar Heating for Residential and Industrial Processes

AN MIT *FUTURE OF SOLAR ENERGY* STUDY
WORKING PAPER

Solar Heating for Residential and Industrial Processes

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MITEI-WP-2015-04

1. Introduction

The sun has been a primary heat source for humans since prehistoric times, but solar heating only began to be used on a large scale to produce hot water for domestic use in the 1960s, primarily in Australia, Israel, and Japan.[1] Over the past 15 years, China has emerged as the world leader in solar water heating (SWH) component manufacturing and end-use demand, as rapid economic development stimulated that country's market for SWH technology. Today, SWH is the most mature and widespread solar technology for generating heat, and its contribution to global energy use rivals that of other solar energy technologies like photovoltaics (PV) and concentrated solar (thermal) power (CSP).

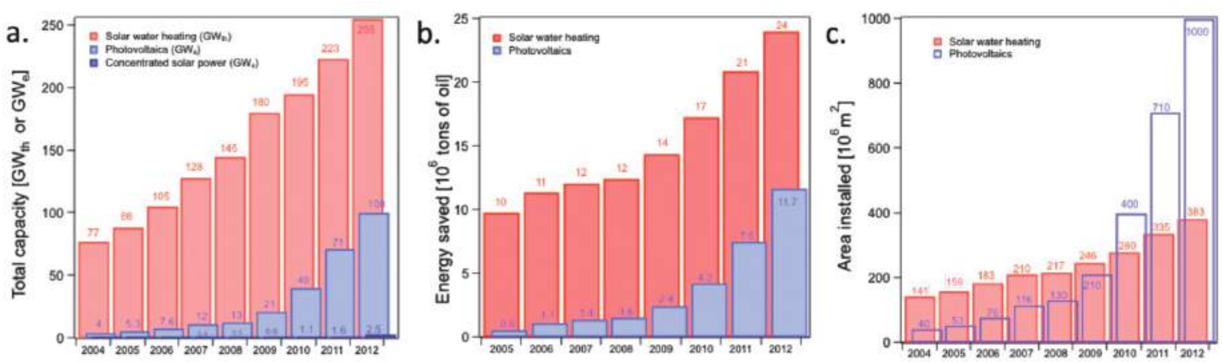
Since SWH converts sunlight into heat rather than electricity, there is no direct metric for comparing SWH, PV, and CSP deployment. Figure 1 displays three different ways of comparing SWH to solar technologies for generating electricity:

a) Total power capacity expressed as gigawatts of thermal power (GW_{th}) for SWH and as gigawatts electric power (GW_e) for PV and CSP,[i]

b) Energy saved expressed in metric tons of oil and,

c) Area installed.[2,ii]

Figure 1 Global Installed Capacity for Different Solar Technologies



Note: (a) Total cumulative power capacity installed worldwide for SWH, PV, and CSP. SWH capacity is expressed in GW_{th}, while PV and solar thermal are expressed in GW_e.[1] (b) Energy savings from solar technologies are expressed in millions of tons of oil. The chart shows that SWH displaces more fossil fuel for heat generation than any other solar technology. (c) Global area devoted to PV and SWH installations, in millions of square meters.[2,3,ii]

[i] SWH power capacity is measured in GW_{th}, which is a measure of thermal power. PV power capacity is measured in GW_e, which is a measure of electric power. The distinction is made because of the different uses of thermal and electrical energy, which must be considered when comparing the output of thermal and electric technologies. In particular, GW_e is fully converted to GW_{th} when electricity is used to produce heat; however, only about 30% of GW_{th} is converted to GW_e when heat is used to generate electricity.

[ii] The area for installed SWH capacity is calculated by using the conventional factor of 0.7 kW_{th}/m^2 to derive the nominal capacity from the area of installed collectors.[2] The area for installed PV capacity is calculated by assuming 10% efficient solar panels.

Installed SWH capacity has grown relatively slowly compared to other solar energy technologies (at approximately 16%, the average yearly growth rate for SWH from 2004 to 2012 is well below yearly growth rates for PV and CSP, which averaged approximately 51% and 38%, respectively, over the same time period). In addition, the low-grade thermal energy delivered by SWH technology is less widely useful than the electric energy delivered by PV systems.[i] In some countries, residential SWH systems have become nearly ubiquitous: 90% of all homes in Cyprus and Israel make use of SWH.[2] However, in the United States, less than 1% of households use SWH for residential water heating.

This working paper discusses market applications for solar heating, including SWH, solar space heating and cooling, solar heating for industrial processes, and solar cooking. These applications utilize relatively low temperatures (less than 150°C). Applications that require higher temperatures generally use concentrated sunlight and are mostly dedicated to electricity generation, as discussed in Chapter 3 of the MIT *Future of Solar Energy* study. This working paper surveys the current deployment status of solar heating technologies and assesses the potential of SWH in the residential and commercial sectors in the United States. SWH is too expensive to compete with natural gas water heating in the United States, but it can be an economical alternative to electric water heating in some geographic areas.

2. Applications

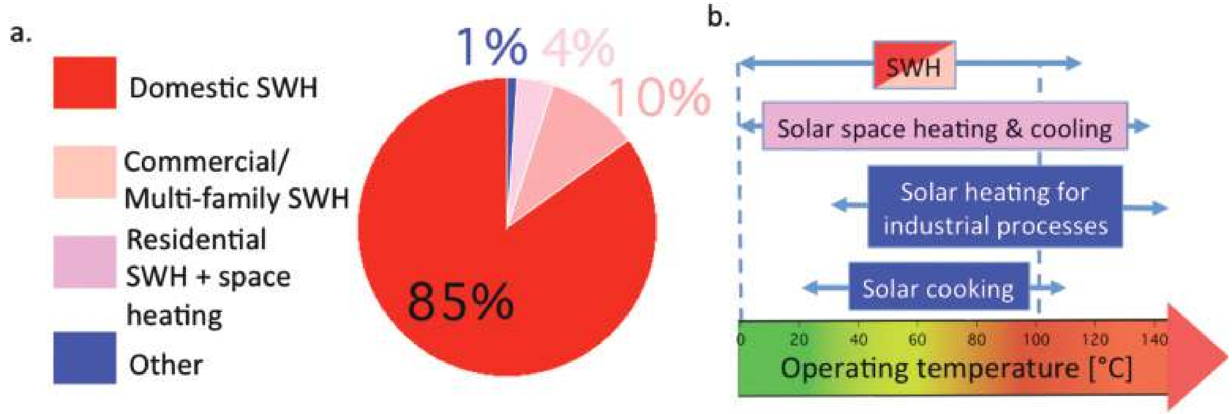
This section reviews leading applications for solar heating. SWH for domestic use stands out as the most developed application of solar heating when compared to commercial/multifamily SWH and residential systems that use SWH plus solar space heating, as shown in Figure 2a. Subsequent sections describe the main solar heating technologies and markets and identify key challenges for large-scale deployment. Our discussion includes three specific applications that account for remaining deployed solar heating capacity in addition to SWH: space heating and cooling (Section 4), heating for industrial processes (Section 5), and cooking (Section 6). All of these applications require the relatively low temperatures that can be achieved using solar heating systems, as shown in Figure 2b.

3. Solar Water Heating

In 2009, water heating for domestic uses accounted for nearly half (approximately 47%) of the total energy used in households worldwide. In the United States, water heating accounted for a much smaller fraction of overall household energy use — approximately 18%.[1] Electric and natural gas water heaters were the most common types of heaters used in developed countries in 2001 (at that time, electric hot water heaters were 44% of the U.S. water heater market, compared to roughly 49% for natural gas water heaters). By contrast, biomass stoves are more common in developing countries and in places where electricity or natural gas is unavailable.[5]

[i] SWH power capacity is measured in GW_{th}, which is a measure of thermal power. PV power capacity is measured in GW_e, which is a measure of electric power. The distinction is made because of the different uses of thermal and electrical energy, which must be considered when comparing the output of thermal and electric technologies. In particular, GW_e is fully converted to GW_{th} when electricity is used to produce heat; however, only about 30% of GW_{th} is converted to GW_e when heat is used to generate electricity.

Figure 2 Solar Heating Applications



Note: (a) The pie chart shows the share of global solar heating capacity used in different applications, indicating that domestic SWH is by far the largest application of solar heating technology at present.[4] (b) Operating temperatures for different solar heating applications. Note that solar cooking systems can reach temperatures as high as 300°C in designs that use parabolic mirrors (see discussion in Section 6).

Because the technology for heating water is simple, global water heating demand could be largely satisfied by SWH. Given the dominance of electric and natural gas water heating systems, however, SWH systems supply only 0.4% of current global energy demand for domestic hot water.[1] Even so, domestic hot water represents the largest single application of solar heating today, or approximately 85% of installed capacity (Figure 2a). The remaining market is divided between SWH for commercial/multifamily use (10% of overall capacity) and systems that combine domestic SWH and solar space heating, also known as combi-systems (4% of overall capacity). Space heating applications are described in detail in Section 4.

Though combi-systems are more complicated and less common than simpler SWH systems, a number of variations of combi-systems may be considered attractive for SWH. The most popular variation replaces the space-heating unit with a PV module, thus producing electricity and harvesting the waste heat that is generated by the PV modules for SWH. Capturing the waste heat also reduces the temperature of the PV module, thereby increasing the module's efficiency over conventional silicon PV modules. In another variation of the combi-system, the SWH unit is replaced with a thermoelectric generator. Thermoelectric devices use temperature gradients to generate electric power. However, combi-systems that consist of a PV module with a thermoelectric unit to harvest the wasted heat are primarily used for electric power generation.

TECHNOLOGY

A SWH system consists of a solar collector that absorbs sunlight and generates heat; a system for circulating the heat transfer medium, which could be water or an antifreeze mixture, so as to transport the collected heat; and a storage tank to store the heated water in an insulated environment.[4,6]

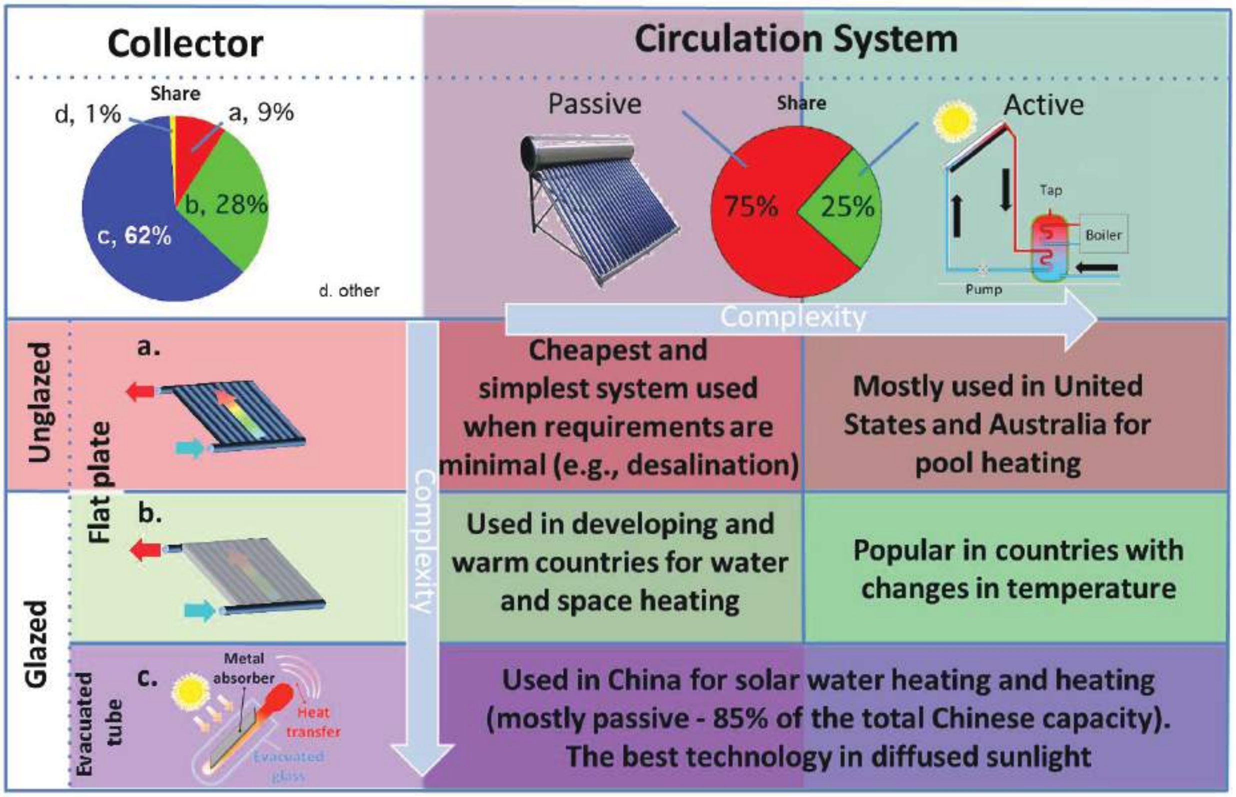
Solar Collectors

Figure 3 shows the three types of solar collectors that are used in SWH systems: unglazed and glazed flat-plate collectors and evacuated tube collectors.

(a) Unglazed flat-plate collectors are the simplest and least expensive type of collector. They consist of dark metal or plastic tubing through which the water to be heated is pumped. Since unglazed collectors lack any kind of insulation or frame, they are relatively low cost. This type of collector is primarily used with a pump to heat swimming pools.

(b) Glazed flat-plate collectors are another cost-effective collector option. Consisting of a metal absorber in a thermally insulated, rectangular housing, they are technologically simple and suited to environments that do not experience extreme temperature

Figure 3 Types of SWH Solar Collectors and Circulation Systems



Note: The pie chart in the left column shows the capacity share of different types of solar collectors used in SWH systems worldwide (listed in order of increasing complexity). The right column depicts active and passive circulation systems for SWH (listed in order of increasing complexity) and gives their worldwide capacity share. Each collector, coupled with a certain circulation system, has specific characteristics that are suitable for certain applications and in certain geographic markets.

variations (e.g., freezing conditions and wide temperature swings). In most countries with wide SWH deployment, flat-plate collectors represent the prevailing technology for domestic SWH. However, due to their popularity in China, evacuated tube collectors dominate the global SWH market.

(c) Evacuated tube collectors are the most efficient of the three types of solar collectors considered here. In these collectors, evacuated glass cylinders enclose metal absorber strips. The glass is evacuated to less than 1% of atmospheric pressure (1 kilopascal), as in the insulating wall of a thermos, to minimize heat loss from the absorber strip to the outside environment. The heat from the metal strips is then transferred to a heat transfer fluid, such as an antifreeze mixture, which remains liquid at high or low temperatures. These collectors are more suitable than flat-plate collectors in colder climates, although they tend to be more expensive. As already noted, evacuated tube collectors dominate the overall SWH market due to their popularity in China.

CIRCULATION SYSTEMS

Solar heating systems utilize one of two types of circulation systems (Figure 3). In an *active circulation system*, a pump circulates water between the hot water storage tank and the collector. A *passive circulation system* relies on the density differential between hot and cold water, rather than on a pump, to circulate the water. The hot water is then collected in a tank on top of the collector.

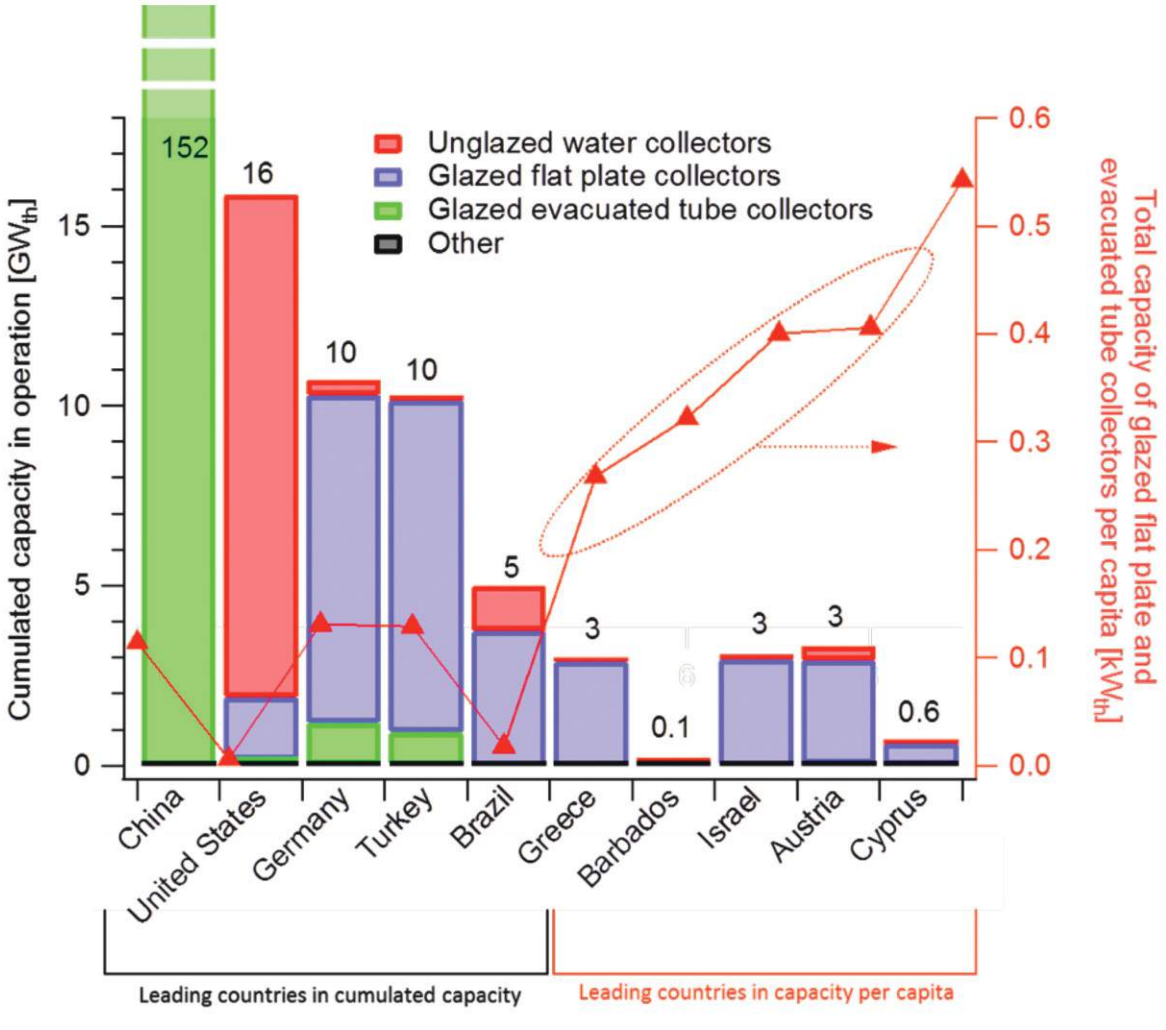
Active circulation systems are generally more efficient than passive systems, but they require some electrical energy to drive the pump. However, passive circulation systems are installed more widely than active systems due to their lower cost (Figure 3). Each collector type, when coupled with an active or passive system, has specific characteristics that make it suitable for certain applications and geographic markets.

SWH systems can also be *direct* or *indirect*. In a direct system, water is heated as it passes through a collector and is then delivered to the point of end use (e.g., showerhead, sink faucet, etc.). In an indirect system, the collector heats a heat transfer fluid (typically an anti-freeze mixture such as propylene glycol). The heat transfer fluid moves the heat to the storage tank through a heat exchanger and then to the end-use point when needed. Indirect systems are suitable for colder climates or locations where there is a possibility of freezing. Even in warmer climates, the heat delivered by solar collectors is usually insufficient to supply 100% of household hot water needs. For residential structures, the heat energy share provided by solar heaters, also known as the "solar fraction," ranges from 50% to 70%. Remaining heat requirements must be met using an auxiliary source, such as a conventional electric or natural gas heater.

CURRENT SWH MARKET PENETRATION

Figure 4 shows total installed SWH capacity for selected countries as of 2011, as well as a breakdown of the different types of collectors used in these systems (left axis). China is by far the market leader with more than 152 GW_{th} capacity in 2011. SWH has spread in China because it is cost competitive with electricity and natural gas in many regions that have high insolation as well as a poorly developed infrastructure for conventional heating. As a result of this high demand, China has a well-developed domestic SWH manufacturing base. The United States is second in SWH deployment, with the vast majority of its capacity in the form of unglazed flat-plate collectors used to heat swimming pools. SWH is deployed extensively in Hawaii where electricity is

Figure 4 Total SWH Capacity for Selected Countries in 2011

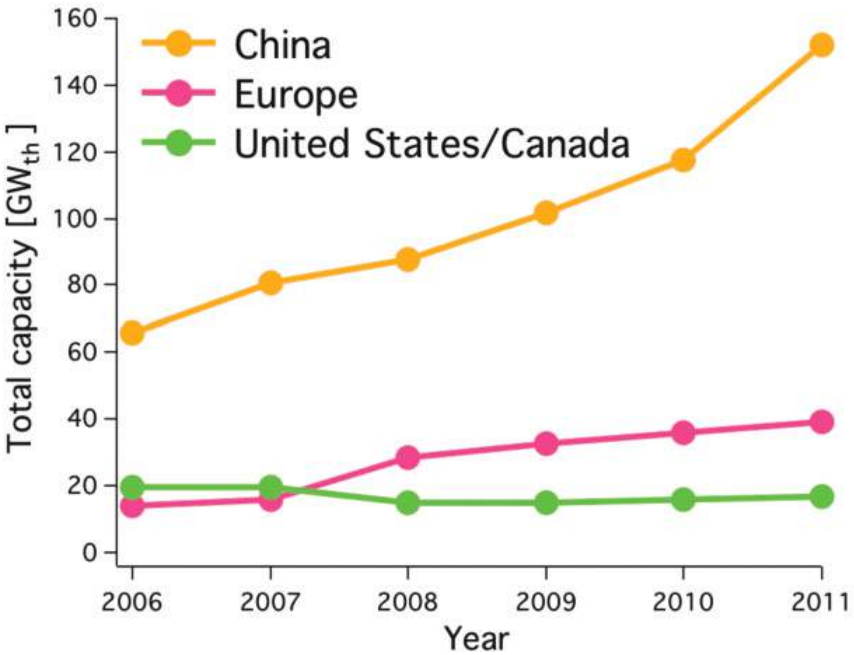


Note: The colors in the bar chart provide a breakdown of the different types of collectors used in installed SWH systems. Per-capita capacity per capita (considering only glazed flat-plate and evacuated tube collectors) is represented by triangular markers on the right axis (lines are to guide the eye). Data adapted from F. Mauthner and W. Weiss, Solar Heat Worldwide, 2013.[2]

expensive and access to natural gas is constrained.[7] European countries and Brazil are the other leading users of SWH; the systems deployed in these countries primarily use glazed flat-plate collectors. On a per-capita basis, the world leader is Cyprus, with 0.55 kWth of installed SWH capacity per capita (Figure 4, right axis).

Figure 5 tracks changes in installed SWH capacity from 2006 to 2011 in several world regions. China (and to a lesser extent Europe) is characterized by rapid growth due to an expanding market for residential and commercial solar hot water and heating. In contrast, there was zero growth in SWH capacity (or negative growth due to the limited lifetime of systems) in the United States and Canada over this time period, due to the fact that SWH technology in these regions is mostly used to heat swimming pools and has not diversified into other applications. Also, China leads the world in installed SWH capacity, accounting for half of installed capacity worldwide.[1]

Figure 5 Total Installed SWH Capacity over the Period 2006–2011 in Different World Regions



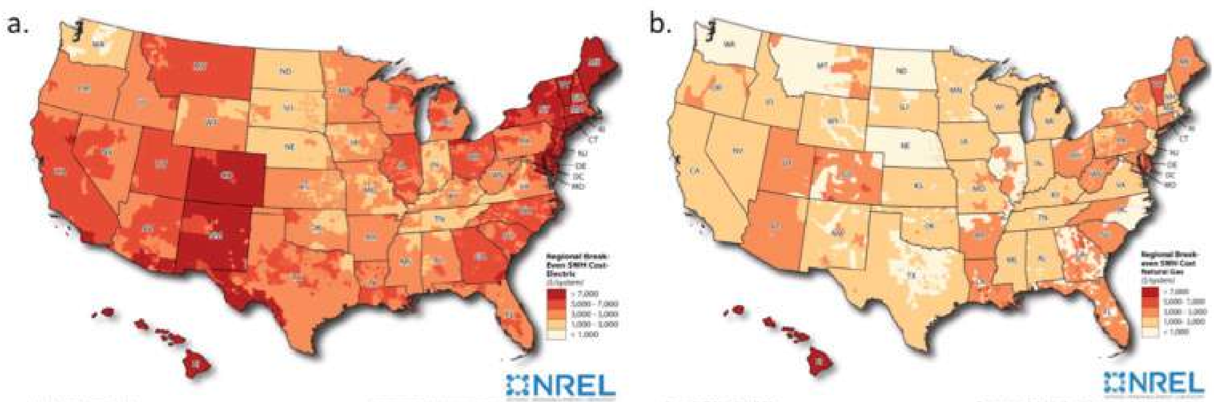
Data adapted from F. Mauthner and W. Weiss, Solar Heat Worldwide, 2013.[2]

ECONOMIC FEASIBILITY AND DEPLOYMENT POLICIES FOR SWH

The economic competitiveness of SWH systems depends on many parameters, such as local insolation, system size, government incentives, and the local price of electricity and natural gas.

A 2011 study by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) evaluated the breakeven cost of a SWH system, where breakeven cost is defined as the cost of the SWH system that is equal, accounting for any fuel costs associated with needed auxiliary heating systems, to the cost of a conventional water heating system plus fuel over its useful lifetime.[7] The NREL analysis considered domestic SWH systems in the United States and used 2008 data for conventional fuel costs. As shown in Figure 6a, the cost of a $7,000 SWH system was below the breakeven cost in a few states (e.g., Hawaii, Colorado, New Mexico, and several north-eastern states) where the conventional alternative was electric heat. In these situations, the lifetime cost of a SWH system was less than that of a conventional water heating system. However, when the conventional alternative is gas heating, SWH costs fall below the break-even point only in Hawaii (Figure 6b) where electricity costs are very high. Thus, even if electric heating were prevalent in all states, widespread adoption of SWH would be unlikely absent without substantial price reductions, subsidies, or favorable carbon pricing.[7] Overall, SWH is not broadly competitive with natural gas water heating in the United States, even at the relatively high natural gas prices that prevailed in 2008.

Figure 6 Breakeven Costs ($/System) for Residential SWH Systems in the United States (Assuming 2008 Conventional Fuel Costs)



Note: (a) Breakeven cost for a SWH system with an electric auxiliary water heater. (b) Breakeven cost for a SWH system with a natural gas auxiliary water heater.[7, iii]

[iii] Electricity price in the NREL analysis varies from 0.06 $/kWh (Idaho) to 0.27 $/kWh (Hawaii) and natural gas price varies from 0.91 $/therm (Utah) to 4.32 $/therm (Hawaii).

The cost-competitiveness of SWH technology varies across countries. A 2009 study of SWH systems in China, found that, despite higher equipment costs (for a hot water supply of 100 liters/day at approximately $279 per SWH unit compared to $185 for an equivalent electric water heater and $156 for an equivalent gas water heater), the longer lifetime and lower operating/maintenance costs of SWH systems resulted in lower average annual lifetime system costs ($29 for SWH, compared to $101 for an electric water heater and $87 for a gas water heater).[8]

Another study, however, found that — even with favorable economics — SWH faces additional barriers to widespread adoption, such as high up-front capital cost, reliability concerns, and, except in China, low public awareness. These barriers limit the number of SWH suppliers and retailers, which in turn leads to a lack of competition. High capital costs suggest that incentive policies may be warranted in many developing countries.[9]

In Tunisia, the government facilitated large-scale adoption of SWH systems through a combination of favorable financial and regulatory policies. Starting in 1997, a capital subsidy of 35% was available for all newly installed SWH systems. In addition, end-user financing was introduced widely through domestic banks in 2005. Under this program, lenders were encouraged to build dedicated SWH loan portfolios. Initial subsidies on capital and interest rates provided through participating banks were slowly phased out as demand grew. Currently, Tunisia retains some indirect tax incentives for SWH deployment, including exemption from value added taxes (VAT) and reduced duties on imported SWH equipment.[9]

Carbon pricing mechanisms provide another type of financial support that could help accelerate SWH technology deployment as a valuable component of climate change mitigation efforts.[10]

Finally, high SWH penetration rates in countries such as China (where SWH has reached 50% penetration in urban areas) and Israel (where 90% of domestic residences have SWH systems) are the direct result of successful support policies and other factors:[11,12]

1. **Concerted research and development (R&D) efforts** — Solar energy was given priority in R&D programs and regional strategies.

2. **Regulatory policies** — Energy-efficiency mandates and building regulations required the use of SWH in new construction. For example, since 1980, Israel has required that all new buildings incorporate solar technologies to meet at least part of their heating needs. In 2006, Spain mandated the installation of solar collectors on all new and renovated buildings. Portugal followed quickly with a similar mandate. In the United States, Hawaii now requires that all new single-family homes have SWH systems.

3. **Development of an integrated domestic supply chain** — As noted earlier, China has more than 3,000 SWH manufacturers serving its large domestic market.

4. **Favorable solar resources**

5. **Major subsidies and/or cost reductions** — These countries used a variety of economic incentives to promote SWH investment, including direct financial subsidies, low-interest loans, and regional investment subsidies.

6. **Public education for consumers and lenders**

7. **Training programs for installation and maintenance technicians**

8. **Stringent quality standards for system hardware with standardized product testing and product verification**

A combination of some of the above-mentioned policies, implemented at the right time, has also helped the SWH market grow in countries such as Tunisia and Barbados in recent years.[9]

4. Solar Space Heating and Cooling

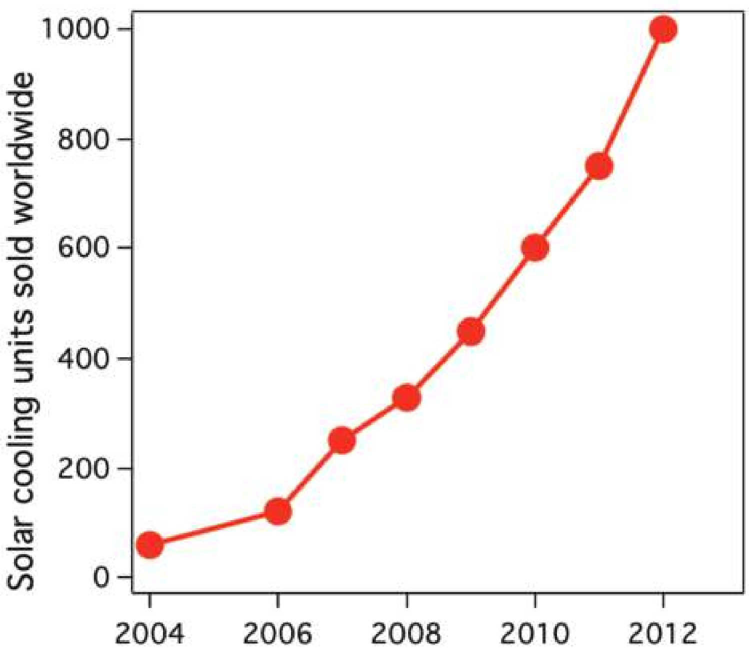
The next sections of this report discuss three applications of solar heating that do not involve water heating: 1) solar space heating and cooling, 2) solar heating for industrial processes, and 3) solar cooking. Although solar technologies have the potential to displace residential-sector use of fossil fuel and biomass in all of these applications, such technologies have not yet been fully developed and adopted. In 2009, space heating accounted for approximately 28% of total household energy consumption worldwide (the corresponding figure in the United States, approximately 41%, is substantially higher). Space cooling was responsible for 4% of household energy use worldwide and 6% in the United States.[13,14] In developed countries, electricity and natural gas are the most common fuels used for space heating.

Less than 1% of total solar heating capacity worldwide is currently used for space heating. Where solar space heating technology is deployed today, it is typically found in combination with SWH systems; these combi-systems are described in Section 3 of this paper. In active solar space heating systems, perforated dark metal panels are installed on the walls of a building, leaving an air gap between the plates and the wall. Vents allow ambient air to pass through the perforations, where the air is then heated and circulated. Passive solar space heating systems do not require any ventilation and are increasingly used for efficient space heating and lighting.[15]

Solar space cooling systems use sorbent (adsorption or absorption) materials (e.g., water and ammonia) or a solid/liquid desiccant (e.g., silica gel and zeolite). Solar heat is used to regenerate the coolant.[15] In other words, in these systems, the traditional electric compressor is replaced by a solar-assisted thermal sorption cycle. Because this technology is still under development and suffers from a lack of standardization, widespread adoption has been challenging. However, the number of solar cooling systems installed worldwide, including small (less than 20 kilowatt) and large (greater than 1.5 megawatt) installations, has grown in recent years (Figure 7).[1,2]

Some alternative cooling systems couple a traditional compressor-based air-conditioning system with a PV module to reduce energy usage. In these solar cooling systems, some electricity is still needed to run the attached elements, such as pumps and fans. One of the biggest advantages of these systems is that the daily peak of energy consumption for air-conditioning units coincides roughly with the hours of the day when insolation is most intense and PV output is highest. Thus, solar cooling systems are most effective at reducing cooling loads at those times when energy costs are highest.

Figure 7 Global Sales of Solar Cooling Systems



Data adapted from W. Weiss, I. Bergmann, and R. Stelzer, "Solar heat worldwide," AEE INTEC, Austria, 2011.

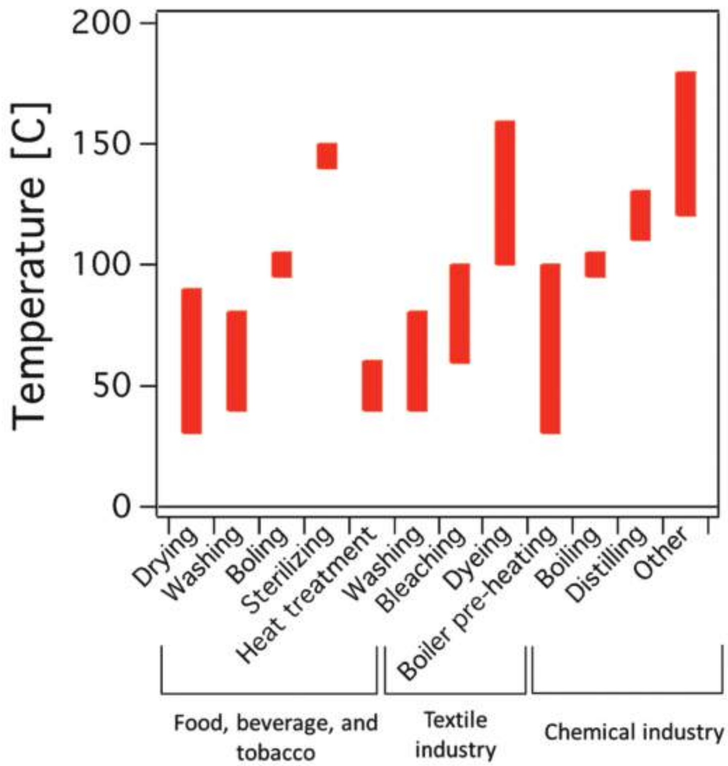
5. Solar Heating for Industrial Processes

In 2007, solar heating for industrial processes contributed a very small fraction — approximately 0.001% — of the total energy used for industrial processes worldwide. The technical potential for solar heating in industrial applications is estimated to total about 3.5% of overall industrial energy use.[16] In 2007 alone, industrial processes accounted for around 25% of total world energy demand. Currently, conventional fossil fuels supply most of the industrial sector's heat energy needs.[17]

The relatively modest temperatures that can be achieved using solar heating technologies (i.e., temperatures below 180°C) are potentially useful for many processes in the agriculture and industry sectors (including in the food, beverage, tobacco, textile, and chemical industries), as shown in Figure 8. In particular, cleaning processes (e.g., for containers and utensils/equipment in the food and chemical industries and for laundering in the textile industry) and subsequent drying processes often require temperatures in the range attainable with solar heating. Furthermore, it is often possible and cost-effective to retrofit solar heating technology because SWH equipment can be installed on existing water storage tanks. Other processes that can make use of solar heating include evaporation, sterilization, pasteurization (which needs temperatures below 105°C), and the preheating of boilers.

Finally, large-scale crop drying in the agriculture sector could significantly benefit from solar heating. For example, unglazed solar heat collectors are used to dry agricultural products in Switzerland.[17]

Figure 8 Range of Temperatures Required for Various Industrial Processes



6. Solar Cooking

Cooking accounted for approximately 21% of total household energy use worldwide in 2011 (approximately 4% of total household energy use in the United States) and about 5% of overall global energy use in all sectors.[17] In some developing countries, cooking can account for as much as 60% of total household energy use.[18] In developed countries, most cooking is done with conventional fossil fuels or electricity, whereas in developing countries, biomass is more commonly used. Solar cooking could displace the use of biomass, which is often a highly polluting and unsafe source of energy for cooking in developing country households. Solar cooking also generates positive social benefits in terms of providing energy security for rural households and time savings for people who otherwise have to devote hours each day to collecting biomass.

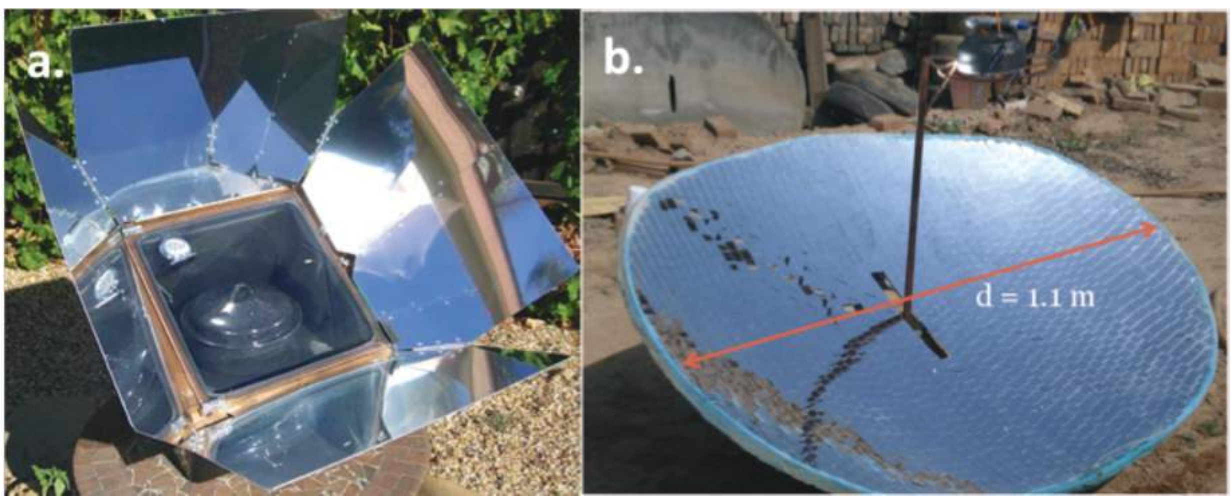
There are many types of solar cookers — for simplicity, we divide them into two groups: 1) box cookers (Figure 9.a) and 2) parabolic-shaped cookers (Figure 9.b).[19,20,21] Box cookers, the simplest and most cost-effective option, utilize both direct and diffuse solar radiation and can reach temperatures up to 150°C. Parabolic-shaped cookers are more sophisticated than box cookers; their efficiency depends on the quality and size of the optical system and on the presence of a tracking system. A collector area of approximately 1.5 square meters (m^2), as in Figure 9b, produces 600 W_{th}, which is comparable to the heat production of conventional commercial stoves (at approximately 1000 W_{th}).

An issue for solar cooking concerns its utility for evening meal preparation. To extend their use into evening hours, solar cookers may be integrated with heat storage systems (e.g., reservoirs filled with sand, vegetable oil, or a phase change material) or they can be combined with auxiliary electric heaters that operate on batteries or grid electricity.[22,23,24]

7. Conclusions

Solar heating can be used in a range of simple applications and markets. This paper has discussed the use of solar energy for water heating, space heating and cooling, industrial processes, and cooking. SWH — mostly for residential use — is by far the most deployed application for solar heat, with China being the largest market. The next largest market for SWH is the United States, where this technology is mostly used to heat swimming pools. In these countries, however, SWH accounts for only a very small fraction of the total energy used for water heating. SWH is much more

Figure 9 Solar Cookers



(a) Traditional box cooker with four reflectors (b) Concrete-based parabolic solar cooker widely deployed in other countries — in Cyprus, for example, 90% of all homes have SWH systems. A challenge for more widespread deployment of solar heating in the United States is to diversify solar heating technology to a wider range of applications in the residential, commercial, and industrial sectors.

Estimates of the cost of various SWH systems suggest that this technology is currently too expensive to compete with the leading incumbent natural gas technology in most areas of the United States. In these areas, subsidies, mandates, or a price on carbon would be required to overcome solar heating's current cost disadvantage. SWH systems are, however, competitive with electric water heating in several states. In other countries, favorable financial policies and incentives to overcome capital cost barriers have been successful at bringing about the relatively widespread deployment of SWH systems.

8. Acknowledgments

We thank Patrick Brown, Joel Jean, Timothy Osedach, Robert Stoner, and the entire MIT *Future of Solar Energy* study team for their valuable guidance, insights, and suggestions. We also thank Marika Tatsutani and Rebecca Marshall-Howarth for their thoughtful editing.

Notes

[1]"Technology Roadmap Solar Heating and Cooling," 2012. (OECD/IEA, 2012)

[2]W. Weiss, I. Bergmann, and R. Stelzer, "Solar heat worldwide," AEE INTEC, Austria, 2011.

[3]"Renewables GLOBAL FUTURES REPORT 2013. " REN21

[4]R. Shukla, K. Sumathy, P. Erickson, and J. Gong, "Recent advances in the solar water heating systems: A review," *Renew. Sustain. Energy Rev.*, vol. 19, 173–190, Mar. 2013.

[5]P. Denholm, *The technical potential of solar water heating to reduce fossil fuel use and greenhouse gas emissions in the United States*. National Renewable Energy Laboratory, 2007.

[6]K. Hudon, T. Merrigan, J. Burch, and J. Maguire, "Low-Cost Solar Water Heating Research and Development Roadmap," *Contract*, vol. 303, 275–3000, 2012.

[7]H. Cassard, P. Denholm, and S. Ong, "Break-even cost for residential solar water heating in the United States: key drivers and sensitivities," *Contract*, vol. 303, 275–3000, 2011.

[8]"Background Paper : CHINESE RENEWABLES STATUS REPORT," 2009.

[9]J. A. Haselip, I. Nygaard, U. E. Hansen, and E. Ackom, *Diffusion of renewable energy technologies: case studies of enabling frameworks in developing countries*. Danmarks Tekniske Universitet, Risø National laboratoriet for Sustainable Energy, 2011.

[10]B. S. Milton and S. Kaufman, "Solar Carbon Solar Water Heating as a Climate Protection Strategy : The Role for Carbon Finance," no. January, 2005.

[11]M. Raisul Islam, K. Sumathy, and S. Ullah Khan, "Solar water heating systems and their market trends," *Renew. Sustain. Energy Rev.*, vol. 17, 1–25, Jan. 2013.

[12]W. Li, G. Song, M. Beresford, and B. Ma, "China's transition to green energy systems: The economics of home solar water heaters and their popularization in Dezhou city," *Energy Policy*, vol. 39, no. 10, 5909–5919, Oct. 2011.

[13]"Residential Energy Consumption Survey (RECS) - Energy Information Administration." http://www.eia.gov/consumption/residential/

[14]*Energy Technology Perspectives 2014*. IEA, 2014.

[15]"Solar Energy Perspectives," 2011. (International Energy Agency, 2011)

[16]"Renewable Energy in Industrial Applications." *Renewable Energy in Industrial Applications* (UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION)

[17]C. Philibert, "BARRIERS TO TECHNOLOGY DIFFUSION: THE CASE OF SOLAR THERMAL TECHNOLOGIES," Oct. 2006.

[18]A. R. Carmody and A. U. Sarkar, "SOLAR BOX COOKERS : TOWARDS SUSTAINABLE ENERGY STRATEGY FOR SUB-SAHARAN AFRICA," *Renew. Sustain. Energy Rev.*, vol. 1, no. 4, 291–301.

[19]www.solarcookers.org

[20]N. L. Panwar, S. C. Kaushik, and S. Kothari, "State of the art of solar cooking: An overview," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, 3776–3785, Aug. 2012.

[21]M. Bansal, R. P. Saini, and D. K. Khatod, "Development of cooking sector in rural areas in India — A review," *Renew. Sustain. Energy Rev.*, vol. 17, 44–53, Jan. 2013.

[22]R. Amatya and R. J. Ram, "Solar Thermoelectric Generator for Micropower Applications," *J. Electron. Mater.*, vol. 39, no. 9, 1735–1740, Apr. 2010.

[23]A. Saxena, S. Lath, and V. Tirth, "Solar Cooking by Using PCM as a Thermal Heat Storage," *MIT Int. J. Mechancial Eng.*, vol. 3, no. 2, 91–95, 2013.

[24]R. M. Muthusivagami, R. Velraj, and R. Sethumadhavan, "Solar cookers with and without thermal storage — A review," *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, 691–701, Feb. 2010.

Acronyms

CSP	Concentrated Solar Power
GW_e	Gigawatt Electric
GW_{th}	Gigawatt Thermal
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
R&D	Research and Development
SWH	Solar Water Heating
VAT	Value Added Tax

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