Technology Roadmap

Solar Heating and Cooling

International Energy Agency

INTERNATIONAL ENERGY AGENCY

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Foreword

Current trends in energy supply and use are patently unsustainable – economically, environmentally and socially. Without decisive action, energy-related emissions of carbon dioxide (CO_2) will more than double by 2050 and increased oil demand will heighten concerns over the security of supplies. We can and must change our current path, but this will take an energy revolution and low-carbon energy technologies will have a crucial role to play. Energy efficiency, many types of renewable energy, carbon capture and storage (CCS), nuclear power and new transport technologies will all require widespread deployment if we are to reach our greenhouse gas (GHG) emission goals. Every major country and sector of the economy must be involved. The task is also urgent if we are to make sure that investment decisions taken now do not saddle us with sub-optimal technologies in the long term.

Awareness is growing of the urgent need to turn political statements and analytical work into concrete action. To spark this movement, at the request of the G8, the International Energy Agency (IEA) is leading the development of a series of roadmaps for some of the most important technologies. By identifying the steps needed to accelerate the implementation of radical technology changes, these roadmaps will enable governments, industry and financial partners to make the right choices. This will in turn help societies make the right decisions.

The global energy need for heat is significant in both OECD and non-OECD countries: in 2009 the IEA reported that global energy demand for heat represented 47% of final energy use. Solar heat thus can make a substantial contribution in meeting climate change and security objectives.

Solar heating and cooling (SHC) is a straightforward application of renewable energy; solar domestic hot water heating is already widely used in a number of countries but on a global level contributes to 0.4% only of energy demand for domestic hot water. Moreover, SHC also includes technologies for other purposes such as space heating and space cooling, and hot water for industrial processes. As different SHC technologies are at widely differing stages of development and use, policy support must offer custom-made solutions.

This roadmap envisages that by 2050, solar energy could annually produce 16.5 EJ of solar heating, more than 16% of total final energy use for low temperature heat, and 1.5 EJ solar cooling, nearly 17% of total energy use for cooling. For solar heating and cooling to play its full role in the coming energy revolution, concerted action is required by scientists, industry, governments, financing institutions and the public. This roadmap is intended to help drive these necessary developments.

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Executive Director

This roadmap was drafted by the IEA Renewable Energy Division in 2012. It reflects the views of the International Energy Agency (IEA) Secretariat, but not necessarily those of IEA member countries. For further information, please contact paolo.frankl@iea.org.

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Key findings

Solar heating and cooling (SHC) can provide low-carbon emission energy from solar resources that are widespread throughout the world. SHC describes a wide range of technologies, from mature domestic hot water heaters to those just entering the demonstration phase, such as solar thermally driven cooling. This roadmap envisages development and deployment of solar heating and cooling by 2050 to produce 16.5 EJ (4 583 TWh_{th}; 394 Mtoe) solar heating annually, more than 16% of total final energy use for low temperature heat, and 1.5 EJ solar cooling, nearly 17% of total energy use for cooling by that time. It would include the following contributions:

- Solar collectors for hot water and space heating could reach an installed capacity of nearly 3 500 GW_{th}, satisfying annually around 8.9 EJ of energy demand for hot water and space heating in the building sector by 2050. Solar hot water and space heating accounts for 14% of space and water heating energy use by that time.
- Solar collectors for low-temperature process heat in industry (<120°C) could reach an installed capacity of 3 200 GW_{th}, producing around 7.2 EJ solar heat per year by 2050. Solar process heat accounts for 20% of energy use for low temperature industrial heat by that time.
- Solar heat for cooling could reach a contribution of 1.5 EJ per year from an installed capacity of more than 1 000 GW_{th} for cooling, accounting for nearly 17% of energy use for cooling in 2050.
- Swimming pool heating could reach an installed capacity of 200 GW_{th}, producing annually around 400 PJ solar heat by 2050.
- By achieving the above mentioned deployment levels, solar heating and cooling can avoid some 800 megatonnes (Mt) of CO_2 emissions per year by 2050.
- Achieving this roadmap's vision requires a rapid expansion of solar hot water heating in the building sector, including in solar supported district heating, as well as in industrial applications. Dedicated policy support should overcome barriers related to information failures, split incentives and high up-front investments.
- While a number of industrial and agricultural processes can use low-temperature flat-plate collectors, advanced flat-plate collectors and concentrating technology should be further developed to produce medium-temperature heat. Industrial process heat offers enormous potential in sectors that use low- and medium-temperature heat for processes such as washing, leaching (mining industry), drying of agricultural products, pre-heating of boiler feed water, pasteurisation and cooking.
- The development of compact storage will allow heat to be used when the load is required, aiding the deployment of solar space heating in individual buildings. Dedicated research, development and demonstration (RD&D) resources could make compact storage commercially viable between 2020 and 2030.
- Solar cooling could avoid the need for additional electricity transmission capacity caused by higher average peak loads from the rapidly increasing cooling demand in many parts of the world. It can also allow for a more optimal use of solar energy applications for domestic hot water, space heating and cooling. With substantially higher RD&D resources, standardised, cost competitive and reliable solar cooling systems could enter the market between 2015 and 2020.

Key actions in the next ten years

Concerted action by all stakeholders is critical to realise the vision laid out in this roadmap. In order to stimulate investment, governments must take the lead role in creating a favourable investment climate for widespread use of solar heating and cooling. In particular, governments should:

- Create a stable, long-term policy framework for solar heating and cooling; establish medium-term targets to maximise the effective use of mature and nearly mature technologies, and long-term targets for advanced technologies that have yet to reach the market.
- Introduce differentiated economic incentives on the basis of competitiveness per technology by means of transparent and predictable frameworks to bridge competitive gaps. Incentives could for example be based on feed-in tariffs or renewable portfolio standards for commercial heat and subsidies or tax incentives for end-user technologies. Economic incentive schemes should be independent of state budget

procedures to avoid “stop-and-go” policies where, for example, sudden withdrawal of incentives can destabilise the market.

- Address barriers such as information failures, up-front investment of technologies, lack of quality standards and the ‘split-incentive’ problem (where the investor in SHC technology does not reap the benefits of reduced energy costs). This can be done through awareness raising campaigns, industry training and education, support for new business models and modified regulations.
- Provide RD&D funding and support mechanisms to enable promising pre-commercial solar heating and cooling technologies to reach high volume commercial production within the next 10 years.
- In developing countries, expand the efforts of multilateral and bilateral aid organisations to accelerate the deployment of mature and competitive solar heating and cooling technologies, addressing both economic and non-economic barriers.

Introduction

There is a pressing need to accelerate the development and deployment of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. This challenge was acknowledged by the ministers from the G8 countries, China, India and South Korea, in their meeting in June 2008 in Aomori, Japan, where they declared the wish to have IEA prepare roadmaps to advance innovative energy technology.

> *"We will* ***establish an international initiative with the support of the IEA*** *to develop roadmaps for innovative technologies and co-operate upon existing and new partnerships, including carbon capture and storage (CCS) and advanced energy technologies. Reaffirming our Heiligendamm commitment to urgently develop, deploy and foster clean energy technologies, we recognise and encourage a wide range of policy instruments such as transparent regulatory frameworks, economic and fiscal incentives, and public/private partnerships to foster private sector investments in new technologies...."*

To achieve this ambitious goal, the IEA has undertaken an effort to develop a series of global technology roadmaps. The roadmaps will enable governments, industry and financial partners to identify and implement the steps they need to take to accelerate the required technology development and uptake.

The underlying objective of this roadmap is to advance the global uptake of solar heating and cooling technology in OECD countries as well as in developing countries and transition economies.

Rationale for solar heating and cooling

Solar heating and cooling (SHC) technologies can have an important role to play in realising targets in energy security and economic development and in mitigating climate change. Solar heating and cooling technologies have specific benefits. They are compatible with nearly all sources of back-up heat and almost universally applicable due to their ability to deliver hot water, hot air and cold air. Further, solar heating and cooling technologies can increase resilience against rising energy prices as most costs are incurred at the moment of investment, ongoing operating costs are minimal and there is almost no exposure to the volatility of oil, gas or electricity prices. Local energy supply leads to reduced energy transmission, which enhances efficiency and cost effectiveness. Moreover, solar heating and cooling creates regional and local jobs – since a large portion of the value chain (engineering, design, installation, operation and maintenance) cannot be delocalised. Solar heating and cooling technologies based on flat-plate or vacuum tube collectors are relatively simple (mainly using basic raw materials such as metals), offering opportunities for local manufacturing and local economic development, in developing as well as developed economies.

In addition to replacing fossil fuels that are directly burned for heat production, solar heating technologies can replace electricity used for hot water and space heating. This would be especially welcome in warm climate countries without a gas infrastructure and lacking alternative heating fuels (*e.g.* limited biomass resources in cities). For example, in South Africa electric water heating accounts for a third of average household (coal-based) power consumption (IEA, 2009). Solar thermal cooling technology can also reduce electric grid loads at times of peak cooling demand by fully or partially replacing conventional electrically powered chillers or room air conditioning. Solar cooling technologies benefit particularly from the strong correlation between supply of the solar resource and energy demand for cooling. The addition of heat storage can also fully or partially cover cooling demand after sunset.

Solar heating and cooling technologies use renewable energy resources to generate heating and cooling while producing very low levels of greenhouse-gas (GHG) emissions (Box 1).

Definitions and opportunity analysis

Solar energy conversion consists of a large family of different technologies, with a broad range of applications. Whereas solar technologies can deliver heat, cooling, natural lighting, electricity, and fuels, this roadmap concentrates on the use of solar energy in heating and cooling applications.[1]

1 Technologies included in future deployment scenarios in this roadmap are solar hot water heaters, individual and collective solar combisystems for domestic hot water and space heating, solar supported district heating, solar air-conditioning and cooling, industrial process heat, and unglazed collectors for swimming pool heating. Other active solar heating technologies such as water treatment and seawater desalination and solar cooking are briefly discussed but were not included in the projection modelling exercise.

Box 1: Environmental and social impact of solar heating and cooling technologies

The production of a test solar hot water (SHW) system in Italy was calculated to produce about 700 kg of CO_2 – as a result of energy consumption and material use during manufacturing, installation, maintenance, disposal and transport – with emissions recovered within about two years of use of the equipment through the emissions saved by solar water heating (Ardente *et al.*, 2005). In Australia, the life-cycle emissions of a SHW system were also calculated to be recovered fairly rapidly, where a system would have about 20% of the impact of an electrical water heater and half of the emissions impact of a gas water heater (Crawford *et al.*, 2003).

Solar heating and cooling technologies in general do not have controversial side-effects such as visual impact, noise, odour or landscape pollution or subsidence. Few countries still have regulations hindering solar collector placement on roofs (often related to the visual impact on historic buildings). The use of free-standing thermosiphon systems (see "Current technologies") on flat roofs can be visually intrusive and, in some countries, has led to disputes over property rights. In China, some property management companies, *e.g.* in the municipality of Dalian, have objected to these systems. However, it is often not the collector that is considered a problem but rather the thermal storage above it. The recent development of pumped systems in high-rise buildings in China should consequently reduce this problem.

For reasons of clarity, this roadmap discusses active solar heating and cooling technologies only, leaving out passive solar heat technology.[2] Using solar energy for passive heat applications is comparatively straightforward, because any object placed in the sun will absorb part of the incoming solar radiation and convert it into thermal energy. However, specialised techniques used in "active" technologies allow for more efficient use of the captured solar heat. The selection of active collector technology (evacuated spaces, optical coatings or mirrors) depends on the application and the temperature at which heat is required. Temperature levels in active solar thermal technologies can vary from as low as 25°C for swimming pool collectors to 1 000°C in concentrated solar technology. The latter higher-temperature technology is typically used in power production, from which reject or excess heat can be used for other thermal applications. This principle of thermal 'cascading' can also be used in other solar thermal technologies and applications to increase total system efficiency, provide multiple services, maximise the solar fraction (solar heat utilisation) and ensure maximum system utility.

Several solar heating technologies are already relatively mature and can be competitive in certain areas in applications such as domestic hot water heating and swimming pool heating. Solar assisted district heating and low-temperature industrial applications are in the advanced demonstration stage and close to commercialisation in some European countries. Other applications, such as solar space cooling and solar space heating at medium and high temperatures (>100°C), although cost competitive under certain conditions, require further development to achieve cost effectiveness, market entry and widespread uptake. Targeted R&D, more demonstration, industry training and development, case study dissemination, and standards development are critical to ensuring significant levels of adoption.

Solar heat can contribute significantly to the global energy need for heat. In 2009, the IEA reported that global energy demand for heat represented 47% of final energy use, higher than final energy for electricity (17%) and transport (27%) combined.[3] The large proportion of heat in final energy demand explains the substantial contribution that renewable heat – and thus solar heat – could make in meeting climate change and energy security objectives. Solar heating and cooling technologies have the potential to make an even more significant

2 Passive solar buildings maximise the free inputs of solar energy as heat during cold seasons, and protect the building's interior from too much sunshine in warm seasons while allowing enough daylight to reduce the need for electric lighting. Passive solar technology is a very effective and cost-efficient technology but is distinct from active solar heating and cooling technology.

3 The remaining final energy is used for "non-energy use", covering fuels used as raw materials.

global contribution, through increased deployment in countries that have not yet discovered their potential and through a wider range of applications in countries that have shown continued growth in solar heat utilisation in past years.

Technology and product development will enable solar heating and cooling to enter new markets and service broad and changing energy demands throughout the season in cold as well as warm climate countries. Providing solar space cooling, solar space heating and hot water from one unit can maximise the solar fraction (the proportion of energy provided by solar), environmental outcomes and end-user benefit. This roadmap envisages development and deployment of solar heating and cooling by 2050 to produce 16.5 EJ solar heating annually, more than 16% of total final energy use for low temperature heat[4], and 1.5 EJ solar cooling, nearly 17% of total energy use for cooling by that time, following the IEA Energy Technology Perspectives 2012 2D scenario (2DS).[5]

Purpose, process and structure of this roadmap

This roadmap aims to identify the primary actions and tasks that must be addressed to accelerate solar heating and cooling development and deployment globally. Some markets are already experienced in this context, but many countries have only just started to consider solar heating and cooling technology as a possible contributor to their future energy mix. Accordingly, milestone dates should be considered as indicative of relative urgency, rather than as absolutes.

The IEA convened a first Solar Heating and Cooling Roadmap Workshop in Paris, France, on 28 and 29 April 2011, focusing on defining technology boundaries, economics and non-economic barriers. A second meeting in Kassel, Germany, on 28 August 2011 as a side event to the ISES Solar World Congress 2011 focused on technology development and discussed preliminary findings for the roadmap vision. A third workshop on 16 November 2011 in Beijing, China, concentrated on the specific challenges in China. A final workshop was organised on 2 December in Sydney, Australia, as a side event of the 49th Australian Solar Energy Society (AuSES) Solar 2011 conference. This workshop focused on solar heating and cooling in warm climates and sought to establish conclusions from the first three workshops.

This roadmap is organised into four major sections. It starts with the status of solar heating and cooling today, focusing on resources, technology and economics. It continues with a vision for future deployment of solar heating and cooling. After that, milestones for technology improvements are described. The roadmap concludes with the discussion of the policy framework required to overcome economic and non-economic barriers and support necessary RD&D activities.

This roadmap should be regarded as a work in progress. As global efforts to encourage solar heating and cooling advance, new data will provide the basis for updated analysis. Moreover, as the technologies, markets, and regulatory environments in the heating and cooling sectors continue to evolve, further analyses will need to be performed, existing analyses updated and progress against the roadmap monitored.

4 In this roadmap we use the following definitions for low, medium and high temperature heat, as was also used in the EU project Ecoheatcool (www.euroheat.org/ecoheatcool):
- low temperature heat lower than 100°C;
- medium temperature heat between 100°C and 400°C;
- higher temperature heat: over 400°C.

5 In 2009, worldwide final energy for heat was 173 EJ (IEA, 2012). In the *IEA Energy Technology Perspectives 2012* 2DS final energy for heat is projected to be 198°EJ in 2050 (IEA, *ibid*).

Solar heating and cooling today

Development of solar heating and cooling

Solar heating

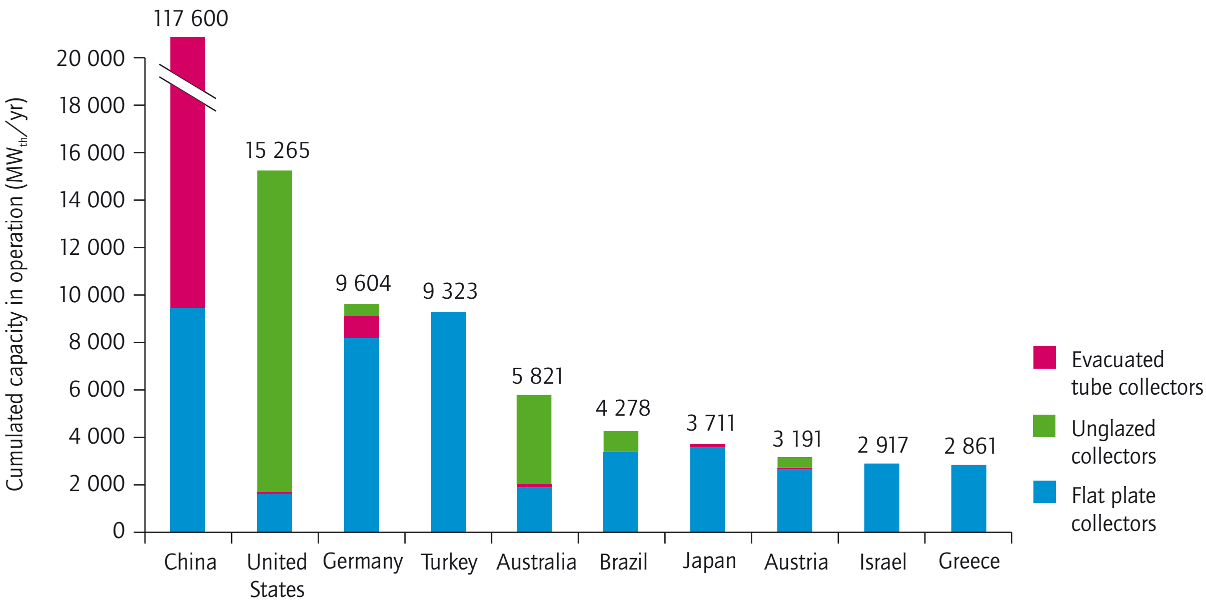
Solar heat can be captured by a variety of technologies and utilised in a wide number of applications. The most mature technology, the solar domestic hot water system, has a long history but was first deployed on a large scale in the 1960s in countries such as Australia, Japan and Israel (IEA, 2011a). Since then some markets have shown strong increased deployment as a result of the introduction of long-term subsidy schemes or solar obligations (*e.g.* subsidies in Austria and Germany, and solar obligations in Israel) or as a result of solar hot water systems' competitive advantages over alternative technologies (*e.g.* Cyprus). Over the past 15 years, China's economic development has spurred the market for solar hot water heating in terms of both system component manufacture and end-use demand.

By the end of 2010, the solar thermal collector capacity in operation worldwide equalled 195.8 GW_{th}, corresponding to 279.7 million square meters; by the end of 2011 it was estimated to have grown by 25%, to 245 GW_{th} (Weiss and Mauthner, 2012). Of this, 88.3% comprised flat-plate collectors (FPC) and evacuated tube collectors (ETC), 11% unglazed water collectors and 0.7% glazed and unglazed air collectors.

The vast majority of glazed and unglazed water and air collectors in operation are installed in China (117.6 GW_{th}), Europe (36.0 GW_{th}), and the United States and Canada (16.0 GW_{th}, mostly unglazed collectors), which together account for 86.6% of total installed (Figure 1).

The market for solar heating technology has seen substantial growth rates over the past decade, especially in Europe and China. In Europe, the market size more than tripled between 2002 and 2008 (Arizu, D. *et al.*, 2011). However, the 2008 financial crisis and the subsequent economic slowdown, affecting in particular the construction sector, resulted in decreases of 10% in 2009 and 13% in 2010, although the market still increased by an average 12% per year from 2000 to 2010 (ESTIF, 2011). Conversely, in China the use of solar domestic hot water heaters is still growing rapidly (Figure 2). They are increasingly popular due to their cost-effectiveness compared to electric and gas heaters: the average annual cost over the lifetime of an electric water heater is USD 95 and a gas water heater USD 82 whereas a solar water heater only has a USD 27 average annual cost (IEA, 2010). The market shares of the three types

Figure 1: Total installed capacity of water collectors in operation in 10 leading countries by the end of 2010



Source: Weiss and Mauthner, 2012.

of domestic water heating systems in China have dramatically changed over just a decade: whereas solar water heaters had a market share of 15% in 2001, they reached a market share of 50% in 2008 (REN21, 2009).

Data on large scale solar heating and cooling plants (>500 m² collector area; >350 kW nominal thermal power) are not separately reported but a 2010 inventory (Dalenbäck, 2010) stated that at the time about 130 operating solar thermal plants were reported in Europe, with a total capacity of 170 MW_{th} (240 000 m²), which corresponds to less than 1% of the total solar thermal installations in Europe.

Solar cooling

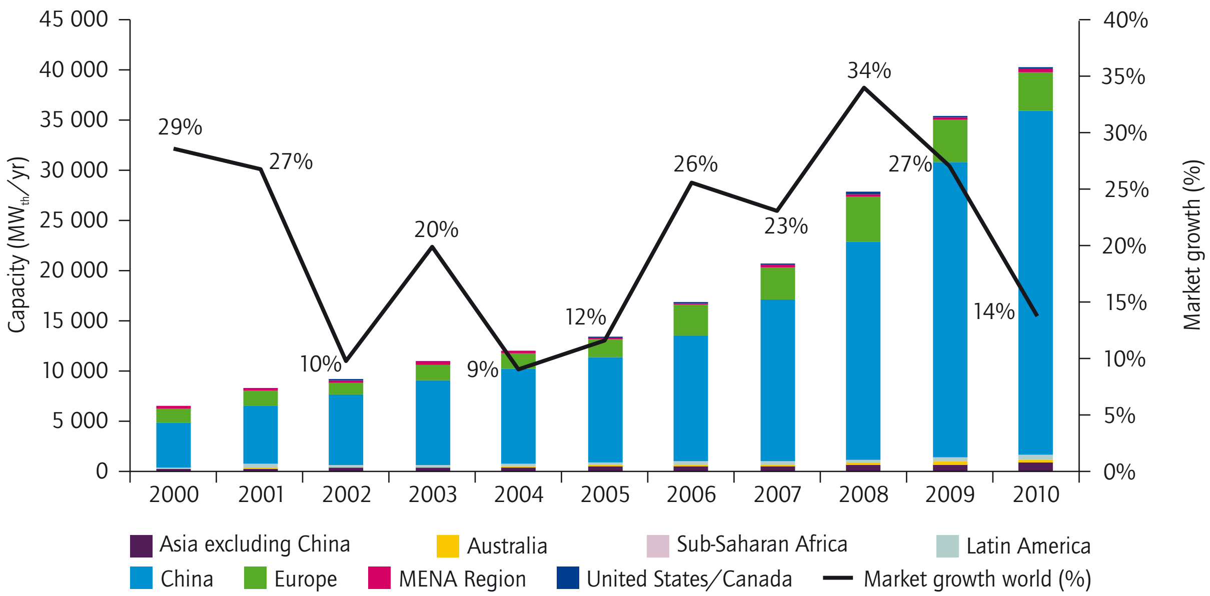
In 2011, worldwide, about 750 solar cooling systems were installed, including installations with small capacity (<20kW) (Mugnier and Jakob, 2012). Recently a number of very large installations have been completed or are under construction. Examples are the system at the headquarters of the CGD bank in Lisbon, Portugal with a cooling capacity of 400 kW and a collector field of 1 560m²; and the system installed at the United World College in Singapore, completed in 2011, with a cooling capacity of 1 470 kW and a collector field of 3 900m². This Singapore installation is reportedly fully cost competitive and was executed on an energy services company (ESCO) model under which the customer is not exposed to equipment or project costs, rather the ESCO sells the resultant cooling capacity to the customer.

While the economics of large systems have to date been more favourable due to economies of scale and demand and equipment limitations in smaller capacities, the installation of small (<20kW) solar cooling "kit" systems for residential application has increased considerably recently, especially in Spain (Henning & Wiemken, 2007). However, this trend almost completely halted in 2008 due to the economic crisis. A market of several hundred kits still exists in 2011, mainly in Central Europe and in dry and sunny climates (Middle East, Australia, Mediterranean islands).

Solar resources

Many regions of the world have enough solar resource to drive solar heating and cooling technologies; even in the cloudiest regions the resource can be suitable for certain solar thermal technologies. For example, flat-plate and unglazed

Figure 2: Annual newly installed capacity of flat-plate and evacuated tube collectors by economic region



Note: Sub-Saharan Africa: Namibia, South Africa, Zimbabwe. Asia: India, Japan, Korea South, Taiwan. Latin America: Brazil, Chile, Mexico. Europe: Albania, EU 27, Norway, Switzerland, Turkey. MENA Region: Israel, Jordan, Morocco, Tunisia.

Source: Weiss *et al.*, 2012.

collector based systems, including most solar water heating systems (see Section 2.3.1), can use both direct and diffuse solar radiation, so even under cloudy conditions there is some resource available for conversion into heat. For concentrating collectors, which are more efficient at higher temperatures (see Section 2.3.2) the available solar resource is limited by direct irradiance from the sun. In these cases, the best resource areas are those where cloud cover is limited, such as in deserts and subtropical regions.

The amount of solar radiation at the Earth's surface that is theoretically available is illustrated by averaged irradiance maps such as the one shown in Figure 3. These maps identify regions of solar resource at the Earth's surface and indicate good potential locations for solar thermal technology.

The technical potential for solar energy for heating and cooling systems is thus vast. Deployment of technical potential is mainly limited by land and/or roof space availability and by the proximity of heating and cooling demand. Only one study is known to have estimated the technical potential for solar water heating on the basis of assumed available roof area for solar PV applications and the irradiation per region (Hoogwijk and Graus, 2008). On the basis of rather restrictive roof availability assumptions, the technical potential for solar water heating was estimated to amount to 3 415 TWh/yr (or 123 EJ/yr) in the long term.[6]

Current technologies

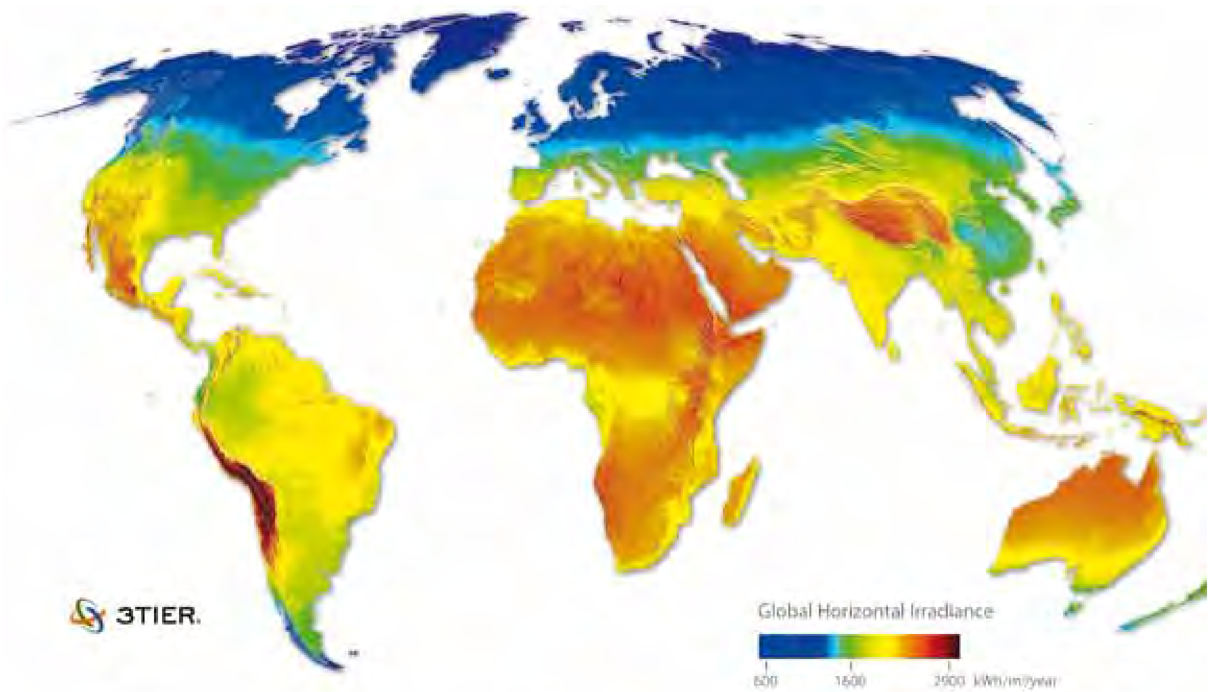
Non-concentrating solar thermal technologies

A broad variety of non-concentrating solar thermal collectors are available. There are two main types: flat-plate, which can be glazed or unglazed; and evacuated tubes. There are a wide range of solar thermal collector designs, but they have a number of components in common.

The **absorber** is responsible for collecting the incoming near-infrared and visible solar radiation (and is hence dark in colour to maximise

6 As a benchmark, in 2009 worldwide final energy for heat was 173 EJ (IEA, 2012). In the IEA *Energy Technology Perspectives 2012* 2DS scenario, final energy for heat is projected to be 198 EJ (*ibid.*).

Figure 3: Satellite-derived solar resource map



Note: As solar radiation passes through the earth's atmosphere, some of it is absorbed or scattered by air molecules, water vapour, aerosols, and clouds. The solar radiation that passes through directly to the earth's surface is called direct solar radiation. The radiation that has been scattered out of the direct beam is called diffuse solar radiation. The direct component of sunlight and the diffuse component of skylight falling together on a horizontal surface make up global solar radiation. See also www.eppleylab.com/Radiation.htm.

Source: 3Tier.

absorption).[7] Most collectors have an absorber that also reduces the release of the infrared radiation, ensuring as much heat as possible is retained. These are called **selective absorbers**.

All collectors have a **circuit** through which the heat transfer fluid flows. To minimise heat losses and maximise system efficiency, the heat exchange efficiency between this circuit and the absorber must be maximised. To achieve this many designs locate the absorber directly on the external surface of the hydraulic circuit.

With the exception of unglazed collectors mainly used for swimming pool heating, most non concentrating collectors have a **housing**. This reduces energy losses to the environment from both the absorber and fluid circuit heat exchanger, and protects both elements from degradation. Clearly, the part of the housing facing the sun must be transparent (*e.g.* glass cover) to allow solar radiation to reach the absorber.

Here a distinction can be made between:

- **Flat-plate collectors**, where the housing is a shallow box, comprising a casing (aluminium, steel, plastic or sometimes wood), insulation material (mineral or rock wool) or vacuum to reduce thermal losses on the back of the collector, and one or two transparent layers of low iron, tempered solar glass (sometimes including an antireflective coating which increases transmissivity of the cover) (Figure 4 left).

7 Dark surfaces indicate a particularly high degree of sunlight absorption. Nevertheless, there are new collector designs where the absorber is not dark-coloured, in order to improve the aesthetic integration with a particular building.

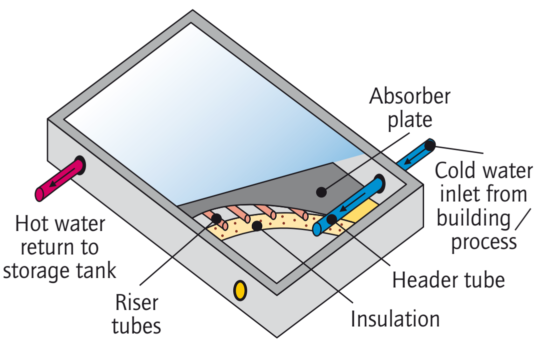
- **Evacuated tube collectors**, where the housing is a glass tube with vacuum inside, so that the heat losses to the environment are very low (Figure 4 right). Evacuated tube collectors can be classified as direct flow tubes and heat pipe tubes. The most popular direct flow tube is the Sydney tube, also known as a twin-glass tube or thermos flask tube, which is the main solar thermal product in China. Its main feature is that the vacuum is located between two glass tubes fused together. The outside of the inner tube is coated with a selective surface.

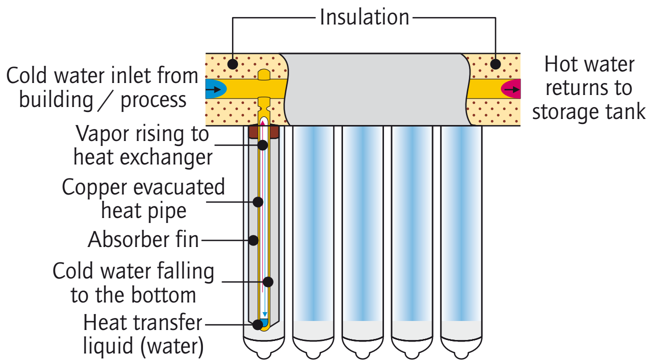
Evacuated tube collectors that are well insulated perform better where the load requires higher temperatures and the ambient temperatures are lower. They also work better than flat-plate collectors in low irradiation conditions, so are likely to be favoured in locations with overcast skies.

Solar air heating systems capture the energy from the sun in an absorbing medium and use it to heat air. Solar air heating systems can also be used in process heat applications, *e.g.* for crop drying, and in buildings for space heating or air conditioning. Solar air collectors are commonly divided into two categories:

- Unglazed air collectors consist of a metal or plastic absorber without covering, and are primarily used to heat ambient (outside) air instead of recirculated building air for commercial, industrial, agriculture and process applications.
- Glazed air collectors are usually used to heat recirculating (conditioned) building air and primarily for space heating. These collectors often have an energy collecting surface integrated into the building's façade.

Figure 4: Flat plate collector (left) and evacuated tube collector (right)





Source: Victoria Sustainability.

Concentrating solar technologies

Concentrating solar technologies focus sunlight from a large aperture area onto a small area by means of lenses or mirrors. When the concentrated light is converted to heat, very high temperatures can be produced: the higher the concentration ratio the higher the maximum temperature. Thus far, high concentrating, sun tracking, solar technologies are mainly used to produce high-temperature heat to drive steam turbines and produce electricity. However, they can also be used in heat applications; or waste or surplus heat can be utilised in combined heat and power (CHP) installations. Concentrating solar thermal collectors generally need to track the sun (with one or two axis tracking). Only devices with very low concentration can be mounted stationary or with simply seasonal tracking.

The solar energy used by high concentrating solar technologies is measured as direct normal irradiance (DNI), which is the energy received directly from the sun on a surface tracked perpendicular to the sun's rays (IEA, 2010a). Concentrating solar technologies require clear skies and sufficient DNI to reach high levels of performance. This requirement limits favourable areas for its deployment.

The **compound parabolic concentrator** (CPC) is a reflector type used with both non evacuated flat-plate collectors and evacuated tube collectors. It is typically designed for a concentration ratio <2, which allows for stationary mounting (*i.e.* does not require tracking) and makes use of not only the direct radiation but also most of the diffuse radiation. A special CPC design is the so called maximum reflector collector, which can achieve higher efficiencies in spring and autumn while preventing overheating in summer due to an asymmetric reflector trough.

High concentrating, sun tracking, solar technologies can generate temperatures high enough to operate a thermodynamic cycle and produce electricity, but they can also be used in (process) heat applications. High concentrating solar technologies have been described extensively in the IEA's Concentrating Solar Power roadmap (IEA, 2010b).[8]

Solar cooling technology

Solar cooling technology uses heat in a thermally-driven cooling process. Within solar cooling, there are two main processes:

- **Closed cycles**, where thermally driven sorption chillers produce chilled water for use in space conditioning equipment (air handling units, fan-coils, chilled beams, *etc.*).
- **Open cycles**, also referred to as desiccant evaporative cooling systems (DEC), typically use water as the refrigerant and a desiccant as the sorbent for direct treatment of air in a ventilation system.

For closed cycle systems, two types of sorption processes exist: adsorption and absorption based systems.[9] Based on closed cycle sorption, the basic physical process underpinning both technologies consists of at least two chemical components, one of them serving as the refrigerant and the other as the sorbent. The efficiency of closed cycle systems can vary depending on the driving temperature (see Box 2).

While closed cycle systems produce chilled water, which can be supplied to any type of air-conditioning equipment, open cooling cycles produce conditioned air directly. Thermally driven open cooling cycles are based on a combination of evaporative cooling and air dehumidification by a desiccant (*i.e.* a hygroscopic, moisture absorbing material).

Solid desiccant cooling systems are mature commercial technologies and have reached a visible market penetration in some areas (*e.g.* supermarkets in the United States). In general, desiccant cooling systems are an option with centralised ventilation systems, offering the ability to pre-treat air entering a conditioned space.

Solar cooling has a number of attractive features compared with its alternatives. Since maximum solar radiation usually coincides with peak cooling demand, solar cooling can help reduce electrical network peaks associated with conventional cooling. If widely deployed, solar cooling will reduce the need for expensive additional electricity network resources associated with electrically powered cooling. Avoiding additional electricity transmission and distribution reinforcement driven by peak cooling loads can lead to substantial cost reductions. Moreover, solar thermal cooling can also deliver cooling in the evening when using thermal storage.

Outside the summer period, solar cooling systems can be used for other heating purposes such as domestic hot water preparation or space

8 www.iea.org/papers/2010/csp_roadmap.pdf

9 Adsorption is the bonding of a gas or other material on the surface of a solid; in the absorption process a new compound is formed from the absorbent and working fluids (IEA, 2011a).

Box 2: Efficiency of closed cycle cooling system

Currently, absorption chillers are the most common thermally-driven cooling process in solar cooling installations. Common absorption cooling pairs include ammonia-water and water-lithium bromide, with many sorption chillers available commercially over a range of capacities, but few at capacities of 100 kW_{th} or less. The so-called "single effect" absorption chillers typically need heat with temperatures in the range of 70 to 100°C, and achieve a coefficient of performance (COP) of about 0.7. Adsorption chillers are able to work at lower temperature ranges (down to 55°C), however this leads to an inferior COP (nearly 0.6).

"Double effect" absorption chillers achieve higher efficiencies by using two thermal generators operated in series, which work at different temperatures. This arrangement allows a higher COP, in the range of 1.1 to 1.2, however higher driving temperatures in the range of 150 to 180°C are required. The higher driving temperatures necessitate a more complex collector technology. These systems are only available for large capacities, of 100 kW and above. Recently triple-effect cycles have entered the market, achieving COP values in the range of 1.6 to 1.9 and requiring driving temperatures of 200°C to 250°C.

Beyond thermal efficiency of the chillers, another important figure for solar thermal cooling efficiency is the COP_{el}, presenting the overall solar cooling system electrical efficiency: the ratio of "produced" cold per unit of electricity that is needed to run the full system (mainly pumps and fans).

heating. Open cycle solar cooling offers humidity management as well as space cooling. Also solar thermal cooling, just as any other absorption chiller, does not use refrigerants (CFCs and HCFCs, used in electric compression chillers) which are harmful greenhouse gases.

However, solar cooling is still in the early stages of market development; costs need to be reduced through further development and increased deployment. A standardised, effective and simplified range of technology arrangements require development – particularly for single-family and multi-family dwellings – to enable solar cooling to compete with conventional and supported renewable technologies and achieve widespread deployment. Quality assurance and system certification procedures are also needed to help stimulate the market by building buyer confidence (Mugnier and Jakob, 2012).

Enabling and related technologies

Although not necessarily required for system operation, enabling and related technologies capable of supporting the deployment of solar heating and cooling systems can play an influential role in the potential applications, market consideration and perception of solar heating and cooling technologies. For example, improvements in thermal storage could extend operational hours and improve market perceptions. Equally, improvements in system control, particularly achieving reductions in parasitic electrical consumption (electricity consumed but not contributing to output, see below), have the potential to increase performance and cost effectiveness.

A heat **storage** device collects the heat transferred from solar thermal collectors so that it can be accessed and utilised when the load is required. Storing solar heat – *i.e.* keeping the fluid warm enough for domestic space heating and cooling and hot water – for one or two days is a common practice with acceptable cost for conventional hot water usage. Seasonal heat storage can be important in climates with prolonged periods of seasonally low solar irradiation levels, where heat storage would ideally need to be able to bridge several months. In countries with high irradiation and long summers, seasonal storage could entirely replace any other heating system. In general, a higher storage capacity enables a higher utilisation of solar thermal energy (solar fraction).

Four main types of thermal energy storage technologies can be distinguished (ESTTP, 2007):

- **Sensible heat storage** systems make use of the heat capacity of a material. When heat is stored, the temperature of the material increases. The vast majority of systems on the market are of this type and use water as a heat storage and transfer medium. Storing sensible heat at higher temperatures than 100°C requires pressurised liquid water or other materials such as concrete, molten salts, etc. Where air collectors are used, heat can be stored in rock beds or other thermal mass.

- **Latent heat storage** systems utilise the phase-change properties, either melting or evaporation, of a material. If the temperature range is small, then this type of storage can be more compact than heat storage in water. Most latent heat storage technologies currently used are for low-temperature storages in building structures to improve their thermal performance, or in cold storage systems.

- **Sorption heat storage** systems use water vapour uptake by a sorption material. The material can be either a solid (adsorption) or a liquid (absorption). These technologies are still largely in the development phase, but some are on the market. In principle, sorption heat storage densities can be more than four times higher than sensible heat storage in water.

- **Thermochemical heat storage** systems store energy by way of a chemical reaction. Some chemicals store heat 20 times more densely than water, but more common storage densities are eight to ten times higher. Few thermochemical storage systems have been demonstrated. The materials currently under investigation are salts that can exist in anhydrous and hydrated form.

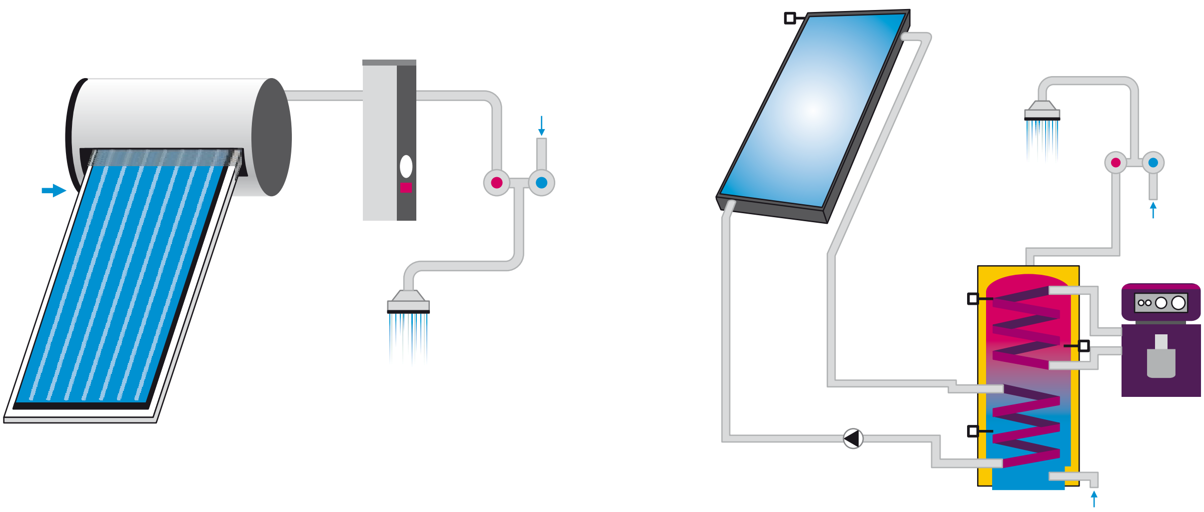
Except for thermosiphon and natural flow systems, most solar heating and cooling systems require fluid circulation with a pump managed by a **control system**, where both the pump and the control system consume electric power (parasitic consumption). Typically, ancillary solar equipment consists of a microprocessor controller, sensors for the detection of input parameters (temperature) and actuators such as pumps and valves. Maximising system output while minimising component cost and parasitic power consumption are critical for system optimisation and peak efficiency. Solar thermal systems are often part of a more complex heating, ventilation and cooling (HVAC) system, which in turn is part of a larger system, *i.e.* the building itself. Technologies which aid the integration of solar heating and cooling systems into HVAC systems and building systems are important factors in widespread deployment of solar heating and cooling systems.

Solar heating and cooling applications

Systems with natural and forced circulation

Solar thermal systems in building applications come in two main types, **thermosiphon** (**natural circulation**) and **pumped** (**forced circulation**) systems (Figure 5). Thermosiphon systems, common in frost-free climates, rely on the fact that heated liquids are lighter than cooler ones in order to circulate the heat transfer fluid to the heat storage. This avoids the need for pumping and the associated costs, but means that

Figure 5: Scheme of a thermosiphon (natural) circulation system (left) and a pumped (forced) circulation system (right)



Source: Dr. Valentin Energiesoftware GmbH.

the heat storage needs to be placed on the roof above the collector, limiting its size because of its weight. Pumped circulation systems allow the separation of the collector and the heat storage, so the storage can be placed within the dwelling. They are more complicated since they require pumps and a control system to optimise operation. Solar thermal systems in buildings can either be used for domestic hot water production or for a combination of domestic hot water and space heating.

Solar domestic hot water heating in buildings

Individual domestic hot water systems are generally relatively small systems with a collector size of between 3m^2 and 6m^2, with storage of between 150 litres and 300 litres. Solar domestic hot water systems can be designed to cover from 30%, in combination with a back-up system, to close to 100% of the domestic hot water demand, depending on collector area, storage size and climate. These systems can exist of either **thermosiphon** (**natural circulation**) or **pumped** (**forced circulation**) systems.

Solar combi-systems for domestic hot water and space heating

Solar heating systems for combined domestic hot water and space heating, so-called "combi-systems", are essentially the same as solar water heaters in terms of the type of collectors and the transportation of the produced heat to the storage device but mainly exist of **pumped** (**forced circulation**) systems. The solar combi-system has a larger collector area and generally larger storage to meet the space heating needs, given that water heating averages only one fifth of the total space and water heating demand in existing buildings in OECD countries. In typical single-family houses in a mid-European climate, such systems can provide fossil fuel energy savings in the range of 25% to 30%. Both solar combi-systems and domestic hot water systems need, at present, an auxiliary energy source (biomass, gas, oil or electricity) to cover the part of the heating demand not covered by the solar thermal system. The use of solar combi-systems is not widespread, in part due to the lack of low-cost compact thermal storage. However, in some countries (*e.g.* Germany, Austria) combi-systems can account for about 50% of annually installed capacity. Solar combi-systems are well suited to middle and high latitudes, due to significantly higher solar radiation in the transitional periods around winter (September-October and March-May) and the significant heating demand in these latitudes at that time.

Large-scale solar systems and solar district heating

Solar thermal systems supplying heating or cooling to the building sector can also be found in large-scale applications used for district heating, multi-family buildings or block heating plants. These systems can vary from tens to hundreds of square meters of collectors and have recently showed to represent an important share in some European markets such as in France (Uniclima, 2012). Solar energy can be an attractive low-cost source of heat for district heating systems, where typical working temperatures range from 30°C to around 100°C for water storage. District cooling systems, which are starting to become more common in order to reduce peak load demand on the electricity system, could also utilise large-scale solar thermal plants. The large-scale of the solar collector fields and associated storage offer improved economics due to a better ratio of storage volume to collector surface.

Solar industrial process heat

A number of industrial sectors use a significant proportion of their process heat at temperatures <120°C and are therefore likely to have a strong potential for solar thermal to meet their process heat needs. Examples of these sectors are transport equipment, machinery, mining and quarrying, food and tobacco, and textiles and leather. Many processes and activities common to these sectors can use solar thermal systems such as washing, leaching (mining industry), cooking, drying, pre-heating of boiler feed water and space heating in industrial buildings. Solar thermal technologies used for low-temperature applications in industry are similar to those in buildings: typically, flat-plate or evacuated tube collectors.

Solar crop drying, an important agricultural process in developing countries, can also use much simpler collectors, such as perforated roof panels through which air is drawn via small openings in the panels and then ducted to feed the dryers.

For medium and high-temperature applications, concentrating solar technology will be needed, although these applications will be limited to areas with good DNI.

Figure 6: Solar district heating at the Island of Ärö, Ärösköping, Denmark. Installed collector capacity: 4.9 MW (7 000 m²)

Source: ARCON Solar, 2010.

Water treatment and seawater desalination

Demand for water desalination is expected to keep growing in regions that are known for water shortages – which often have very good solar resources. Desalination can come from distillation or reverse osmosis technology, with the first being preferred for more saline water (IEA, 2011a). Distillation requires large amounts of thermal energy, which could come from concentrating solar technologies.

Solar cooking

In general, experiences with solar cooking are mixed, due to mismatches with traditional cooking habits and increased cooking times. However, it is successful in a number of contexts, such as community cooking in India. Here, concentrating technology is used on different scales, either to directly heat a pan or to produce steam for large scale kitchens serving up to 10 000 people a day (Singhal, 2011).

Swimming pool heating

In North America (United States and Canada) and Australia, unglazed water collectors for swimming pool heating are the dominant application of solar thermal technology (Weiss *et al.*, 2011). Unglazed collector designs used for swimming pools are an affordable technology that increases the temperature of the fluid in the collector by 10°C to 20°C above ambient temperature.

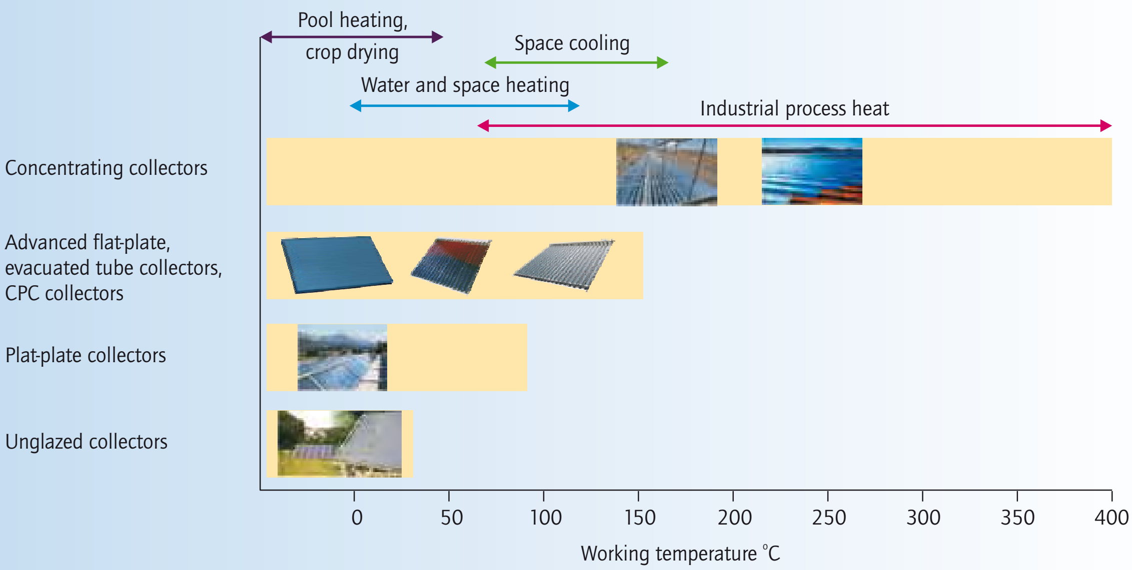
Solar heat for cooling applications

An interesting application of solar heat utilisation is building space cooling due to the convenient coincidence between the availability of maximum solar irradiance and the peak demand for cooling, particularly in commercial buildings. Some solar cooling technology such as desiccant cooling can extend comfort by also managing humidity levels. Industrial refrigeration, as in the food processing sector, is also an attractive candidate for solar thermal air conditioning technology.

Box 3: Overview technologies with general characteristics

Figure 7 presents an overview of different types of SHC technology and their temperature ranges, in combination with the working temperatures required for different applications of solar heat.

Figure 7: Solar collectors and working temperatures for different applications

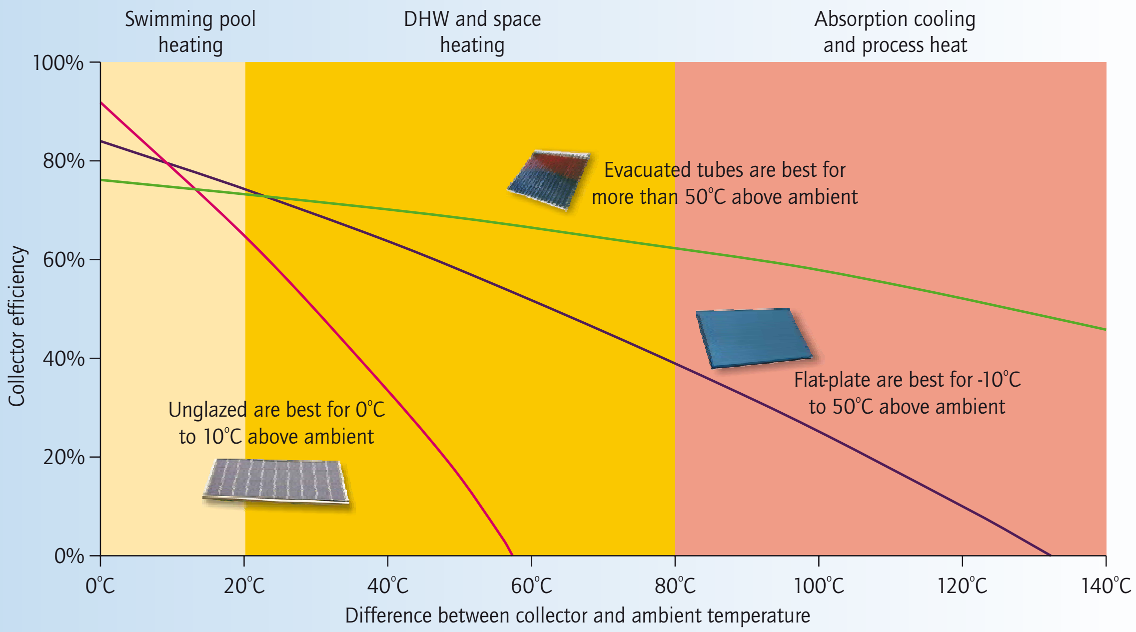


Note: adapted from the IEA Solar Heating and Cooling Implementing Agreement.

Box 3: Overview technologies with general characteristics (continued)

The efficiency of a solar collector will vary depending on the temperature difference between the collector and its surroundings. In Figure 8, the slopes of the lines represent their heat loss factors. The steeper the slope, the more the collector loses heat as temperature increases. Evacuated tube collectors generally start off with lower efficiency than flat plate collectors. However, as the temperature of the collector increases, the efficiency in vacuum tube collectors decreases less rapidly than for flat plate collectors due to the insulation of the vacuum.

Figure 8: Collector efficiencies at different temperature differences



Economics today

Like many renewable energy technologies, solar water heating is characterised by higher upfront investment costs and lower operation and maintenance (O&M) costs than conventional technologies.

Total investment costs for a solar thermal system consist of:

- basic equipment including the solar collectors;
- additional equipment such as collector mounting components, storage vessel and plumbing;
- installation labour costs, which may include system design, assembly and scaffolding.

Investment costs for solar water heating depend on system design and application characteristics, the complexity of the chosen technology and market conditions in the country of operation. Thermosiphon systems using natural circulation avoid the need for pumping and the associated equipment, installation and operating costs but are mainly limited to frost free climates. In other regions, higher-cost forced circulation systems will be required.

Apart from the system type, costs of labour and design characteristics and the size of the local solar heating and cooling market can also considerably influence the overall investment costs. In smaller domestic applications, installation costs can be as high as 50% of overall investment costs, especially in countries with high labour costs and lack of market competition. This means that installed solar heating and cooling system costs may not benefit from the economies of scale seen with other renewable energy equipment. Investment costs for a domestic hot water system can vary around the world by a factor of almost 10, from USD 250/kW_{th} to USD 2 400/kW_{th}.

Large-scale solar hot water systems, whether used in district heat, industrial applications or commercial buildings, do benefit from economies of scale: installation costs comprise a smaller share of total investment costs. A recent market boom in large-scale solar heating for district heating operators in Denmark, has resulted in more market competition and lower investment costs per kW_{th}. Investment costs for the most cost effective Danish systems are USD 350 to USD 400/kW_{th} and heat prices correspondingly down to USD 35 to USD 40/MWh_{th}[10]. Experience in mainly European large-scale systems indicate investment costs ranging from USD 350/kW_{th} to USD 1 040/kW_{th}.

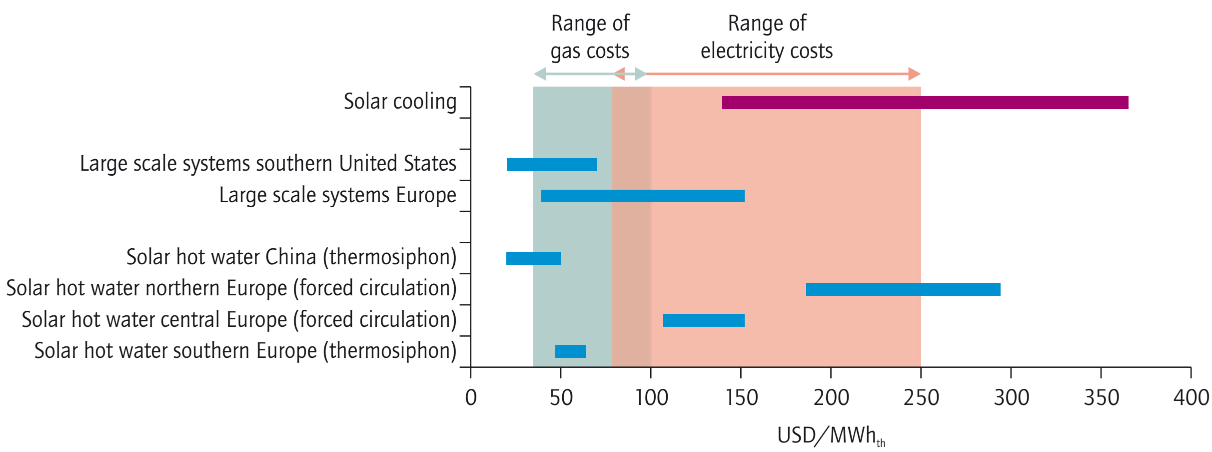
Investment costs for solar cooling are difficult to assess due to the emerging status of the technology – limited experience and a high proportion of demonstration projects, which may include a large amount of R&D funding. Despite this there are a number of available examples of solar cooling installations that have been realised without subsidies, *e.g.* in tropical regions with high electricity costs. Estimates of solar cooling investment costs for medium to large systems range from USD 1 600/$kW_{cooling}$ to USD 3 200/$kW_{cooling}$.

10 Investment costs and actual production of solar district heating in Denmark can be found at www.solvarmedata.dk.

Operation and maintenance costs for solar heating and cooling systems are generally low as the systems require no fuel and use little electricity (to run auxiliary systems such as circulation pumps). However regular servicing and light maintenance by a trained technician is required for absorption and adsorption chillers to maintain vacuum seals. Maintenance for desiccant systems is simple and unspecialised, usually limited to air filter changes or cleaning, whereas operation of these systems is subject to more complex control strategies.

As a result of the diverging investment costs for different solar heating and cooling technologies, solar heat costs will vary widely depending on the technology and the local market conditions. Figure 9 illustrates solar heat costs of a number of heating and cooling technologies, by technology type and region. The range of costs represented is a result of diverging investment costs depending on the complexity of the system, relative competition in the market, diverging discount rates and a range of operation and maintenance costs (assumptions behind cost calculations are shown in Appendix I).

Figure 9: Costs of solar heating and cooling (USD/MWhth)



Note: Costs of solar cooling: USD/$MWh_{cooling}$.

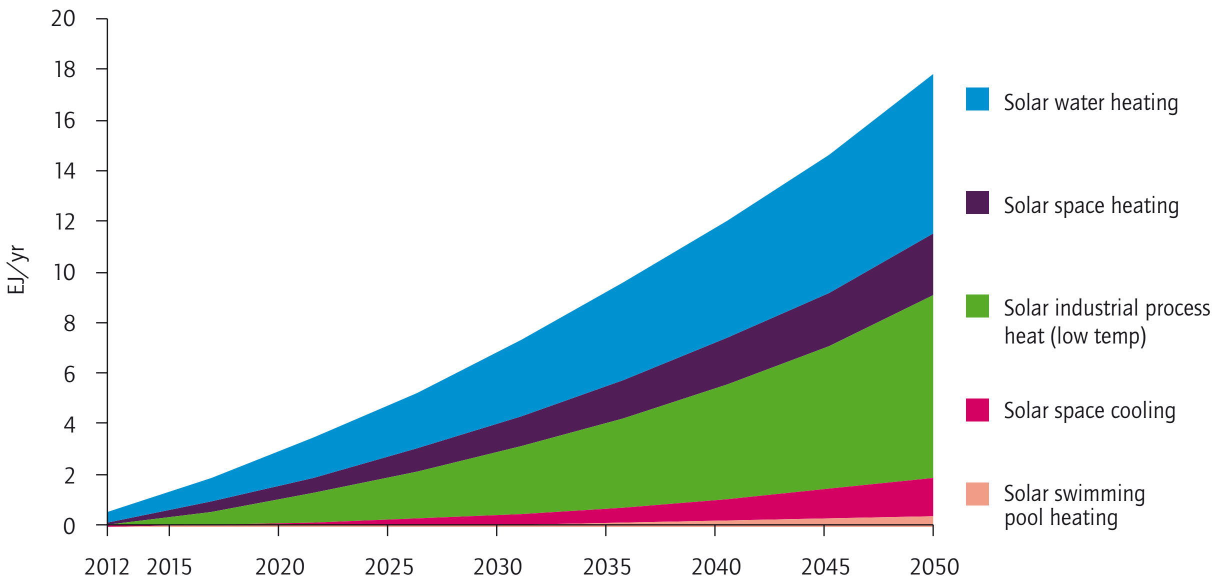
Vision for solar heating and cooling deployment

Deployment of solar heating and cooling to 2050

This roadmap envisages development and deployment of solar heating and cooling by 2050 to produce 16.5 EJ (4 583 TWh_{th}; 394 Mtoe) solar heating annually, more than 16% of total final energy use for low temperature heat, and 1.5 EJ solar cooling, nearly 17% of total energy use for cooling by that time. It would include the following contributions (Figure 10):

- Solar collectors for hot water and space heating in buildings could reach an installed capacity of nearly 3 500 GW_{th}, satisfying annually around 8.9 EJ of energy demand for hot water and space heating in the building sector by 2050. Solar hot water and space heating accounts for 14% of space and water heating energy use in buildings by that time.
- Solar collectors for low-temperature process heat in industry (<120°C) could reach an installed capacity of 3 200 GW_{th}, producing around 7.2 EJ solar heat per year by 2050. Solar process heat accounts for 20% of energy use for low temperature industrial heat by that time.
- Solar heat for cooling could reach a contribution of 1.5 EJ per year from an installed capacity of more than 1000 GW_{th} for cooling, accounting for nearly 17% of energy use for cooling in 2050.
- Swimming pool heating could reach an installed capacity of 200 GW_{th}, producing annually around 400 PJ solar heat by 2050.
- By achieving the above mentioned deployment levels, solar heating and cooling can avoid some 800 megatonnes (Mt) of CO_2 emissions per year by 2050.

Figure 10: Roadmap vision for solar heating and cooling (Exajoule/yr)



Building sector: solar hot water and space heating

This roadmap's vision for solar heating and cooling in the building sector and for industrial solar process heat is based on the *ETP 2012* 2DS scenario (IEA 2012). The *ETP 2012* 2DS scenario describes how the energy economy may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2009 levels (Box 4).

The deployment goal for solar hot water and space heating in the building sector in the *ETP 2012* 2DS scenario is that installed solar thermal capacity will increase by more than 25 times today's level to almost reach

Box 4: *Energy Technology Perspectives 2012* 2°C Scenario (2DS)

This roadmap outlines a set of technologies, along with policies and measures, to help achieve a global pathway for solar heating and cooling deployment to 2050. It starts with the IEA *ETP* 2DS, which describes how energy technologies across all energy sectors may be transformed by 2050 to achieve the global goal of reducing annual CO_2 emissions to half that of 2009 levels (IEA, 2012b). The model used for this analysis is a bottom-up TIMES model that uses cost optimisation to identify least-cost mixes of energy technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The *ETP* global 28 region model permits the analysis of fuel and technology choices throughout the energy system. The detailed representation includes about 1 000 individual technologies. The model has been developed over a number of years and has been used in many analyses of the global energy sector. It is supplemented by detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

ETP 2012 considers other scenarios. The 6DS, the baseline scenario in the Technology Roadmap series, considers only current policies and that no major new policies to reduce GHG emissions will take place in the coming decades. The 4DS includes new policies that are in the pipeline today and are projected to be implemented and enforced in the future, resulting in a 4°C increase of the global average temperature.

Achieving 2DS will be very challenging; some of the rates of change (*e.g.* annual change in sales of new technologies) in the 2DS are historically unprecedented. To achieve such a scenario, strong policies will be needed from governments around the world. Over the next 20 years, important technology advances are needed in many areas.

3 500 GW_{th}[11] by 2050, amounting to a 8.9 EJ annual solar heat production by that time (Figure 12).[12] This implies installed capacity growth of an average 8% per year until 2050. It also assumes low-cost compact thermal storage becoming available, with initial deployment between 2020 and 2025 and large-scale deployment from 2030.

Figure 11 shows that solar hot water and space heating in the building sector is applicable in all regions, as a result of its competitiveness in non-OECD warm climate regions and policy support in OECD countries. Some regions show more growth in solar hot water and space heating than others. For example, in Other Developing Asia it is assumed that traditional biomass is replaced by solar water heating whereas at the same time, domestic water heating plays an important role in final energy consumption in the building sector. As a result, solar hot water and space heating represents more than 40% of final energy used for this purpose in the building sector by 2050. On the other hand, in India, domestic hot water heating demand is considered to be less dominant and therefore solar hot water is expected to play a modest role only.

In this vision, solar hot water and space heating in buildings will increase by on average 7.1% annually between 2010 and 2050, while the total energy used for water and space heating increases only 1.3% (or 0.8 EJ). By 2050, solar hot water accounts for 25% of water heating energy use, while solar space heating will have a 7% share of energy use for space heating by that time (Figures 12 and Figure 13). The greatest potential for solar heat in buildings will thus consist of solar domestic hot water heating, where the potential by 2050 is about 2.5 times higher than solar space heating potential.

11 In order to make the installed capacity of solar thermal collectors comparable with that of other energy sources, in 2004 in a joint meeting of the IEA SHC Programme and major solar thermal trade associations, representative associations from Austria, Canada, Germany, the Netherlands, Sweden and United States as well as the European Solar Thermal Industry Federation (ESTIF) and the IEA SHC Programme agreed to use a factor of 0.7 $kWth/m^2$ to derive the nominal capacity from the area of installed collectors. This IEA roadmap uses installed solar heating and cooling capacity figures in order to be able to compare with other roadmaps.

12 Due to modelling restrictions, solar district heating is not included in this roadmap vision for solar domestic hot water and space heating in buildings.

Figure 11: Roadmap vision for solar hot water and space heating in buildings (Exajoule/yr)

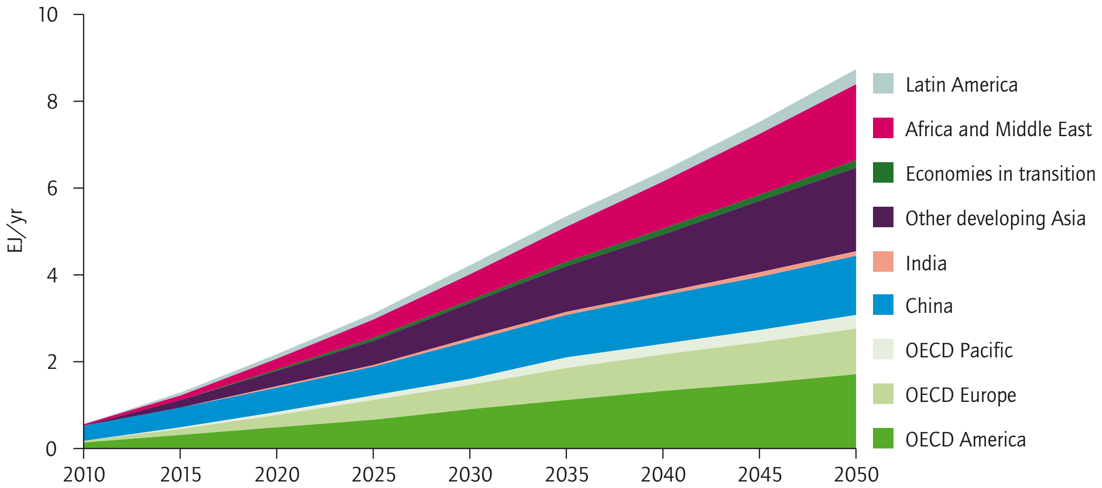


Figure 12: Roadmap vision for solar hot water in buildings in relation to total final energy use for hot water (Exajoule/yr)

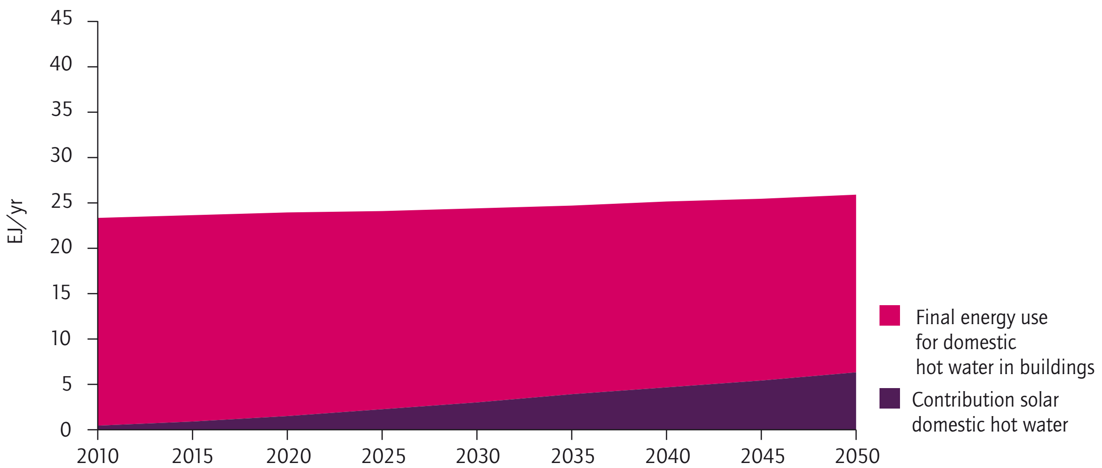
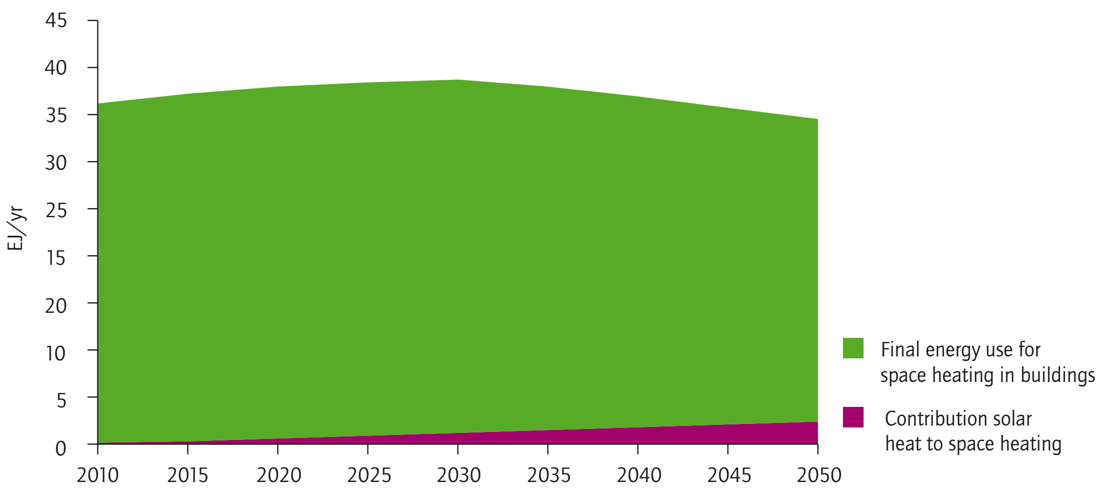


Figure 13: Roadmap vision for solar space heating in buildings in relation to total final energy use for space heating (Exajoule/yr)



Industrial sector: process heat

In the vision described in this roadmap, solar heat has a significant role to play in the industrial sector. By 2050, the *ETP 2012* 2DS scenario estimates the potential for solar heat in industrial applications to contribute up to 7.2 EJ per year, on the basis of an installed capacity of over 3200 GW_{th}, in industrial low-temperature applications up to 120°C (Figure 14).[13]

The largest potential for solar industrial heat can be found in China, where the existing solar collector industry will easily facilitate the transfer of the current technology towards industrial applications (see also Box 5). In general, shares of low-temperature solar process heat per region are explained by the solar resources and the structure of the respective industry. In regions with relatively high shares of industry in need of low-temperature process heat, such as China, potential for low-temperature solar heat is higher than in regions where industry is dominated by high-temperature needs in *e.g.* the cement, iron and steel, chemicals, pulp and paper and aluminium industries.

13 Due to modelling restrictions, medium and high-temperature process heat and district heating is not included in this roadmap vision for industrial process heat.

Figure 14: Potential for solar thermal industrial process heat (Exajoule/yr)

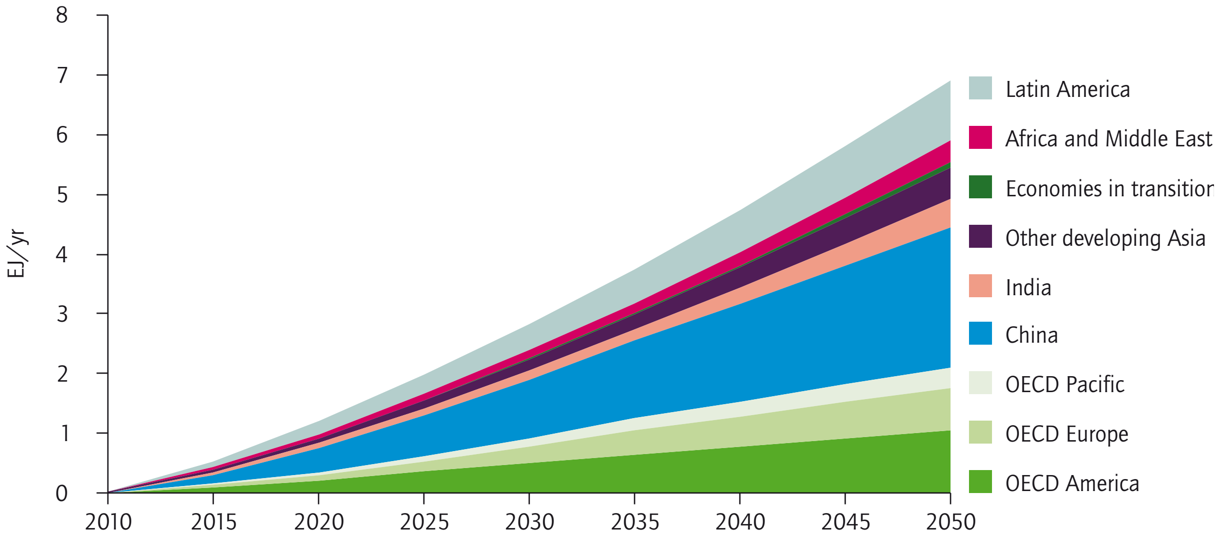
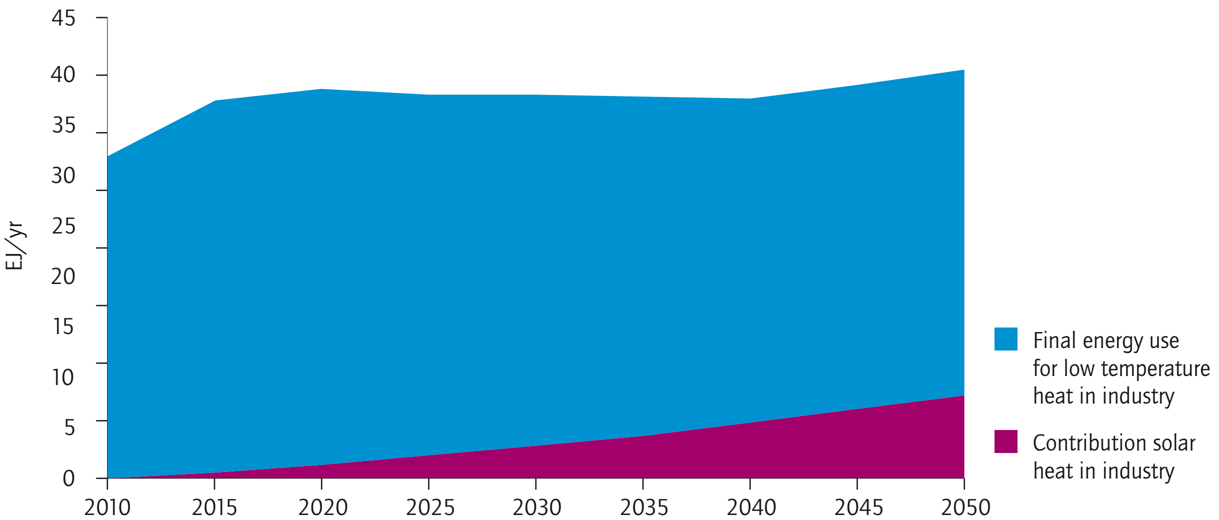


Figure 15: Roadmap vision for solar industrial heat in relation to total final energy use for low temperature industrial process heat (Exajoule/yr)



Box 5: Solar heating and cooling perspectives in China

Solar heating and cooling in China today

In 2010 total SHC capacity in China was 117.6 GW_{th}, amounting to 60% of global SHC capacity in that year (Weiss, 2012). The use of solar thermal collectors in China has grown rapidly in just one decade, from 10.5 GW_{th} in 1998. The success of solar water heating in China is explained by its competitiveness compared to alternative technologies. Although the upfront capital cost of solar water heaters is higher than for electric or gas water heaters, the average annual investment over the lifetime of the heater is only a fourth to a third of gas water and electric water heaters. China is also a major exporter of solar water heaters, with the value of exports increasing nearly six-fold from 2001 to 2007 (IEA, 2010).

Vision for deployment

The Chinese government has announced targets for solar heating and cooling as part of the country's Renewable Energy Law. The 12^{th} five-year plan proposes to increase the country's solar water heating capacity to 280 GW_{th} by 2015 and 560 GW_{th} by 2020. These targets are to be apportioned to regional administrations, which will then be expected to introduce policies to achieve them. Apart from domestic hot water, the Chinese government foresees a need to expand SHC deployment to industrial applications in order to realise the 2015 and 2020 targets.

Technological challenges

Whereas a number of SHC technology development challenges are identical worldwide, there are some specific to China. While solar domestic hot water applications are a mature technology for low-rise buildings in China (mainly in rural applications), the strong development of high-rise buildings in urban areas requires technological adjustments. The dominant technology in use today is the thermosiphon system but forced circulation will be needed to reach all stories in high-rise development. Also alternative collector placements, such as on balconies, will be necessary since roof areas are often too small to fulfil a reasonable proportion of demand in all apartments.

The application of solar heating and cooling in China has thus far been limited to domestic hot water heating. Enormous potential exists to expand this to space heating in combination with low-temperature (underfloor) hydronic heating, especially in northern China. Building integration of SHC applications will be a very important element in all future developments. Chinese solar collector manufacturers are also looking to develop medium-temperature flat-plate collectors for use in industrial processes. Solar cooling is a new market in China, and has only recently attracted the interest of research institutes and industry. Expectations are that after 2020 this will become a very important market in China.

Non-technological challenges

Current institutional barriers include the absence of mandatory installation of hot water systems in new construction, and of energy billing on the basis of floor surface area instead of energy use. Moreover, Chinese energy statistics lack solar heating and cooling data, which complicates policy making to encourage solar heating and cooling.

Policy encouraging solar heating and cooling

Following the apportionment of national targets to regional administration, the city of Beijing introduced solar obligations for all new buildings as of March 2012. These obligations relate to low-rise as well as high-rise buildings. As Beijing often acts as an example to the rest of the nation, it is expected that other regional administrations will follow.

Manufacturers state that additional (government) policy support will be needed to achieve the targets formulated for 2015 and 2020, and especially to increase SHC deployment in industrial applications.

Since India has a higher share of these energy intensive industries, its shares for low-temperature process heat are somewhat lower. Interestingly, in some regions, like Latin America, a shift from (modern) biomass towards solar heat is expected as a result of competition for biomass resources.

In this vision, final energy demand for low temperature process heat in industry will increase to 35.5 EJ by 2050, with low-temperature solar process heat accounting for 20% of total energy use for low temperature industrial heat (Figure 15).

For developing and least developed countries, where the advancement and modernisation of the food industry has a critical role to play in delivering food security, solar thermal systems can help to stabilise food prices by reducing their connection to the volatile prices of oil and other energy commodities (UNIDO, 2011).

Building sector: solar thermal cooling applications

The *ETP 2012* 2DS scenario describes how solar cooling can start to deliver considerable contributions, especially after 2030 when costs of solar cooling technology are expected to rapidly reduce while electricity costs are expected to continuously increase.

In the *ETP 2012* 2DS scenario, installed solar cooling capacity will increase from the very low deployment levels today to reach more than 1 000 GW_{th} for cooling[14] by 2050, amounting to 1.5 EJ annual solar cooling production by that time (Figure 16). The largest share of solar cooling potential can obviously be found in warm climate regions.

On a regional basis, both China and Other Developing Asia will have shares of solar that would be around 30% of cooling energy needs by 2050. In Africa and the Middle East solar cooling will add up to 23% of total final energy used for cooling in 2050. Some other regions, like Latin America, may seem to show modest numbers but that is due to the modest size of their economies: in this region solar cooling may represent nearly 16% of energy demand for cooling by 2050.

In this vision, final energy demand for cooling will increase to almost 9 EJ by 2050, with solar cooling accounting for nearly 17% of total energy use for cooling (Figure 17).

14 In order to make the installed capacity of solar thermal collectors comparable with that of other energy sources, in 2004 in a joint meeting of the IEA SHC Programme and major solar thermal trade associations, representative associations from Austria, Canada, Germany, the Netherlands, Sweden and United States as well as the European Solar Thermal Industry Federation (ESTIF) and the IEA SHC Programme agreed to use a factor of 0.7 kW_{th}/m^2 to derive the nominal capacity from the area of installed collectors. This IEA roadmap uses installed solar heating and cooling capacity figures in order to be able to compare with other roadmaps.

Figure 16: Roadmap vision for solar cooling (Exajoule/yr)

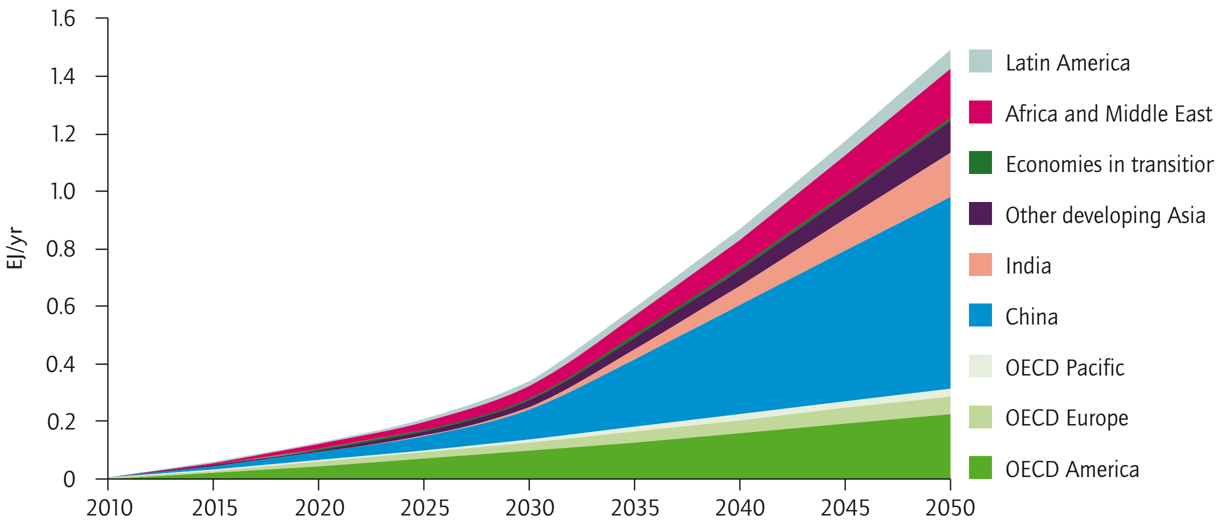
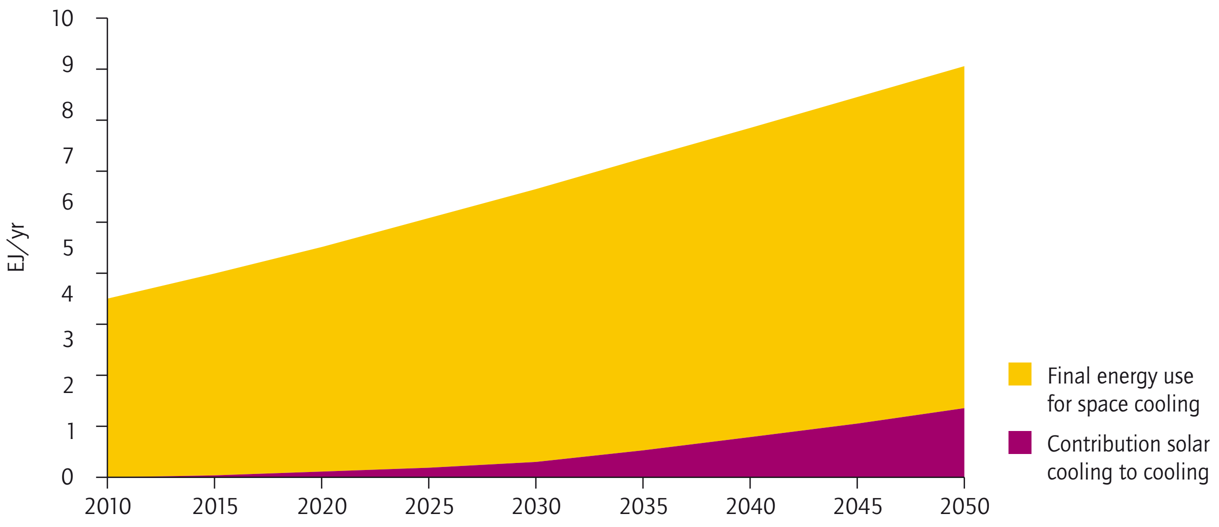


Figure 17: Roadmap vision for solar cooling in relation to total final energy use for cooling (Exajoule/yr)

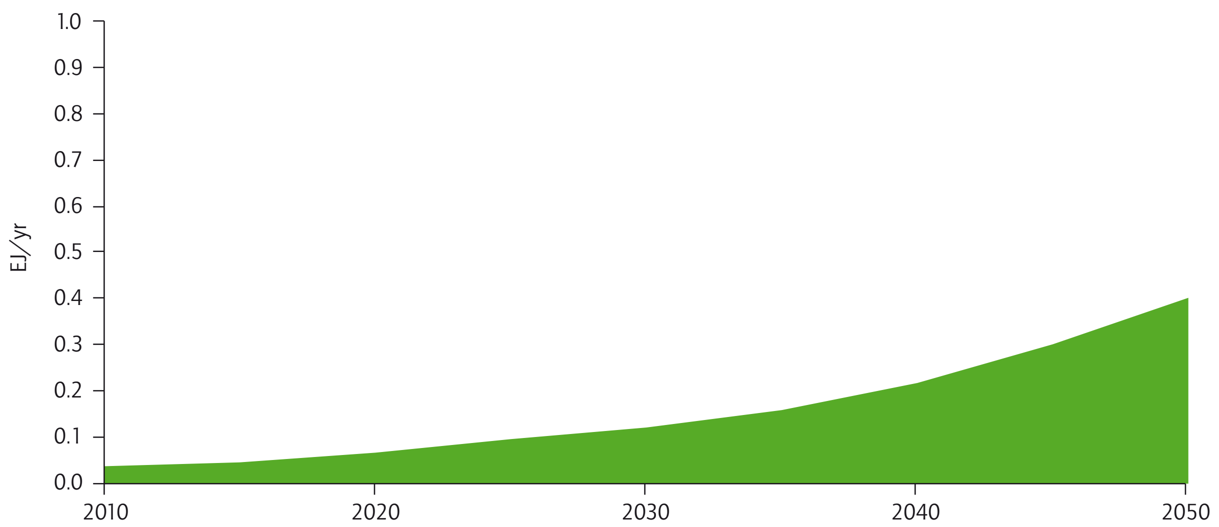


Swimming pool heating

Market development of unglazed collectors for water heating, mainly used for swimming pool heating, shows different rates of development in different countries in recent years, varying from the previously constant growth rates of around 5% per year (Weiss *et al.*, 2011).

Unglazed solar collectors for swimming pool heating are in most cases already competitive with alternative fuels: current capacities in many countries have been realised without any policy support. One exception is in Spain, where solar pool heating is mandatory. The roadmap vision assumes policy intervention for solar pool heating becoming more widespread in the near future, with unglazed solar collectors showing a constant annual growth rate of 6%, starting from the current installed capacity of some 20 GW_{th}. This implies unglazed solar collectors for water heating will reach a capacity of 205 GW_{th}, amounting to an annual 400 PJ heat production, by 2050 (Figure 18).

Figure 18: Roadmap vision for swimming pool heating (Exajoule/yr)



Technology development: actions and milestones

Solar heat

Flat-plate and evacuated tube systems for heat applications

Mature solar thermal technologies are commercially available for the building sector, but further development is needed to provide new products and applications, reduce the cost of systems and increase market deployment. With the right mix of RD&D, industry development and consistent market deployment programmes, even in severe climates, by 2030 it could be economically viable to build new low-energy houses that satisfy their small residual heat demand with solar heat. A number of R&D and technology development challenges should be addressed in order to make this feasible.

Apart from their possible contribution to passive building design, building envelopes will need to become solar collectors themselves, so both the performance of collectors and their direct integration into buildings needs to be improved. This should lead to the development of multifunctional building components which act as elements of the building envelope and as solar collectors. Planning regulations will need to protect solar access to integrated solar collectors (which will in some cases be on vertical surfaces) to avoid performance reductions due to shading.

The development of new components for use in collectors – such as plastics, functional coating of absorbers (optimised to resist stagnation temperatures[15]) and new polymer materials that resist deterioration from UV exposure – should help to reduce the life-cycle cost and improve the economics of solar thermal systems.

On-site installation challenges and maintenance work are sometimes seen as bottlenecks to increased deployment of solar heating equipment. In order to reduce the need and time for on-site installation and to address the system integration challenges, a transition towards standardised kits and plug-and-function solar thermal systems is needed. This will not only reduce installation costs but should also improve performance and reliability of solar thermal systems. Such developments would be especially relevant for retrofitting existing buildings.

For the industrial sector, more product development is needed in order to be able to tap into the enormous potential for solar process heat. It has been estimated that 30% of process heat demand in the European industry sector consists of low-temperature heat, less than 100°C (Werner, 2006). This opens up a considerable potential for solar heat supply by advanced flat-plate and evacuated tube collectors that can supply temperatures up to 120°C already today. At the same time some 25% of process heat is estimated to use temperatures between 100°C and 400°C (ibid). Current solar collectors covering these temperature levels are not yet market mature. In this respect, double glazed flat-plate collectors with anti-reflection coated glazing, stationary CPC collectors and Maximum Reflector Collectors should be further developed and commercialised. Challenges consist of material resistance to high temperature levels and durability of components.

Large scale solar heating systems are increasingly applied in Europe and can offer additional potential in a relatively unexplored market. System designs have thus far been unique engineering projects. Large scale system deployment can benefit from the development of more standardised pre-engineered solutions and increased knowledge of system design.

Large scale seasonal storage is close to being cost effective and will substantially increase the potential for solar district heating. The combination of large scale solar district heating (or cooling), seasonal storage, heat pumps and combined heat and power production can work effectively with dynamic renewable electricity production – using large thermal storage as a buffer for variations in load and production of both heat and electricity.

15 Stagnation temperatures are those that are so high that the heat transfer fluid will not circulate and degenerates.

This roadmap recommends the following actions:	Milestone timeline	Stakeholder
Integrate solar collectors in building surfaces.	2012-20 (Develop new integrated building products by 2020)	Research institutes, SHC industry, architects/ building industry
Use alternative materials, technologies and manufacturing techniques for system cost reduction and performance improvement.	2015-20 (30% system cost reduction by 2020)	Research institutes, SHC industry
Address challenges in system design by development of standardised kits and plug-and-function systems.	2012-20	SHC industry
Expand development of collectors that cover temperature gap between 100°C and 250°C.	2012-20	Research institutes/universities, SHC industry
Address challenges in development of medium to large-scale systems by developing pre-engineered solutions and improving system design knowledge.	2012-20	SHC industry

Concentrating solar for heat applications

Concentrating solar heating technology development today is mainly focusing R&D resources on goals related to power production, *e.g.* realising higher temperatures. But the thermal energy produced by concentrating solar technology can also be used for heat applications, *e.g.* for high-temperature industrial processes in areas with good levels of direct normal irradiance (DNI) although this application has thus far received far less attention. Parabolic trough collectors, parabolic dishes and linear concentrating Fresnel collectors can be adapted to serve medium-temperature process heat applications. This requires development of, for example, smaller scale concentrating solar collectors, which can be installed on rooftops of industrial production halls, and which produce the appropriate temperatures for the processes.

Deployment of concentrating solar technology in industry will need adapted industrial system designs and optimisation of industrial processes to increase the potential integration of solar concentrating technology. Standardised system integration for solar heat in industrial processes is needed to encourage this use of concentrating solar technology.

This roadmap recommends the following actions:	Milestone timeline	Stakeholder
Adapt concentrating solar technology for heat applications (smaller scale, adjustable temperature levels and building integrated solutions).	2012-20 (2020: concentrating solar technology for heat market mature)	Research institutes/universities, SHC industry
Develop and standardise system integration concepts for solar heat in industrial processes.	2012-30	Research institutes, SHC industry, heating industry (*e.g.* boiler manufacturers), facility management providers

Solar heat for cooling

Improved solar cooling systems offer the potential to address the expected rise in cooling demand in a number of regions with good solar resources. Solar thermally driven cooling is still in an early phase of development and a number of RD&D challenges need to be addressed to enable increased deployment.

Solar cooling systems require optimised thermally-driven cooling cycles (sorption chillers and desiccant systems), with higher coefficients of performance (thermal COP and electrical COP_{el}), lower cost and easier hybridisation with other waste heat, backup heating and backup cooling technologies. On the component level, this will require RD&D into new sorption materials, new sorption material coatings for heat exchange surfaces and new heat and mass transfer systems. It will also require the design of new thermodynamic cycle systems. Increasing use of desiccant, double effect and even triple effect cycles with storage will enable a wider range of applications to be addressed and simplified options for end users.

These technological developments will need to be complemented by design guidelines, system certification, labelling and tools specifically developed for solar cooling systems and applications. Within the next three to five years, a special focus will be needed to launch long-term field tests and in parallel to develop appropriate training materials for installers and engineers.

The introduction of solar cooling standards, standardised kits and plug-and-function systems will reduce, focus and simplify the range of possible solutions into a workable set covering all major potential applications. Small-scale system design requires R&D effort in order to develop low-cost systems, integrate them with existing equipment and optimise operation in new developments. Whereas large scale thermally driven cooling is already available, and is favoured by economies of scale, small scale technology is still emerging and requires low-cost systems with minimal maintenance requirements. Small-scale technology development should focus on compact machines with higher COPs at low driving heat temperatures.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Increase thermal COP and electric efficiency of solar thermally driven cooling systems (COP_{el}), including developing new cycles and storage.	2012-20 (2020: COP_{el} >10 for the whole system)	Research institutes, SHC industry, cooling industry
Address challenges in system design by developing standardised kit solutions and plug-and-function systems.	2012-20 (2020: standardised solar thermally driven cooling technology commercially available)	SHC industry, cooling industry
Develop small scale thermally driven solar cooling technology for single family and multi-family dwellings.	2015-25 (2025: small and medium scale residential solar thermally driven cooling technology commercially available)	Research institutes, SHC industry, cooling industry
Develop integrated thermally driven solar cooling and heating technology, including compact storage.	2015-30 (2017: first systems demonstrated 2030: integrated solar thermally driven cooling and heating tech. [incl. compact storage] commercially available)	Research institutes, SHC industry, cooling industry
Explore potential for retrofitting existing vapour compression systems into solar thermally driven cooling.	2020-30	Research institutes, SHC industry, cooling industry

In the longer term, solar thermal technology should be able to deliver small and medium scale systems for both heating (space heating and domestic hot water) and cooling, compatible with compact thermal storage. For large systems (more than 50 kW cooling capacity), technical developments are required to improve efficiency and cost competitiveness. That will involve system packaging and standardisation, and innovations to simplify system operation and maintenance.

Thermal storage

In the case of sensible heat storage using water, large scale stores are required to store enough energy for inter-season use. Although large scale sensible heat storage can already be deployed, *e.g.* for district heating systems, the volumes required make it difficult to store the summer's heat for use in winter in residential dwellings where space is at a premium. Therefore, developing new, cost-effective, compact season-scale heat storage technologies is crucial for the commercialisation of solar thermal systems. To meet these requirements new materials and technologies must be developed.

Basic research in new materials to store large amounts of thermal energy in limited space (high energy density) is essential, with thermochemical systems being the front-running technology for the most compact systems. The materials in existing systems, based on phase change materials (PCMs) and sorption should be improved or replaced by better materials. Development of optimised heat and mass transfer devices (reactors) for sorption and thermochemical storage also needs attention. The capacity to operate consistently over a high number of charging and discharging cycles is critical for most thermal energy storage applications, so the stability of materials in the systems is very important – not only the storage medium itself but also materials used in systems components such as containers, reactors, heat exchangers and pipes.

In order to facilitate the uptake of solar heat in industrial processes, research is needed into new materials for medium-temperature storage. Thermal storage working on medium temperatures, between 100°C and 300°C, enables the integration of solar thermal technology into industrial processes and the optimisation of these processes. Materials have to be developed that are more cost-effective than the presently available technologies such as steam storage. Heat exchangers and reactors have to be developed for charging and discharging the new materials. Industry and research institutes should co-operate in the development and demonstration of solar thermal systems with storage for integration into industrial processes.

Expertise from development in other areas, such as R&D into lower melting temperature salts for concentrating solar power (CSP) technology and thermochemical materials (TCM) development, could prove beneficial for the SHC sector. Collaboration between sectors should be encouraged and several storage technology development lines should be followed in parallel, including advanced water, PCM, sorption and thermochemical systems. Other components and auxiliary equipment should be developed in parallel.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Continue developing promising materials for compact thermal energy storage, particularly phase change materials, sorption and thermochemical materials. Validate stability of materials and performance characteristics. Create linkages with other sectors, for instance R&D into thermal storage for CSP and industrial processes.	2012-25 (2020: small scale low cost compact thermal heat storage available with target storage density 1 000 MJ/m^3)	Research institutes/universities, chemical industry
Research new materials for medium-temperature storage, between 100°C and 300°C, such as phase change, sorption and thermochemical materials. Demonstrate systems in which the new storage technologies are integrated.	2012-20 (2018: first systems demonstrated in a number of sectors)	Research institutes, SHC industry

Hybrid applications and advanced technologies

Solar heating and cooling technology is very suitable for combination with other (renewable) energy technologies. Applying solar heating and cooling technology in combined or integrated solutions serves to maximise the yield and thereby economics of solar heating technology and/or to optimise the use of limited available roof surface. Examples are photovoltaic/solar thermal hybrid (PV-T) collectors and SHC technology combined with heat pumps or with biomass boilers.

PV-T collectors are seen as a promising technology which can potentially provide the most efficient way to use solar energy and avoid roof competition: it first converts solar radiation into electricity and then removes and uses the remaining thermal energy for (water) heating. PV-T collectors have been under development for some time but are not yet market ready. Increasing competition for roof surface with recent strong growth in photovoltaic applications may be a driving force for redeveloping PV-T collectors. Recent efforts in improving PV-T collectors have focused on improving thermal and electrical efficiency of covered PV-T collectors (Dupeyrat *et al.*, 2011). Remaining challenges to be solved are reducing heat losses, protection against overheating, combination of layers and improving economics.

Solar assisted heat pumps can reduce the temperature lift that the heat pump will have to bridge, thus improving their performances. In the case of ground source heat pumps injecting solar heat into the ground, these can also help in balancing the underground temperature in cases where the borehole is somewhat shorter than needed or when there is more heat extraction in winter than recharge from cooling in summer. Today, over 90 solar assisted heat pump systems have been identified in Europe, but their performance has not yet been systematically evaluated (IEA SHC, 2011). Evaluating performance of currently existing solar assisted heat pump systems should lead to development of higher performance kit systems and more robust solutions to the technical challenges.

Solar heating systems that are combined with biomass boilers can provide 100% renewable heating systems. The combination is technically straightforward, but is rarely offered as a standard product, so it requires unique design and production for each installation. Evaluating the performance of currently existing solar assisted biomass boilers should lead to development of high-performance kit systems.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Develop PV-T technology to make it commercially viable.	2012-20 (2020: PV-T commercially available)	Research institutes, SHC industry, PV industry
Evaluate the performance of current hybrid solar systems incorporating heat pumps and develop these into kit systems for both heating and cooling with an overall electrical COP>5.	2012-20 (2015: Solar heat pump hybrid kit systems commercially available)	SHC industry
Evaluate performance of current hybrid solar systems incorporating biomass boilers and develop these into kit systems.	2012-20 (2015: Solar biomass hybrid kit systems commercially available)	SHC industry

Policy framework: actions and milestones

Regulatory framework and support incentives

In several markets, the benefits of solar heating and cooling are seen not only as reducing CO_2 emission but also as alleviating concerns about electricity peak load costs. Governments should take a broad perspective when (re)considering their countries' solar heating and cooling potential. They should then establish medium-term targets for (nearly) mature technologies and long-term targets for advanced technologies to exploit the potential for solar heating and cooling. Clear and ambitious targets are needed when considering the introduction of regulatory and support incentives. Addressing all economic, non-economic and technical barriers in a holistic approach is more likely to ensure the success of a support scheme.

Where solar heating and cooling technologies are not yet able to compete with conventional fossil fuel alternatives, effective and predictable economic incentive schemes are required. These should take into account the advantages of renewable heat as a displacement technology (for example in reducing fossil fuel use or load on the electrical network), as well as the characteristics of different types of end users. Further, SHC technologies must be able to compete on a level playing field with other renewable and non-renewable technologies by being equally eligible for incentives, market support and qualification to participate in trading schemes.

Different end-user groups may need different incentive structures to drive purchases. Small scale applications are unmetered because the heat output is directly used on site. Therefore these small scale applications might benefit most from upfront financial incentives. In medium and large scale applications it is often useful and more feasible to meter heat output. Incentive schemes based on heat output, such as feed-in tariffs, thus make more sense in medium and large scale applications.

In order to avoid "stop-and-go" policies, as have often been experienced in the past for solar heating and cooling support, it is recommended to search for options to make economic incentive schemes independent from annual government budget appropriations. Green and white certificates provide a market-based mechanism that has been used with success, *e.g.* in Australia.[16] Recent initiatives have explored the possibility of adding a levy on fossil fuel consumption for heat generation (oil, gas and coal). Other well-known examples are the CO_2 taxes that have been assessed in Sweden and Denmark, and are thought to have strongly influenced the energy mix for heat and power. In the United States, legislation or regulation adding a small per-unit charge on electricity and natural gas purchases by end-users has been widely accepted by "ratepayers". This mechanism avoids the annual budget appropriation problem, as rules or laws so applied can remain in force for a number of years, and can be extended when nearing expiration.

Other examples of policies encouraging solar heating and cooling are regulatory approaches such as solar obligations or solar ordinances, which impose an obligation on parties specified in legislation to source a minimum amount of their energy use from solar heat. Since a solar obligation incentivises one specific technology, such policies may be most suitable where there is no competition from other renewable technologies for the same purpose. Alternatively, new and emerging technologies should have regular and reasonable opportunities to be assessed for eligibility and inclusion in the scheme. Other regulatory approaches consist of requiring a share of a building's heating demand to be generated by renewable energy: this type of obligation allows for competition among renewable (heating) technologies.

It is clear that requirements for building permits should not hinder the installation of solar systems; indeed, building permits should be designed to facilitate easy integration of SHC technology. In many locations solar systems may be installed without permits, or with free permits, except for historical buildings.

16 See also http://ret.cleanenergyregulator.gov.au and www.veet.vic.gov.au.

This roadmap recommends the following actions:	Milestone timeline	Stakeholder
Set medium-term targets for (nearly) mature solar heating and cooling technologies (solar low-temperature heat) and long-term targets for advanced technologies (high-temperature heat and solar cooling).	2012-25	Governments, industry associations
Introduce differentiated economic incentives – such as feed-in tariffs or renewable portfolio standards for commercial heat and subsidies or tax incentives for end-user technologies – by means of a transparent and predictable framework to bridge their respective competitive gaps.	Start 2012, phase out depending on development of competitiveness	Governments
Make economic incentive schemes consistent over a period to allow time for industry to plan and develop with certainty. Avoid "stop-and-go" policies by separating funding for support schemes from annual state budgets.	Start 2012	Governments
Consider regulatory approaches such as solar obligations or building regulations.	Start 2012, phase out depending on development of competitiveness	Governments
Consider and evaluate renewable energy technologies such as solar cooling as possible solutions to electrical network constraints and enable solar heating and cooling technologies to compete on a level playing field with other renewable and non-renewable technologies.	Start 2012	Governments

Addressing non-economic barriers

From the demand side perspective, barriers hindering the uptake of solar heating and cooling include a general lack of information about solar heating and cooling technology and potential. Some countries have chosen to carry out awareness raising campaigns, building up understanding and confidence in the technology. Important stakeholders can also be addressed with specific actions, *e.g.* tackling the low priority given to energy issues in the building sector when compared to other costs for private persons or companies (IEA, 2007).

Increasing transparency on energy costs – including external factors that are not included in the market price for energy such as the costs of natural resource depletion, health impacts from pollution and climate change – should help consumers and project developers to receive accurate price signals reflecting the true cost of energy use.

It should be emphasised that, overall, the benefits of implementing a solar heating and cooling system are substantial, despite so-called "transaction costs": resource requirements including gathering the necessary information, project design, and financing required for a successful project. The information barrier can be addressed by increasing awareness of the potential of solar heating and cooling under specific climatic conditions and for specific applications. Several examples exist of public tools to gauge the potential of solar heating and cooling on the basis of climate conditions and comparison to conventional alternative technology (Box 6).

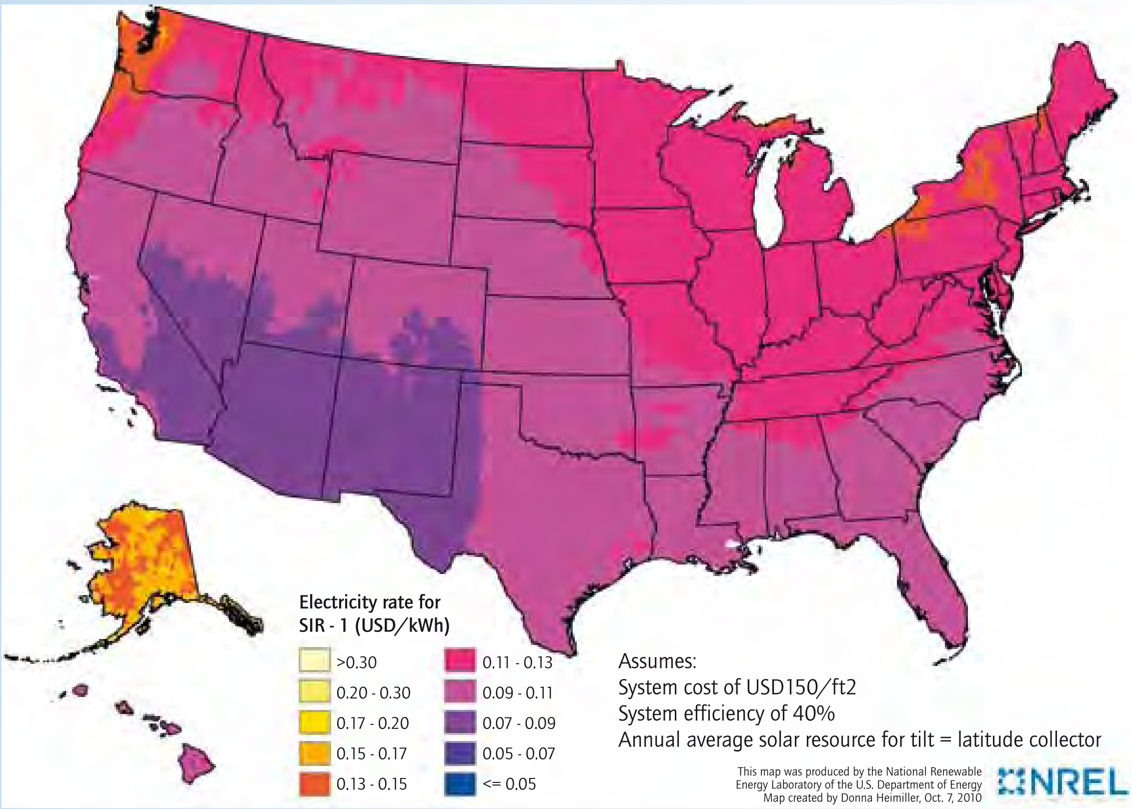
Solar heating and cooling technology has a higher upfront capital cost than conventional technologies. This poses a barrier to investment, as decision

Box 6: Addressing information and awareness barrier

In the United States, the National Renewable Energy Laboratory (NREL) has created a user-friendly tool for assessing where and under what conditions a solar heating system can add value. Through the use of GIS, NREL examined the viability of solar hot water systems in the country. The map shows where solar hot water heating is cost-effective today in comparison to an electric water heater. The areas where cost-effective solar systems could be installed now are deemed to be those with a calculated savings-to-investment ratio of 1 or higher. At commercial electric rates of USD 0.15/kWh or more, however, solar water heating systems would be cost-effective for nearly any federal facility in the country.

Several other websites address the information barrier to solar heating and cooling systems. *E.g.* an overview of rebates in Victoria, Australia is given at: www.sv.sustainability.vic.gov.au/energy_efficiency/shw_rebate_public/systemslist.asp?selection=1 whereas ret.cleanenergyregulator.gov.au/Hot-Water-Systems/Eligible-Solar-Water-Heaters/eligible-swhs shows the performance of solar hot water systems for a renewable energy certificate scheme in Australia. Information on estimated savings on a weekly basis for different regions in Victoria, Australia based on the solar insolation for that week can be found at: www.resourcesmart.vic.gov.au/for_households/hot_water_2675.html.

Figure 19: Viability of solar hot water systems compared to electric water heaters (United States)



Note: Electricity rate for savings-to-investment ratio = 1 for solar hot water systems compared to electric water heaters (not considering incentives).

Source: NREL, 2011.

makers, especially private homeowners, may not be willing to make large upfront investments. Private households have *e.g.* been described to use implicit discount rates in the order of 25% to 75% for energy investment decisions, which substantially increase the hurdle for any upfront investment. There is a need for new business models that improve the bankability of these investments and several examples are available which can be facilitated by policy intervention (IEA RETD, 2012). For example, policy makers could well stimulate energy service companies (ESCo's) to support major solar heating and cooling deployment projects, *e.g.* by facilitating access to finance and changing procurement rules for public buildings. Such facilitation process should come with a full set of quality requirements leading to insurance of long term performance and reliable solar systems. For smaller residential and commercial buildings, they could stimulate business models such as on-bill financing.

Solar water heating technology is not highly complicated and the required capital investment for manufacturing is low, so businesses can enter the market relatively easily. This means that countries can easily adopt policies and strategies to increase solar adoption and create employment opportunities, thereby improving local economies. However, without careful oversight of quality through testing and certification of products, systems and personnel, lower-quality products and lack of after-sale service could damage the reputation of the industry (REN21, 2009). In addition, the lack of product standardisation at regional or global level can make it difficult for companies to enter global markets. Support mechanisms should take quality standards into account, thus ensuring an efficient and judicious use of public funds.

An example of a well-functioning quality standard for solar heating and cooling products is the Solar Keymark, which is widely used throughout Europe and increasingly recognised worldwide. ISO and CEN are currently developing a single collector standard for the global market. However, available quality systems around the world tend to focus on collectors, without taking into account the impact on performance of the rest of the system. The quality assurance of the whole SHC system needs higher priority and funding.

In retrofit applications on existing buildings, small scale installers of conventional heating and cooling systems often act as "gatekeepers" between suppliers of products and building owners. In cases of equipment failure the building owner may follow a least-cost approach, rely on the installer's advice or proceed with whatever option can be supplied and installed immediately to minimise downtime. If the installer is also offering a maintenance contract on heating and cooling equipment, they will not usually be inclined to recommend the installation of non-conventional products, including solar heating systems. This barrier can be addressed by offering training and education in solar heating and cooling technology for architects, installers and installation engineers. It should encourage SHC deployment, educating consumers to request SHC technology and encouraging SHC supply channels so that the technology is available for immediate supply and installation.

A well-known barrier for the uptake of solar heating and cooling systems in the building sector is the "split-incentive" dilemma. For example, rental property owners have little incentive to invest if their tenants pay the energy bill. Conversely, the tenant may not be interested in a solar system investment either, as they may move out of the building before recovering their investment via reduced energy costs. One solution to this barrier might be to introduce regulations under which investment costs for renewable energy improvements made by building owners may be recovered through a cost-share arrangement and effected through higher rental prices. For tenants, the decrease in energy costs due to solar energy improvements can be structured to offset the rental price increase.

From the supply or new construction perspective, barriers to the increased uptake of solar heating and cooling systems are caused in part by the nature and complexity of the heat market. The relatively small size of individual suppliers of solar heating and cooling equipment and the fragmentation of the building product supply chain inhibits a holistic approach to new building design and construction. The stand-alone nature of the small scale solar heating and cooling suppliers and competition with the larger conventional heating and cooling industry can have a negative impact on the deployment of solar heating and cooling technology. The solar heating and cooling industry and the conventional heat industry could both benefit from synergy and added value in cases where solar heating and cooling could be incorporated into the product ranges of the conventional heating industry.

This roadmap recommends the following actions:	Milestone timeline	Stakeholder
Address information barriers and create public, business and professional awareness of the potential of solar heating and cooling in specific climates and for specific applications.	2012-20	Governments, SHC industry, research/education institutes, NGOs
Support and facilitate the introduction of new business models that address financing and up-front investment barriers for technologies.	2012-20	Governments
Develop quality insurance methods, certification and standards at system level, to be included in support mechanisms, ensuring an acceptable quality of solar heating and cooling products is achieved.	2012-20	Governments, SHC industry, installers, research institutes
Introduce training and education in solar heating and cooling technology for architects, engineers, designers, owners, facility managers, consultants and installers.	2012-20	Education institutes, SHC industry, governments
Address "split-incentive" problem by adjusting regulations in the (social) rental sector so that building owners are incentivised to act even if they do not experience its direct benefits.	2012-20	Governments
Strive towards synergy between the solar heating and cooling industry and the conventional heating, cooling and air conditioning industry.	2012-30	SHC industry, conventional HVAC industry

Research, development and demonstration support

Solar heating and cooling technologies have differing levels of maturity. Whereas solar domestic hot water technology is relatively mature, solar cooling is currently in the demonstration/pre-industrial phase and therefore has significant potential for improvement. Compact seasonal heat storage is still in the early development phase: in order to make very high solar fractions in solar space heating possible, continued development work is crucial. Hybrid solar assisted systems and PV-T systems offer promising potential but are still in the demonstration phase. Long term, sustained and substantially greater research, development and demonstration (RD&D) resources are needed to improve designs and accelerate cost reduction in order to bring novel solar heating and cooling concepts to market.

Important R&D priorities for solar heating and cooling are:

- Improvement of solar hot water systems by integrating solar collectors in building components, by using alternative materials and by developing standardised kits and plug-and-operate systems.
- Development of collectors that cover the current temperature gap between 100°C and 250°C.
- Adaptation of CSP power technology to heat applications (smaller scale, adjusted temperature levels) and to building integration (for cooling applications).
- Improvement of solar cooling technology by increasing thermal COP and COP_{el} (overall electrical efficiency) through further development of new cycles, optimised heat rejection systems, reduced parasitic consumption and new storage concepts; by development of small-scale solar thermal

driven cooling products for small commercial buildings, single and multi family dwellings; and by developing standardised kits and plug-and-play systems.

- In time, development of integrated solar thermal driven heating and cooling technology, including compact storage.
- Continued development of promising materials for compact thermal energy stores, particularly phase change and thermo-chemical materials. This should include validating stability, performance characteristics and cycle life of materials; and creating linkages with other sectors, including R&D into molten salt storage for CSP.
- Development of PV-T technology and hybrid systems with heat pumps and biomass boilers into commercially viable technology and development of hybrid systems into kit (packaged) systems.

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Increase public RD&D funding.	2012-20	Governments
Ensure sustained RD&D funding in the long term through private-public partnerships.	2020-40	Governments and private sector

International collaboration and deployment in emerging and developing economies

International collaboration will ensure that important issues are addressed making full use of areas of national expertise and taking advantage of existing RD&D activities and infrastructure. One example of collaboration in the field of solar heating and cooling is the IEA Solar Heating and Cooling Implementing Agreement, one of 42 such initiatives covering the complete spectrum of energy technology development. The Solar Heating and Cooling Implementing Agreement includes technology experts from 20 countries and the European Union; amongst which China, South Africa and Singapore participate as non-member countries. The Agreement serves to share good practice among member countries and sponsors, and works to establish common research agendas on specific topics. Participation by more countries with an interest in solar heating and cooling, whether IEA members or not, would further strengthen this Implementing Agreement. Other examples of collaboration are the International Solar Energy Society (ISES), the International Association of Plumbing and Mechanical Officials (IAPMO), ISO TC 180, the European Solar Thermal Industry Federation (ESTIF) and the European Technology Platform on Renewable Heating and Cooling.

Solar heating and cooling can play an important role in many developing countries, as certain solar heating and cooling technologies are mature and relatively affordable. Moreover, in many developing countries demand for cooling and for hot water is expected to grow, while solar resources are often good. In many large cities in developing countries hot water for showers is produced by electricity and takes up a large part of the domestic electricity demand (mainly in peak hours). It will therefore be crucial to consider the specific policy framework and particular needs of developing countries to achieve the level of solar heating and cooling deployment envisioned in this roadmap.

In some new solar heating and cooling markets, challenges include achieving a well-functioning market infrastructure with an effective supply chain of manufacturers. The key strategic decision for programme sponsors in this phase is the division of resources between infrastructure support and financial incentives to stimulate market demand. While rebates and other incentives boost sales in the short run, investing in infrastructure can help build a self-sustaining market. Innovative support schemes initiated by development banks should be able to address both non-economic and economic barriers to solar heating and cooling deployment in developing countries.

The concentration of R&D in a small number of markets has led to knowledge being concentrated in markets that do not necessarily have the best solar resources. Countries with a good solar resource but less experience should benefit from the knowledge available elsewhere by participating in schemes that allow for easy knowledge transfer. To ensure technology access and transfer, co-operation in RD&D should be enhanced among industrialised and developing countries, as well as among developing countries. For example, the European solar cooling market is small, so cost reduction as a result of increased deployment (learning rates) will happen slowly. Solar cooling needs to be deployed in niche markets where there are very high electricity prices or oil based systems (islands, etc).

This roadmap recommends the following actions:	***Milestone timeline***	***Stakeholder***
Expand international R&D collaboration, making best use of national competencies.	Start 2012	Research institutes, governments, SHC industry, International collaboration networks
Develop mechanisms that address both economic and non-economic barriers to solar heating and cooling utilisation in developing countries.	Start 2012, phase out as technology becomes competitive	Development banks, NGOs, governments
Develop schemes to transfer knowledge from high solar system utilisation regions to those with good solar resource but less experience.	Start 2012	Governments, NGOs, Research institutes, SHC industry, International collaboration networks

Conclusions and role of stakeholders

This roadmap has responded to requests for deeper analysis of the growth pathway for solar heating and cooling, a key renewable energy source. It envisages development and deployment of solar heating and cooling by 2050 to produce 16.5 EJ solar heating annually, more than 16% of total final energy use for low temperature heat, and 1.5 EJ solar cooling, nearly 17% of total energy use for cooling by that time. This roadmap describes approaches and specific tasks for RDD&D; financing mechanisms; legal and regulatory frameworks; public engagement; and international collaboration. It provides regional projections for solar heating and cooling from 2010 to 2050. Finally, this roadmap details actions and milestones (see below) to aid policy makers, industry and power-system stakeholders, research institutes, and multilateral development banks, in supporting the successful implementation of solar heating and cooling.

The solar heating and cooling roadmap is part of a process that must evolve to take into account new technical and scientific developments, policies and international collaborative efforts. The roadmap has been designed with milestones that the international community can use to ensure that solar heating and cooling development efforts are on track to achieve the reductions in greenhouse-gas emissions that are required by 2050.

Stakeholder	Action items
Governments	• Set medium-term targets for (nearly) mature solar heating and cooling technologies (solar low-temperature heat) and long-term targets for advanced technologies (high-temperature heat and solar cooling). • Introduce differentiated economic incentives – such as feed-in tariffs or renewable portfolio standards for commercial heat and subsidies or tax incentives for end-user technologies – by means of a transparent and predictable framework to bridge their respective competitive gaps. • Make economic incentive schemes consistent over a period to allow time for industry to plan and develop with certainty. Avoid “stop-and-go” policies by separating funding for support schemes from annual state budgets. • Consider regulatory approaches such as solar obligations or building regulations. • Consider and evaluate renewable energy technologies such as solar cooling as possible solutions to electrical network constraints and enable solar heating and cooling technologies to compete on a level playing field with other renewable and non-renewable technologies. • Address information barriers and create public, business and professional awareness of the potential of solar heating and cooling in specific climates and for specific applications. • Support and facilitate the introduction of new business models that address financing and up-front investment barriers for technologies. • Develop quality insurance methods, certification and standards at system level, to be included in support mechanisms, ensuring an acceptable quality of solar heating and cooling products is achieved. • Address “split-incentive” problem by adjusting regulations in the (social) rental sector so that building owners are incentivised to invest in SHC technology even if they do not benefit directly. • Increase R&D funding in the short term and ensure sustained RD&D funding in the long term through private-public partnerships. • Develop schemes to transfer knowledge from high solar system utilisation regions to countries with good solar resource but less experience with the technology.

Stakeholder	Action items
Solar heating and cooling industry	• Work towards greater integration of solar collectors in building surfaces. • Develop alternative materials, technologies and manufacturing techniques to reduce system cost and improve performance. • Address challenges in system design by developing standardised kits and plug-and-function systems. • Develop quality insurance methods, certification and standards at system level, to be included in support mechanisms, ensuring an acceptable quality of solar heating and cooling products is achieved. • Address challenges in development of medium to large scale systems by developing pre-engineered solutions and improving system design knowledge. • Integrate solar thermal in district heating and cooling networks and establish seasonal storage. Enable seasonal heat storage to act as buffers for the electricity grid via heat pumps and CHP. • Adapt concentrating solar technology to different heat applications (smaller scale, adjustable temperature levels and building integrated solutions). • Develop and standardise system integration for solar heat in industrial processes. • Increase thermal COP and COP_{el} (electrical efficiency) of solar thermally driven cooling systems; develop new cycle and storage systems (with cooling industry). • Address challenges in system design by developing standardised kit solutions and plug-and-function systems (with cooling industry). • Develop small scale thermally driven solar cooling technology for single family and multi-family dwellings (with cooling industry). • Develop integrated thermally driven solar cooling and heating technology, including compact storage (with cooling industry). • Explore potential for retrofitting of existing vapour compression systems into solar thermal cooling (with cooling industry). • Develop PV-T into commercially viable technology (with PV industry). • Evaluate the performance of current hybrid solar systems incorporating heat pumps and develop these into kit systems for both heating and cooling with an overall electrical COP>5. • Evaluate performances of current hybrid solar systems incorporating biomass boilers and develop these into kit systems. • Introduce training and education in solar heating and cooling technology for architects, engineers, designers, owners, facility managers, consultants and installers. • Seek synergies between solar heating and cooling industry and conventional heating, cooling and air conditioning industry. • Expand international R&D collaboration, making best use of national competencies.

Stakeholder	Action items
Research institutes/ universities	• Develop integration of solar collectors in building surfaces. • Research alternative materials, technologies and manufacturing techniques to reduce system cost and improve performance. • Expand development of collectors that cover temperature gap between 100°C and 250°C. • Adapt concentrating solar technology to different heat applications (smaller scale, adjustable temperature levels and building integrated solutions). • Develop and standardise system integration for solar heat in industrial processes. • Increase thermal COP and COP_{el} (electrical efficiency) of solar thermally driven cooling systems, including developing new cycles and storage (with cooling industry). • Address challenges in system design by developing standardised kit solutions and plug-and-function systems (with cooling industry). • Develop small scale thermally driven solar cooling technology for single family and multi-family dwellings (with cooling industry). • Develop integrated thermally driven solar cooling and heating technology, including compact storage (with cooling industry). • Explore potential for retrofitting of existing vapour compression systems into solar thermal cooling (with cooling industry). • Continue developing promising materials for compact thermal energy storage, particularly phase change materials, sorption and thermochemical materials. • Validate stability of materials and performance characteristics for compact thermal energy storage; create linkages with other sectors (*e.g.* R&D into thermal storage for CSP and industrial processes. • Develop and demonstrate heating and cooling systems with integrated, advanced compact thermal energy storage systems (based on PCMs, sorption or chemical reactions) to optimise performance and reduce costs. • Research new materials for medium-temperature storage, between 100°C and 300°C, such as phase change, sorption and thermochemical materials. Demonstrate integrated systems. • Develop PV-T into commercially viable technology. • Introduce training and education in solar heating and cooling technology for architects, engineers, designers, owners, facility managers, consultants and installers. • Expand international R&D collaboration, making best use of national competencies. • Develop schemes to transfer knowledge from high solar utilisation regions to countries with good solar resource but less experience.
Multilateral/bilateral development banks	• Develop mechanisms that address both economic and non-economic barriers to solar heating and cooling utilisation in developing countries.

Appendix I: Assumptions for solar heat cost calculations

	Thermosiphon Southern EU	Forced circulation central EU	Forced circulation northern EU	Solar cooling	Large scale EU
Investment costs (USD/kW)	630	850-1 900	1 600-2 400	1 600-3 200	350-1 040
Collector yield (kWh/m²a)	685	395	360	395-685	685
Discount rate	3%-6%	3%-6%	3%-6%	3%-6%	3%-6%
Lifetime (yrs)	15	20	20	20	20
Operation and maintenance	0.5-1.5%	0.5-1.5%	0.5-1.5%	0.5-1.5%	0.5-1.5%

Note: Actual observed system prices can go beyond these ranges.

Appendix II: Abbreviations, acronyms and units of measure

Abbreviations and acronyms

CHP	combined heat and power
COP	coefficient of performance
CSP	concentrating solar power
ETC	exchange traded commodity
FPC	Federal Power Commission
GIS	green investment scheme
kW_{th}	kilowatt thermal
$kW_{cooling}$	kilowatt cooling
NREL	National Renewable Energy Laboratory
PCM	phase change materials
PV-T	photovoltaic-thermal
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RED	IEA Renewable Energy Division
SHC	solar heating and cooling
TCM	thermochemical materials
USD	United States dollar

Units of measure

kW	Kilowatt (10^3 Watt)
MW	Megawatt (10^6 Watt)
kWh	Kilowatt-hour
MWh	Megawatt-hour
GW	Gigawatt (10^9 Watt)
TJ	Terajoule (10^{12} Joule)
PJ	Petajoule (10^{15} Joule)
EJ	Exajoule (10^{18} Joule)

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