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ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

IRENA
International Renewable Energy Agency

Solar Heat for Industrial Processes

Technology Brief

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

Insight for Policy Makers

Solar thermal can fulfill a substantial amount of heat demand in industrial and agricultural food processes within any given country and irrespective of the geographical location. In developed economies, solar thermal can provide technically about half of this energy consumption by supplying hot water and steam in a temperature range of up to 400°C. In developing countries, especially in those where agriculture, the textile, brick and food processing industries are important sub-sectors, solar thermal energy can provide hot air and hot water needed for curing, drying, dyeing, washing, boiling, pasteurisation and sterilisation.

In general, there are three groups of solar thermal technologies that are useful for industrial process heat: solar air collectors, solar water systems, and solar concentrators. **Solar air collectors** are found primarily in the food processing industry to replace gas- or oil-based drying or to reduce food spoilage due to open- air drying. They can be built locally, and their cost depends on local building materials and labour. Conventional **solar water systems**, like flat-plate collectors (FPC) or evacuated tube collectors (ETC), are primarily used in residential applications, but they can readily be installed on industrial rooftops to provide heat demand of up to 125°C. More than one hundred systems exist around the world. A small number of large international companies sell these technologies, but the majority of solar water heating systems are manufactured locally by small- and medium-size enterprises. This is especially the case in countries like Brazil, China, South Africa and Turkey where the costs are three to ten times lower than in the United States or in European countries. A number of more advanced FPC and ETC designs are currently on the market and can generate temperatures of up to 250°C; however, they are also more expensive than conventional FPC and ETC. **Solar concentrators** include parabolic dish collectors, linear parabolic trough collectors and linear Fresnel collectors. In India, local manufacturers sell mainly parabolic dish collectors that can generate temperatures of up to 400°C. Around 80 commercial projects are installed in India, mostly for community solar cooking. The other two types of solar concentrators are similar to those used to produce concentrated solar power. Around twenty commercial systems currently exist around the world.

Deployment levels are mainly determined by the economic competitiveness of solar thermal systems. Key challenges for solar thermal heat in industrial applications are the short pay-back times that are expected (< 3 years), the relatively low fossil fuel prices charged in the industrial sector and the integration into existing industrial processes. The majority of industrial heat demand (75%) takes place in large complex industrial sites. Although solar thermal energy could save costs in the long run, the complexities of integrating new heat sources into existing processes creates possible risks that the bulk producing industries try to avoid. One opportunity is to integrate solar thermal heating plants during the construction of new industrial plants. For small- and medium-size industrial plants, solar process heat could reduce the dependence on volatile fossil fuel prices. The key challenge is to maximise the share of heat provided by solar heating. This means that solar heating needs to be accompanied by storage to allow process heating during non-sun hours, storage for non-production hours, or more advanced control systems to optimise the usage of solar heating. For small- and medium-size enterprises, rooftop space and finance opportunities for the upfront costs are the key barriers.

Despite the technical potential, as well as the potential economic benefits of using solar heat in industry, actual deployment levels remain quite low. To achieve higher market penetration, policy options are: create more awareness of the benefits of solar process heating, especially in industrial clusters of small- and medium-size enterprises; provide financing mechanisms to cover upfront costs; and consider whether support for solar thermal could be an alternative to fossil fuel price subsidies to national industries. Furthermore, solar process heat technologies can be supported by local manufacturing, as showcased in India, thus providing a mutually reinforcing strategy to support a healthy national industry.

Technical Highlights

- **Process and Technology Status –** Solar heating technologies collect thermal energy from the sun and use this heat for drying purposes, for space heating/cooling or to provide process heat. With advanced solar process heat technologies, temperatures of up to 400°C can be provided, potentially fulfilling almost 50% of heat demand in the industrial sector (IRENA, *in press*). Heat in the lower temperature range (<80°C) can easily be provided with systems commercially available, such as flat plate collectors (FPC) and evacuated tube collectors (ETC). For medium temperature processes, new advanced collector designs has been successfully developed. Ultra-high vacuum FPC or ETC with concentrators can also generate temperatures of up to 200°C. Solar concentrators like parabolic dish collectors, parabolic trough collectors and Linear Fresnel collectors can generate compressed steam with temperatures of up to 400°C. Most solar thermal systems for industrial process heat are small-scale pilot plants. Only a third of the 140 projects has collector areas > 500 m^2, and the four largest projects (all FPC) account for 49% of the installed thermal capacity. The solar thermal plant opened in a copper mine in Chile in 2013 now accounts for 28% of installed capacity. Additionally, almost 80 parabolic dish collectors are used for community cooking in India, around 40 MW_{th} in total. Countries with high sun hours (*e.g.* India, Mexico, and countries in the Middle East/the Arabian peninsula) are seen as growth markets.

- **Performance and Costs –** The costs of solar heat for industrial process heat strongly depend on process temperature level, demand continuity, project size and the level of solar radiation of the site. For conventional FPC and ETC, investment system costs range between EUR 250–1000/kW in Europe, and around EUR 200–300/kW in India, Turkey, South Africa and Mexico. The energy costs for feasible solar thermal systems range from eurocents 2.5 to 8/kWh, and a European roadmap targets solar heat costs of eurocents 3–6/kWh (ESTIF, 2014). For concentrated systems, heating costs are in the range of eurocents 6-9/kWh with a target of eurocents 4-7/kWh for concentrating systems by 2020 (ESTIF, 2014). Concentrated systems include Parabolic Dish Collectors (developed and used in India) with costs ranging from USD 400–1 800/kW, Parabolic Trough Collectors with costs ranging from USD 600–2 000/kW, and Linear Fresnel collectors in the range of USD 1200–1800/kW. In comparison, the same technology is used in concentrated solar power (CSP) plants with costs of around USD 34 000–6 000/kW (IRENA, 2015). A number of developments are pursued to reduce the costs of solar process heating systems. For conventional FPC and ETC, the use of polymers to replace steel and copper components are considered for future cost reductions, as well as more modular designs to allow for easier integration into industrial rooftops. For concentrating systems, the integration and optimisation of solar process heating into existing and newly built industrial plants will be an essential technology improvement.

- **Potential and Barriers –** Globally, industrial process heat accounts for more than two-thirds of total energy consumption in industry, and half of this process heat demand is low- to medium-temperatures (< 400°C). Currently, approximately 40% of industrial primary energy consumption is covered by natural gas and approximately 41% by petroleum. This means that there is a technical potential to provide around 15 EJ of solar thermal heat by 2030 (around 10% of industrial energy demand) while the share of solar thermal deployed in the industrial sector could reach 33% (IRENA, 2014a). Prime application areas for solar thermal systems are in the food, beverage, transport equipment, textile, machinery, and pulp and paper industries, where roughly 60% of the heating needs can be met by temperatures below 250°C (POSHIP, 2001). Smaller systems include absorption/adsorption chillers or other thermal chillers, and the drying of agricultural products. The use of solar process heating technologies is still supported by research and demonstration funding, as well as government subsidies. However, the first turn-key projects that take advantage of the low lifetime costs of solar process heating are appearing. An important barrier for the deployment of solar process heat is the structure of the industrial sector. The energy-intensive industries account for 75% of heat demand, but consist of only 30 000 to 60 000 plants. For larger industrial plants, integration into existing and optimised process heating streams, as well as the lack of familiarity with the technology, constitute critical bottlenecks. The other 95% of the industrial plants are small- and medium-size enterprises. This means that solar process heat technologies need to be tailored to provide the specific energy demand needs at individual locations. Two smaller application areas are the use of solar thermal systems to drive absorption/adsorption chiller machines or other thermal chillers, and the active use of solar heating for drying agricultural products. For smaller industries, the economic viability of solar heat for industrial process systems is hampered by high upfront costs, even if the overall lifetime cost would be lower. However, the increasing temperature ranges covered by solar process heating and the increasing costs and volatility of fossil fuel prices are improving the economics.

Process and Technology Status

Solar heating and cooling technologies collect the sun's thermal energy and transfer it into a heat transfer fluid. If the heat transfer fluid is water or air, the warm water or warm air can be directly used or piped to a storage tank. In indirect systems, the heat transfer fluid passes through a heat exchanger to warm the process fluid. In the case of solar cooling, the warmed fluid is used in a device called an absorption chiller to drive the cooling of process fluids. 99% of solar heating and cooling technologies is used to provide warm water or space heating in residential homes (IEA-SHC, 2013), but it can also be used to provide process heat for industrial processes. In the latter case, the technologies are similar to those used in residential applications with three exceptions: 1) the amount of heat and cooling required in industrial processes is much larger; 2) heat and cooling needs are often continuous (Saygin *et al.*, 2011) so additional complex control systems are needed; and 3) the temperature levels required for process heat are often higher so concentrators and other advanced technologies are needed to raise the temperature. The use of solar energy in industrial processes has been studied since the 1970s (SERI, 1980; Fuller, 2011), but due to high capital costs and low costs for coal and gas for industrial applications, only limited deployment has taken place over the last thirty years.

Solar process heat technologies can be sub-divided into two broad technology areas. Large-scale **solar dryers** are mainly applied in the food processing industry and use either natural-circulation or forced-convection equipment to collect the sun's radiation for drying applications. **Solar process heat collectors** are used to provide hot water or space heating in a variety of different industry sectors.

Solar air heating

Solar air heating technologies are mainly used to prevent spoilage and lengthen shelf life, maintain or enhance product quality and facilitate transportation of natural food products (and are referred to as solar dryers), or to pre-heat air for boilers. Although solar air heating technologies have been used for centuries, new developments in convection design and thermal energy storage are increasing the range of applications for this technology, especially to replace traditional biomass or fossil fuels as a source for drying purposes in developing countries.

The simplest and most commonly used method for food applications is drying in the open air (also called sun drying). Under these circumstances, however, food products are susceptible to spoilage, infestation, contamination and animal attacks. A number of industries use gas or coal to dry their products, but this ends up accounting for around 50% of their operational expenses. Solar drying technologies can address some of these issues by providing a cheap resource and a more consistent and higher temperature air flow to dehydrate products. However, they also require capital investments, maintenance and a back-up heating system to ensure drying when sun is not available (Weiss and Buchinger, 2010).

Figure 1: Direct solar drying for food drying in India

Photograph: Arun Energy

Solar drying technologies can be grouped according to two dimensions: 1) direct versus indirect solar dryers and 2) active/passive solar dryers. Direct solar dryers are the cheapest option and can be used at the household level with a capacity of 30-50 kg of crop per batch (Bala and Debnath, 2012). However, they are also used for larger industrial drying processes up to 1000 m^2 (see Figure 1). Indirect solar dryers are more expensive but avoid food quality loss due to direct contact with UV radiation. Passive systems use air circulation driven by natural convection and wind pressure.

Active systems control the air flow rate by fans (see Figure 2). Active systems can reduce drying time by a third, and use up to six times less space. However, they require up to 2-5 kWh of electricity per tonne of product electricity to run the fans (possibly via solar PV panels) and are more expensive (Weiss and Buchinger, 2010; Warwick WRI, 2007). Flat plate collectors and evacuated tube collectors (see below) have been used in combination with heat exchangers to preheat air, for example in the tea sector in India.

Figure 2: Solar air heating system in textile industry in Vietnam

Photograph: Grammer Solar

Solar heat collectors

Solar process heat installations used for industrial use are similar to those used in residential buildings, especially for those applications where only low (< 150°C) to medium (150°C – 400°C) temperatures are required. For higher temperatures (>400°C), more advanced or concentrated solar collectors are required. Solar thermal systems that use reflectors, lenses or other optical elements to redirect and concentrate solar radiation onto an absorber are called "solar concentrating collectors" (SRCC, 2014).

Solar Thermal Systems for Low Heat (< 150°C)

Conventional flat-plate collectors (FPC) and evacuated tube collectors (ETC) both provide temperature levels up to 120°C. Flat plate collectors use copper tubes carrying a heat transfer fluid running through an insulated, weather-proof box with a dark absorber material and thermal insulation material on the backside that also prevents heat loss. They can produce temperature levels of up to 100°C. ETC use rows of glass tubes, each of which contains a heat pipe collector with a heat transfer fluid surrounded by a vacuum, which greatly reduces heat losses. Conventional ETC can provide temperatures of up to 120°C and are more suitable for use in in cold climates.

For low-temperature applications, such as sewage treatment sewage processing in cold climates, there is also a good potential for unglazed collectors. Unglazed collectors are primarily used to heat swimming pools or in tropical regions, but when a low solar fraction is acceptable and a small temperature increase can make an important contribution, unglazed systems are much more cost effective than glazed systems in industrial applications.

Solar collector technology, especially FPC and ETC technology, is mature and has enormous potential for low temperature industrial process heat systems, especially in regions with growing industry like India and China. Another application area for solar is in thermally driven desalination processes with operating temperatures of up to 110°C (IRENA, 2012a), especially in regions with high solar irradiance and where solar thermal can replace oil as a fuel.

There are a number of techniques that are used to create higher temperatures. First, various advanced designs have been developed for FPC and ETC, such as transparent insulation material for FPC (up to 150°C) (Beikircher *et al*., 2014), multiple glazing for FPC (up to 110°C) (Foeste, *et al.*, 2014), or the use of inert gas or an ultra-high vacuum (up to 150°C). Another option is to place the ETC and FPC on trackers so that they face the sun throughout the day.

Solar Concentrators for Medium Heat (150°C- 400°C)

For medium temperature process heat applications, some advanced FPC designs with ultra-high vacuums are available to provide temperatures up to 200°C. However, the main technology used for medium temperature heat are **solar concentrator technologies**. In the simplest case, compound parabolic concentrators (CPCs) are fitted behind the vacuum tubes of the ETC, reflecting both direct and diffuse sunlight onto the absorber (also called CPC vacuum tubes). Similar concentrators can be used for FPC. Depending on the configuration of the mirror, concentration factors of up to 4:1 can be achieved, although typically CPC concentration is around 1.5 or lower. Combined with ultra-high vacuum technology, these ETC can provide nominal temperatures up to 200°C (Benvenuti, 2012; TVP Solar, 2012).

Other solar concentrators for process heat are similar to technologies used to produce concentrated solar power (CSP), except that in most cases, they are smaller in size (from 10 kW to 2 MW). Instead of using the heat to produce power however, the heat is directly used in industrial processes. Examples of solar concentrators are parabolic dishes (with flat or curved glas, fixed or moving focus), parabolic trough concentrators and Linear Fresnel collectors. The concentrators can use various shapes (*e.g.* troughs, cylindrical discs,mirror-strips) to concentrate the sunlight onto the absorber.

Parabolic dishes were already used in antiquity, and consist of a parabolic reflector dish focusing sunlight onto the focal point in front of the dish (Carbon Trust, 2013). The dish can consist of flat mirrors attached to wooden, steel or aluminium frames. Some dishes are static and need to be manually adjusted (2-3 times a day) to follow the sun, while others track the sun automatically. One particular design is the Scheffler dish, which was popularised in India. Another example is the ARUN-160 dish, a two-way tracking parabolic dish with an aperture area of 160 m^2, weighing around 20 tonnes and generating 100-120 kg of steam per hour (between 80-100 kW of thermal output) (Clique Solar, n.d.).

Parabolic trough collectors use curved glass to focus the sunlight on heat receivers (i.e. steel tubes or evacuated glass tubes) placed on a focal line (AEA, 2010; IRENA and IEA-ETSAP, 2013).

Linear Fresnel collectors are similar to parabolic trough collectors, except for mirrors that are placed on a horizontal surface at different angles to a fixed receiver located several meters above the mirror field (IRENA and IEA-ETSAP, 2013). Furthermore, for industrial process heat production, Linear Fresnels often need to be adapted to available rooftop and land areas around the industrial site, resulting in different lengths of collector rows and different orientations (Heimsath, *et al.,* 2014). These high-concentration collectors can produce temperatures up to 400°C and are extremely interesting for industrial process heat applications. Renewed interest in these technologies has led to new prototype development in several research institutes around the world (Abdulateef, *et al.*, 2009) and they are becoming more popular, especially for district heating and cooling.

The choice of heat transfer fluid becomes important for medium temperature requirements in solar process heat technologies. Direct systems (or open-loop systems) can use water or air as the heat transfer fluid directly in their processes. However, air has a low heat capacity and water a low boiling point and may be corrosive or deposit minerals in the collector. In indirect systems (or closed-loop systems), some alternative heat transfer fluids are glycol and hydrocarbons (with lower freezing points suitable for cold climates), refrigerants (with high thermal capacity but with low boiling points), molten salt (with typical melting point above 140°C and high thermal capacity), or advanced heat transfer fuels (enhanced performance but also more costly). Other considerations are the costs of the heat transfer fluid, degradation (due to higher temperatures) and the viscosity (higher viscosity means more energy required for pumping).

The selection of an appropriate solar collector basically depends on five factors: 1) operating temperatures; 2) thermal efficiency; 3) energy yield; 4) cost; and 5) the space occupied (Kulkarni, *et al.,* 2009; Fernandez-Garcia *et al.,* 2010). Other aspects, such as the possibility of roof integration or system size, also have to be considered. Furthermore, the choice depends on the technology used to provide the heating or cooling services. For example, different cooling technologies require different temperature levels to provide the heat to drive the regeneration processes (Abdulateef, *et al.,* 2009).

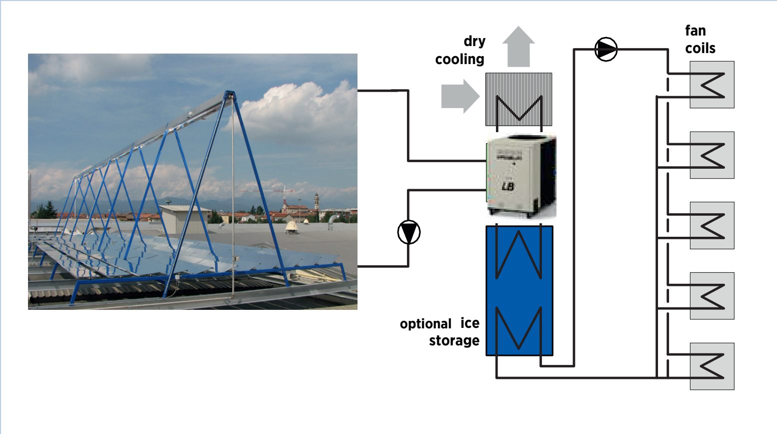
Solar cooling

Besides heating applications, solar thermal systems can also meet cooling demands. In this case, solar thermal cooling systems can be used to replace gas-driven or electricity-driven absorption/adsorption chillers or to replace electricity-driven, vapour-compression air conditioning systems.

Absorption and adsorption chiller systems use liquid or solid refrigerants to cool the environment. In absorption chillers (the most common system), solar energy is used to regenerate the absorber fluid, which contains the refrigerant after it has been evaporated. Two common systems are: closed absorption chiller systems with ammonia-water (NH_3/H_2O) (Figure 3) or water-lithium-bromide ($H_2O/LiBr$) (Figure 4) as refrigerant/absorber fluids. Desiccant systems are used to provide air conditioning, and use a desiccant material to absorb or adsorb warm water from the air and pass cooled air back into the building. Solar energy is used to regenerate the desiccants. Single effect chillers, like desiccant cycles, have lower efficiency but also require lower temperatures (70°C to 100°C) to operate. Double- and triple-effect absorption chillers are only available for capacities of 100 kW or more and have higher efficiencies but also higher heat requirements of 150–180°C and 200–250°C, respectively (IEA, 2012).

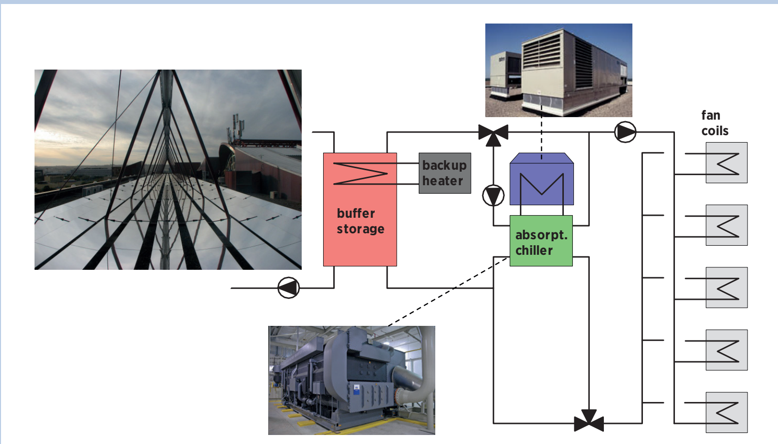
Most thermally-driven chillers used in industry have large cooling capacities (> 100 kW) and require high temperatures (> 100°C) and so cannot be driven by conventional solar thermal collectors. However, the market has changed, with the working temperature requirements for chillers decreasing and the temperature range from advanced solar water heaters and solar concentrators increasing (IEA-SHC, 2013). These higher temperatures from solar process heat installations and solar collectors are also needed to couple them to more efficient double- and triple-effect chillers. Furthermore, a number of companies in Austria, China, Germany, India, Italy, Ireland and Japan now offer standard system designs to integrate and complement other systems (Augsten, 2012). Consequently, FPC and ETC can now be used to drive air-conditioning systems and slab cooling in the

Figure 3: Schema of solar thermal cooling with a ammonia-water Chiller



Haberle, 2011

Figure 4: Schema of solar thermal cooling with double-effect water-lithium-bromide Chiller



Haberle, 2011

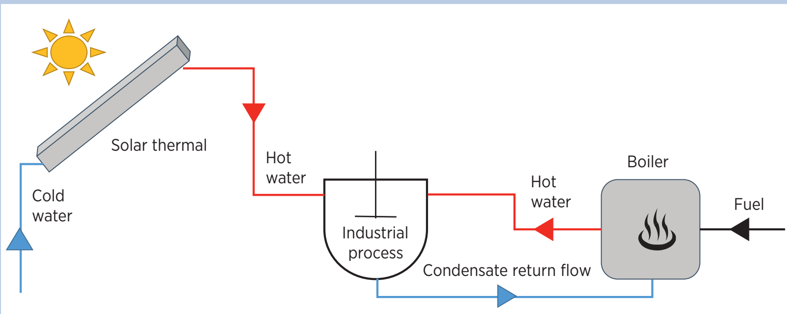
range of +20°C to –10°C, while solar concentrators can be used to drive refrigeration up to – 20°C (Jakob, 2014).

In 2013, an estimated 1000 solar cooling systems were installed, of which 135 were large-scale systems (Jakob, 2014). In 2007, only 10% of the larger-scale systems were for industrial applications (IEA-SHC, 2007). Recent examples in industry include a cooling system in a cosmetics factory in Greece in 2007 (2x 350 kW cooling with 2 700 m^2 of FPC with adsorption), a winery in Tunisia in 2012 (12 kW cooling) and, in India, around ten projects providing solar cooling, mostly for space cooling (Sun Focus, 2013; Sun Focus, 2014). Furthermore, a solar thermal–biomass hybrid cold storage system has been developed to provide refrigeration for farm products (15 kW cooling capacity) (Sun Focus, 2014).

Integration of solar heat into industrial processes

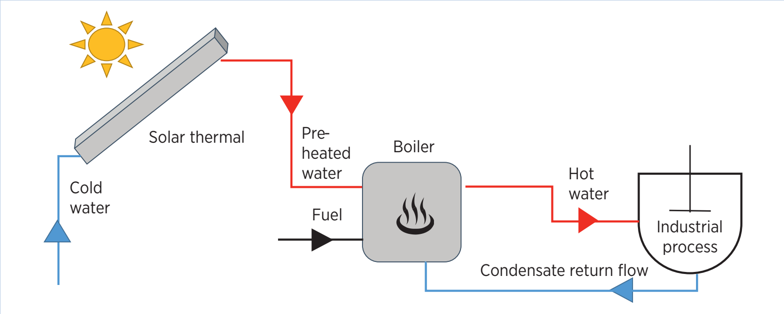
Most industrial processes require both heating of a fluid stream (*e.g.* hot air streams, hot water, replenishment of water in baths) and heating of some reservoir (*e.g.* ovens, liquid baths) (POSHIP, 2001). Existing heating systems for industrial process heat are based on steam or hot water from a boiler, which mainly uses fossil fuels like oil, gas and coal or electricity generated by different sources. Solar process heating systems can supply up to 20% of heating demand of a plant (called the solar fraction). A limiting factor for solar thermal integration is often roof space (*e.g.* in breweries and dairies in Germany) (Mueller, *et al.*, 2014).

Figure 5: Principles for solar thermal systems for direct heating to process equipment



Based on SO-PRO, 2011

Figure 6: Principles for feeding solar thermal heat for pre-heating of supply water for steam boilers



Based on SO-PRO, 2011

Integration of solar thermal systems into industrial process heat can be done in the following three ways: 1) as a heat source for direct heating of a circulating fluid (*e.g.* feed-up water, return of closed circuits, air preheating) (SO-PRO, 2011; Reddy, *et al.*); 2) in processes with low temperature requirements (Figure 5); and 3) as an additional source for pre-heating of supply water for steam boilers (Figure 6) or direct integration of solar heating into fossil-fuelled industrial steam boilers (Hafner, *et al.*, 2014). In the first case, storage will be an important component to ensure that heat is available throughout the day. The second and third options can be used when heat supply demand is larger than can be provided by solar heating or if temperature needs are too high for a solar thermal system (SO-PRO, 2011).

Integration of solar heat systems into industrial applications requires storage and control strategies to handle the non-continuous supply of solar energy (Atkins, *et al.*, 2010; Schramm and Adam, 2014). The accurate design and sizing of a solar thermal system, taking into account the specific demand profile, can be carried out by dynamic system simulation software, such as TRNSYS (Kummert, 2007). The required solar collector's size, its energy delivery and the corresponding solar fraction depend on solar collector specification data and average monthly data on temperature and solar irradiance, which can be obtained from resources like IRENA's Global Atlas for renewables[1].

1 http://globalatlas.irena.org

Installed capacity and market potential

With low- and medium-temperature heat accounting for 45% of total industrial process heat use, solar thermal systems have a large potential (IRENA, 2014b). Solar thermal technology can also provide an alternative to cooling processes in sectors, such as the food and tobacco sector where most product cooling is currently done by electric chillers (IEA, 2007a; Taibi *et al.,* 2012).

Almost all industrial process heat demand requires heat in temperature ranges that can be provided by a solar thermal system. Typical applications and the most promising sectors of industry suitable for solar thermal systems for industrial applications are listed in Table 1. Most applications are in the low- to medium-temperature ranges.

An extremely high percentage of heat demand in the low temperature range is found in food, beverages, paper and textiles with medium temperature ranges in the plastics and chemical industries. These industries require more than 50% of their total process heat in the temperature range up to 250°C for such diverse applications as drying, cooking, cleaning, extraction and many others.

Table 1: Industrial processes and temperature levels

Industrial Sector	Unit operation	Temperature range (°C)
Food	Drying	30-90
	Washing	60-90
	Pasteurising	60-80
	Boiling	95-105
	Sterilising	110-120
	Heat Treatment	40-60
Beverages	Washing	60-80
	Sterilising	60-90
	Pasteurising	60-70
Paper Industry	Cooking and Drying	60-80
	Boiler feed water	60-90
	Bleaching	130-150
Metal Surface Treatment	Treatment, electro-plating, etc.	30-80
Bricks and Blocks	Curing	60-140

Industrial Sector	Unit operation	Temperature range (°C)
Textile Industry	Bleaching	60-100
	Dyeing	70-90
	Drying, De-greasing	100-130
	Washing	40-80
	Fixing	160-180
	Pressing	80-100
Chemical Industry	Soaps	200-260
	Synthetic rubber	150-200
	Processing heat	120-180
	Pre-heating water	60-90
Plastic Industry	Preparation	120-140
	Distillation	140-150
	Separation	200-220
	Extension	140-160
	Drying	180-200
	Blending	120-140
Flour By-products	Sterilising	60-90
All Industrial Sectors	Pre-heating of boiler feed water	30-100
	Industrial solar cooling	55-180
	Heating of factory buildings	30-80

Kalogirou, 2003

The paper and food industries have the biggest heat demand. Considerable heat demand also exists in the textile and chemical industries.

The deployment of solar thermal in industrial applications is rapidly growing, albeit from a very low level. In 2010 the IEA-SHC reported about 42 MW_{th} worldwide (60 000 m^2) (Weiss, 2010; Lauterbach *et al.*, n.d). In 2014 around 140 solar thermal plants for industrial applications were reported worldwide with a total capacity of over 93 MW_{th} (>136 000 m^2) (AEE INTEC & PSE, 2014). Only 18 plants have collector areas larger than 1 000 m^2; most other plants are small-scale pilot projects. Around 70% of the installations use conventional FPC and ETC.

The geographical markets and sectors for solar process heating are also rapidly changing. An overview: In 2007 around 80 projects using conventional FPC and ETC, mostly in the food and beverage (*e.g.* drying, washing, pasteurising processes) and textile sectors (*e.g.* washing and bleaching processes) were identified (Vannoni, 2007; Hess and Oliva, 2010; Weiss, 2010; Hennecke, 2012). Austria, with approximately 20 projects, followed by Germany, Greece, Italy, Spain and the USA (with around 10 projects each) were the countries with the largest number of installations in 2007.

Seven years later, some projects (*e.g.* two solar process heating systems in a poultry-processing and textile plant in Egypt) have been abandoned (UNEP, 2010) while deployment in China (ten projects), France (18 projects), Mexico (15 projects) and, most importantly, India (86 projects) has increased. At the end of 2012, India had 7 967 m^2 of solar concentrator systems for solar cooling and a total of 27 972 m^2 of solar concentrator-based systems for industrial heating applications (REN21, 2014). The largest solar process heating plants today are the 32 MW_{th} solar thermal plant in a copper mine in Chile (opened in October 2013), that supplies around 85% of heat demand, followed by a 9 MW_{th} system for a textile plant developed in 2008 in China, followed by a 5.5 MWth food processing plant developed in 2012 in the USA.

In 2013, India was the lead country and 61% of its solar thermal capacity was used for industrial process (including community cooking); in total, 78 commercial applications of solar concentrators (all parabolic dish collectors) were installed (88% for solar cooking) (Sun & Wind Energy, 2014). Furthermore, there are currently around eight projects using FPC, ETC and Linear Fresnel collectors for solar process heating (AEE INTEC & PSE, 2014) in operation. As the largest milk producer in the world, India's dairy sector is also one of the most interesting application areas where up to 13% of process heat could be supplied by solar thermal (GIZ, 2011). Figure 6 shows an example in the dairy industry in India. Out of the top ten companies supplying solar process heating plants, four are parabolic dish suppliers from India. An important driver for the deployment of solar concentrators in India are the capital subsidies (up to 60%) provided by the Indian Government and a UNDP-GEF project (Sun Focus, 2014). Furthermore, the Middle East and the Arabian Peninsula are seen as potential growth markets (Sun & Wind Energy, 2014). For example, one interesting application is the use of solar thermal heat in oil recovery (GlassPoint, 2013; Scheuerer, 2013).

Based on a global assessment of process heating requirements, IRENA has estimated a total potential for solar thermal of 15 EJ (out of 160 EJ total process energy demand in 2030) (IRENA, 2014b). New capacity investments occurring between 2010 and 2030 offer important potential to deploy renewable energy

Figure 6: Application of parabolic dish (Arun dish) in the dairy industry in India

Photograph: Clique Solar

technologies. The chemical sector accounts for half of this potential due to the fact that two-third of the existing capacity will reach end-of-life before 2030, providing the opportunity for integrating solar thermal process heat capacity in conjunction with new construction. Furthermore, the chemical sector has a high share of low- and medium-temperature heat demand in its production processes (>50%). The pulp and paper, food and tobacco and other small sectors account for the remainder of the solar thermal potential (i.e. sectors with high shares of low- and medium-temperature heat demand in their production processes). In terms of capacity figures, this means a growth from 93 MW_{th} in 2014 to around 850 GW_{th} in 2030 (almost 10 000 times more capacity) to fulfill this potential. 700 GW_{th} of the 850 GW_{th} would be located in non-OECD countries (IRENA, 2014b). Without considerable cost reductions and continued fossil fuel subsidies to industry, the global potential is closer to 470 GW_{th}.

Figure 7: Application of an "enclosed trough" for enhanced oil recovery

Photograph: GlassPoint Solar

The economically realisable potential, however, is much lower. Considering fossil fuel prices and technology learning curves for solar process heat, IRENA estimates that 3.3 EJ (~180 GW_{th}) of this potential can be deployed cost-effectively if technology costs for solar process heating technologies continue to decrease—but only 0.5 EJ (~30 GW_{th}) if prices remain at current levels. This is equivalent to 3-20% of the low- and medium-heat temperature demand from additional plants built between 2010 and 2030 (IRENA, 2014b). For 2050, a potential of 5.6 EJ (~300 GW_{th}) has been estimated (UNIDO, 2011). A number of country studies regarding solar process heating potential are available for Germany (Lauterbach, *et al.*, 2013), India (ABPS Infrastructure Advisory Private Ltd., 2011; GIZ, 2011), the Mediterranean region (UNEP, 2010) and South Africa (Du Plessis, 2011).

The potential for solar air heating is primarily restricted to the food processing and tobacco industry, although it is also used in brick production. However, it can still provide sufficient energy savings if fossil fuels are replaced. Typically, around 5-25 GJ per metric tonne (GJ/t) of dried product is used in conventional drying processes. Energy requirements for drying of primary meat or fish are higher; in the range of 17-25 GJ per tonne of dried product due to heat losses. If fossil energy is used, this may amount to at least USD 100 per metric tonne of product[2].

The potential for solar cooling is estimated to be in the range of 0.1 EJ by 2030, mainly replacing electricity-driven refrigeration in the food and tobacco sectors (IRENA, 2014b). Solar thermal cooling on islands, for example, could provide the necessary thermal cooling storage for the agricultural sector and fishing industry (IRENA, 2012b). For 2050, the IEA estimates that solar cooling could reach a contribution of 1.5 EJ per year from an installed capacity of more than 1000 GWth for cooling, accounting for nearly 17% of energy use for cooling in 2050 (IEA, 2012).

2 Assuming a heating oil price of USD 0.8 per litre and 5 GJ per metric tonne.

Performance and costs

Large-scale FPC and ETC have been deployed in a number of demonstration projects since the 1980s. The most important technical challenges encountered are corrosion and leakages of the pipes, malfunction of the tracking systems, or dust leaking into the collectors (UNPE, 2010). More advanced designs for FPC and ETC have addressed many of these problems, however these designs are also more expensive. The capacity factors are highly region-specific and can range from 4% (*e.g.* Japan) to 16-20% (*e.g.* UAE/India) to 29% (*e.g.* Mexico) (Carbon Trust, 2013).

In India, solar parabolic dishes have developed very rapidly and are currently the most commercially viable product for solar process heating. Indian manufacutring companies (*e.g.* Taylormade Solar Solutions Pvt Lt., Sharada Inventions Pvt. Ltd, Megawatt Solutions Pvt. Ltd., and Clique Developments Ltd.) dominate this market. Parabolic trough and Linear Fresnel concentrators have been successfully deployed across multiple applications and subsectors with Trivelli Energia Sri, Solitem and NEP Solar AG being the market leaders for parabolic trough collectors (i.e. 23 commercial systems in total) and Industrial Solar GmbH and Chromasun, Inc. being the market leaders for Linear Fresnels (i.e. 14 commercial systems in total) (Sun & Wind Energy, 2014).

Figure 8: Installation of 7 460 m^2 of ETC in a printing and dyeing plant in China

Photograph: AEE INTEC

Table 2: Investment costs per kW_{th} for selected solar thermal industrial process heat plants in operation

Country	Year of installation	Collector type	Installed capacity (kW_{th})	Cost (EUR/ kW_{th})
Austria	1994	FPC	62	470
	2001	FPC	29	680
	2002	FPC	30	498
	2004	FPC	36	961
	2013	FPC	1064	271
China	2008	FPC	9000	122
	2011	ETC	4025	248
	2012	ETC	441	272
Germany	1996	FPC	17	803
	1998	FPC	106	1062
	1998	ETC	18	960
	2008	ETC	280	857
	2010	FPC	400	523
Greece	1993	FPC	119	217
	1999	FPC	1890	691
	2001	FPC	706	247
India	2011	FPC	84-302	216
	2011	ETC	97-369	203
Israel	2014	FPC	30.5	607
Italy	2003	FPC	78	745
	2004	FPC	188	584
	2005	ETC	47	1097
	2005	FPC	10	1240
Portugal	1992	FPC	462	445
Spain	1994	FPC	97	662
	1997	FPC	182	541
	2002	FPC	106	638
	2004	FPC	357	752
	2011	FPC	176	744
Turkey	2013	FPC	490	237
Viet Nam	2009	ETC	700	286
	2012	ETC	494	91
USA	2012	FPC	5462	1373

Between 50-70% of the total costs in solar thermal technology are related to the capital, while the remainder covers installation and integration (Carbon Trust, 2013). In terms of component costs, the collector and its installation account for 50%, piping for 20%, the buffer storage and heat exchanger for 11% and control systems for 5% (SO-PRO, 2011). For parabolic dishes, like the ARUN 160 Dish, the price of the collector accounts for 75% of the total project cost (Sun Focus, 2014a).

The total investment costs for solar thermal systems range from EUR 180-500/m^2, leading to average energy costs of EUR 0.02-0.05/kWh for very low-temperature applications and EUR 0.05-0.15/kWh for medium-temperature systems (Battisti, *et al.,* 2007; SO-PRO, 2011). In comparison, in 2000 investment costs were in the range of EUR 250-500/m^2 (POSHIP, 2001). Per kW_{th}, this equates to solar thermal systems in the range of EUR 450-1100/kW_{th} with few exceptions and differences at national level. In Austria and Spain, the investment cost (plant size < 350kWth) is in the range of EUR 470-700/kW_{th}, while costs calculated for Germany and Italy are higher on average (GMT Research, 2010; Battisti *et al,* 2007). It should be noted that the cost of standard FPC and ETC collectors (2-2.5 m^2) have halved between 1995 and 2010 (Stryi-Hipp, 2013), although this trend is not evident in the project data provided in Table 2. The project data does show that FPC and ETC deployment in India and Turkey are, in many cases, 50% cheaper. Similarly, the costs for solar process heat in South Africa are estimated to be 25–50% cheaper than in Europe (de Lange, 2013). Some indicative costs are summarised in Table 2 (Battisti, *et al.*, 2007; GIZ, 2011; Tchance, 2011; Sun Focus, 2013; AEE INTEC & PSE, 2014; SEIA, 2014).

Most technologies are provided by local companies, similar to those operating in the residential sector. However, for the larger projects, there is international transfer of technologies (*e.g.* the FPC solar process heat plant in Chile, which was a turn-key project implemented by the Danish company, SunMark.)

Table 3 provides an overview of the costs for solar concentrators: solar parabolic dish (USD 400-900/kW) and Scheffler dish (USD 900-1900/kW) are more expensive than conventional FPC and ETC but permit higher temperature ranges. A number of more specialised companies are operating in this sector. Parabolic trough costs are estimated to be in the range of USD 600-2 000/kW. In comparison, the capital costs for concentrated solar plants (essentially the same collectors but combined with storage and turbines to produce power) are in the range of USD 3 400 – 6 000/kW (IRENA, 2015).

In the future, solar thermal collectors can be made even more cost-effective if tailored to the specific process heating needs. The IEA (2009) suggests that costs can be reduced by as much as 20% when a country's total installed capacity

Table 3: Costs of concentrators

	Specific thermal power (kW/m²)	Location	Cost (USD/m²)	Cost (USD/kW)
CPC vacuum tube	0.60-0.65	China	130	200-220
		Europe	450-900	690-1500
	0.3	India [a]	333	1133
Parabolic dish fixed	0.21-0.31	India	113-300	365-1430
Parabolic dish tracking	0.34-0.74	India [b,c]	300-600	600-1760
Parabolic trough	0.50-0.56	Europe	650	1160-1300
	0.22- 0.28	India [d]	445	1580-2040
	0.55-0.7	Mexico	400-629	570-1100
Linear Fresnel	0.50-0.56	Europe	650-900	1160-1800

[a] PWC, 2013a, [b] PWC, 2013b, [c] PWC, 2013c, [d] PWC, 2013d
(UNDP, 2008; Sun Focus, 2013)

doubles. Furthermore, large-scale applications can benefit from economies of scale and lowered investment costs, thus increasing the project's economic viability (Abdulateef, *et al.* 2009).

Recent assessments in Europe suggest cost reductions of 43% by 2020 (ESTTP, 2012), and an industry roadmap for Europe targets a system price (inclusive storage) of EUR 350/kW$_{th}$ and solar heating costs of eurocents 5-8/kWh by around 2016/2017 for conventional systems reaching a solar fraction of 10-20%, and a systems price (exclusive storage) of EUR 400/kW$_{th}$ for higher-temperature systems (< 250°C). For 2020, the roadmap targets system costs of EUR 250/kW$_{th}$ for conventional systems, and EUR 300/kW$_{th}$ for systems with higher temperature ranges (ESTIF, 2014). These are ambitious targets, especially compared to IEA estimates of cost reductions in the range of 35-50% for solar heating and 35-45% for solar cooling by 2030 (IEA, 2007), and assumptions that investment costs between 2007 and 2050 can be reduced by 60% by 2050 (Taibi *et al.,* 2012). Key factors for cost reductions are automation of production processes, modular designs for easier installation and integration onto industrial roofs, optimised tracking systems, standardisation and certification, and material replacement of copper and steel with aluminium and polymers.

Figure 9: Application of parabolic trough collector in a dairy processing plant in Mexico

Photograph: Inventive Power A.S.

The costs of solar air heating technologies, especially direct passive systems, are highly dependent on local circumstances, such as the costs of bricks, cement, wood, glass and labour to build the solar dryers (Weiss & Bruckheimer, 2010). For active systems, costs range from EUR 300 – 450/m^2 (AEE INTEC & PSE, 2014). One of the largest solar air heating systems (420 m^2) is installed in Viet Nam and has an investment cost of EUR 290/m^2 (see Figure 2).

Drivers and Barriers

The key drivers for solar heating and cooling technologies in industrial processes are: 1) reducing risks associated with increasingly volatile and rising prices for coal, oil and natural gas; 2) eliminating fuel costs; 3) reducing carbon emissions;

and 4) energy needs due to localised production. The current costs of industrial solar thermal systems are determined by a relatively small number of suppliers of these highly sophisticated technologies. Although these technologies are high performers, they are generally too costly for the global market. The experience in the Indian market has shown that equipment manufactured locally reduces capital costs and creates added value and local business opportunities along the supply chain (IRENA, 2014b).

The main barriers to increased deployment of solar industrial process heat and cooling systems are as follows:

– **High investment costs and lack of finance options:** All solar process heat systems involve high initial investments in advance of a practically cost-free harvesting period. However, proper maintenance is required to ensure that the systems operate optimally over their full lifetime expectancy. The up-front costs particularly hamper deployment in small- and medium-size enterprises where financing is not available. For larger systems, the first turn-key projects are already beginning to appear. The development of market models, where solar process heating systems are installed and maintained by energy service companies (ESCOs), is a possible way forward (ESTIF, 2014).

– **Fossil fuel pricing:** In many countries, energy prices for industrial users are subsidised or discounted to support industrial development. This reduces the economic viability of solar process heating systems (Frein*, et al.*, 2014).

– **Public awareness:** An important barrier to wider deployment of both solar heat and cooling technologies is the lack of (technical) information transfer. The number of solar process heat systems is very limited and most decision makers in the relevant industries do not have much information or first-hand experience with solar industrial process heat systems. This is likely a key barrier to wider adoption of solar industrial process heat technology. In many countries, national development plans consider only centralised solutions. The economic and practical advantages of solar heat for industrial process heat systems need to be highlighted. Also, the energy system is often not seen as the core component of the production system. Consequently, businesses often prefer conventional systems that are more familiar to them. For example, after 15 years of operation, two solar process heating systems were removed from a textile and poultry processing plant soon after the companies changed owners in 2005 (UNEP, 2010). A possible solution for going forward is to mandate an assessment of solar process heating technologies in energy audits (ESTIF, 2014). A number of studies aim at increasing market awareness of solar air-conditioning and refrigeration with a major focus on improved components and systems concepts (IEA-SHC, 2009).

– **Scaling issues:** In emerging economies with high solar irradiation, small- and medium-size enterprises (SMEs) are an interesting market for solar thermal systems for three reasons. First, SMEs often rely on volatile and expensive fossil fuels for heat production and solar thermal systems reduce their dependence on fossil fuels and contribute to the reduction of operating costs of the SMEs. Second, the heat demands per plant are relatively small compared to the energy-intensive industry, which makes the integration of solar heating systems easier. Third, the sheer number of SMEs present could result in rapidly declining costs due to learning-by-doing and more effective operations by installers. This could create a virtuous circle in which, with declining costs and more experience, the deployment of solar heating systems is accelerated in this market segment (IRENA, 2014b).

– **Lack of suitable design guidelines and tools:** There are few professionals and research institutes with adequate experience in solar heat for industrial process heat systems. Training and dissemination of existing knowledge and concepts are needed to overcome this problem.

Table 5 – Summary Table: Key Figures and Data for Solar Heat for Industrial Processes

Technical Performance	Typical current international values and ranges	
Energy Input/Output	Sunlight/Thermal energy (Heat/Cooling)	
Process Heat Demand		
Low Heat (<150°C)	**Medium Heat (150°C – 400°C)**	**Solar Thermal Cooling**
Conventional ETC (120°C)	Linear Fresnel (50-400°C)	Conventional FPC/ETC (20°C to -10°C)
Conventional FPC (100°C)	Multiple glazing FPC (265°C)	Solar Concentrators (-20°C)
Transparent insulation FPC (150°C)	Parabolic Trough Collectors	
Inert gas/High Vacuum FPC (80-150°C)	Compound Parabolic Concentrators (200°C)	
Sector	**Temperature Range,°C**	**Heat Intensiveness**
Food	30-120	LOW
Beverages	60-90	LOW
Paper	60-150	LOW
Metal Surface Treatment	30-80	LOW
Textile Industry	30-180	LOW-MEDIUM
Chemical Industry	120-260	MEDIUM
Plastic Industry	120-220	MEDIUM
Pre-heating of boiler feed water	30-100	LOW
Industrial Solar Cooling	55-180	LOW-MEDIUM
Heating of factory buildings	30-80	LOW

Projections	Typical current international values and ranges		
Sectoral Heat Demand	**High Energy Intensive**	**Low Energy Intensive**	**Solar Thermal Cooling**
Energy Potential, EJ	1.3 (2030 estimate)	1.2 (2030 estimate)	1.5 (2050 estimate)
Share of Total Process Heat Demand, %	2	2	17

Technology Variant	CPC vacuum tube			Parabolic dish fixed	Parabolic dish tracking	Parabolic trough			Linear Fresnel
Specific thermal power (kW/m²)	0.60-0.65		0.3	0.21-0.31	0.34-0.74	0.50-0.56	0.22- 0.28	0.55-0.7	0.50-0.56
Location	China	Europe	India[a]	India	Indiab,c	Europe	Indiad	Mexico	Europe
Cost (USD/m²)	130	450-900	333	113-300	300-600	650	445	400-629	650-900
Cost (USD/kW)	200-220	690-1500	1133	365-1430	600-1760	1160-1300	1580-2040	570-1100	1160-1800

[a] PWC, 2013a, [b] PWC, 2013b, [c] PWC, 2013c, [d] PWC, 2013d

System Size	<0.07MW (<100m²)	0.07-0.35MW (100 -500m²)	0.35-0.7MW (500-1000m²)	> 0.7 MW (>1000m²)	Total
Number of Systems[a]	36	50	29	19	134
Installed Capacity, MW_{th}[b]	1.3	8.2	14.2	73.3	97
Installed Collector Area, m²	1 796	11 710	20 227	104 783	138 515
Total investment Costs, USD[c]	932 780	3 259 531	3 710 595	18 036 294	25 939 200
Average Investment Cost, USD/kW_{th}	1241	786	602	665	679

[a]Data based on AEE INTEC & PSE (2014) last accessed 07 Aug 2014

[b]Default value calculated by multiplying the gross collector area by 0.7 kWth/m² (IEA SHC, 2014a)

[c]Costs calculated for 67 projects in database with available data (1 EUR = 1.338 USD)

References and Further Information

Abdulateef, J.M. *et al.* (2009), "Review on solar-driven ejector refrigeration technologies", Renewable and Sustainable Energy Reviews, 13(6-7), 1338, 2009, http://www.sciencedirect.com/science/article/pii/S136403210800110X.

ABPS Infrastructure Advisory Private Ltd. (2011), "Final Report on Market Assessment of Solar Water Heating Systems in Industrial Sectors", submitted to Ministry of New and Renewable Energy, May 2011, http://mnre.gov.in/file-manager/UserFiles/Report_Market_Assessment_of_SWH_in_Industrial_Sector.pdf.

AEA (American Energy Assets) (2010), "Industrial Process Steam Generation using Parabolic Trough Solar Collection", Public Interest Energy Research (PIER) Program, November 2010, http://www.energy.ca.gov/2011publications/CEC-500-2011-040/CEC-500-2011-040.pdf.

AEE INTEC & PSE (2014), "Database for applications of solar heat integration in industrial processes", SHIP database, http://ship-plants.info/, accessed: August 2014.

Augsten, E. (2012), "Europe/Asia: Solar Cooling Gains Traction", Solar Thermal World, 3 September 2012, http://solarthermalworld.org/content/europeasia-solar-cooling-gains-traction.

Battisti, R. *et al.* (2007), Solar Heat for Industrial Processes. Existing Plants and Potential for Future Applications, in Proceedings of the ESTEC 2007, p. 31-38, Freiburg, Germany, 2007

Beikircher, T. *et al*. (2014), "Flat Plate Collector for Process Heat with Full Surface aluminium Absorber, Vacuum Super Insulation and Front Foil", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 9-17, http://www.sciencedirect.com/science/article/pii/S1876610214002653.

Benvenuti, C. (2012), "Vacuum for Thermal Insulation: The SRB Solar Panel as an example, SRB Energy Research.

Carbon Trust (2013), "Small-scale Concentrated Solar Power: A Review of Current Activity and Potential to Accelerate Deployment", March 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191058/small_scale_concentrated_solar_power_carbon_trust.pdf.

Chaudhari, A.D., S.P. Salve, (2014), "A Review of Solar Dryer Technologies", International Journal of Research in Advent Technology, vol.2, no.2., February 2014, http://www.ijrat.org/downloads/feb-2014/paper%20id-22201488.pdf.

Clique Solar (n.d.), "Fully automatically tracked Arun dish technology", http://mnre.gov.in/file-manager/UserFiles/Brief_Arun_Technology.pdf.

de Lange, B. (2013), "Solar Heat in Industrial Processes. It's applicability in South Africa", Centre for Renewable and Sustainable Energy Studies, University of Stellenbosch, 8 October 2013, http://www.crses.sun.ac.za/files/services/events/forums/services_events_forum_delangeOct2013.pdf.

Du Plessis, P. (2011), "The Potential of Solar Process Heat for South African Industry", MSc thesis, Energy Research Centre, University of Cape Town, June 2011, http://www.crses.sun.ac.za/files/research/completed-research/solar/Thesis_Pduplessis(2011)_final.pdf

ESTIF (European Solar Thermal Industry Federation) (2014), "Solar heating and Cooling Technology Roadmap", European Technology Platform on Renewable Heating and Cooling, June 2014, http://www.estif.org/fileadmin/estif/content/projects/ESTTP/Solar_H_C_Roadmap.pdf.

ESTTP (European Solar Thermal Technology Panel) (2012), "Strategic Research Priorities for Solar Thermal Technologies", European Technology Platform on Renewable Heating and Cooling, Brussels, December 2012, http://www.rhcplatform.org/fileadmin/Publications/Solar_thermal_SRP.pdf.

Fernandez-Garcia, A. *et al.* (2010), "Parabolic trough solar collectors and their applications", Renewable and Sustainable Energy Reviews, 14(7), 1695, http://www.sciencedirect.com/science/article/pii/S1364032110000675.

Foeste, S. et al. (2014), "Performance and reliability of a high efficiency flat plate collector – final results on prototypes", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 48-57, http://www.sciencedirect.com/science/article/pii/S1876610214002690.

Frein, A., et al. (2014), "Solar thermal plant integration into an industrial process", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 1152-1163, http://www.sciencedirect.com/science/article/pii/S1876610214003920.

Fuller, R.J. (2011), "Solar industrial process heating in Australia: Past and current status", Renewable Energy, 36(1),216, 2011, http://www.sciencedirect.com/science/article/pii/S096014811000279X.

GIZ (2011), "Identification of Industrial Sectors Promising for Commercialisation of Solar Energy", Commercialisation of Solar Energy in Urban and Industrial Areas – ComSolar, http://mnre.gov.in/file-manager/UserFiles/identification_of_ insdustrial_sectors_promising_for%20_commercialisation_of_solar_energy_ComSolar.pdf.

GTM Research (2010), "U.S. Solar Market Insight: 2010 Year in Review", Solar Energy Industries Association. 2010. http://www.seia.org/galleries/pdf/SMI-YIR-2010-ES.pdf.

Haberle, A. (2011), "Solar generation of Industrial Process Heat", PSE AG, Intersolar Europe Conference, 2011, http://www.mss-csp.info/documents/solarpraxis/a.-haberle-pse-ag-solar-generation-of-industrial-process-heat.

Hafner, B., *et al.* (2014), "Development of an Integrated Solar-fossil Powered Steam Generation System for Industrial Applications", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 1164-1172, http://www.sciencedirect.com/science/article/pii/S1876610214003932.

Heimsath, A. *et al.* (2014), "Quantifying optical loss factors of small linear concentrating collectors for process heat application", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 77-86, http://www.sciencedirect.com/science/article/pii/S1876610214002720.

IEA (International Energy Agency) (2009), "Renewable Energy Essentials: Solar Heating and Cooling", International Energy Agency. http://www.iea.org/papers/2009/Solar_heating_cooling.pdf.

IEA (2012), "Solar Heating and Cooling Roadmap", http://www.iea.org/publications/freepublications/publication/Solar_Heating_Cooling_Roadmap_2012_WEB.pdf.

IEA (2014), "Heating without Global Warming. Market Developments and Policy considerations for Renewable Heat", OECD/IEA 2014, http://www.iea.org/publications/freepublications/publication/FeaturedInsight_HeatingWithoutGlobalWarming_FINAL.pdf.

IEA-SHC (International Energy Agency Solar Heating and Cooling Programme) (2007), "Overview on World Wide Installed Solar Cooling Systems", 2nd International Conference Solar Air Conditioning, October 2007, http://task38.iea-shc.org/data/sites/1/publications/task38-Overview.pdf.

IEA-SHC (2008), "Potential for Solar Heat in Industrial Processes", IEA-SHC Task 33 and Solar PACES Task IV: Solar Heat for Industrial Processes, Madrid 2008, http://www.aee-intec.at/0uploads/dateien561.pdf.

IEA-SHC (2011), "Solar Cooling Position Paper", Task 38: Solar Air-Conditioning and Refrigeration, October 2011.

IEA-SHC (2013), "Executive Summary: Solar Cooling Position Paper", Task 38: Solar Air-Conditioning and Refrigeration, December 2013, http://www.iea-shc.org/data/sites/1/publications/IEA-SHC-Solar-Cooling-Position-Paper--Executive-Summary.pdf.

IEA-SHC (2014), "Solar Heat Worldwide. Market and Contribution to the Energy Supply 2012", http://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2014.pdf.

Iglauer, O. (2013), "Solar Process heat for Sustainable Automobile Manufacturing – Synergies of a Strong Cooperation, Technology Workshop on Solar Process Heat for Industry, 15 March 2013, Brussels, http://www.rhc-platform.org/fileadmin/user_upload/Structure/Solar_Thermal/Download/130315_Workshop_SPHI_Solar_process_heat_for_sustainable_automobile_manufacturing_-_O_Iglauer.pdf

IRENA (International Renewable Energy Agency) and IEA-ETSAP (International Energy Agency – Energy Technology Systems Analysis Programme) (2012), "Water Desalination Using Renewable Energy", Technology Brief, March 2012, http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I12%20Water-Desalination.pdf.

IRENA (2012), "IRENA Renewable Energy Islands Initiative", Renewables and Islands Global Summit, 5-6 September 2012, Malta http://www.irena.org/DocumentDownloads/events/MaltaSeptember2012/Dolf_Gielen.pdf.

IRENA (2014a), "REmap 2030: A Renewable Energy Roadmap", June 2014, Abu Dhabi, http://irena.org/remap/REmap_Report_June_2014.pdf.

IRENA (2014b), "Renewable Energy in Manufacturing, A Technology Roadmap for REmap 2030", June 2014, Abu Dhabi, http://irena.org/remap/REmap%202030%20Renewable-Energy-in-Manufacturing.pdf.

IRENA (2015), "Renewable Power Generation Costs in 2014", January 2015, Abu Dhabi, http://costing.irena.org

IRENA (*in press*), "Renewable energy technology options for the industry sector: Assessment of the global and regional potentials until 2030", Abu Dhabi.

Jakob, U. (2014), "Technologies and Perspectives of Solar Cooling systems", AHK Conference Sydney, Australia, 24th march 2014, http://www.docstoc.com/docs/169908741/DrJakob_Green_Chiller_Assoc.pdf.

Kalogirou, S. (2003), "The potential of solar industrial process heat applications", Applied Energy, v. 76, p.337-361, http://www.sciencedirect.com/science/article/pii/S0306261902001769.

Kulkarni, G.N. *et al.* (2008), "Design of solar thermal systems utilizing pressurized hot water storage for industrial applications", Solar Energy, 82(8), 686, http://www.sciencedirect.com/science/article/pii/S0038092X08000431.

Kummert, M. (2007), "Modelling Solar Thermal Systems", Modelling Renewables Workshop, Scottish Energy Systems Group, 24 January 2007, http://www.sesg.strath.ac.uk/Presentations/Modelling_Solar_Thermal.pdf.

Lauterbach, C. *et al,* (2012), "The potential of solar heat for industrial processes in Germany", Renewable and Sustainable Energy Reviews, v.16, p.5121-5130, http://www.sciencedirect.com/science/article/pii/S1364032112003073.

Mueller, H. *et al,* (2014), "Development of an Evaluation Methodology for the Potential of Solar-thermal Energy Use in the Food Industry", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 1194-1201, http://www.sciencedirect.com/science/article/pii/S187661021400397X

PWC (2013a), "Using non imaging concentrator for boiler feed water preheating", ITC factory, Bangalore, http://www.cshindia.in/images/pdf/ITC.pdf.

PWC (2013b), "Using ARUN dish for washing application", Mahindra Vehicle Manufacturers Limited, Chakan, Pune, http://www.cshindia.in/images/pdf/M&M_1.pdf.

PWC (2013c), "Using Scheffler dish for Steam pressing", Purple Creations, Baramati Pune, http://www.cshindia.in/images/pdf/PCPL.pdf.

PWC (2013d), "Using parabolic trough for phosphating process", SKF Technologies, Mysore, http://www.cshindia.in/images/pdf/SKF.pdf.

Saygin, D. *et al,* (2011), "Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector", Energy, v.39, i.6, p.5779-5790., http://www.sciencedirect.com/science/article/pii/S0360544211003446.

SEIA (Solar Energy Industries Association) (2014), "Saving Money and Energy: Solar Heating & Cooling is Paying Big Dividends for U.S. Businesses", http://www.seia.org/news/new-cost-saving-report-highlights-value-solar-heating-cooling.

Scheuerer, M. (2013), "Integration of Solar Process Heat Systems", Joint Saudi-German CSP Workshop, Deutsches Industrienetzwerk Concentrated Solar Power, 19-20 November 2013, http://saudi-sia.com/wp-content/uploads/2013/05/Integration_of_Solar_Process_Heat_Systems.pdf.

Schramm, S., Adam, M. (2014), "Storage in Solar Process Heat Applications", Energy Procedia, Proceedings of the 2nd International Conference on Solar

Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 1202-1209, http://www.sciencedirect.com/science/article/pii/S1876610214003981.

SERI (Solar Energy Research Institute) (1980), "Applications and System Studies for Solar Industrial Process Heat", January 1980, http://www.nrel.gov/docs/legosti/old/481.pdf.

Sharma, A., *et al,* (2009). "Solar-energy drying systems: A review". Renewable and Sustainable Energy Reviews 13, pp. 1185-1210.

Silva, R., *et al*, (2014), "Process heat generation with parabolic trough collectors for a vegetables preservation industry in Southern Spain", Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013), v. 48, p. 1210-1216, http://www.sciencedirect.com/science/article/pii/S1876610214003993.

SO-PRO (2011), "Solar Process Heat Generation: Guide to Solar Thermal system Design for Selected Industrial Processes", www.solar-process-heat.eu.

SRCC (Solar Rating & Certification Corporation) (2014), "SRCC Standard 600 2014-07 Minimum Standard for Solar Thermal Concentrating Collectors, 15 july 2014, http://www.solar-rating.org/standards/SRCC_Standard_600_For_Solar_Concentrating_Collectors.pdf.

Stryi-Hipp, G., (2013), "Welcome to the Technology Workshop on Solar Process Heat for Industry", Technology Workshop on Solar Process Heat for Industry, 15 March 2013, Brussels , http://www.rhc-platform.org/fileadmin/user_upload/Structure/Solar_Thermal/Download/130315_Workshop_SPHI_RHC-technologies_-_G_Stryi-Hipp.pdf.

Sun Focus (2013), "India's Quest for Solar Steam and Process Heat", Special Issue: Fixed focus elliptical solar dishes (Scheffler), Issue 2, October-December 2013, http://www.in.undp.org/content/dam/india/docs/EnE/SunFocus-Oct-Dec-2013.pdf.

Sun Focus (2014a), "India's Quest for Solar Steam and Process Heat", Special Issue: CSTs for Industrial Application, Issue 3, January-March 2014, http://www.in.undp.org/content/dam/india/docs/EnE/Sun%20Focus-Jan-Mar%2014.pdf.

Sun Focus (2014b), "Solar Thermal Cooling Technologies", Issue 4, April-June 2014, http://www.in.undp.org/content/dam/india/docs/EnE/Sun%20Focus_Apr-Jun%202014.pdf.

Sun & Wind Energy (2014), "The World of Solar Process Heat", volume 3, p.36-45.

TVP Solar (2012),"MT-Power: High-vacuum flat solar thermal panel for medium temperature applications", Product Datasheet, www.tvpsolar.com.

Tchance, B.F. (2011), "Solar Industrial Process Heat", http://www.ansole.org/download/webinar/solar%20process%20heat.pdf.

Taibi, E. *et al,* (2012), "The potential for renewable energy in industrial applications", Renewable and Sustainable Energy Reviews, v. 16, i. 1, p. 735-744, http://www.sciencedirect.com/science/article/pii/S1364032111004497.

Tiwari, G., *et al,* (2013), "A Comparative Study of Commonly Used Solar Dryers for India", International Journal of Current Engineering and Technology, http://downloads.hindawi.com/journals/energy/aip/794752.pdf

UNEP (United Nations Environment Programme) (2010), "Solar Heat for Industrial Processes (SHIP): State of the art in the Mediterranean region", Technical Study Report, http://www.b2match.eu/system/stworkshop2013/files/SHIP.pdf?1357835481.

UNEP (2014), "Solar Water heating Techscope Market Readiness Assessment", http://www.in.undp.org/content/dam/india/docs/EnE/solar-water-heating-techscope-market-readiness-assessment.pdf.

UNIDO (United Nations Industrial Development Organization) (2011), "Renewable Energy in Industrial Applications. An assessment of the 2050 potential", http://www.unido.org/fileadmin/user_media/Services/Energy_and_Climate_Change/Energy_Efficiency/Renewables_%20Industrial_%20Applications.pdf.

Warwick HRI (2007), "Direct energy use in agriculture: opportunities for reducing fossil fuel inputs", May 2007, Warwick WRI, the University of Warwick, Warwick, United Kingdom.

Weiss, W. (2013), "Potential of Solar Process Heat", Technology Workshop on Solar Process Heat for Industry, 15 March 2013, Brussels, http://www.rhc-platform.org/fileadmin/user_upload/Structure/Solar_Thermal/Download/130315_Workshop_SPHI_Potential_of_Solar_Process_Heat_-_W_Weiss.pdf.

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