THE PRESENT AND FUTURE USE OF SOLAR THERMAL ENERGY AS A PRIMARY SOURCE OF ENERGY

By Cédric Philibert

International Energy Agency, Paris, France

1. Introduction

The radiative energy from the Sun that keeps our planet warm exceeds by far the current primary energy supply used by mankind for its comfort, leisure and economic activities. It also exceeds vastly other energy sources at ground level such as geothermic or tidal energy, nuclear power and fossil fuel burning. Sunrays also drive hydraulics, wind and wave power and biomass growth.

Mankind's total primary energy supply (TPES) was 433 Ej in 2002, including non-commercial biomass, equivalent to a continuous power consumption of 13.75 TW. The IEA projects for 2030 a TPES of about 688 Ej, equivalent to 21.8 TW of power (IEA 2004). This compares to the solar radiation intercepted by the Earth of 173,000 TW, of which 120,000 TW strike the Earth's surface. Solar energy is thus the primary energy source on our planet's surface – and exceeds 8,000 times our primary energy supply. Fulfilling global energy needs as projected for 2030 would require covering about 0.6% of emerged lands with 10% net efficient solar conversion systems.

Another indication of the abundance of solar energy is, somewhat paradoxically, the threat of climate change itself. The increases in the atmospheric concentrations of well-mixed greenhouse gases from the pre-industrial to present time result mainly from the combustion of fossil fuels for energy purposes. They entail a marginal increase in the Earth and atmosphere's capacity to trap the sunrays' radiative energy, acting as a gigantic solar collector, called the radiative forcing of climate and estimated to be 2.43 Wm^{-2}±10%, which compares to the averaged continuous amount of solar energy on Earth of about 235 Wm^{-2}. This suggests that solar energy has the potential to help solve the problem it creates.

Indeed, the prospects of climate change and, eventually, fossil fuel depletion, trigger a growing interest in renewable energies in general, solar energy in particular. The benefits of renewable energy systems were clearly defined in a political declaration agreed to by government representatives of 154 nations at the international "*Renewables 2004*" conference held in Bonn, June 2004 as a follow-up to the 2001 World Summit Sustainable Development, Johannesburg. Benefits outlined included energy supply security, equity and development, improved health, overcoming peak oil price fluctuations, provision of clean water, close association with energy efficiency measures, climate change mitigation, and the common belief that *"there will be no need for war over solar energy"*.

The drawbacks are well-known: the solar radiation reaching the earth is very dilute (only about 1 kW_{th} per square meter), intermittent (available only during day-time), and unequally distributed over the surface of the earth (mostly between 30° north and 30° south latitude).

Various technologies, however, can be used to overcome the difficulties in making sunlight a usable form of energy for all purposes.

Solar “thermal” energy designate all technologies that collect solar rays and transform their energy into usable heat, either for directly satisfying heating needs (notably space heating, water heating – and space cooling) or for producing electricity and fuels. The latter includes concentrating solar power technologies, and other concepts such as solar updraft towers and ocean thermal energy. This paper thus considers all direct forms of solar energy except photovoltaic, assessing resource potential, technology status, and supporting policies.

2. Solar heat

At present, solar heating provides by far the largest solar contribution to energy needs. The main technologies belong to either “passive” and “active” solar energy forms. Passive solar energy relates to the design of buildings collecting and transforming solar energy used for passive heating, daylighting and natural ventilation. Active solar energy relates to the use of solar collectors for water or space heating purposes, active solar cooling, heat pumps, desalinisation and industrial high temperature heat.

2.1 Passive solar architecture

Passive solar energy does not show up in energy statistics as collecting data would be hugely expensive, requiring close building by building examination. Passive solar energy is usually considered from the demand side as part of energy savings potential rather than from the supply side. Through a combination of a high-performance thermal envelope, efficient systems and devices, and full exploitation of the opportunities for passive solar energy, 50 to 75% of the energy needs of buildings as constructed under normal practice can be either eliminated or satisfied through passive solar means. In the industrialized world, buildings use 35 % to 40 % of total primary use of energy. Letting the sun heat buildings in winter, and letting daylight enter them to displace electric lighting, are the least cost solar energy forms.

A science and an art

Passive solar heating can involve extensive sun-facing glazing, various wall- or roof-mounted solar air collectors, double-façade wall construction, air-flow windows, thermally massive walls behind glazing, or preheating of ventilation air through buried pipes.

Lighting and ventilation can be directly supplied through solar energy: interior light through a variety of simple devices that concentrate and direct sunlight deep into a building, and ventilation through the temperature and hence pressure differences that are created between different parts of a building when the sun shines. The building façade can be used to generate and channel airflows that remove heat that otherwise add to the cooling load, or which can be used to preheat ventilation air when heating is required.

Efficient passive solar architecture is as much an art as a science. There is no one-fits-all recipe. Quite the opposite, each building requires a close adaptation to its natural environment and climate, and the needs of its inhabitants. Buildings made during the era of cheap oil and standardised building materials and concepts are more often the examples not to follow. Very often traditional materials and knowledge can be a great source of inspiration for designers and architects. This may be especially true in hot climate where a reasonable level of comfort can be provided with a variety of energy-efficient devices high-inertia materials to avoid using air-conditioning systems.

Innovative materials

This does not preclude, however, the use of modern computer software or up-to-date materials, with emerging new standardised materials for walls, doors and windows. For example, spectrally selective windows can maximise sunlight to replace lighting while minimising increased cooling requirements from solar radiation. Electro-chromatic windows have small voltages that cause the window to change from a clear to a transparent coloured state, or vice versa. They can minimise both winter heating requirement and summer cooling needs. Simulations of energy use in office buildings with the climate of New York State indicate that such windows can achieve a savings in combined lighting and cooling electricity use of up to 60%, depending on the building characteristics and window area (Lee *et al.*, 2002). Another technology under development is thermochromatic glazing, which automatically permits penetration of solar radiation when and only when heating is desired, eliminating the need for sensors.

Beyond architecture

Passive solar architecture extends to the buildings' neighbourhood, as pergolas, vegetation, fountains, spraying devices may offer either winter protection against cold winds or summer protection against sunrays or both. One step further is urbanism, as the spatial organisation of buildings strongly influences cooling and heating loads. Lessons can be taken from many old cities in various climates. Modern urbanisation, with its large energy consumption, creates heat island effects that reduce winter power loads but increase summer power loads. Modern efforts, such as Tokyo's, aim at increasing the cities' vegetal cover to reduce cooling loads.

Policies

Policies to support the development of solar passive architecture are very diverse. They range from support to R&D and qualification of modern building materials to training programmes for architects, engineers and technicians to outreach efforts. One interesting example is the yearly contest "solar homes and buildings" run by the French NGO Observ'ER.

2.2 Active solar heat

Small scale, low temperature solar thermal systems can supply heat for domestic hot water and space heating in residential, commercial and institutional buildings, schools, hotels, swimming pools; crop drying; industrial process heat;, desalination; and solar-assisted district heating. The main collector technologies include unglazed, glazed flat plate and evacuated tubes. The technology may be considered mature but continues to improve. Aluminium, being cheaper and lighter than copper, is being used in manufacturing absorbers. Laser welding technology makes it possible to have a perfectly smooth absorber surface and obtain a homogenous colour.

Efficiency, capacities, output

The efficiency of solar collectors (heat delivered to where it is wanted divided by incident solar energy) depends on the design of the collector and on the system of which the collector is a part. "Combisystems" are solar systems that provide space and water heating. Annually averaged collector efficiencies of 40-55% are feasible for domestic hot water, while annual averaged solar utilisation (which accounts for storage losses and heat that cannot be used) of 20-25% have been obtained in combisystems. Depending on the size of panels and of storage tanks and of the building thermal envelope, 10-60% of the combined hot-water and heating demand can be met at central and northern European locations.

Solar collectors of all types have a nominal peak capacity of about 0.7 $kW_{th}.m^{-2}$. However, the estimated annual solar thermal energy production from the collector areas in operation depends on the solar radiation available, the outside temperature and the solar thermal technology used. For example, in Austria, estimated annual solar yields are for flat-plate collectors. Estimated annual yields for glazed flat-plate collectors are 1000 $kWh_{th}.m^{-2}$ in Israel, 700 $kWh_{th}.m^{-2}$ in Australia, 400 $kWh_{th}.m^{-2}$ in Germany and 350 $kWh_{th}.m^{-2}$ in Austria –

where they reaches 550 $kWh_{th}.m^{-2}$ for vacuum collectors and 300 $kWh_{th}.m^{-2}$ for unglazed collectors.

Costs can also be very different. In Greece a DHW thermo-siphon system for one family unit of 2.4 m^2 collector and 150 l tank costs € 700. In Germany, where solar radiation is lower, a similar system (4–6 m^2 and 300 l tank) costs around € 4500. Water heating systems are more profitable in sunny and hot areas, but this is not the case with respect to space heating. In warm sunny places output of solar systems is bigger but largely wasted as heating loads are small and the cold season short. In colder areas a lower output is better used as heating loads are higher and the cold season longer. The same solar system that get 40% savings on heating expenses in north France, i.e. € 730 to € 900 yearly revenues, provide in south France 80% savings, i.e. € 120 to € 180 yearly revenues only. (Lenormand, 2005).

Active solar heat can also be used for desalination, using various processes. Their full description would be beyond the scope of this paper.

Market

About 140 million m^2 of solar thermal collector area are in operation around the world, and the annual newly installed area is more than 10 million m^2. The total installed capacity is thus approaching 100 GW_{th} – more than the global wind power electric capacity. China is the world lead market, with an installed capacity one third of the world total, almost exclusively evacuated tubular collectors. Their total surface now exceeds 22 millions m^2. In the US, Canada and Australia swimming pool heating is dominant with an installed capacity of 18 GW_{th} of unglazed plastic collectors. Europe and Japan provide about 10 and 9 GW_{th} respectively with flat-plate and evacuated tube collectors. Almost all use water as heat transfer fluid – air collectors only represent 1% of the global market.

In Europe, lead markets are Germany, Greece and Austria. The highest collector surface area per inhabitant is Cyprus with 582 m^2, far above Austria 297 m^2 and the EU average of 33.7 m^2 (EurObserv'ER 2005).

Solar cooling

Solar thermal energy can be directly used for cooling and dehumidification. Cooling technologies include single- and double-effect absorption chillers, adsorption chillers, and solid or liquid desiccant systems. There are about 45 solar air conditioning systems in Europe, with a total solar collector area of about 19,000 m^2 and a total capacity of about 4.8 MW chilling power. A prototype indirect-direct evaporative cooler has been recently developed in California. The coefficient of performance (cooling power divided by fan power, a direct measure of efficiency) ranges from about 12 to about 40. Simulations for a house in a variety of California climate zones indicate savings in annual cooling energy use of 92 to 95%. In humid climates the energy savings would be much less, although savings in such climates can be enhanced using liquid desiccants that can be regenerated with solar thermal energy. Cost, however, is a significant impediment to solar air conditioning, as capital costs are several times those of conventional electric vapour-compression systems. Costs per unit energy are reduced if a solar thermal collector is designed to be used for both summer cooling and winter heating.

District systems, heat pumps

District heating and cooling systems can be made solar and combined with some form of thermal energy storage. By 2003, eight solar-assisted district heating systems had been constructed in Germany. 30 to 95% of total annual heating and hot water requirements can be provided under German conditions, though at relatively high costs (from 16 eurocents to 42 eurocents per kWh_{th}). Other such systems exist in Sweden, Denmark, The Netherlands, Austria and other countries. The largest of these, in Denmark, involves 1300 houses, a 70,000 m^3 gravel-pit for storage, and a 30% solar fraction.

Heat pumps use an energy input (almost always electricity) to transfer heat from a cold medium (the outside air or ground in the winter) to a warmer medium (the warm air or hot water used to distribute heat in a building). Heat pumps are said to use respectively geothermal energy or solar energy when they use the ground or the outside air as heat source. During hot weather, the heat pump can operate in reverse (transferring heat from a hot to a cold medium), thereby providing cooling. The coefficient of performance (COP) of a heat pump is the ratio of heat supplied to energy used. Minimising the temperature lift, by drawing heat from a relatively warm source (such as the ground rather than the outside air in winter) and by distributing the heat at the lowest possible temperature, can dramatically improve the performance. A low distribution temperature in turn requires a large radiator surface, such as floor radiant heating systems. The COP of a conventional system is 2-2.5. It increases to 3.5-7.0 for a radiant heating system. The ground can also serve as a low-temperature heat sink in summer, increasing the efficiency of air conditioning as well. Almost all new single-family houses in Sweden are equipped with exhaust-air heat pumps (about 4000 per year by 1997), and another 5-10,000 per year are installed in Germany.

High temperature heat

High temperature solar heat requires concentrating solar rays. One US company is commercialising solar roof technology that includes a high-temperature concentrating solar collector, a natural daylighting system, a radiant barrier, an insulating system, an optional means to capture passive solar heat in the winter and the roofing system. Temperatures up to more than 400°C are claimed. The collected energy can be used for industrial processes, absorption cooling, desalinisation and water purification, as well as secondary space heating and domestic hot water uses. (Mills, 2004)

Less important from an energy standpoint are the industrial or research devices, such as the solar furnace at Odeillo (France), that are used in particular to test materials' resistance to very high temperatures.

Policies

Many industrialised and developing countries alike have implemented policies to support research and development efforts, as well as the deployment of active solar technologies. Tax credits and grants constitute usually the core of these programmes, alongside qualification of materials guaranteeing performances. One the most ambitious programmes seems to be the German *Solarthermie 2000 Plus* which aims to increase the annual solar contribution to heat and hot water demand with individual solar thermal installations from the current 10-30% to 60%. In particular, seasonal storage is sponsored. Grants up to 50% of the investment costs are provided. Research and development programmes.

Since 1977 the International Energy Agency's solar heating and cooling "implementing agreement" offers a framework to the international co-operation in this area. The activities undertaken by the programme ranged from producing reports on the solar thermal collector market in IEA countries and on solar energy activities in IEA countries to starting new work in the areas of storage, industrial process heat, and building energy analysis tools.[1]

---

[1] See its website at www.iea-shc.org

3. Solar Power and Fuels

Concentrating solar technologies provide all solar thermal electricity today, and about half of the world’s total solar electricity. They hold the greatest promises for the future, for producing electricity as well as hydrogen or other fuels. Other concepts, however, such as solar updraft towers and ocean thermal energy, may find their place in the future global renewable energy portfolio.

3.1 Concentrating solar power

Concentrating solar power technologies (CSP) only use direct sunlight, concentrating it several times to reach higher energy densities – and thus higher temperatures when the light is absorbed by some material surface. Heat is then used to operate a conventional power cycle, for example through a steam or gas turbine or a Stirling engine, which drives a generator. These two basic features have two important consequences. First, CSP are best suited in areas with high direct solar radiation. These areas are widespread, but not universally found over the globe. The world potential seems, however, very important, as electricity demand is rapidly growing in most of these populated areas. A development of interconnection would make it even larger.

Second, because it uses a thermal phase, CSP technologies can easily make power production firm and even dispatchable, either by storing the heat in various forms, or by backing its production by some fossil fuel burning – in both cases using the same steam generators, turbines and generators. Storage or back-up by fuels is also possible with wind power or solar PV, but the necessary additional investments will be much more important than for concentrating solar.

Thus, CSP plants displace capacities, not only energy, from other sources. Their back-up from fossil fuel or heat storage gives a much greater value to the electricity produced by moving it over time to better match the peaking load. Heat storage also opens up the possibility of continuous, solar only operations. There is no single, one-fits-all optimum design and operating mode: it will more likely depend on the needs of the utility.

The technologies and their costs

CSP technologies are usually categorised in three different concepts: troughs, towers and dishes (see Figure 1). They work as follows:

- *Troughs:* parabolic trough-shaped mirror reflectors linearly concentrate sunlight on to receiver tubes, heating a thermal transfer fluid which is then used to produce superheated steam.
- *Towers:* Central receivers use numerous heliostats to concentrate sunlight on to a central receiver on the top of a tower.
- *Dishes*: Parabolic dish-shaped reflectors perfectly concentrate sunlight in two dimensions and run a small engine or turbine at the focal point.

The solar flux concentration ratio typically obtained is at the level of 30-100, 500-1 000, and 1 000 – 10 000 suns for trough, tower, and dish systems, respectively.

Trough plants

From 1984 to 1990 Luz International Ltd built a series of nine solar electric generating systems (SEGS) in the Californian Mojave desert, ranging from 14 to 80 MW_e unit capacities and totalling 354 MW_e of grid electricity. The $1.2 billion raised for these plants were from private risk capital investors and institutional investors (notably subsidiaries of East Cost utilities). These ventures were significantly aided by federal and State tax incentives (from 35% in 1984-1986 to 10% in 1989) as well as attractive long term power purchase contracts.

Luz became bankrupt in 1991, when falling fossil fuel prices coincided with the withdrawal of tax credits and a change in the mandatory purchase contracts. However, all nine SEGS plants are still in profitable commercial operation with a history of increased efficiency and output as the operators improved their procedures (Mariyappan, 2001). These plants, benefiting from an average annual insolation of over 2700 kWh.m^{-2}, have generated more than 10 billion kWh, with a highest annual plant efficiency of 14% and a peak solar-to-electricity of about 21% having been reached. Up to 2003 included, they produced more electricity than all PV devices in all IEA member countries (IEA, 2005, p.72).

The essential component of a SEGS plant is the field of parabolic-trough collectors, aligned north to south. Their basic element is the solar collector assembly module, with its own parabolic collector, sun-tracking and local control systems. The collector is a glass reflector (of typical aperture of 5 meters) which focuses the solar radiation directly onto a receiving metal tube enclosed in a vacuum with a glass envelope. A mineral oil is circulated as heat transfer fluid within this receiver. Working temperatures were raised from about 300°C to about 400°C from the first to the last SEGS plants. For most 30 MW$_e$ plants, investment costs was about $ 3.9 per watt, while levelised electricity cost went from $ 0.24 per kWh for SEGS-1 to $ 0.12 per kWh for SEGS-VIII & IX (80 MW$_e$ each). However, the solar only power cost of these plants would be higher, close to $ 0.16 per kWh.

A legal condition for benefiting from attractive purchase contracts was to limit back-up from fossil fuels to 25% of annual primary energy supply. Nevertheless, this back-up proved instrumental in lowering generation costs. More importantly, it helps guaranteeing the capacity in peak and mid-peak hours (partly after sun set), which provides the bulk of the plants' financial revenues (Pharabod and Philibert 1991). Except for SEGS-1, no heat storage had been installed on the plants.

The 150 MW$_e$ Kramer Junction solar power park that gathers SEGS III to VII achieved a 37% reduction in operation and maintenance costs between 1992 and 1997, and averaged 105% of rated capacity during the four-month summer on-peak period (12 noon to 6 pm, weekdays).

Although SEGS have proven to be a mature electricity generating technology, they do not represent the end of the learning curve of parabolic trough technology. For example, today's parabolic trough developers state that their new collectors are 20% more efficient than those of the most recent SEGS – and some have demonstrated such improvements in fields.

Moreover, various new concepts have been developed from the basis of the parabolic trough technology. Some options are as follows:

- Integrated solar combined cycle systems would integrate a parabolic trough with a gas turbine combined-cycle plant, the solar heat supplementing the waste heat from a gas turbine to augment power generation in the steam Rankine bottoming cycle. This would reduce costs mainly by increasing the solar to electricity efficiency.

- Direct solar steam, where steam is generated at high pressure and temperature directly in the parabolic troughs (or Fresnel reflectors). This would reduce costs by eliminating the need for costly mineral oil and heat exchangers and reduce efficiency losses. This option might, however, make storage more complex.

- Linear Fresnel (fragmented) reflectors approximate parabolic shape. This lowers efficiency but reduces drastically capital costs thanks to a low cost structure, a low cost fixed receiver composed of mild steel pipe, and exceptionally low reflector costs.

- Molten salts use in trough field, an option under investigation by the Italian ENEA (2003) would allow raising temperature and efficiency, thus reducing costs. The challenge seems to protect molten salts from freezing in the solar field at cold nights.

Dishes and towers

The potential for improvements is probably even greater with the less mature dish and tower technologies. With two dimensions of concentration, dishes and solar towers can reach higher temperature and offer higher conversion efficiencies.

There are a wide number of past and ongoing demonstration projects using parabolic dishes, mostly in Europe or in the US. Capital costs are currently estimated above $ 10 per watt but might fall drastically with mass production. Dishes may find a niche market in remote applications or smaller isolated grids, competing in sunny areas with photovoltaic electricity. With respect to grid-connected plants, however, the technology may have reached an important step in August and September 2005 when Southern California Edison and San Diego Gas and Electric signed 20-year power purchase agreements with Stirling Energy Systems for 500 MW_e and 300 MW_e, respectively, of solar power to be generated by Stirling solar dishes.

There have been a dozen of solar towers built in the 80s as research and demonstration projects around the world, with capacities ranging from 0.5 to 10 MW_e. None is still under operation. The most recent has been Solar Two, built in California in 1996. This 10-MW_e was operated from 1997 to 1999, successfully demonstrating advanced molten-salt power technology. The low-cost molten-salt storage system allowed solar energy to be collected during the sunlight hours and dispatched as high-value electric power at night or when demanded by the utility (Mariyappan 2001). Heliostats represent the largest single capital investment in a central receiver plant. Capital costs for a 10 MW_e plant are estimated $ 70 million but would be lower for a 100 to 200 MW_e plant, the size that most experts believe would be optimal.

Tower technologies will likely produce power on grids from large plants, as trough plants do However, a new concept of “multitower solar arrays” is being developed that targets smaller urban capacities on building roofs or ground areas such as parking lots (Mills, 2004). The technology is based on a unique, optical concentration technology which allows extremely closely spaced reflectors (>90% of ground area).

While there remains a large potential for cost reductions from research and development on all elements of this technology, from global concepts to almost all elements, this potential could only be reached if there is an active marketplace for these technologies and entrepreneurs capable of integrating lessons from experience as well as concepts and materials from laboratories. The costs reductions experienced in only seven years by the Luz Company offer a clear case for learning by doing improvements.

An active market place could also presumably reduce costs by mass production, economies of scale, reduction of risk premium and risk mitigation costs as the market develops, and learning by doing. Upon reaching 5.000 MWe of new solar capacity, solar generation cost would be fully competitive with fossil-based grid connected power generation cost, according to the CSP industry. In-depth studies such as Sargent & Lundy (2003) have given credit to such claims. As notes the Department of Energy (DOE 2002), parabolic trough technology has demonstrated a reduction in the cost of electricity of 15 percent with every doubling of cumulative installed capacity – and similar cost reductions have been demonstrated for other power technologies.

World potential

Expansion of CSP technologies will be limited, however, by the availability of the resource. They require a minimum of yearly direct insolation of about 2,000 kWh.m-2, and insolation of 2,500 kWh.m-2 is more likely to favour competitiveness – though costs will also depend on land costs (SEGS plants expand on about 2 ha per MWe), local construction and operating costs, and other local factors.

There exists no reliable map of the world indicating normal direct solar radiation. Estimates must be made on the basis of global solar radiation crossed with data relative to annual duration of sunlight (defined as hours when the sun is directly visible) and maps of climate and vegetation to take into account atmospheric humidity and interference. Ultimately, suitable areas are likely to be found in arid and semi-arid conditions in tropical areas. Figure 2 provides one such attempt to map worldwide suitable resources for concentrating solar resources (Pharabod an Philibert 1991). Some other maps are somewhat more optimistic and include larger parts of Russia, China, the US, Latin America and central Africa in areas suitable for concentrating solar.

The South-Western United States, some areas of Southern America, the Middle East, central Asian countries from Turkey to parts of India and China, North Africa, South Africa, and parts of Australia figure amongst the most promising areas are. Ironically, the best places are all found in countries with no quantitative CO_2 emissions targets under the Kyoto Protocol – many developing countries, Australia and the US.

Even the sunniest European countries can only be rated a second choice for the quality of their direct solar radiation resource. A striking example of the importance of the high quality of the solar resource is the proposal of the Italian ENEA to build concentrating solar power plants in North-Africa, rather than in Italy, and to import the power for satisfying the EU directive on renewable share of electricity production. The difference in solar resource more than offsets the costs of transmissions (ENEA 2003).

Although only a part of the world population lives in suitable areas for concentrating solar technologies, it is far from negligible. Suitable areas count no less than 80 multi-million inhabited cities (out of 340 total), and gather populations with fast-growing energy needs, with relatively high time coincidence between peak load and sunlight. Exports to neighbouring countries – in particular when they accept to pay a higher price for green electricity – would further increase the potential market. Other resource constraints may arise from limited water availability, which dry cooling towers may help overcome.

According to the US Department of Energy (DOE 2002), CSP plants on about three percent of the available land located within regions of premium solar resources could produce over 1,000 TWh_e of electricity each year, almost equalling the 1999 Western States' consumption. Perhaps even more strikingly, enough electric power for the entire US economy could be generated by covering about 9 percent of Nevada—a plot of land 100 miles on a side—with parabolic trough systems.

A scenario set up by the European Solar Thermal Power Industry Association (ESTIA) in cooperation with Greenpeace (Aringhof et al. 2003) envisages a world capacity of 21,450 MW_e of concentrating solar power, producing 54.6 TWh_e in 2020. Because CSP uses conventional technologies and materials (glass, concrete, steel, and standard utility-scale turbines), production capacity can be rapidly scaled to several hundred megawatts/year, using existing industrial infrastructure.

Such a scenario does not represent an ultimate limit for CSP technologies. According to the IEA (2003), before 2030 some 4,700 GWe of total power capacity is expected to be built worldwide, either as additional capacity or in replacement of existing capacity. The Greenpeace-ESTIA scenario considers that in 2040, CSP plants could total 630 GWe. This would probably represent a significant market share of power investments in sunny regions, as well as some exports to neighbouring areas (see, e.g., Figure 3) – which, assuming a world with relatively high oil, gas and coal prices and CO2 pricing might not be unrealistic.

For concentrating solar technologies to further expand its market share would likely require unforeseeable progress in techniques for power transport, possibly from superconductivity. It is also possible that some energy-intensive industries shift production to areas with lower electricity costs – assuming other production factors can be provided as well.

Apart from producing electricity, concentrating solar technologies have a broad range of other current or potential uses, either to provide direct heating or cooling (these have been mentioned above) or to produce solar fuels, as will be shown below.

Policies and markets

In the success of the SEGS projects in the United States, the State policy was decisive in providing sufficient incentives but the international cooperation also played its role. Several IEA countries joined forces in 1977 in the IEA Implementing Agreement now called SolarPaces[2], sharing the cost and the effort for the demonstration of tower, trough and dish technologies at the *Plataforma Solar de Almería* in Spain, where the parabolic mirror technology was proven.

The capability of solar thermal power plants to generate the lowest cost commercial scale bulk electricity and their ability to dispatch power as needed during peak demand periods have motivated several national and/or local governments to revive support the large-scale implementation of this technology. Among them Spain and the US state of Nevada have implemented in 2004 the most favourable regulatory and tariff framework for concentrating solar plants. A dozen other countries have projects in development or consideration.

In Spain, a Royal Decree established in March 2004 the same incentive premiums in the order of € 0.18Euro per kWh for photovoltaic and concentrating solar plants up to 50 MW_e capacity each. This incentive immediately attracted commercial developers. The forerunners are the Abengoa Group, who has broken ground for a 10 MW_e tower plant named *PS10* in July 2004, and the Solar Millennium Group together with the ACS Cobra Group, who will soon start the construction of a first 50 MW_e plant called *AndaSol* in Andalusia. This trough plant of 0,5 km^2 mirrors will store heat for hours to closely follow power peak loads.

In Nevada, the state renewable portfolio standards initiated the first long term power purchase agreement of concentrating solar electricity signed between the public utility companies Nevada Power and Sierra Pacific and the US developer Solargenix. The construction of a 50 MWe trough plant was expected at the end of 2005, with 0,3 km^2 mirrors and storage of less than one hour to guarantee the capacity. In June 2004, the Governors of seven South-Western US States (New Mexico, Arizona, Nevada, California, Utah, Texas and Colorado) voted a resolution calling for the development of 30 GW_e of clean energy in the West by 2015, of which 1 GW_e would be of solar concentrating power technologies. In November 2004 the US Department of Energy decided to back this plan and to contribute to its financing.

With the financial support of the global environmental Facility (GEF) Egypt, India, Mexico, Morocco, now joined by Algeria, have long been planning to build large integrated solar combined-cycle power plants (ISCC) in the range 150-250 MW_e. Trough fields would contribute for 100 MW_{th} or more (about 35 MW_e). However, none of these projects has yet broken ground, for a great variety of reasons. In particular, the risks involved by this innovative gathering of two technologies may have compound with the country risks to make

---

[2] See its website at www.solarpaces.org

the projects overly ambitious for an industry that has long been lacking more secure markets in industrialised countries (Philibert 2004). The situation is rapidly evolving.

Algeria has become in February 2004 the first North African Country to implement national incentive premiums (feed-in law) for the market introduction of ISCC. In May 2005, the agency New Energy Algeria (NEAL) launched an invitation to tender for SPP 1, a 150 MWe ISCC plant. It will be the first of a series with the aim to achieve a global capacity of 500 MWe by 2010. NEAL expect at medium term to be able to export to Europe 6 000 MWe from hybrid solar-gas power plants. It estimates that *"the Algerian potential is enough to supply the total needs of Europe"* and already foresees hydrogen production.

Early July 2005, the request for proposals for the 228 MW$_e$ ISCC project at Ain Beni Mathar was sent out to pre-qualified bidders by the Moroccan *Office national d'électricité* (ONE). Contract award is expected for early 2006 and start of operation at the end of 2008.

In August 2005 the Egyptian *New and Renewable Energy Agency* (NREA) has published in August 2005 an invitation for prequalification to build a 110 MW$_{th}$ trough solar field to be integrated in a 150 MW$_e$ combined cycle gas fired power plant at Kuraymat.

The Government of Israel decided in November 2002 to introduce to its electricity market until 2005 the CSP as a strategic ingredient, with a minimal power unit of 100 MW$_e$. The project is carried forward by the Ministry of National Infrastructures.

In Italy, the ENEA is developing a trough plant concept based on molten salts as heat transfer fluid. It aims at building large scale plants in North-Africa and import the power, to benefit from the green electricity price arising from the implementation of the EU directive on renewable in electricity production.

Australia intends to add a "coal saver" of CLFR 4 MW$_e$ to an existing 1 440 MW$_e$ coal plant at Stanwell in Queensland to demonstrate the compact linear Fresnel reflector concept. The project, estimated to cost AU$ 7 million, received a technology commercialisation grant of AU$ 2 million from the Australian Greenhouse Office.

In South-Africa, Eskom is considering the building of 100 MW$_e$ solar-only tower plant at Northen Cape. Other projects have been considered in Brazil, Greece, Iran and Jordan, and may surface again.

3.2 Hydrogen and other fuels

Solar hydrogen and fuels can be produced by a variety of means. Photovoltaic cells in association with electrolysis are often quoted but may not be the most cost-effective. Indeed, warm waters require less power for being electrolysed and integrated systems are being developed associating PV, solar water-heating and electrolysers. More significant are the various possibilities offered by concentrating solar power technologies.

A mid-term goal may be the introduction of solar heat (above 800 K) in the steam-reforming of natural gas, oil or other fuels. It is currently the dominant technology for producing hydrogen, and about 40% of the feedstock needs to be burned to supply process heat. Another option is the solar-assisted steam-gasification of coal or other solid fuels. CO_2 emissions would be reduced from the outset, and their capture and storage largely facilitated. Capture would be even trivial with solar-assisted thermal decomposition of fuels, preferably gaseous or liquids, which yields a carbon-rich condensed phase and a hydrogen-rich gas phase, offering a natural phase separation.

Requiring greater research and development efforts, hydrogen production is possible in the longer term without any contribution from other fuels, via solar thermochemical processes Hydrogen could be produced, for example, via direct thermal dissociation of water at 2 500 K or thermal decomposition of hydrogen sulfide at 1350-1600 K. Metals also are attractive candidates for storage and transport of solar energy. They may be used to generate either high-temperature heat via combustion or electricity via fuel cells and batteries. Metals can also be used to produce hydrogen via a water splitting reaction; the hydrogen may be further processed for heat and electricity generation. (Steinfeld and Palumbo 2001).

The chemical products from any of these power generating processes are metal oxides which, in turn, need to be reduced and recycled. The conventional extraction of metals such as zinc, iron, magnesium, and other from their oxides by carbothermic and electrolytic processes discharges vast amounts of greenhouse gases and other pollutants to the environment, derived mainly from the combustion of fossil. These emissions can be substantially reduced, or even completely eliminated, by using concentrated solar energy as the source of high-temperature process heat. Concentrated solar energy may also be used for the processing of high-temperature and energy-intensive commodities, from cement to fullerenes and carbon nanotubes, metallic carbides and nitrides (ceramics), aluminum-silicon alloys, biofuels, charcoal and syngas.

3.3 Other concepts

Producing electricity with dilute solar energy can follow several roads, all characterised by relatively low efficiencies.

Evacuated tubes

Evacuated tube collectors are now being adapted to efficient operation at up to 185 °C, and will be suitable for use with a new generation of organic Rankine cycle (ORC) turbines. In these, a micro turbine generator is driven by a closed loop of working fluid. The working fluid is heated to produce vapour, which drives a micro generator, and then condenses back to a liquid whence the cycle recommences. The overall efficiency of the system is about 7% and the electricity costs seem close to that of photovoltaic. However, this technology may offer more dispatchable or even round-the-clock electricity thanks to affordable heat storage and thus compete with photovoltaic.

Solar Ponds

In a solar pond, layers of water with increasing salt content fill a shallow pond. The sun’s rays are absorbed in the lower layers of the pond. The temperature gradient between the upper and lower layers of the pond drives a heat engine. Both of these systems (ponds and chimneys) are simple and relatively low cost. Their primary disadvantage is low solar conversion efficiency (under 1%).

Ocean thermal energy

Ocean thermal energy conversion (OTEC) involves capturing the energy from the temperature difference between warm surface water in tropical and sub-tropical latitudes and the colder water at depths of 1000 m or greater. Foreseen by Jules Vernes in the XIX° century, OTEC was demonstrated by George Claude in the 1930s with the 2,2 MW_e floating plant *La Tunisie*. Since 2001, India is testing a 1 MW_e demonstration plant on board the *Sagar Shakthi*, off the Tuticorin harbour in Tamil Nadu. From a theoretical standpoint, ocean currents offer an immense source of renewable energy, but cost estimates vary widely. The initial applicability will likely be for tropical island nations where power is presently provided by expensive diesel generators.

Another concept of Ocean thermal energy that would capture the temperature difference between surface water and the atmosphere would use solar chimneys (see below).

Besides Ocean thermal energy strictly speaking, the cooling capacity of the Ocean and other water sources raise a growing interest for energy saving in cooling building and cities.

Solar Chimneys

A solar updraft tower power plant – sometimes also called 'solar chimney'– is a solar thermal power plant that combines a solar air collector and a central updraft tube to generate a solar induced convective flow which drives pressure staged turbines to generate electricity (see Figure 4).

The first experimental plant with a peak output of 50 kW was built in 1981 at Manzanares (Spain) with funds provided by the German Ministry of Research and Technology and demonstrated the concept. The tower was 195 m high. A 200 MW_e solar towar is currently projected in Australia by the company Enviromission Ltd. Its collector would be a glass structure of 5 km diameter and its tower would be 1 km high.

Solar updraft towers can use all available solar light and do not need direct sunlight only, which is an advantage over CSP technologies that allow them to be installed in a greater variety of climates. Thermal storage is offered by the ground itself and can be enhanced by water-filled bags in the collector for base load electricity production. Indeed, economies of scale are important for this technology as the power output is a function of the size of the collector multiplied by the tower’s height, as long as the outer temperature decreases when the height increases.

Solar updraft towers may have various advantages over CSP technologies: they use all available solar light and do not need direct sunlight only, which allow them to be installed in a greater variety of climates; thermal storage is offered by the ground itself and can be enhanced by simple water-filled bags in the collector for base load electricity production; the technology is simpler. A disadvantage is a much lower efficiency, close to 1%, thus requiring much larger land areas for similar capacities. As such, they may find their way in tropical areas where insufficient direct sunlight does allow for effective CSP technologies.

Solar updraft towers may even be used… in polar areas, according to Bonnelle (2003), by exploiting the temperature difference between the cold oceanic waters and the much colder atmospheric air. This would be a novel form of Ocean thermal energy.

4. Conclusions and recommendations

Two families of technologies emerge from this review for their maturity: the active and passive use of low-temperature thermal heat for direct water and building heating and ventilation or cooling, and the concentrating solar power technologies for producing electricity. Other technologies necessitate further research, demonstration and development efforts before being available for wider dissemination. Together, these two technologies offer an enormous potential worldwide for clean and carbon-free energy production, for the first in delivering energy services such as water heating, space heating or cooling, for the second in producing dispatchable or even base load electricity.

Low temperature solar thermal technologies have costs that vary greatly. They range from already cost-effective applications to schemes more likely to become cost-effective when R&D efforts, economies of scale and learning by doing processes will have reduced costs. Another possibility is that competing technologies become more expensive, due to higher fossil fuel prices and economy-wide carbon externality costs. Beyond economic consideration effective policies seem to require a great variety of instruments to inform consumers and train professionals. One key strategy for market acceleration may also be removing trade and investment barriers between countries.

Concentrating solar power technologies would become competitive in the world's solar belt when a concerted effort for building about 5 GW_e worldwide has been made. Current projects total one order of magnitude below this figure. Policy makers from countries with the necessary solar resource or willing to take part should agree on ways to rapidly scale up this effort. Experience suggests that industrialised countries must be part of the effort and that domestic policies providing sufficient feed-in tariffs are required. "Obligations" made to utilities to raise the share of renewable electricity in their fuel mix have proven an effective tool and should be further developed.

References

Aringhoff, R., C. Aubrey, G. Brakmann & S. Teske, 2003. *Solar Thermal Power 2020*, Greenpeace International/European Solar Thermal Power Industry Association, NL

Bonnelle, Denis, 2003. *Vent Artificiel "Tall is Beautiful"*, Editions du Cosmogone, Lyon

DOE (US Department of Energy), 2002. *Feasibility of 1,000 Megawatts of Solar Power in the Southwest by 2006*, Report to Congress, August, Washington D.C

ENEA, 2003. *Harnessing Solar Energy as High Temperature Heat.* ENEA, Rome

EurObserv'ER, 2005. Solar thermal barometer, *Systèmes Solaires* 168, Paris: 39-56

IEA, 2005. *Renewables Information 2005*. OECD/IEA, Paris

Lenormand, Patrick, 2005. Solaire thermique dans le Nord, *Systèmes Solaires* 168, Paris: 30

Mariyappan, J. 2001. Solar Thermal Thematic Review. in Michael Geyer, *SolarPACES Annual Report 2001*, Deutsches Zentrum fûr Luft- und Raumfahrt e.V., Köln

Mills, D.R., 2004. Advances in solar thermal electricity Technology, *Solar Energy* **76**: 19-31

Pharabod, François and Cédric Philibert, 1991. *LUZ solar power plants : Success in California and worldwide prospects*, Deutsche Forshungsanstalt fûr Luft- und Raumfahrt e.V. for IEA-SSPS (SolarPACES), Köln

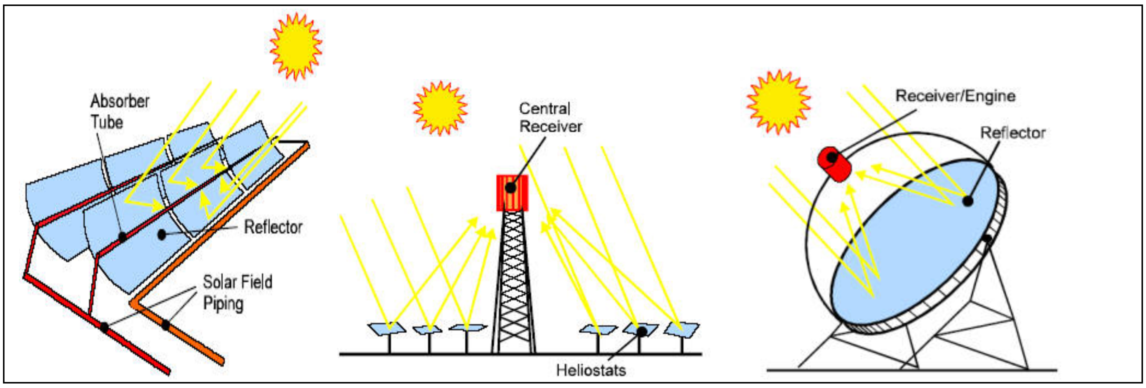
Philibert, Cédric, 2004. *International Energy Technology Co-operation Case Study 1: Concentrating Solar Power Technologies.* OECD/IEA Information Paper, Paris

Sargent & Lundy Consulting Group, 2003. *Assessment of parabolic trough and power tower solar technology cost and performance forecasts*, prepared for Department of Energy and National Renewable Energy Laboratory, Chicago, IL, May

Schlaich, Jörg, Rudolf Bergermann, Wolfgang Schiel, and Gerhard Weinrebe, 2003. *Design of Commercial Solar Updraft Tower Systems – Utilisation of Solar Induced Convective Flows for Power Generation.* Schlaich Bergermann und Partner, Stuttgart

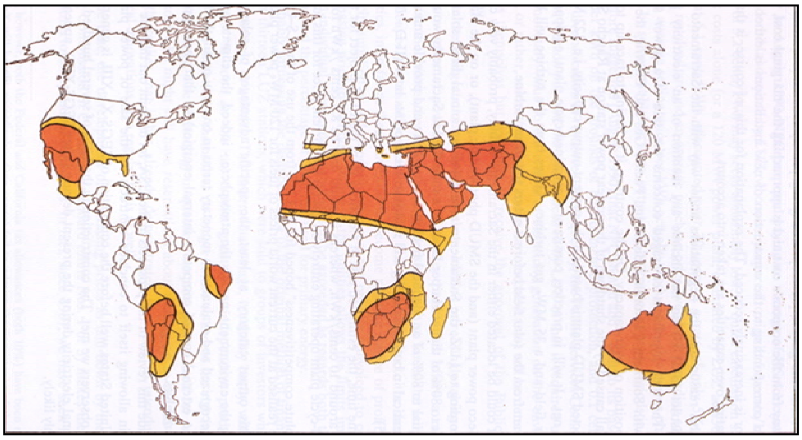
Steinfeld, Aldo and Robert Palumbo, 2001. Solar Thermochemical Process Technology, in R.A. Meyers (ed.), *Encyclopedia of Physical Science & Technology*, Academic Press, **15**: 237-256

Figure 1: Troughs, towers and dishes



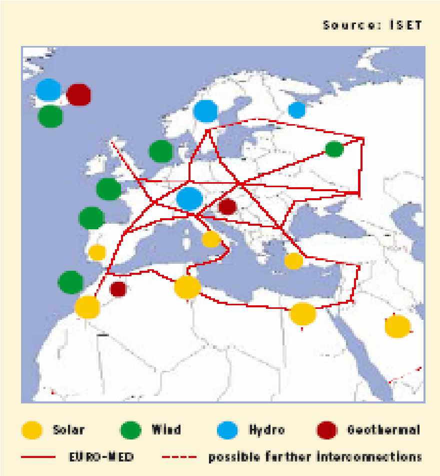
Source: SolarPaces' website

Figure 2: Suitable areas



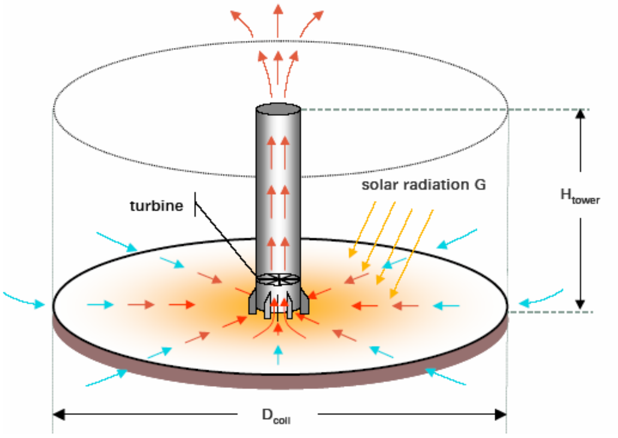
Source: Pharabod and Philibert 1992

Figure 3: Vision of a Euro-Mediterranean grid with large renewable resources



Source: Institut für Solare Energieversorgungstechnik, Germany

Figure 4: Solar tower updraft principle



Source: Schlaich et al., 2003