Concentrating solar thermal power

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In addition to wind and photovoltaic power, concentrating solar thermal power (CSP) will make a major contribution to electricity provision from renewable energies. Drawing on almost 30 years of operational experience in the multi-megawatt range, CSP is now a proven technology with a reliable cost and performance record. In conjunction with thermal energy storage, electricity can be provided according to demand. To date, solar thermal power plants with a total capacity of 1.3 GW are in operation worldwide, with an additional 2.3 GW under construction and 31.7 GW in advanced planning stage. Depending on the concentration factors, temperatures up to 1000°C can be reached to produce saturated or superheated steam for steam turbine cycles or compressed hot gas for gas turbine cycles. The heat rejected from these thermodynamic cycles can be used for sea water desalination, process heat and centralized provision of chilled water. While electricity generation from CSP plants is still more expensive than from wind turbines or photovoltaic panels, its independence from fluctuations and daily variation of wind speed and solar radiation provides it with a higher value. To become competitive with mid-load electricity from conventional power plants within the next 10–15 years, mass production of components, increased plant size and planning/operating experience will be accompanied by technological innovations. On 30 October 2009, a number of major industrial companies joined forces to establish the so-called DESERTEC Industry Initiative, which aims at providing by 2050 15 per cent of European electricity from renewable energy sources in North Africa, while at the same time securing energy, water, income and employment for this region. Solar thermal power plants are in the heart of this concept.
1. Introduction

Owing to the depletion of fossil energy carriers and the environmental problems associated with the combustion of the associated hydrocarbon-based fuels, the European Union has established challenging targets for a transition to a sustainable energy provision. A special interest lies in the electricity sector which is responsible for about 40 per cent of worldwide greenhouse gas emissions. Here, the combination of increased user and generation efficiency must be complemented by a rapidly increasing contribution of renewable energies. To achieve this, research, development and market introduction programmes have been initiated. Significant progress has been made, particularly in wind and photovoltaic power, but the associated electricity generation costs are still significantly higher than those for conventional technologies. In addition, the time-dependent and fluctuating nature of most renewable electricity generating technologies requires fossil backup capacities, as large-scale storage of electricity is only possible in areas suitable for pumped hydropower or compressed air storage.

Solar thermal power plants that concentrate the direct solar radiation (i.e. concentrating solar power, CSP) to drive conventional steam and gas turbine cycles have the potential to resolve this problem, as they can be combined with large high-temperature heat storage facilities. While this technology has been known for about 100 years, new developments and market introduction programmes have recently triggered worldwide activities.

To identify the potential of electricity generation from CSP plants, a worldwide dataset of direct normal irradiation (DNI) from the NASA Surface Meteorology and Solar Energy Program (SSE) v. 6.0 is used. It is based on 22 years of data and has a spatial resolution of about 100 km, which is considered sufficient to assess the potential of CSP plants on a global scale. Site exclusion criteria such as slope greater than 2 per cent, land coverage like permanent or non-permanent water, forests, swamps, agricultural areas, shifting sand dunes, including a security margin of 10 km, salt pans, glaciers, settlements, airports, oil or gas fields, mines, quarries, desalination plants, protected areas and restricted areas were applied to identify areas unsuitable for construction of solar thermal power plants. If DNI and site exclusion maps are combined, the global map of annual direct normal irradiance for potential CSP sites given in Figure 1 is obtained [1]. The global technical potential of CSP amounts to almost 3 000 000 TWh yr$^{-1}$, which is about 150 times the present world electricity consumption of 21 000 TWh yr$^{-1}$.

2. Basic technology of solar thermal power plants

Solar thermal power plants are recognized as suitable technology for bulk electricity generation in the 10–1000 MW range [2]. In comparison with most other technologies for electricity generation from renewable energies, concentrating solar thermal energy has the advantage that it is a proven technology with an industrial base, which can be integrated into (existing or new) conventional thermal power plants to provide firm capacity with thermal storage and/or fossil backup. It can also serve different markets, such as bulk power, remote power, process heat and desalination. Figure 2 shows the four basic design options which are presently under consideration:

- line-focusing systems in which (linear Fresnel or parabolic trough) collectors focus radiation 60–100 times onto an absorber pipe to heat oil, molten salt or steam to temperatures up to 500°C,
- point-focusing central receiver systems (solar tower plants) where numerous heliostats supply up to 1000 times concentrated solar radiation to a central receiver where steam, molten salt or hot air are heated to temperatures up to 1000°C, and
- dish-Stirling systems where a dish-shaped mirror focuses solar radiation up to 3000-fold into the receiver cavity of a Stirling engine.

The typical performance of these technologies is shown in Table 1, which has been adapted from IEA [3]. Data for parabolic troughs, linear Fresnel and tower are for commercial plants based on
DNI averaged annual sum
[kWh m⁻² yr⁻¹]

- < 2000 or excluded
- 2000 – 2100
- 2100 – 2200
- 2200 – 2300
- 2300 – 2400
- 2400 – 2500
- 2500 – 2600
- 2600 – 2700
- 2700 – 2800+

DNI data based on NASA SSE v. 6.0
http://eosweb.larc.nasa.gov/sse/

Data provided by DLR (2008) for EU-project REACCESS

Figure 1. Annual sum of DNI for potential global CSP sites [1]. (Online version in colour.)

linear Fresnel  parabolic trough  solar tower  dish-Stirling

Figure 2. Types of concentrating solar thermal power plants. (Online version in colour.)

A Rankine cycle and using synthetic oil or steam as heat transfer fluids. Data for parabolic dishes are for dish-Stirling systems.

One of the most critically discussed issues with respect to CSP application is the significant consumption of cooling water for the power plant condensers. A typical 50 MWₑₑ parabolic trough plant in Spain uses about 0.5 million m³ of water per year. For tower technologies, cooling water consumption may be somewhat lower (around 2 m³ MWh⁻¹) than for parabolic trough systems owing to their greater potential for increased efficiency. Conversely, the lower efficiencies of linear Fresnel systems tend to result in water consumption at the higher end of the range given in table 1. Obviously, these levels of water consumption are not acceptable for arid regions. However, dry cooling substantially reduces water consumption with a limited impact on plant efficiency and
Table 1. Current performance indices of plants based on the four main CSP technologies [3].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Peak solar to electricity conversion efficiency (%)</th>
<th>Annual solar-to-electricity efficiency (%)</th>
<th>Water consumption, for wet/dry cooling (m³ MWh⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic trough</td>
<td>23–27</td>
<td>15–16</td>
<td>3–4/0.2</td>
</tr>
<tr>
<td>Linear Fresnel system</td>
<td>18–22</td>
<td>8–10</td>
<td>3–4/0.2</td>
</tr>
<tr>
<td>Solar tower (central receiver system)</td>
<td>20–27</td>
<td>15–17</td>
<td>2–3/0.2</td>
</tr>
<tr>
<td>Parabolic dish</td>
<td>20–30</td>
<td>20–25</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

generating costs. For a 100 MW trough plant, adoption of dry cooling instead of wet cooling reduces water consumption by about 93 per cent. The penalty on the generating efficiency is 1–3 percentage points (with respect to nominal power). Annual production of electricity is reduced by 2–4% because of a 9–25% increase in the parasitic power requirements associated with the additional equipment for dry cooling depending on different site characteristics. As a result, generating costs increase by 3–7.5% compared with water cooling [4]. In addition to cooling, water is also required for cleaning the mirrors. Depending on the location, cleaning may be required in weekly or two-weekly intervals, involving an additional water consumption of 20–40 l yr⁻¹ m⁻² mirror area. This is about 2 per cent of the cooling water consumption of a standard parabolic trough plant.

In comparison with most other electricity generating technologies, the energy payback time of CSP plants is short, i.e. about 6–12 months of an assumed lifetime of 30 years [5]. The cumulative non-renewable primary energy needed to produce 1 kWh of electricity is about 0.05 kWh which is about half of that of wind, and a factor of 30–60 lower than for fossil fuel fired plants [6]. CSP plants are significantly more material intensive than conventional power plants or wind power plants. Nevertheless, over 95 per cent of these materials are glass, steel and concrete, which are commonly available and may be recycled. The only toxic or flammable substance used to a significant extent is the synthetic heat transfer oil presently in use for temperatures up to 400°C. As outlined later in this paper, attempts are underway to replace this fluid by water/steam, molten salt or even a common gas.

3. Solar thermal power plants in operation and construction

In total, solar thermal power plants with a capacity of 1.3 GW are presently in operation worldwide. From this, 850 MW are installed in Spain, 480 MW in the USA, 5 MW in Australia and 2 MW in other countries. Another 2.3 GW of solar thermal plant capacity is presently under construction, of which 1350 MW will be generated in the USA, 780 MW in Spain, 100 MW in the Middle East and North Africa (MENA) region, 20 MW in India, 5 MW in Italy, 4 MW in China, 3 MW in Australia and 18 MW in other countries [7].

The most advanced plants in terms of commercial installations are parabolic trough plants. Nine such solar electricity generating systems with a total capacity of 354 MW peak electricity were built in the Californian Mojave desert during the 1980s, which since then have been feeding more than 17 TWh of electricity into the Californian grid. In July 2007, Acciona completed the construction of 65 MWel parabolic trough plant Nevada Solar One with an investment cost of about 250 million US$. This power plant operates in solar-only mode without heat storage or fossil fuel backup. Owing to the excellent solar radiation conditions in Nevada and the limitation to operation during solar hours, electricity generation costs of 11 ¢/kWh (year 2007 purchasing power) can be achieved.

In spring 2009, Spanish company ACS/Cobra and German Solar Millennium Group completed construction of the 50 MWel parabolic trough plant ANDASOL 1 near Granada, Spain. The general lay-out of this plant is shown in figure 3. Identical plants ANDASOL 2 and 3 were completed in 2009 and 2011. Figure 3 shows a picture of ANDASOL 1 and 2. Since these plants...
Figure 3. ANDASOL 1 and 2 plants near Granada, Spain (courtesy ACS/Cobra). (Online version in colour.)

provided a blueprint for many subsequent developments, they are described in more detail:
consisting of 596 solar collector assemblies of 150 m length and an aperture of 5.70 m (i.e. collector
area approx. 510 000 m²), each, the ANDASOL plants are the world’s largest solar power plants,
at present. Each plant is designed to generate approximately 179 GWh of electricity per year
to supply some 200 000 people with solar electricity. Curved float glass mirrors from Flabeg
Company, which has already provided the mirrors for the plants in California and Nevada, are
mounted on a metal space frame structure to approximate the ideal parabola. The stainless steel
absorber tube developed and manufactured by Schott Company is surrounded by an evacuated
glass tube and coated with a special selective optical surface to minimize thermal losses. Thermal
oil is heated to temperatures up to 400°C, and generates steam at 375°C and 100 bar for driving
a conventional Siemens steam turbine. The collector field is designed to provide, under good
solar conditions, more energy than the turbine can accept. This surplus energy is used to charge
a heat storage, which can provide the required energy input to the turbine system during periods
of insufficient solar radiation. The storage consists of two large tanks of 14 m height and 36 m
diameter, containing 26 000 tonnes of storage medium (liquefied nitrate salt mixture). If heated
from 300°C to 400°C, the stored heat capacity provides 7–8 h of operation capacity. Thus, the
yearly electricity production is extended from 2000 h to close to 3800 full-load hours. Heat is
transferred from or to the thermal oil in an oil-to-salt heat exchanger. The salt is pumped through
this heat exchanger from the cold tank to the hot tank during charging and vice versa during
discharging periods. Construction time for each ANDASOL plant was barely 2 years. Electricity
generation costs with the ANDASOL plants are around 21 €cent kWh⁻¹ (the Spanish feed-in tariff
is around 27–29 cent kWh⁻¹). However, it must be considered that this is dispatchable, high-value
electricity due to the buffering and extending effects of the heat stores, with an hourly electricity
supply into the grid which can be guaranteed more than 24 h in advance. In addition, solar
radiation conditions in southern Spain (DNI about 2100 kWh m⁻² yr⁻¹) are less favourable than in
other locations such as California, Nevada or the Maghreb region. Typically, levellized electricity
costs are expected to decrease by about 5 per cent for each 100 kWh m⁻² yr⁻¹ improvement over
this value [8].

Following the successful development of the ANDASOL plants, a substantial number of other
parabolic trough plants has been developed and taken into operation in Spain and in the USA.
Updated numbers may be found on the homepage of the European Solar Thermal Electricity
Association (ESTELA) [7].

Solar tower plants may reach higher temperatures and hence higher thermodynamic
efficiencies than linear concentrating plants, because of their high concentration factors. Several
demonstration and semi-commercial plants have successfully been taken into operation. With
respect to market introduction and commercial competitiveness, they are still somewhat behind
parabolic trough plants, despite advantages such as higher efficiency and suitability for hilly
terrain. They have, however, medium- to long-term potential to produce electricity at lower
costs than trough plants, owing to the higher efficiencies which may be achieved at receiver
temperatures exceeding 800°C.

In April 2007, Spanish company Abengoa Solar took into operation PS10, a 10 MW el solar
tower power plant that is shown in the background of figure 4. Seven hundred mirrors with an
area of 120 m² each focus on a receiver at the top of an 80 m tower. In the first stage, saturated
steam with a moderate temperature of 260°C is generated; available heat storage will allow
continuing electricity production for up to 1 h under cloudy conditions. Annual efficiencies
(defined as the ratio of generated electricity per year, divided by the direct radiation on the
mirrors) are about 16 per cent. With total investment cost of around 36 million €, this power
plant is not yet economic, even under the conditions of the Spanish energy feed-in law. PS20,
a second Abengoa tower plant with a capacity of 20 MW el, which is shown in the foreground
of figure 4, was taken into operation in spring 2009. The PS20 plant has a tower of 165 m in
height and 1225 mirrors of the same size as those of PS10. It also operates at comparable pressures
and temperatures.

Another large solar tower plant with 20 MW el capacity, GEMASOLAR, was taken into
operation in 2011. It is jointly owned by MASDAR and SENER. The particular attractiveness of
this tower plant is that it is operating with molten salt as a heat transfer medium which is stored
in large containments with a thermal storage capacity of 800 MW th, sufficient for up to 15 h of
full-load operation. This large storage capacity is achieved by the fact that the salt is heated in the
central receiver from an inlet temperature of 285°C to an outlet temperature of 565°C.

Most recently, US company Solar Reserve announced the completion of the world’s tallest solar
power tower with a height of about 165 m plus an additional 30 m for the molten salt receiver.
This installation is part of a 110 MW solar thermal plant with 10 000 heliostats. The predicted
levellized cost of electricity (LCOE) is below 10 €cent kWh⁻¹. This will, however, strongly depend
on whether the plant will be operated with thermal storage for extended hours of solar electricity
production or in hybrid mode with substantial contributions from natural gas.

While dish-Stirling systems have the highest electricity generation efficiency (up to 35%), they
are presently limited to typically 10–30 kW capacity per unit. Hence, a large number of systems
will be required to generate bulk electricity in the MW range. Several announcements have been
made in the past about large solar farms involving hundreds or even thousands of dish-Stirling
units generating electricity below 10 €cent kWh⁻¹. However, only few individual demonstration
units have ever been built and successfully operated to date. Considering the complexity of
these systems and the large number of moving parts, this technology will find it difficult to
compete with, for example, concentrating photovoltaics, which has demonstrated first large-scale
installations and is already close to achieving these cost targets.
4. Present and anticipated cost of electricity

A precondition to the success of concentrating solar thermal power is that the electricity generation costs must become comparable with those of conventional power generating technologies. Since CSP technology only entered the commercial market less than 10 years ago, its produced electricity is still more expensive than onshore wind and photovoltaic power, even in good solar locations. LCOE for the presently built solar thermal power plants is of the order of 15–25 €cent kWh\(^{-1}\) [8], depending on location, size and solar share. Assuming a learning rate of 20 per cent (i.e. 20% reduction in LCOE for every doubling of installed power), this cost will drop to half once a total capacity of 10 GW has been installed worldwide. This is sufficient to compete in a number of market segments with electricity from fossil fuels and should be reachable in 10–15 years. Once this is achieved, the installation of new solar thermal power plants will increase dramatically, as this technology will become the lowest cost option for dispatchable bulk electricity production in many areas of the world.

To achieve the required cost reduction, mass production of components, increased plant size and planning/operating experience must be accompanied by technological innovations which are presently in the development or even demonstration stage. This includes heat storage in the GWh range for temperatures up to 800\(\degree\)C, the use of molten salt as heat carrier or direct steam generation at 500\(\degree\)C within hundreds of kilometres of absorber tubes in parabolic trough collectors, central solar receivers for temperatures up to 1000\(\degree\)C to drive supercritical steam cycles or gas turbines, resource-efficient cooling of condensers, transient models of multi-scale processes for optimized process control as well as solar thermal desalination, fuel up-grading and hydrogen production systems. The scale of construction, the high temperatures and the naturally transient operation provide formidable challenges for academic and industrial R&D. To become relevant for industrial application, this knowledge must be linked with new developments in materials science, energy economy and meteorology.

Despite its undoubted advantages, the present market penetration of CSP technology is somewhat less favourable than expected a few years ago. While there are no problems with the basic functionality of these plants and their performance according to design specifications, the anticipated cost reduction targets have not yet been achieved, because of the increased cost of components (e.g. turbines) and base materials (e.g. steel). In comparison, LCOE from wind turbines and photovoltaic plants has decreased even more rapidly than expected. In good locations in North Africa, wind power may be generated at 6 €cent kWh\(^{-1}\) while concentrated photovoltaic plants are offered at 10–12 €cent kWh\(^{-1}\). If there is a sufficiently good correlation between electricity demand and sunshine or wind, and as long as the existing electricity grid has the capacity to cope with substantial fluctuations in power, solar thermal power plants to date are at an economic disadvantage.

This will, however, change dramatically once electricity from renewable sources will achieve a substantial share (e.g. in excess of 20%) in the total electricity mix and will have to be supplied according to demand rather than availability. Figure 5 shows the results of a study done at the German Aerospace Centre (DLR) for a good solar and wind site in Egypt, if a base load of 10 MW was to be supplied by a combination of renewable and fossil technologies [9]. For a typical week in spring, a 10 MW\(_{\text{peak}}\) photovoltaic installation will require 75 per cent fossil backup, a 10 MW wind installation 60 per cent fossil backup, while a 10 MW CSP installation with 18 h storage performs with only 10 per cent fossil backup which can be provided directly to the existing steam turbine cycle. In order to de-carbonize the generation of electricity down to the levels targeted by the European Union for 2050 (80–95% reduction in greenhouse gas emissions), it is, therefore, of strategic importance to continue with the development and implementation of solar thermal power plants.

In the meanwhile, CSP plants with storage capacity may be installed in sun-rich countries to supply balancing power (peak load), which is already competitive with the presently used generation based on gas turbines and jet fuel or diesel. For a typical Maghreb country with no notable fossil fuel reserves, figure 6 shows the development of peak-, mid- and base-load
electricity cost assuming an annual increase in diesel, light oil and heavy oil prices of 1.5 per cent starting from a price of $75 per barrel of crude oil in 2007. It should be noted that the actual cost escalation has been considerably steeper. Furthermore, a modest increase in electricity demand of 3.5 per cent and a lifetime of 40 years for all existing conventional electricity generating facilities have been assumed. This diagram also includes the projected reduction in LCOE for new CSP plants installed in the indicated years with a very conservative learning rate of 12 per cent. It can be seen from this chart that the CSP cost curve already undercuts the peak-load cost curve and will reach the mid-load cost curve by 2020. To replace the majority of peak load, only a solar multiple (SM) of 1 (i.e. no heat storage) is required, whereas increasing amounts of storage have been included in the simulation for the mid load (SM = 2) and base load (SM = 3.5). Hence, by merely replacing old conventional power plants which have gone out of operation and also providing for the increased electricity demand, the installed capacity of solar thermal power plants may grow as shown in figure 7, without additional cost to the consumer. Such an analysis also applies for countries which use their substantial fossil reserves for providing highly subsidized electricity for their own consumption. For example, Saudi Arabia now consumes about one-third (trend
increasing) of its oil production for its own energy demand, most of it for the generation of electricity. This oil is presently provided at a price which is significantly more than one order of magnitude below the revenue (shadow price) it would generate if sold on the international market. The Saudi government is now intending to adjust the internal energy cost to market prices and use the additional revenue to balance social hardness resulting from this measure. Such a measure will not only strengthen the efficient use of energy, but also the introduction of renewable energy technologies.

5. Concentrating solar power plants in planning stage

To achieve the cost development outlined in figure 6, market stimulation mechanisms must be provided to encourage industry to invest in construction of further power plants, additional
production capacities and further technological developments. Successful completion of the actual projects will significantly accelerate future expansion of this technology, since technical and economic risks become much more quantifiable. Investment companies worldwide have entered into the solar thermal power plant market so that the actual number of projects which are presently under development or consideration is almost impossible to follow. This increasing competition will, in addition to improved know-how and mass production of components, contribute to the required cost reduction.

In addition to the power plants described in §3, numerous other plants are in an advanced development process, worldwide. This is much more than wishful thinking, as indicated by the facts that for many projects long-term electricity supply contracts have already been signed, land been purchased or leased, environmental permits been granted, grid connection points been established and financial contracts been negotiated.

According to a recent report by EASAC [6], CSP installations for 27314 MW are presently planned in the USA, 1497 MW in MENA, 839 MW in Spain, 817 MW in Australia, 600 MW in India, 381 MW in China and 263 MW in the rest of the world. It is obvious that not all of these projects will ultimately turn into reality, the actual numbers depending on the development of costs and market introduction mechanisms. Nevertheless, they provide a sound basis to support the cost reduction outlined in §4.

6. Technology development

Mass production, large plant size and industrial experience alone will not be sufficient to reach the required cost reduction. Accompanying R&D activities required to reach the cost target of 7–10 €cent kWh\(^{-1}\) within the next 10–15 years are described in [11]. Figure 8 shows the cost reduction potential of the main components of solar thermal power plants. Since, independent of CSP technology, about 40 per cent of present installation costs are due to the solar field, any increase in the efficient use of the solar heat directly transfers into a reduction of the LCOE. The biggest single potential for increased power plant efficiency lies in the increase of the operating temperature of the thermodynamic cycle. In the following, some promising developments are described, which have already reached demonstration status. A detailed compilation of research and development requirements for all solar thermal power generation technologies is under preparation by ESTELA [7] and should be available by mid-2012.
Table 2. Qualitative assessment of different heat transfer media (courtesy Siemens AG). Reference value ‘0’; ‘+’ or ‘++’ better; ‘−’ or ‘−−’ worse than reference.

<table>
<thead>
<tr>
<th></th>
<th>synthetic oil</th>
<th>steam/water</th>
<th>molten salt</th>
<th>ionic liquids</th>
<th>sulfur</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature stability</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>−</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>heat storage</td>
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<td>−</td>
<td>++</td>
<td>0</td>
<td>+</td>
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<td>++</td>
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<tr>
<td>cost</td>
<td>0</td>
<td>++</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>0</td>
</tr>
</tbody>
</table>

(a) Parabolic trough system development

All present, parabolic trough plants use synthetic heat transfer oil as heat transfer medium. However, this established technique is known to have severe limitations. For example, the maximum operation temperature of the heat transfer oil is about 400°C which is used to produce steam at 375°C and a pressure of 100 bar. This results in a power block efficiency of 37 per cent. It is, therefore, most likely that next generation parabolic trough plants will be using different heat transfer media. From table 2, steam/water and molten salts have the highest potential for innovation. It is, therefore, not surprising that the main R&D activities are focused on these two media.

(i) Direct solar steam generation

Direct solar steam generation in the absorber tubes of parabolic trough collectors is a promising option for improving the economy of solar thermal power plants since all oil-related components become redundant and steam temperature (and hence efficiency) can be increased [12]. Disadvantages are the high pressure of operation in the collector loop (particularly with respect to the rotating pipe connections between collectors), the complicated process control to avoid instabilities and the problem of heat storage from the generated steam. Steam temperatures up to 400°C at 100 bar pressure have been reached within the framework of a European project undertaken over 6000 operating hours at the Plataforma Solar de Almería in Spain. The 2 MW th test loop with 700 m length and an aperture of 5.70 m has been custom-designed and constructed for the purpose of demonstrating safe operation and controllability under constant and transient operating conditions. Dynamic modelling of the operation of solar thermal power plants with direct steam generation is essential for optimized operation, owing to transients occurring during daily start-up/shut-down as well as cloud-related changes in radiation conditions. Using the simulation tool Dymola/Modelica, it was possible to develop validated control algorithms for complete collector fields [13].

(ii) Molten salt

Several investigations in the USA have demonstrated the suitability of molten salt as a cost-effective heat transfer medium for solar tower plants, which can at the same time also be used as heat storage medium. Typically, nitrate salt mixtures with suitable melting temperatures are used for this purpose. The 10 MW Solar 2 project from 1996 to 1999 has demonstrated advantages and problems of this technology. The above-mentioned GEMASOLAR (originally Solar Tres) solar tower plant in Spain has been a successful continuation of this development.

Advantages of molten salts are the operation at low pressure (because of the high boiling temperature), 10 times reduced purchasing cost as well as environmental compatibility if compared with synthetic oil, storability in tanks and reduced storage volume for the same capacity due to higher temperatures, which are presently limited to 390°C by the maximum
operating temperature of the heat transfer oil. Problems are the corrosiveness of salts, but mainly poor heat transfer coefficients and operational problems associated with the high melting temperatures around 220°C. The latter requires overnight circulation with high heat losses and backup procedures during unexpected plant shut-down. Therefore, new salt mixtures with lower melting temperature are investigated to reduce the risk of freezing.

Operation of parabolic trough collectors with molten salt has been successfully demonstrated by the Italian National Agency for New Technologies, Energy and the Environment (ENEA) in more than 5000 h of operation with more than 500 start-up and shut-down cycles. Molten salt receiver technology developed by ENEA is now commercialized by Italian company Archimede Solar Energy in cooperation with Siemens AG. The aim is to increase the solar loop outlet temperature to 550°C; a 5 MW pilot plant has been completed in Sicily [14].

(b) Fresnel collectors for solar thermal power plants

A possible alternative to parabolic trough collectors is the linear Fresnel collector. Replacing the curved mirrors by flat mirrors, this system has the potential to achieve lower investment costs than parabolic trough collectors, because of the use of lower cost materials and simpler design, which is also less sensitive to wind forces. On the other hand, the simple optical design of the Fresnel system leads to a lower optical efficiency of the collector field, requiring about 33–60% more mirror aperture area for the same solar energy yield compared with the parabolic trough. In order to provide quantifiable information about the benefits and disadvantages of Fresnel technology, a 100 m long and 20 m wide pilot facility with 1 MW thermal power was taken into operation in 2007 on the Plataforma Solar de Almería in Spain, to identify under which conditions Fresnel systems may be advantageous [15,16].

Several commercial linear Fresnel systems have recently been developed and built. Figure 9 shows the 1.5 MWel prototype Fresnel plant manufactured by NOVATEC which was taken into operation in Spain in 2009. Notable innovations are the novel Fresnel construction, air-cooling and cleaning robots. Compared with the typical parabolic trough, the linear Fresnel collector system designed by NOVATEC shows a weight reduction per square metre of mirror area of 80 per cent. Fresnel systems may be particularly advantageous if high electric efficiency is not the overriding target, i.e. for combined heat and power supply. Linear Fresnel plants with a total capacity of 30 MWel are presently under construction in Spain.

(c) Central receiver systems

(i) Volumetric central solar receiver

Present central receiver plants use bundles of steel tubes on top of a tower to absorb the concentrated solar heat coming from a heliostat field. However, the temperatures which can be achieved in such a system are limited by the thermal stability of the steel and the poor heat transfer inside the tubes. The latter can be improved by replacing steam or air by molten salt (see GEMASOLAR plant) or a liquid metal as heat transfer media. Another option to reach higher temperatures, and hence achieve higher efficiencies, without overheating the tube walls is the volumetric receiver. A wire mesh is directly exposed to the incident radiation and cooled by air flowing through that mesh. Such a receiver can readily achieve 800°C. For even higher temperatures, the wire mesh screen is replaced by porous SiC or Al2O3 structures [17]. This set-up has been tested on the Plataforma Solar de Almería in Spain at 200 kWth scale, reaching temperatures in excess of 1000°C at receiver efficiencies close to 90 per cent. A 1.5 MWel demonstration plant for this technology with 20 000 m² heliostat area and a 50 m tower was completed in August 2009 near Jülich, Germany, and will be operated by DLR as an experimental facility for a number of years, after which it is expected to feed electricity into the German grid for another 15 years.
Figure 9. (a) 1.5 MW<sub>e</sub> NOVATEC linear Fresnel collector prototype plant, with (b) cleaning robots. (Online version in colour.)

(ii) Solar gas turbine

High electricity generation efficiencies may be reached with solar-heated gas turbines, which may even be increased further in combined cycle processes (figure 10). These systems have the additional advantages that they can also be operated with natural gas during start-up and with a high fossil-to-electric efficiency when solar radiation is insufficient. Hence, no shadow capacities of fossil fuel plants are required and high capacity factors are provided all year round. In addition, the specific cooling water consumption is reduced significantly compared with steam cycle systems. Gas turbines require high solar receiver outlet temperatures and heat transfer efficiencies. This can be achieved in volumetric receivers covered by a dome-shaped quartz glass window to contain the pressurized air [18], as shown in figure 11. This system has been demonstrated for receiver outlet temperatures up to 1050°C, pressures up to 15 bar and an electrical power output of 230 kW on the Plataforma Solar de Almería [18]. It is estimated that commercially competitive electricity production costs below 6–8 €cent kWh<sup>−1</sup> may eventually be possible at good locations and with large centralized solar thermal tower plants. For smaller units, the combined provision of electricity, heat and cold is an attractive alternative if electricity is generated by a micro gas turbine heated from a pressurized receiver. The waste heat from the gas turbine is then used for hot water/steam production and/or for central air conditioning via an absorption refrigeration system. This combined usage results in a high overall energy efficiency of the complete plant.
(iii) Other solar tower concepts

US company eSolar has developed a cost-effective, utility-scale solar power tower plant technology using mass-manufactured components designed for modularity and rapid deployment. Contrary to recent trends towards large heliostat sizes in excess of 100 m², the eSolar heliostats are 1.14 m² only, and do not require in-ground installation with the associated cost and construction time. Each receiver/tower/heliostat field module generates steam for 2.5–3 MW electricity and comprises rectangular north and south facing subfield heliostats that reflect concentrated sunlight onto a receiver located on top of a 50 m high tower between the subfields. The receiver is a natural-circulation boiler consisting of economizer, evaporator and superheater panels which absorb the concentrated sunlight in dual cavities. Steam/water at 440°C and 6 MPa are separated in a steam drum on top of the tower, and then the steam is superheated and fed to a central steam turbine. To demonstrate this technology, eSolar has built and is currently operating a commercial demonstration facility, called Sierra, in Lancaster, CA, USA. This power plant demonstrates the functionality of two full-scale receiver/tower/heliostat field modules powering a 5 MW turbine generator. eSolar has recently announced commercial development partnerships, power purchase agreements, and initial commercial plants [19]. In the USA, they have partnered with electricity generator NRG Energy to develop and build 500 MW in the southwest USA. The first joint project will be a 92 MW facility (two co-located 46 MW plants) located near Santa Teresa, NM, USA. Other joint projects include 245 MW developments in California for Southern California Edison, as well as an additional 92 MW facility for Pacific Gas & Electric.

In the Negev desert, Israeli company BrightSource has built a pilot-scale central tower solar plant which achieves steady-state conditions with superheated steam of 130 bar at 530°C [20]. The process transforming subcooled liquid into superheated steam was demonstrated with a maximum performance of 5.34 MW net thermal input. A solar field of 1640 heliostats covering an area of 40 000 m² concentrates solar radiation on a steam boiler placed atop a 60 m high tower, converting solar energy into turbine standard superheated steam. The single mirror heliostats

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**Figure 10.** Solar combined cycle plant. (Online version in colour.)

**Figure 11.** Volumetric receiver for solar gas turbines [18]. (Online version in colour.)
have a size of 3.21 m × 2.25 m (total reflecting area: 7.2 m²). The originally flat mirrors are constrained by the support structure into a paraboloid shape. Following the initial demonstration, BrightSource has now designed a new generation of heliostats, which use two mirrors positioned vertically for improved performance. The solar field control systems communicate with each heliostat individually. Using weather conditions (insolation, attenuation, etc.), solar field data (e.g. solar field availability, performance) and operational parameters the best aiming point for each heliostat is selected about once a minute in order to maximize performance.

A first solarized micro gas turbine with 100 kW_{el} has been demonstrated by Israeli company AORA. In contrast to the previously described solar thermal power plants that offer economic efficiency only in sizes of multi-MW, this system allows one to set up solar thermal applications at much smaller scale and are hence easier to build and operate. Micro gas turbines can be hybridized to operate on the sun as well as on other fuel sources, such as diesel and gas, to guarantee uninterrupted power supply (if needed) for 24 h per day.

In the longer term, solar tower plants powering supercritical steam cycles may be an attractive option, owing to the high thermodynamic efficiencies [21]. Considering heat transfer and storage options for these elevated temperatures, receiver designs outlined above may not be suitable. In his doctoral thesis Singer [22], therefore, has undertaken detailed modelling studies on the design of direct absorption particle receivers.

(d) Heat storage

The potential to provide power on demand is the main advantage of solar thermal power plants over other renewable energy technologies, such as photovoltaic or wind. Hence, successful development of efficient and affordable thermal energy storage technologies is decisive for success or failure of all CSP technologies. Figure 12 shows the LCOE generation as a function of storage capacity for a storage cost of 10 €kWh^{-1}. A cost reduction of about 20 per cent seems to be possible if sufficient thermal energy for 10 h full-load operation may be stored. However, this result is somewhat misleading, as the true value of storage is much higher due to the different tariffs for base, mid and peak load. This is particularly important for the Maghreb countries, where a second demand peak occurs shortly after sunset, which can definitely not be covered by photovoltaic and not reliably with wind power.

There are a range of concepts to realize thermal storage depending on the required operational boundary conditions. Since large-scale, high-temperature heat storage is still in the early stage of development (full-size demonstration of molten salt in ANDASOL and GEMASOLAR plants,
Table 3. Comparison of storage density and cost expectations of the technology for heat storage [22].

<table>
<thead>
<tr>
<th>storage concept/material</th>
<th>storage capacity (kWh m(^{-3}))</th>
<th>actual cost (€/kWh(^{-1}))</th>
<th>cost expectation (€/kWh(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensible — liquid (depending on (\Delta T))</td>
<td>30–90</td>
<td>30–70</td>
<td>20–50</td>
</tr>
<tr>
<td>sensible — solid (depending on (\Delta T))</td>
<td>20–100</td>
<td>30–50</td>
<td>15–30</td>
</tr>
<tr>
<td>phase change materials</td>
<td>50–150</td>
<td>80–120</td>
<td>30–50</td>
</tr>
<tr>
<td>thermochemical reactions</td>
<td>250–400</td>
<td>n.a.</td>
<td>10–50</td>
</tr>
</tbody>
</table>

Pilot-size for salt phase change materials (PCMs) and solids, actual and expected costs listed in table 3 (DLR, Institute for Technical Thermodynamics: internal communication (September 2011)) are indicative, at best. State of the art are two-tank systems using a mixture of molten nitrate salts as storage medium. The following concepts are in various stages of development.

(i) High-temperature sensible heat storage

In cooperation with civil engineering company ZÜBLIN AG, DLR has developed a concrete sensible heat storage technology for temperatures up to 500°C, which may reduce storage costs by up to 30 per cent. The technology has been demonstrated with a 27 m\(^3\) concrete storage block which proved to operate stably over several hundred temperature cycles up to 400°C.

(ii) High-temperature latent heat storage

For direct steam generation, latent heat storage is considerably more attractive than sensible heat storage, since a large amount of heat can be stored at almost constant temperature. For the desired temperature range between 300°C and 400°C the heat of solidification of single salts or their mixtures may be used as PCMs. For example, sodium nitrate (NaNO\(_3\)) with a melting temperature of 306°C is suitable to store the heat required to produce steam at 100 bar. In addition to storage capacity (in MWh), the heat duty (in MW) of the storage facility is an essential criterion. Typical storage media have low thermal conductivity between 0.5 and 1 W (m K)\(^{-1}\), which would lead to large heat transfer surface areas between storage and heat transfer media. For high-temperature latent heat storage with high charge/discharge power, DLR developed a sandwich concept using fins made either of graphite foil or aluminium [23], which was successfully tested for more than 170 melting/solidification cycles over 4000 h.

(iii) Combined heat storage

Heat transfer to steam turbine cycles consists of three stages, i.e. heating of the feed-water to the boiling temperature, evaporation and superheating of the steam (figure 13). To maximize the benefits of thermal storage, this may be realized with a three-component storage system where PCM storage will be deployed for the evaporation stage, while concrete storage will be used for preheating of water and superheating of steam. With this approach, the required temperature–entropy curve can be paralleled and exergy losses or pinch points be minimized. A storage system with a total storage capacity of about 1 MWh has been constructed for testing in a conventional power plant in Carboneras (Spain) by a consortium, including ENDESA, SolarMillennium, Flagsol, Schott, Senior Berghöfer GmbH, MAN and DLR [24].

(iv) Heat storage for higher temperatures

Up to 1000°C is another formidable challenge. At present, sensible heat storage in regenerators, similar to cowpers in the steel industry, is the most suitable solution. However, these storage facilities must be adapted to and qualified for the massive size and the highly unsteady operation of solar thermal power plants. The DLR Institute of Technical Thermodynamics is presently...
operating a large test facility that allows the investigation of materials and operating modes for atmospheric and pressurized high-temperature heat storage. In the longer term, reversible exothermic/endothermic chemical reactions may become the best solution for high-temperature heat storage. However, research on this technology is still in its early stages. Major problems are stability of reactants, heat transfer and cost.

7. The DESERTEC concept

Solar thermal power plants require direct solar radiation in excess of 1800 kWh m⁻² yr⁻¹ and are therefore only suitable for locations in the sunbelt of this planet. For a sustainable electricity provision, it will be beneficial to link areas where electricity can be generated economically and reliably with those areas where there is a vast electricity demand and not enough sunshine. Two detailed studies on this subject have been undertaken by DLR on behalf of the German Federal Ministry for the Environment, together with representatives from several countries in the MENA region.

(i) The solar electricity generating potential was thoroughly assessed for each country of the MENA region within the MED-CSP study [9]. Excluded were all areas that are not suitable for CSP operation or already used otherwise. According to this study, the total economic solar electricity generating potential (defined as the amount of solar electricity that can be produced by CSP at less than 0.05 €/kWh⁻¹ (year 2000 purchasing power) in 2025) of the MENA region amounts to 630 000 TWh yr⁻¹. This is three orders of magnitude higher than its present power consumption of about 800 TWh yr⁻¹. Using this huge resource, CSP has the potential to cope with the growing electricity demand and freshwater deficit in MENA, and to export additional electricity to Europe.

(ii) The resources, technologies and costs of electricity exports from MENA to Europe have been investigated in the TRANS-CSP study [25]. By 2050, high-voltage direct current (HVDC) transmission lines with a capacity of 2.5–5.0 GW each may transport about 700 TWh yr⁻¹ of solar electricity from 20 to 40 different locations in MENA to the main centres of demand in Europe (figure 14). Typical losses due to electrical resistance, voltage and AC/DC conversion are only about 3 per cent per 1000 km, which is one-third of comparable high-voltage AC lines. The motivation for this electricity link are low production costs at around 5 €/cent kWh⁻¹ (at year 2000 purchasing power, but not accounting for further cost reduction via carbon credits) and high flexibility for base-, intermediate- and peak-load operation. Transmission costs of electricity from MENA to Europe have been estimated as 1.5 €/cent kWh⁻¹ on top of the local generation costs. In
addition to providing 15 per cent of the European electricity demand, solar power plants in the MENA region will supply about 60 per cent of the local market with inexpensive and environmentally friendly electricity.

To realize the economic and environmental potential of a EU–MENA electricity link, the DESERTEC Industry Initiative (Dii) was founded on 30 October 2009 by industrial organizations ABB, Abengoa, Cevital, Deutsche Bank, E.ON, HSH Nordbank, MAN Solar Millennium, Munich Re, M+W Zander, RWE, Schott and Siemens, as well as the Club of Rome spin-off Desertec Foundation. Since then another 45 companies from Europe and the MENA region have joined Dii, making it a true EU–MENA project (Dii GmbH—Renewable energy bridging continents: http://www.dii-eumena.com).

Over the next years, the main tasks will be to establish the financial, legal and political boundary conditions for the widespread establishment and market penetration of power plants from renewable energies as well as the distribution of electricity within the MENA region and to Europe. After the preparation of a roll-out plan for the whole Mediterranean region and detailed site analyses, first reference plants in the several 100 MW scale are now in advanced planning stage, most probably starting in Morocco (which already has a suitable electricity link with Spain) followed by Tunisia and most probably Algeria. These reference plants, which will be constructed during the period 2013–2020, will still require subsidies, e.g. feed-in tariffs, carbon trading, strategic investments, governmental support, etc., as they are not yet economically competitive with conventional electricity generation. While solar thermal power plants will make the main contribution, other renewable technologies, such as wind and photovoltaics, will be included as well, depending on their local potential for secure and affordable electricity supply. From 2020 to 2035, the first commercially viable projects will be realized at particularly suitable locations in the MENA region, while transnational connections, revisions of regulatory framework and support mechanisms to full phase-out will be established. After 2035, CSP, photovoltaic and wind technologies are mature and fully competitive with all segments of the electricity market without...
subsidies. Market penetration will proceed at an advanced rate due to the rapidly growing electricity demand in the MENA region (presently about 6% per year) and the urgent replacement of existing conventional power plants which have reached the end of their technological and economical lifetime, both in Europe and in MENA. Thus, desert power will become a high priority component in the energy mix of the EU and MENA.

For the people in Europe and in the MENA region, this development presents a unique opportunity and a true win–win situation, as it provides

- sustainable and affordable power,
- new sources of income via clean electricity export to Europe,
- establishment of local industries and thus creation of new employment,
- growth and economic impulses due to substantial investments,
- further economic diversification and regional integration,
- energy feed-in via renewable energy,
- decrease in oil price dependency,
- decrease in CO₂ emissions,
- balancing power for seasonal, diurnal and fluctuating electricity from renewable energies in the EU,
- investment opportunities in North Africa and the Middle East, and
- long-term investment opportunities in renewable energies.

Thus, DESERTEC is not just an economic and environmental scheme but will contribute to increasing the quality of life as well as the social and political stability of the MENA region as a whole.

8. Conclusions and outlook

CSP technology offers a unique opportunity for competitive, secure and sustainable energy for electricity in the sun-rich countries. It is already today a proven technology, the required resources are almost unlimited and the necessary investments can be afforded. In conjunction with heat storage, CSP can provide power on demand, and thus replace expensive peak power plants which use diesel or jet fuel, as well as assist in balancing the electricity provided by fluctuating renewable sources.

In addition to large-scale deployment of new power plants, new technologies and operating concepts will drive down cost to become competitive with mid-load electricity within the next 10–15 years. Many of these new technologies are presently in the development or demonstration stage. Continuing and consistent support is required to develop their technology readiness level to commercial application.

Considering the competition for dwindling fossil fuel resources and environmental constraints, the concept of introducing CSP at a large scale into a technology mix that depends on local conditions and market development is the most promising and the most realistic solution for avoiding cost escalations in the power sector and to secure sustainable provision of the increasing power demand in the coming years.

The countries in North Africa and the Middle East can use their huge solar resources to join an energy link with Europe. Dispatchable electricity imported from the MENA countries will complement and stabilize the fluctuating local renewables in Europe. Within 15–20 years, it will thus be possible to realize an electricity supply which is both less expensive and significantly more environmentally friendly than the present technology mix [25]. The MENA countries will benefit from this concept in terms of sustainable electricity for their own demands, increased employment, electricity exports and fresh water from desalination [26]. Increasing the number of energy sources and the use of local renewables reduces the potential for power shortage and political conflicts, for both the EU and MENA. From a technical point of view, this so-called DESERTEC concept can already be realized today. However, an economic and political
A paradigm shift will be required to make it happen. This will require changes to current legislation to facilitate CO₂ mitigation mechanisms across national and continental boundaries as well as financial incentives. Considering present subsidies for agriculture, coal and nuclear power, as well as costs for security and military conflicts related to the supply of energy, the investment required to establish a commercially viable EU–MENA electricity link based on renewable energies is indeed moderate.

Most of the results presented in this paper originated during the time when the author was a director in the German Aerospace Centre (DLR) and are hence attributed to the work of many colleagues. The author is indebted to the German Government, the European Commission and to many industrial research partners for supporting the DLR R&D activities on solar thermal power plants during the past 30 years.

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