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Concentrating solar power: its potential contribution to a sustainable energy future

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building science into EU policy

EASAC

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Cover image: concentrating solar power test plant at Plataforma Solar de Almeria, Spain. (Photo: DLR, Markus Steur.)

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Foreword

This report has been prepared by EASAC to place before the European institutions in Brussels and Strasbourg a major challenge that could help to improve energy security in Europe over the next 50 years. It is a grand challenge aimed at combining the best European innovation in science, technology and engineering with the skills of visionary politicians and policy-makers.

The European Union (EU) has established challenging targets for making a transition to a sustainable energy system in Europe, including that the EU's electricity supply should achieve essentially zero emissions of greenhouse gases by 2050. Similarly, countries in the Middle East and North Africa (the MENA region) are aiming to sustainably develop their economies, pointing to the need for the associated development of energy infrastructures which are sustainable, particularly in the context of international initiatives to tackle climate change.

Major developments will be needed in renewable energy technologies to enable these aims to be achieved. One such technology is concentrating solar power (CSP) in which a high-temperature heat source is created by concentrating the sun's rays to produce electricity in a thermodynamic cycle. This report presents the results of a study undertaken by the European science academies to examine the potential of CSP to contribute to meeting the desired energy system transitions in Europe and the MENA region, and to consider the scientific, technical and economic developments that will be required to enable that potential to be realised.

The study has confirmed that the solar resource and technological potential are such that CSP based in Southern Europe and the MENA region could make a substantial contribution to future energy needs. Technological developments that are in train, or may reasonably be anticipated, should enable CSP to be cost-competitive with fossil-fired electricity generation at some point between 2020 and 2030 (and potentially earlier in particular circumstances) provided that CSP capacity continues to be deployed at a sufficient rate. Incorporating thermal energy storage in CSP plants enables them to provide dispatchable electricity, and to help achieve reliable operation of an electricity system as the proportion of electricity provided by variable renewable sources, such as wind and photovoltaics, increases.

The challenge for policy-makers is to provide the market-based incentive schemes required to enable this point of cost-competitiveness to be achieved, and to ensure that the electricity markets and grid infrastructures are in place to enable the effective connection of CSP supplies with customers across Europe and the MENA region.

The study has been undertaken against a backdrop of political unrest and democratic reform in several key countries in the MENA region. The solar resource and CSP potential in these countries is particularly favourable, and the technology lends itself to the development of indigenous manufacturing and deployment capacity. Increased EU support for the development of CSP in the MENA region is therefore appropriately being considered as an important component of initiatives to support democratic reforms and to develop a mutually beneficial partnership between Europe and Southern Mediterranean countries. We hope that this report will make a useful contribution to the current debate, and will prove to be a timely input to policy development in Europe and the MENA region.

On behalf of EASAC I would like to express sincere thanks to the working group members for their expertise, time and contributions, and to the working group chair, Professor Robert Pitz-Paal of the Deutsches Zentrum für Luft- und Raumfahrt (DLR), for his leadership of the study. I would make particular mention of our appreciation of the involvement of the working group members nominated by the Egyptian and Israeli Academies who gave us valuable insights into CSP developments in the MENA region. Also, we are very grateful for the inputs of other experts who made presentations to the working group, to the organisations and individuals who provided information to inform the study, and to the organisations – ENEA (the Italian National Agency for New Technologies, Energy and Sustainable Economic Development), in Italy, the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) in Spain, and DLR in Germany and Spain – who hosted working group meetings. Finally I am pleased to acknowledge, and express our thanks for, the financial support provided to the undertaking of the study by the InterAcademy Panel, the global network of science academies.

Professor Sir Brian Heap
EASAC President

Summary

Concentrating solar power (CSP) sits alongside photovoltaic electricity generation as a commercially available renewable energy technology capable of harnessing the immense solar resource in Southern Europe, the Middle East and North Africa (the MENA region), and elsewhere. In CSP a high-temperature heat source is created by concentrating the sun's rays to produce electricity in a thermodynamic cycle. This study by the European Academies Science Advisory Council has examined the current status and development challenges of CSP, and consequently has evaluated the potential contribution of CSP in Europe and the MENA region to 2050, and identified actions that will be required to enable that contribution to be realised.

This report summarises the findings of the study and is intended to inform policy-makers in the European institutions – in particular the European Commission and Parliament – and policy-makers at a national level in Europe and the MENA region.

There are various CSP technologies with different advantages and disadvantages, and CSP plants need to be designed to optimally meet local and regional conditions. Worldwide in 2011, 1.3 GW of CSP were operating and a further 2.3 GW were under construction. Currently, base-load electricity generated by CSP plants located where there are good solar resources costs two to three times that from existing fossil-based technologies without carbon capture and storage. CSP generation costs are on a par with photovoltaics and offshore wind, but are significantly more expensive than onshore wind.

Provided that commercial deployments of CSP plants continue to grow, and that these deployments are associated with sustained research, development and demonstration programmes, CSP generating cost reductions of 50–60% may reasonably be expected over the next 10–15 years. Allowing for some escalation in fossil fuel prices and incorporation of the costs of CO_2 emissions in fossil generation costs (through carbon pricing mechanisms and/or requirements to install carbon capture and storage), it is anticipated that CSP should become cost competitive with base-load fossil-based generation at some point between 2020 and 2030. In specific locations with good solar resources this point may be reached earlier.

CSP plants that incorporate thermal storage and/or supplementary firing offer additional potential benefits beyond the value of the kilowatt-hours that they generate, as they can provide dispatchable power, helping the grid operator to reliably match supply and demand, and maintain grid stability. The value of this capability is context specific, but increases as the proportion of electricity generated by variable renewable sources such as wind and photovoltaics increases. CSP with storage may therefore, in future, offer a cost-effective way of enabling the incorporation of substantial contributions of variable renewable sources in electricity systems.

Environmental impacts of CSP plants are generally low, and may be expected to further improve compared to fossil-fired technologies over time given the relatively early stage of development of CSP. While the construction of CSP plants is more material intensive than fossil-fired plants, the required materials are mainly commonly available, and readily recyclable, materials such as steel, concrete and glass. Given the likely positioning of CSP plants in arid areas, their use of water, particularly for cooling, is an issue pointing to the need to improve the performance of air cooling systems.

The solar resource in Southern Europe is such that CSP could provide a useful contribution to achieving Europe's aim of a zero-carbon electricity system by 2050. Solar resources in the MENA region are even better, and far larger. Once CSP achieves cost parity with fossil-fired generation, these resources have the potential to transform the system of electricity generation in Europe and the MENA region.

Around half of the anticipated reductions in CSP generating costs are expected to come from technology developments, and the other half from economies of scale and volume production. Well-designed incentive schemes will be needed, which reflect the real, time-varying value of generation so that CSP plants are appropriately designed, and which effectively drive research and development activities. The total amount of incentive payments that will be needed to achieve cost parity will depend crucially on how quickly costs reduce as installed capacity increases. Incentive schemes need to ensure that cost data are made available so that the learning rate, and its underlying drivers, can be established and monitored, and consequently energy strategies and incentive schemes can be adjusted as appropriate. Substantial investments will also be needed in transmission infrastructure, including high voltage direct current links between the MENA region and Europe, if substantial quantities of CSP electricity are to be exported from MENA countries to Europe.

The development of CSP in the MENA region is a potentially significant component of initiatives to support low-carbon economic development and political progress in the region as reflected in the Barcelona Process, the Deauville Partnership, etc. CSP technologies (unlike some other renewable energy technologies) lend themselves to high levels of local-deliverables, well-matched to the capabilities of the workforce and industries in the region.

Given the rapidly increasing demand for electricity in MENA countries, much of the electricity generated by CSP plants in the MENA region over the short to medium timescale may, and should, be expected to be used locally rather than exported to Europe, thus avoiding the construction of fossil-fired capacity in the MENA region. Financing schemes, and associated political agreements between the EU and MENA countries, will be needed to enable these short to medium timescale developments. Without financial commitment in the order of billions of euros from Europe, renewable energy technologies including CSP are unlikely to develop quickly in the MENA region.

The challenge is to take a co-ordinated approach, simultaneously addressing the different bottlenecks (investment protection, energy policy incentives, research and development (R&D), etc.), and to identify options which lower the barriers to entry for other actors (manufacturers, finance companies, etc.). For this purpose, a transformation process should be defined that addresses the technical, political and socio-economic factors necessary to achieve integration of EU and MENA energy systems and to strengthen the implementation of renewable options in the MENA region. Co-funding and co-financing options for CSP in the MENA region should be developed by the EU at a substantial scale as part of its neighbourhood policy.

Incentive schemes in Europe and MENA countries should reflect the true value of electricity to the grid, effectively drive R&D, and ensure transparency of cost data. R&D should be funded at EU and national levels to complement commercially funded research. Funding schemes should ensure that market realities are strong drivers of R&D, and that new technologies can progress rapidly from the laboratory, through pilot and demonstration scales, to commercial application.

Further system-simulation studies should be undertaken to look at interaction effects for different shares of renewable energy sources at EU, MENA and EU–MENA levels of power system integration. Understanding from these studies, together with data on the learning rates of CSP and photovoltaics technologies, should be used to guide the development of the optimal mix to harness solar resources.

Capacity-building initiatives should be put in place to support sustainable growth of the necessary technological skills in the relevant countries and regions. Such initiatives may include developing international networks of universities and industrial companies, and programmes for technology transfer from research to industry.

1 Introduction

This report summarises the findings and recommendations of a study of concentrating solar power (CSP) by the European Academies Science Advisory Council (EASAC). In concentrating solar power (also called 'solar thermal electricity') a high-temperature heat source is created by concentrating the sun's rays to produce electricity in a thermodynamic cycle. The study has examined the potential contribution of CSP in Europe, the Middle East and North Africa (the MENA region) over the period to 2050, and the scientific and technical developments that will be required to realise that potential.

Given the energy in the sun's rays falling on Southern Europe and the MENA region, and current technology, CSP could generate more than 100 times the present electricity consumption of Europe and the MENA region. Yet, although some 350 MW of CSP plants were installed in California in the US in the mid-1980s, there has been virtually no commercial development of CSP in Europe and the MENA region until recent years when 'feed-in' tariffs to incentivise CSP in countries such as Spain have sparked a rapid growth in the deployment of commercial CSP plants. Around 1300 MW of CSP plant are now in operation and 2300 MW under construction in more than a dozen countries worldwide. Research and experimental facilities for CSP have been operating in Europe for over 20 years.

Several studies on, and roadmaps for, CSP are available today. In most cases they picture a strong role and contribution of CSP to Europe's and the MENA region's electricity markets in the future, in particular after 2030. This study critically reviews existing work and describes the scientific consensus on the status and prospects of this technology. It also identifies key outstanding issues and where knowledge gaps need to be filled for CSP to fulfil its potential contribution in Europe and the MENA region. Based on these findings, the study makes recommendations on how to improve national and European support programmes for CSP development and deployment.

Specific aims of the study have been the following:

(1) to review the current status of CSP technologies and identify the technological developments and research and development (R&D) needed to achieve reliable operation and cost competitiveness with fossil fuelled electricity generation;

(2) to consider how issues associated with the intermittent nature of CSP for electricity generation due to the daily pattern of insolation and the potential for cloudy days can best be addressed;

(3) to identify the environmental impacts and infrastructure requirements of CSP, and comment on the significance of these in relation to other options for electricity supply; and, consequently,

(4) to develop a view of the potential contribution that CSP located in Europe, the Middle East and North Africa could make to the energy mix in those regions by 2020 and 2050.

This report focuses primarily on the generation of electricity from CSP, but it is recognised that there are other potentially significant 'products' from CSP such as process steam for industry, water desalination, alternative energy carriers such as hydrogen and syngas, and decontamination of water supplies. Although not discussed in detail, much of what is presented in this report on the development of CSP technologies and economics will also be relevant to these alternative applications of CSP.

The study follows on from a previous EASAC study of the European electricity grid, 'Transforming Europe's Electricity Supply – An Infrastructure Strategy for a Reliable, Renewable and Secure Power System' (http://www.easac.eu/fileadmin/PDF_s/reports_statements/Transforming.pdf) which examined the required developments in grid planning, operation and infrastructure in order to enable the integration of substantial contributions of renewable energy sources including CSP.

The study was conducted from June 2010 to September 2011 by a working group (whose membership is listed in Annex 1) comprising experts nominated by EASAC member academies and by the academies of Egypt and Israel, and chaired by Professor Robert Pitz-Paal of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Germany. The working group membership was designed to reflect an appropriately broad spread of expertise, some members working actively on CSP developments, others having a more general overview of the science, engineering and economics of energy technologies. It was considered important to have representatives of countries in the MENA region, so the involvement of nominees of the Egyptian and Israeli Academies has been very welcome.

The working group met four times, in Spain, Italy and Germany, taking evidence from invited experts, visiting R&D and commercial CSP facilities (details are given in Annex 1) and discussing and refining findings and recommendations and the subsequent text of the report. An open call for inputs and evidence was also made. The working group's final draft report was subjected to EASAC's rigorous peer-review process before finalisation and publication in November 2011.

Following a chapter summarising the policy context, the current status of CSP and associated thermal energy storage technologies are described in Chapters 3 and 4. Chapter 5 then discusses the economics of CSP, considering cost reduction potential and consequent time-frames for cost competitiveness, and the value of CSP with storage and/or auxiliary firing in electricity markets. The environmental impacts of CSP are evaluated in Chapter 6 before a review of the potential future contribution of CSP in Europe and the MENA region presented in Chapter 7. Conclusions and recommendations follow, with a bibliography of the references informing this report and annexes providing supporting detail, and a glossary of terms at Annex 2.

2 The policy context

The aims of the study were formulated in the context of current energy related policies, and to address outstanding issues in respect of realising policy aims and developing future energy policies and strategies in Europe and the MENA region.

The EU has established ambitious energy and climate change objectives. EU targets for 2020 include a 20% reduction in greenhouse gas emissions (rising to 30% if international conditions are right) and to increase the share of renewable energy to 20% (European Commission, 2007, 2009, 2010). In the longer term, a commitment has been made to substantially decarbonise energy supply, with a target to reduce EU greenhouse gas emissions by 80–95% compared with 1990 levels by 2050. Re-affirmed by the European Council in February 2011, this objective requires the EU's electricity system to achieve essentially zero emissions of greenhouse gases by 2050 (European Commission, 2011). The central goals of EU energy policy – security of supply, competitiveness and sustainability – have been laid down in the Lisbon treaty (European Union, 2007).

Renewable energy sources are anticipated to play a major role in achieving these longer-term targets, although as yet the relative contributions from individual technologies such as CSP have not been established. An 'energy roadmap 2050' is being prepared by the European Commission which will explore various scenarios of energy mix to meet the 2050 targets and changes in demand patterns, for example due to a potential substantial increase in electricity demand from electric cars (European Commission, 2011b).

However, taking stock of progress, a recent communication from the Commission (European Commission, 2010) concluded, 'the existing [energy] strategy is currently unlikely to achieve all the 2020 targets, and it is wholly inadequate to the longer-term challenges'. It pointed to serious gaps in delivery, and to delays in investments and technological progress.

A European 'Strategic Energy Technology Plan (SET-Plan)' was developed in 2007 to accelerate the development of low carbon technologies (European Commission, 2007b), and subsequently endorsed by the EU in light of the conclusion by the Second Strategic European Energy Review (European Commission, 2008) that, '... the EU will continue to rely on conventional energy technologies unless there is a radical change in our attitude and investment priorities for the energy system.' It describes, '… a vision of a Europe with world leadership in a diverse portfolio of clean, efficient and low-carbon energy technologies as a motor for prosperity and a key contributor to growth and jobs.' It is noted that, 'Extending Europe's leadership in energy technology and innovation' is also one of five key priorities in the EU's more recently formulated energy strategy (European Commission, 2010).

Seven 'roadmaps' have consequently been developed by the European Commission setting out plans for research, development and demonstration activities for the period to 2020. One of these concerns solar power (CSP and photovoltaic) which states an ambition to generate 3% of the EU's electricity from CSP by 2020, and at least 10% by 2030 if collaborative initiatives with the MENA region enable substantial investment in CSP. European Industrial Initiatives, including one on CSP (ESTELA, 2010) have been established to co-ordinate activities across Europe and to propose concrete actions for the period 2010-2020 to implement the roadmaps. At a global level, the International Energy Agency has prepared a technology roadmap for CSP (IEA, 2010b) which projects that CSP could supply over 10% of the world's electricity by 2050, and which identifies key actions needed by governments if this contribution is to be realised.

This study has critically examined these roadmaps and plans for CSP, and looked beyond 2020 to the longer-term opportunities and R&D needs to 2050.

Europe's energy strategy also identifies the development of strong international partnerships, particularly with neighbouring countries, as a key priority (European Commission, 2010). It includes actions to integrate energy markets and regulatory frameworks with neighbouring countries, and the launching of a major co-operation with Africa on energy initiatives. In parallel, the 'Union for the Mediterranean' was established in 2008 (a development of the Barcelona process initiated in 1995) which has launched the 'Mediterranean Solar Plan' as a key initiative. The main objective of the Mediterranean Solar Plan is the development of 20 GW of renewable electricity capacity by 2020 on the south and east shores of the Mediterranean, as well as the necessary infrastructures for the electricity interconnection with Europe (Resources and Logistics, 2010).

Energy demand is increasing rapidly in these Mediterranean countries, having increased by a factor of three between 1980 and 2005, and a further doubling is anticipated by 2020 (Resources and Logistics, 2010). Rising energy demand is being driven by rapid demographic growth, urbanisation and increasing per capita energy consumption. However, incomes remain low compared with Europe. Renewable energy sources have to date made a rather limited contribution to electricity supplies in the region, and with some exceptions (for example, Algeria, Morocco and Tunisia) there are only weak electricity grid interconnections across the region and with Europe. Three integrated solar combined cycle plants, partly based on CSP technology, are operating in Morocco, Algeria and Egypt, and around 15 CSP plants are planned (CSP Today, 2010).

In May 2011, responding to political unrest in the MENA region, the G8 launched the 'Deauville Partnership' aimed at supporting democratic reforms, and developing an economic framework for sustainable and inclusive growth in the region (G8, 2011). The development of solar power is specifically identified in the G8 declaration as an initiative to be supported. The European Commission has identified an 'EU–Southern Mediterranean Energy Partnership', focusing on the development of renewable energy, as a component of its partnership strategy to support democratic reforms and increasing prosperity in the MENA region (European Commission, 2011c, 2011d).

3 CSP technologies and their development

3.1 The basic concept

Solar radiation arriving at the Earth's surface is a fairly dispersed energy source. The photons comprising the solar radiation can be converted directly to electricity in photovoltaic devices, or, in CSP, the solar radiation heats up a fluid that is used to drive a thermodynamic cycle. In the latter case, concentration of sunlight using mirrors or optical lenses is necessary to create a sufficiently high energy density and temperature level. Various strategies have been adopted for concentrating and capturing the solar energy in CSP technologies, giving concentrations of 25–3000 times the intensity of sunlight.

Concentrating systems (which are sometimes also used in photovoltaic devices) can only make use of direct radiation, and are therefore applicable in areas where there are few clouds. In cloudy or dusty areas, photovoltaic technologies (without concentration) are likely to be preferred.

A CSP plant comprises four main sub-systems as shown schematically in Figure 3.1: concentrating system, solar receiver, storage and/or supplementary firing (labelled 'back-up system' in the figure) and power block. They are linked together by radiation transfer or fluid transport. The solar receiver absorbs the concentrated solar energy and transfers it to the heat transfer fluid. Then the heat transfer fluid is used to deliver high-temperature heat to the power block and/or to store solar heat in a hot storage tank. The heat transfer fluid in the solar field and the power block working fluid may be the same, as in a CSP plant using direct steam generation.

3.2 The four CSP technology families

As illustrated in Figure 3.2, there are four main CSP technology families that can be classified according to the way they focus the sun's rays and the receiver technology. In systems with a line focus (Parabolic Trough and Linear Fresnel) the mirrors track the sun along one axis. In those with a point focus (Tower and Parabolic Dish), the mirrors track the sun along two axes. The receiver may be fixed, as in Linear Fresnel and Tower systems, or mobile as in Parabolic Trough and Dish Stirling systems. Figures 3.3–3.6 provide pictures of the solar receivers for each of the technologies.

The CSP technology families differ in how they concentrate the solar radiation, which strongly affects their overall efficiency. The best annual optical efficiency (about 90%) is obtained for the parabolic dish because the concentrator axis is always parallel to the sun's rays. The worst (about 50%) is observed for linear Fresnel systems because of poor performance ('cosine effect') in the morning and in the evening. Intermediate values (65–75%) are obtained for parabolic trough and tower systems. For each family the actual efficiency varies with the location, the time of day and the season of the year.

In each family, various options exist for the heat transfer fluid, the storage technology, and the thermodynamic cycle. Synthetic oil and saturated steam are currently used as heat transfer fluids in commercial plants, while molten salt and superheated steam are coming to the market. Use of air (at ambient pressure or pressurised) and other pressurised gases (for example, CO_2 and N_2) are under development, while helium or hydrogen is used in the Stirling engines used in parabolic dish systems. Liquid molten salt is the only commercial option today for storage for long (some hours) periods of time, allowing electricity production to better match demand. Steam is also used for short time (less than 1 hour) storage. Thermodynamic cycles

Figure 3.1 Main components and sub-systems of a CSP plant including storage.

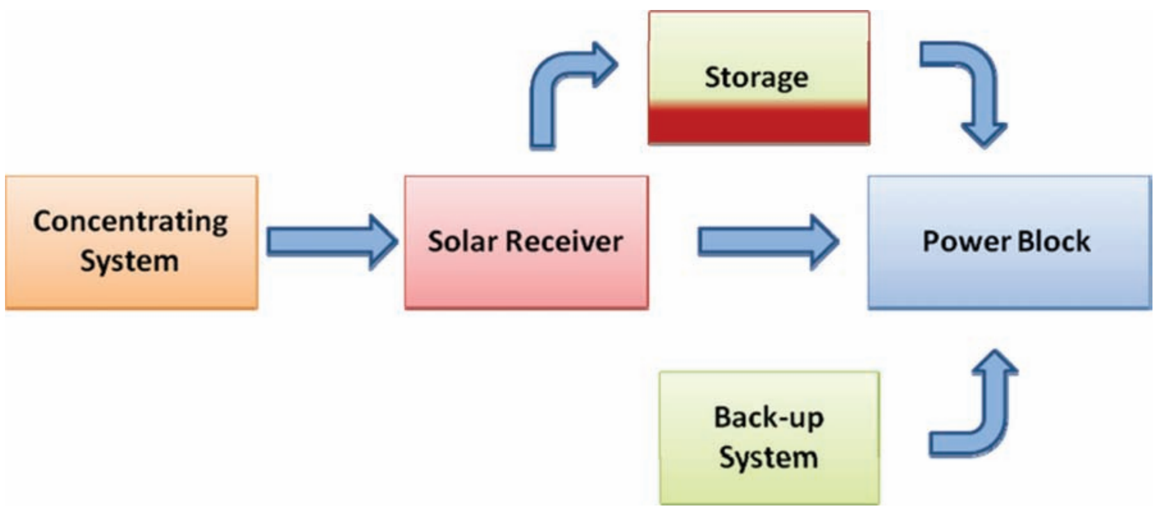
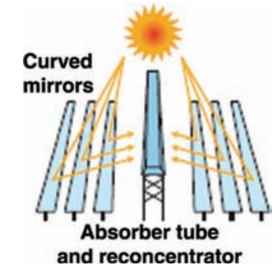
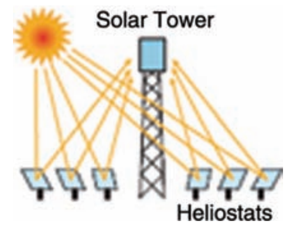


Figure 3.2 The four CSP technology families (after IEA, 2010b).

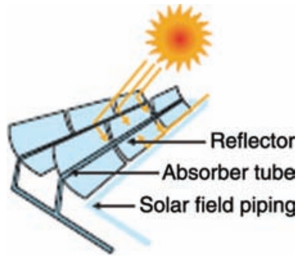
<table>
<tr><th>Focus type
Receiver</th><th>Line focus</th><th>Point focus</th></tr>
<tr><td>Fixed
Stationary receiver that remains mechanically independent of the concentrating system. The attainable working temperature depends of the concentration ratio.</td><td>Linear Fresnel



</td><td>Tower
(central receiver systems)



</td></tr>
<tr><td>Tracking/aligned
The receiver moves together with the concentrating system. Mobile receivers collect more radiation energy than corresponding fixed receivers.</td><td>Parabolic Trough



</td><td>Parabolic Dish

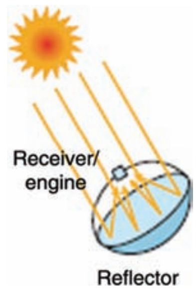


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Figure 3.3 Solar receiver for Linear Fresnel technology (DLR, Markus Steur).

Figure 3.4 Gemasolar plant of Torresol Energy in Andalucia, Spain (Torresol Energy).

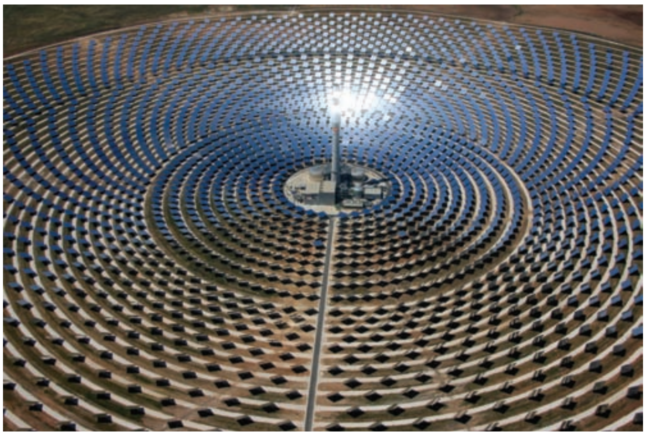


Figure 3.5 Solar receiver for trough technology (DLR, Markus Steur).

are currently steam Rankine cycles, and Stirling cycles for parabolic dish concentrators. Brayton cycles are under development in which a gas turbine is driven by pressurised gas heated by the solar collector. The combination of Brayton cycle that supplies its waste heat to a bottoming Rankine cycle (often referred to as combined cycle) promises the best efficiency and thus the highest electrical output per square meter of collector field.

Figure 3.6 Parabolic dish (DLR, Markus Steur).

3.3 Current performance and development status

The current performance of the four CSP technology families is summarised in Table 3.1. Whereas trough plants are in routine commercial application, tower plants are currently making the transition to commercial application, and linear Fresnel and parabolic dishes are at the demonstration stage, and have not yet reached large-scale commercial application. In all cases, new technological options are at varying stages of development as discussed below.

Water consumption for cooling has the potential to be somewhat lower (around 2 m^3/MWh) for tower technologies owing to their greater potential for efficiency increases than parabolic troughs and linear Fresnel systems. Conversely, the lower efficiencies of linear Fresnel systems tend to result in water consumption at the higher end of the range given in the table.

Dry cooling substantially reduces water consumption with a limited impact on plant efficiency and generating costs. For a 100 MW trough plant, adoption of dry cooling instead of wet cooling reduces water

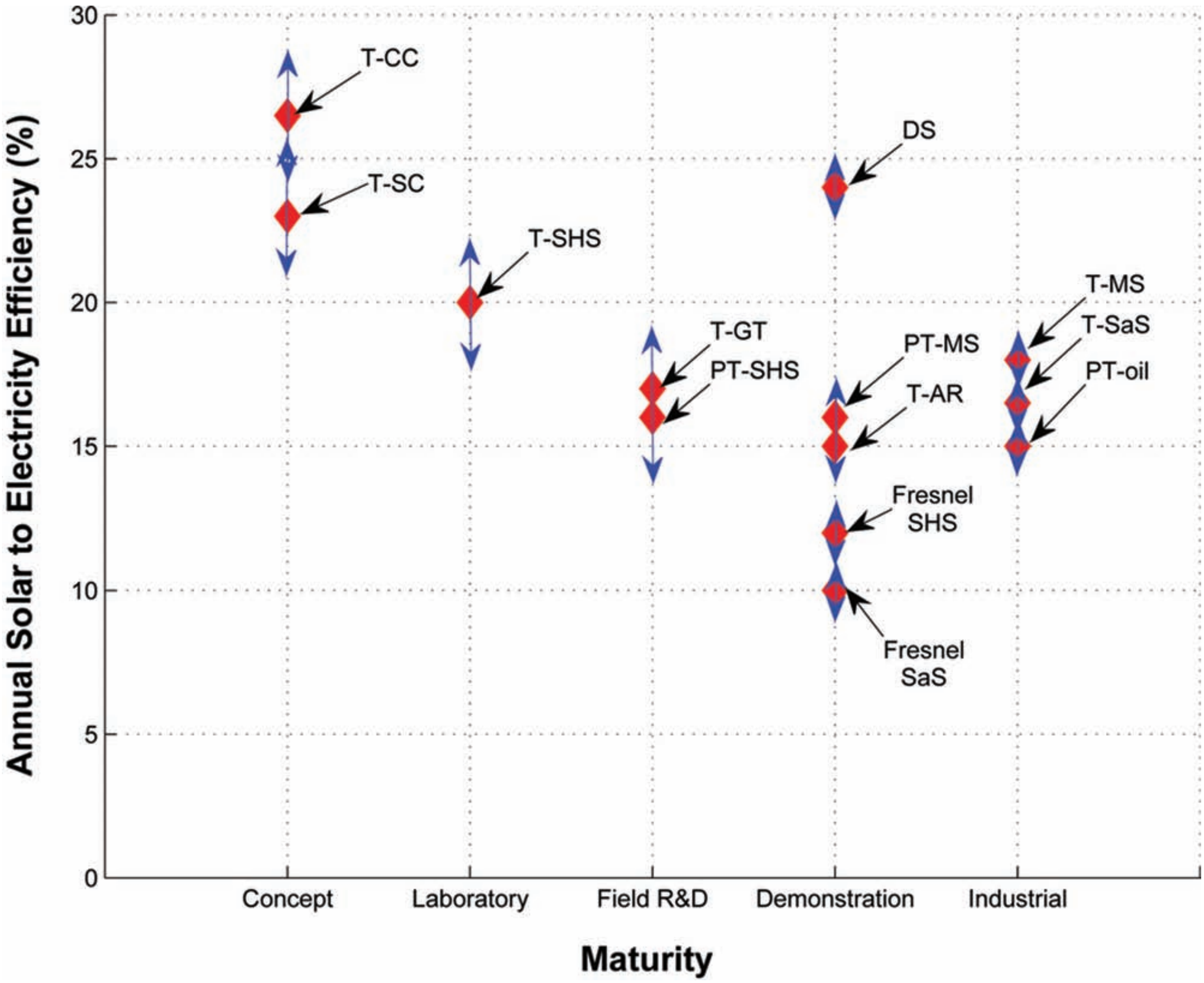
Table 3.1 Current performance of CSP technology families (adapted from IEA, 2010b)
Data for parabolic troughs, linear Fresnel and tower are for commercial plants based on a Rankine cycle and using synthetic oil or steam as heat transfer fluids. Data for parabolic dishes are for dish-Stirling systems.

CSP technology	Peak solar to electricity conversion efficiency (%)	Annual solar-to-electricity efficiency (%)	Water consumption, for wet/dry cooling (m^3/MWh)
Parabolic troughs	23–27	15–16	3–4/0.2
Linear Fresnel systems	18–22	8–10	3–4/0.2
Towers (central receiver systems)	20–27	15–17	3–4/0.2
Parabolic dishes	20–30	20–25	<0.1

Table 3.2 Technical options for each CSP technology family

CSP technology	Technical options
Parabolic troughs (PT)	PT-oil: oil as HTF and molten salt storage PT-SHS: superheated steam as HTF PT-MS: molten salt as HTF and storage
Linear Fresnel systems (F)	Fresnel SaS: saturated steam as HTF Fresnel SHS: superheated steam as HTF
Towers (T)	T-SaS: saturated steam as HTF T-SHS: superheated steam as HTF T-MS: molten salt as HTF and storage T-AR: ambient pressure air as HTF and Rankine cycle T-GT: pressurised air as HTF and Brayton cycle T-SC: supercritical cycle T-CC: pressurised air as HTF and combined cycle
Parabolic dishes (DS)	DS: helium Stirling cycle

Figure 3.7 Annual solar-to-electricity efficiency as a function of development level.



consumption by about 93%. The generating efficiency penalty is 1–3% (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 (the ranges are due to differences in site characteristics). As a result, generating costs increase by 3–7.5% compared with water cooling (after Turchi, 2010).

The technical options for each CSP technology family are not currently at the same level of development. Five development levels can be considered:

- concept;
- laboratory;
- field R&D;
- demonstration;
- industrial/commercial application.

For the four CSP technology families the technical options (mainly differing according to the heat transfer fluid (HTF) used) are listed in Table 3.2. For parabolic troughs, an emergent additional option is the use of compressed gas as the heat transfer fluid and molten salt for storage. However, this option is at a very early stage of development and efficiency data are not yet available.

An annual solar-to-electricity efficiency as a function of development level is plotted in Figure 3.7. The potential improvement in efficiency for tower systems (by around 65%) is clearly shown in this figure. It is noted that, although efficiency improvement is generally a strong driver of generating cost reduction for CSP, alternative strategies may be used to reduce costs, for example by reducing the cost of components of the concentrating system and solar receiver as in linear Fresnel systems.

4 Thermal energy storage technologies

4.1 The basic concept

A distinctive characteristic of concentrating solar power is the inherent option to incorporate thermal energy storage. The main value of adding thermal energy storage is that it enables a CSP plant to provide 'dispatchable power', helping the grid operator to reliably match supply and demand.

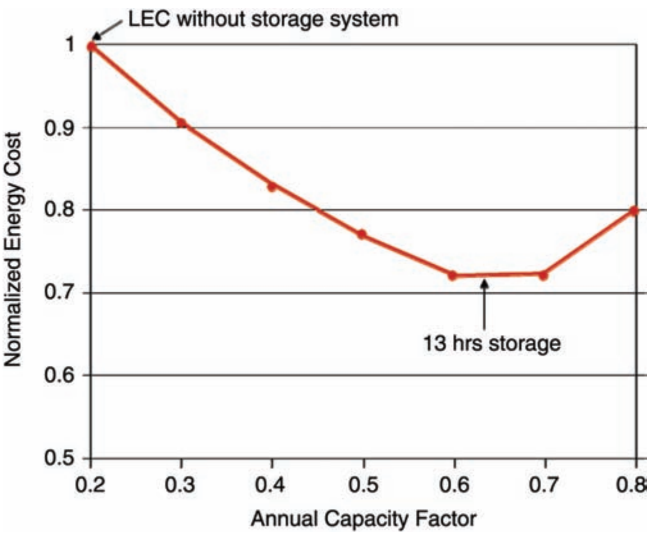
Up to an optimum storage capacity, dependent on the technology and the site characteristics, installing thermal energy storage can provide modest reductions in the cost per kilowatt-hour of electricity produced if it is used to extend the hours in each day when the plant is generating electricity. This is because the investment in a larger solar collector field and the thermal energy storage system itself can, in many cases, be offset by being able to run the power block for a longer period of time. Consequently, the levelised electricity cost (LEC: the average cost of generating a kilowatt-hour of electricity taking account of the capital and operating costs of the plant over its lifetime) of a CSP plant decreases as the size of its storage system increases until it reaches a minimum, beyond which LEC increases. If the storage is only used to shift generation to another time period, the cost of the electricity is increased due to the additional cost of the storage equipment.

Minimising the LEC therefore strongly depends on the boundary conditions and involves a site-specific trade-off between the sizes of the collector field, turbine and storage system. When storage is used to extend the operating hours of the plant, as for example in the Spanish market, this minimum is typically reached for a parabolic trough plant at around 7 hours storage capacity, and for a solar tower plant at around 13 hours (as illustrated in Figure 4.1 for tower technology). The minimum depends on the cost of the storage compared with the power block. For example, thermal energy storage will be more favourable in the tower plant depicted in Figure 4.1 owing to the relatively low specific storage cost achieved through using molten salts both as the storage medium and heat transfer fluid. The minimum may change in future due to technological developments and differences in the relative costs of components. The **optimum** storage capacity will depend also on the time-varying value of electricity and any regulatory constraints, as discussed in Chapter 5.

The value of incorporating thermal energy storage depends on the electricity system into which the CSP plant feeds, including the system's size, the daily and seasonal patterns of demand, and the characteristics of the other generators on the system. Potentially, thermal energy storage, together with the additional option of supplementary firing, has value in the following:

- meeting operational needs such as smoothing output on partly cloudy days and responding to short-term changes in demand;
- preventing heat transfer fluids (in particular, molten salts) from solidifying overnight;
- enabling generation over longer periods of time, or shifting the time of generation, to meet demand, for example in the evening, after sunset; and
- helping the electricity system to accommodate more renewable sources such as wind and wave power which are less controllable.

Figure 4.1 Levelised electricity cost for a solar tower plant with two-tank molten salt storage in California (USA) (Libby et al., 2009).



4.2 Storage technologies

The basic concept of using thermal energy storage to extend the hours of generation of a CSP plant is illustrated in Figure 4.2. The CSP plant includes a solar field which is larger than would otherwise be needed to drive the steam turbine at full capacity. The excess heat generated during the sunnier part of the day is sent to storage, which can then be drawn on later in the day to meet demand for electricity when the sun is no longer shining.

Depending on the extent to which the solar field is over-sized in relation to the turbine capacity, incorporating thermal storage capacity can extend the operating period of the CSP plant by a few hours after sunset up to 24 hour, base-load operation. This over-sizing is quantified by the 'solar multiple', which is the ratio of the actual size of a CSP plant's solar field compared with the field size needed to feed the turbine at design capacity at reference solar conditions, i.e. when direct normal solar irradiance reaches its maximum (typically about 1 kW/m^2). Plants without thermal storage, or with thermal energy storage designed to shift the timing of generation rather than to extend its duration, generally have solar multiples in the range 1.1–1.5, depending primarily on the amount of sunlight the plant receives and its variation through the day. Plants with storage designed to extend the duration of generation may have solar multiples ranging up to 3–4, corresponding to base-load operation.

Figure 4.2 Extending operating hours of a 50 MWe CSP plant with thermal storage, to follow the demand curve of a normal mid-summer day in Spain. Demand curve derived from RED Electrica de España (2011) and CSP load from computer simulation (https://demanda.ree.es/demandaEng.html)

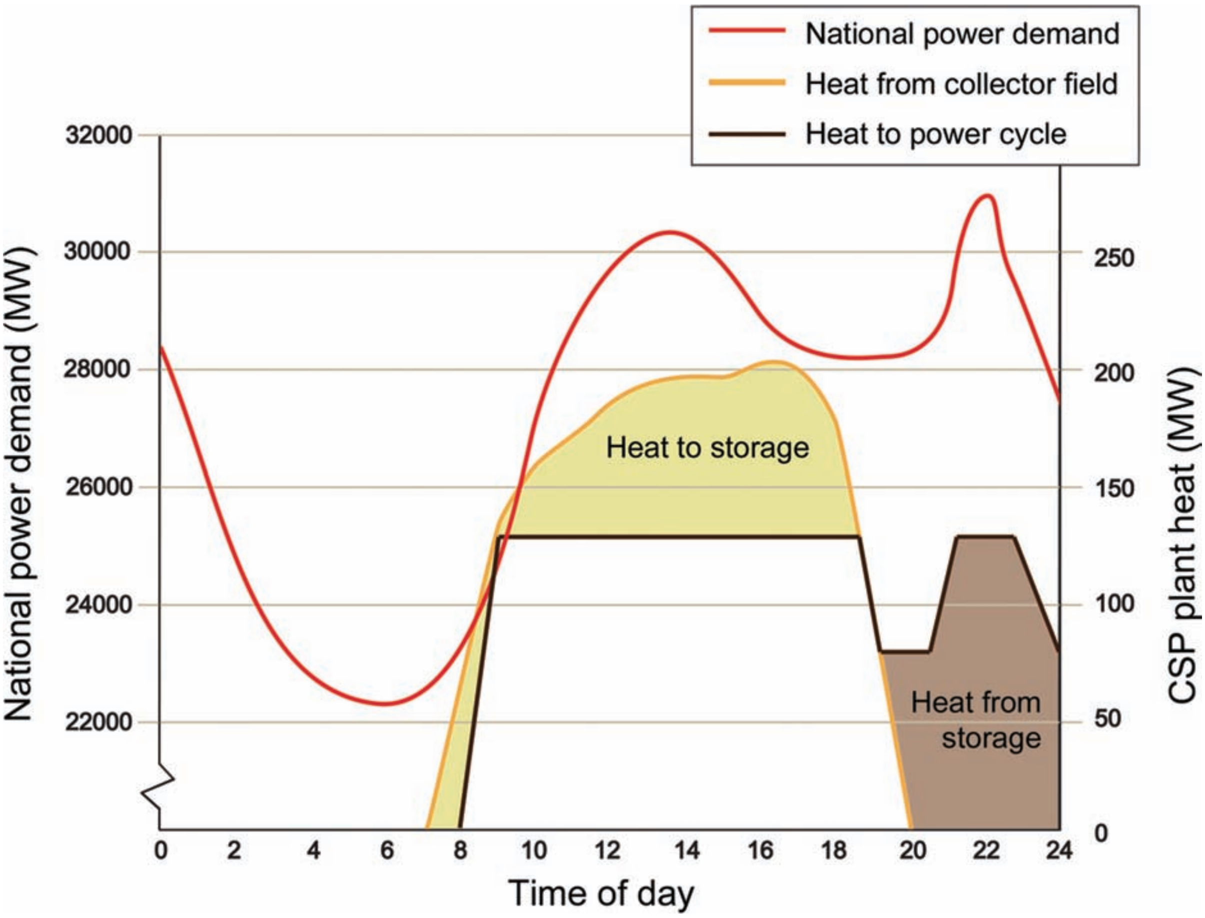


Table 4.1 Thermal energy storage options

Design concept	**Heat storage media**	**Heat transfer fluid**
	Sensible Heat Storage	
Two-tank: *i) direct, ii) indirect* Single-tank: *i) thermocline, ii) stratifying TES/integrated steam generation* Special block for solid materials	Molten salts Inert filler solids Concrete Solids/particles	Mineral oil Molten salts Steam Gas (CO_2, air, helium, etc.)
	Latent Heat Storage	
Special equipment for PCMs	Phase-change materials (PCMs)	Steam
	Chemical Storage	
Special equipment for thermo- chemical products	Thermo-chemical products or solutions	Various

There is a range of technologies and configurations that can be used for thermal energy storage as illustrated in Table 4.1 (see for example, Libby et al., 2009). The options summarised in Table 4.1 are at various levels of development, and the appropriate combination will depend on the required thermal storage capacity and the CSP technology (parabolic trough, tower, etc.). It is noted that thermal energy storage systems have not yet been demonstrated for parabolic dishes, which may limit their ability to compete with photovoltaic systems.

The storage system most commonly used in commercial, parabolic trough plants uses a two-tank, indirect storage approach (Figure 4.3a) in which the thermal oil emerging from the solar collector may be diverted to a heat exchanger where its heat is transferred to the heat storage medium – molten salt (generally, sodium and potassium nitrates). The hot salt can subsequently be used to heat the thermal oil instead of the solar field.

An alternative two-tank system uses direct storage in which the solar field working fluid also acts as the storage medium (Figure 4.3b), removing the need for a heat exchanger, and hence reducing cost and increasing overall efficiency. The technical feasibility of this option has been demonstrated for thermal oil in a parabolic trough plant (the SEGS-1 plant in California), and for molten salts in a parabolic trough demonstration plant (the ARCHIMEDE plant in Sicily, Italy) and in central receiver plants (the SolarTwo plant in California and the Gemasolar plant in Spain). In practice, direct storage using thermal oil is limited to operating temperatures below 400 °C by the thermal stability of the oil, and to low capacity systems due to the fire hazard associated

Figure 4.3a Two-tank indirect thermal energy storage system, where the heat transfer fluid operating in the solar field is coupled by means of an intermediate heat exchanger to a different heat storage medium.

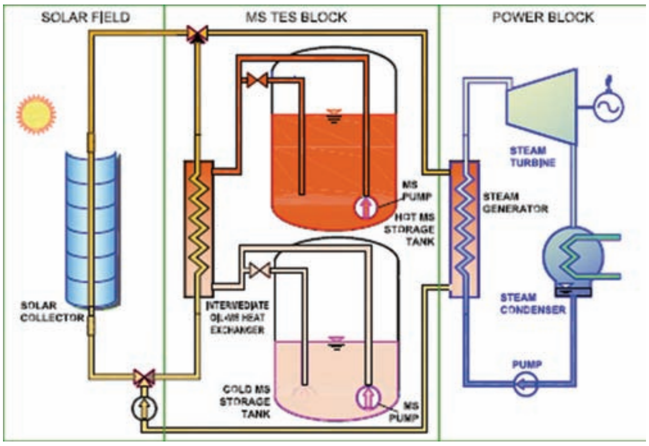


Figure 4.3b Two-tank direct storage system, where the same fluid operates as heat transfer fluid and heat storage medium

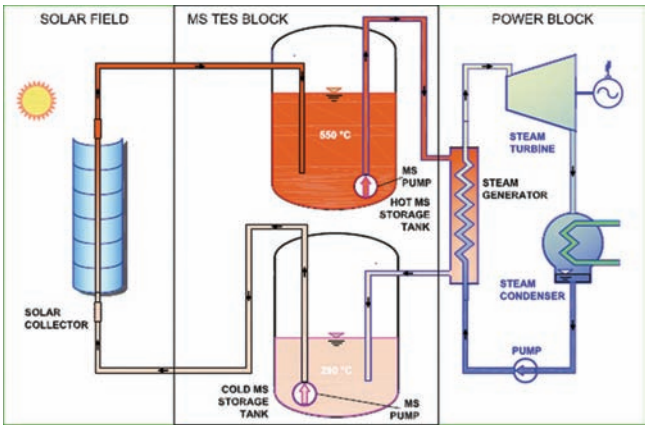


Figure 4.3c Single-tank system with stratification induced by an insulating separation wall consisting of special material of intermediate weight (density) between the hot molten salt zone at 530 °C and cold molten salt zone at 290 °C.

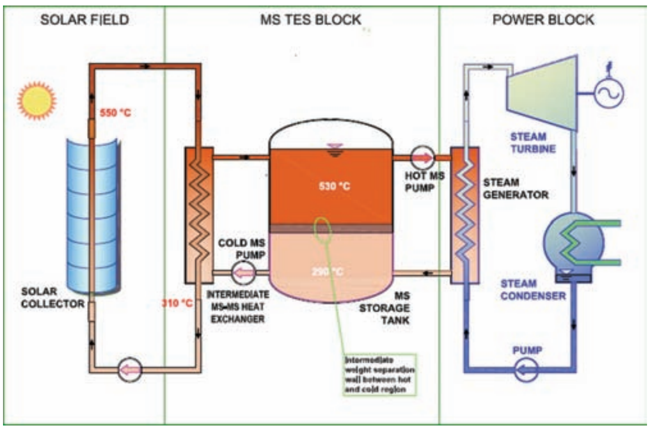
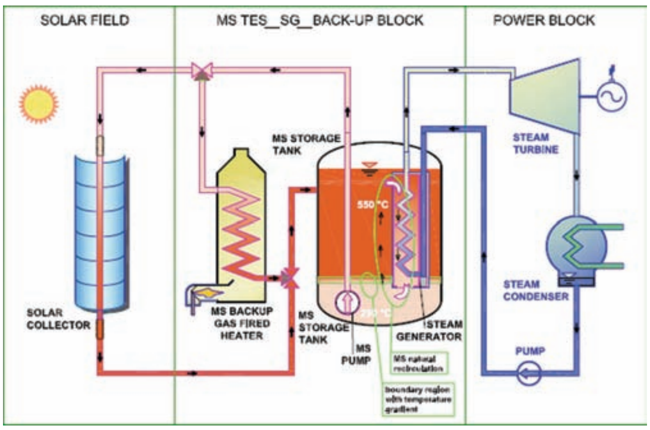


Figure 4.3d Single-tank system with stratification induced by natural recirculation of molten salts (MS) into a submerged steam generator, where a limited boundary region of temperature gradient interfaces a hot MS zone at 550 °C and cold MS zone at 290 °C. A gas fired heater for the MS backs up the solar field in the absence of solar radiation.



with storing large quantities of hot oil. Molten salts have been proven to operate at temperatures up to 570 °C, reducing the amount of salt needed, but long-term experience of the reliability of the concept is not yet available.

Single tank systems are under development using a thermocline or stratification (Figure 4.3c and 4.3d), potentially enabling some reduction in costs. Thermocline storage tanks have been piloted using oil as the storage medium, and also quartz-sand and pebbles as an inert filler. Oil gives high efficiency and reliability, but storage capacity is limited by environmental concerns and, as mentioned above, fire hazards associated with storing large quantities of hot oil. The use of an inert filler can degrade the thermocline, reducing storage capacity and requiring frequent regeneration of the temperature profile inside the tank.

Two approaches for a single tank system with stratification are under development:

- Single-tank system with stratification induced by an insulating, moving horizontal wall inside the tank, holding the hot salt above it and the cold salt below (Figure 4.3c). Cold salt is pumped from the bottom of the tank, through the heat exchanger where it is heated and then sent to the top of the tank. During the charging process the moving wall moves from the top to the bottom of the tank as the amount of hot salts increases inside the tank and the amount of cold salts decreases. This process is reversed when the stored heat is being used to drive the power block. The stratification concept has been patented and a first plant using this type of innovative thermal storage system will shortly be implemented in Spain.

- Single-tank system with stratification induced by molten salt natural recirculation into a submerged steam generator, where a limited boundary region, in which there is a high-temperature gradient, interfaces the hot salt zone and cold salt zone (Figure 4.3d). Gas firing is used to heat the molten salt as a back up in the absence of solar radiation. This innovative and cheaper concept has been patented. A first small prototype is under demonstration in Italy, and will shortly be implemented in plants in Italy and Egypt.

Alternative, developmental systems include the following:

- The use of solid materials for thermal storage, rather than a fluid, has been piloted, and is now being offered commercially based on concrete as the storage medium at capacities up to 1 GWh.

- The use of phase change materials to enable thermal storage as latent heat has been piloted at small scale (<1 MWh) using a mixture of sodium and potassium nitrates to store the latent heat part of the heat released during the phase change from water to steam. This enables heat exchange at close to constant temperature, which is necessary when the CSP system generates steam for the turbine directly in the solar field. Phase change materials need to be developed with higher thermal conductivity and a suitable melting point. An inherent disadvantage is a slightly reduced steam temperature and pressure when the power block is driven from the storage system. In addition, sensible heat storage is required to store the sensible part of the energy during preheating of the water and superheating of the steam.

- Thermal storage using thermo-chemical processes has been tested, but only in small prototypes, and a commercial technology is some way off. The main R&D challenge is the identification of practical thermo-chemical reactions with good stability and affordable operating conditions.

The thermal energy storage system may account for a substantial fraction of the total plant cost, and its performance can influence the operational cost of the plant and the value of its generation. For example, data from Spain for the incorporation of 7.5 hours storage in 50 MW parabolic trough plants indicate that plant investment costs increase from €210 million to €330 million (which includes also costs associated with a 70% increase in the size of the solar field which results in a 70% higher electricity output of the system). The thermal energy storage system itself costs around €40 million: a substantial component of this is the cost of the salt (in this case €0.7 per kilogram). For example, estimations made in Spain indicate that generating costs would reduce from the base case by around 20% when storage and supplementary firing are included. Of this cost reduction, around half is due to the storage facility, so a generating cost reduction of around 10% may be associated with adding storage to a trough plant to extend operating hours. A more significant impact may be enabling the CSP plant to provide dispatchable generation as discussed in the next chapter.

A 10-year research and technology development roadmap has been established for CSP which includes development of thermal energy storage technologies (IEA, 2010b). It aims to assess and enhance thermal energy storage systems for each of the CSP technologies, and to reduce their costs by up to 50% through a combination of incremental and breakthrough developments. A central aim is to increase storage temperatures and hence the amount of energy stored in a given volume, which leads to smaller storage volumes and consequently lower costs.

Table 4.2 Comparison of storage density and cost expectations of the technology for heat storage (DLR, 2011)

Storage concept/material	Storage capacity (kWh/m³)	Actual cost (€/kWh)	Cost expectation (€/kWh)
Sensible: liquid (depending on ΔT)	30–90	30–70	20–50
Sensible: solid (depending on ΔT)	20–100	30–50	15–30
Phase-change materials	50–150	80–120	30–50
Thermo-chemical reactions	250–400	n.a.	10–50

Materials need to be developed which can operate at the consequent higher temperatures.

The roadmap points to the further development and demonstration, over the next few years, of the most promising concepts that are currently at a fairly advanced stage of development. Longer term, more innovative, 'breakthrough' concepts are envisaged to be developed, providing significantly cheaper and more effective thermal energy storage systems. They include the development of solid and chemical heat storage media, as well as gaseous heat transfer fluids, enabling storage temperatures of over 600 °C.

Although there are many promising technical developments and challenges required to achieve more cost-effective thermal storage concepts, the most promising ones are:

- Development of new molten salts which can operate over a wider range of temperatures.
- Development of new phase change materials, with high thermal conductivity and stability, affordable price when mass produced, and suitable melting point. So far, many candidates have been identified, but their cost is too high or their melting temperature is not suitable for CSP plants.
- Development of cheap solid heat storage media with good heat capacity, high thermal conductivity and low thermal expansion. Concrete, pebbles and cofalit are three of the storage media so far evaluated, but a complete system design for large storage systems is only available for concrete, which has a relatively low thermal conductivity.
- Identification of thermo-chemical processes suitable for the temperature range of CSP plants and feasible for commercial implementation at large scale. All the thermo-chemical processes tested so far show significant constraints for large-scale implementation in commercial CSP plants with a high storage capacity.

Table 4.2 gives indicative figures for the specific storage capacities (kilowatt-hours per cubic metre, kWh/m^3) of various technology options for CSP thermal energy storage, and for current and potential future costs.

5 Economics

This chapter considers the economics of CSP plants, starting with a review of current costs and their sensitivities. Subsequent sections then look at the potential for reducing the costs of CSP generation, and the consequences for cost competition with other technologies and when generating cost parity may be achieved.

Incorporation of thermal energy storage and/or auxiliary firing has an impact on the value of CSP generation in electricity markets, an issue which is evaluated in sections 5.5 and 5.6.

5.1 Today's cost of CSP and its sensitivities

The structure of a commercial CSP project is very similar to other large power plant projects and typically involves several players. An 'Engineering, Procurement and Construction' (EPC) contractor and its suppliers provide and warrant the technology to the owner, who finances it through equity investors, banks and eventually public grants. The owner gains revenues from the electricity off-taker (typically the electricity system operator) based on long-term power purchase agreements needed to pay off the debt and operation costs, and to generate a profit. An operation and maintenance company provides services to the owner to operate the plant. This approach results in a complex contractual arrangement to distribute and manage the overall project risk, as the overall project cost of several hundred million euros typically cannot be backed by a single entity. The perception and distribution of risks, as well as local and regional factors, strongly affect the cost, value and profitability of CSP generation which depend on:

- the Engineering, Procurement and Construction price which, in turn, is dependent on technology choice, project size, country, site conditions, land costs, supplier's structure, global prices for steel, etc.;
- annual operation and maintenance costs, determined by technology, size, site, availability of water, etc.;
- annual production of electricity, determined by technology, size, solar resource, and storage capacity;
- the rate paid for each kilowatt-hour (kWh) resulting from the political framework (in particular, the feed-in tariff and any capital subsidies) and the electricity market situation in the country;
- financing costs arising from the interest rate, project risk, technology risk, exchange rate, global economic situation, construction period; and
- project development costs, influenced by country-specific factors such as the legal framework, currency exchange risks, tax and customs duties, etc.

Associated costs which are more difficult to quantify include impacts on rural landscapes, environmental taxes and abatement costs, specific charges on water or CO_2 emissions, and, potentially, displacement of agriculture.

There is therefore no single figure for the costs of electricity from CSP, nor, for similar reasons, for other generating technologies to which it needs to be compared. One approach that is often used to compare costs of electricity generation is to calculate the 'levelised electricity cost' (LEC) which, as mentioned in Chapter 4, relates average annual capital and operating costs of the plant to the annual electricity production. Recognising the limitations of the approach, particularly when comparing fossil-fired and renewable technologies where it does not capture differences in value to the customer, it nonetheless gives a useful 'first cut' view of comparative costs. For comparisons between fossil-fired plants and CSP with storage and/or supplementary firing, its limitations are less significant as the technologies offer similar services. Recent studies (IEA 2010b; Turchi 2010b; Kost and Schlegl 2010) give levelised costs of electricity from CSP of 15–22 € cents/kWh (20–29 US $ cents/kWh) in 2010 monetary values, depending on technology, size and solar resource.

To present an illustrative comparison of CSP electricity costs with other options, cost estimates for different technologies have been made taking data from a single source (US Department of Energy, 2010), and a simplified equation used to evaluate the LEC. The results are summarised in Table 5.1 (Annex 3 provides details of the assumptions and calculations).

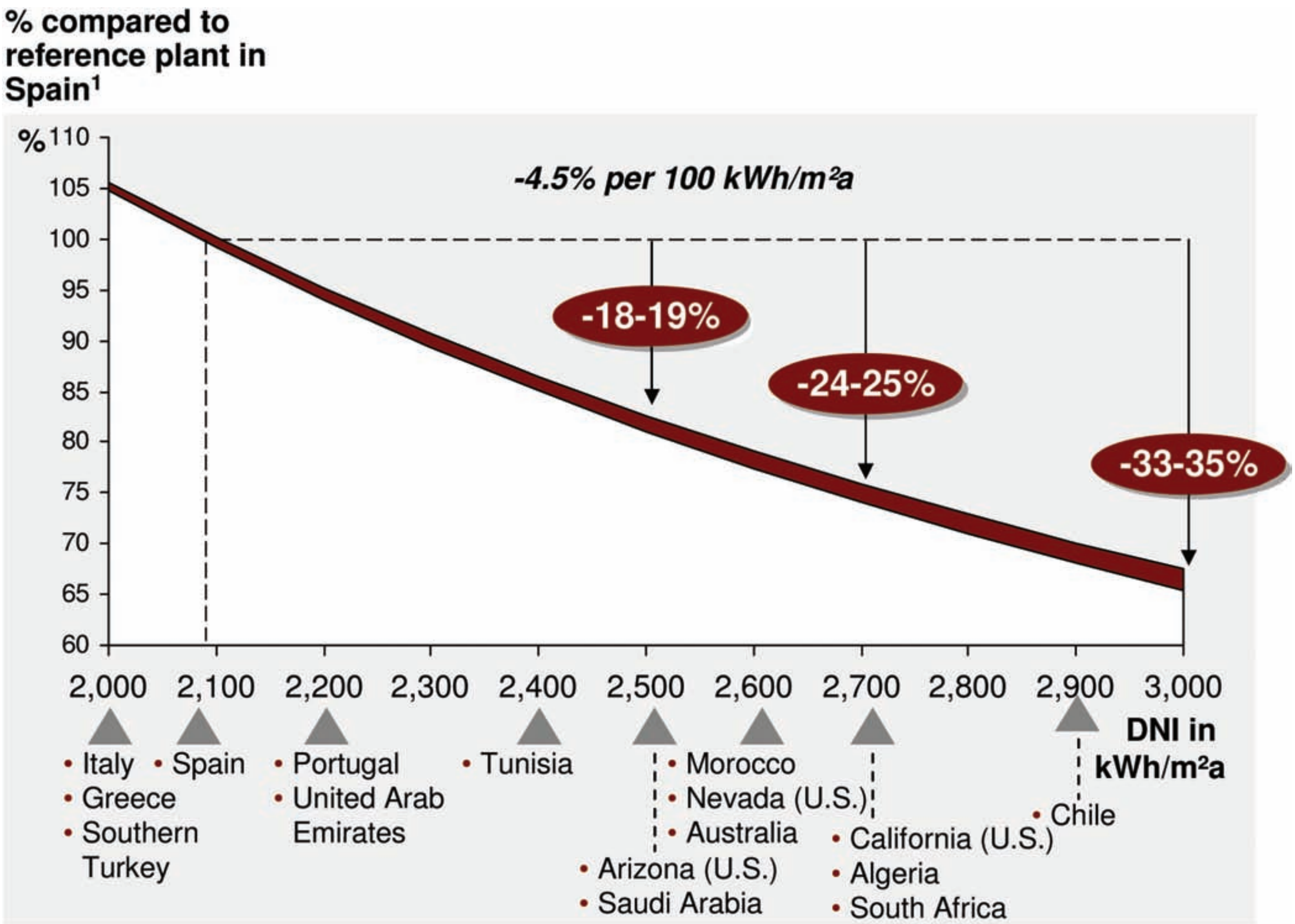
This analysis has assumed that the renewable energy systems (wind, photovoltaic (PV), and CSP) are positioned to have a favourable solar or wind resource and financing conditions. For CSP a direct normal insolation (DNI) in Phoenix, Arizona (2500 kWh/m² per annum) is considered. The solar resource in Southern Europe is typically about 20% lower, whereas some sites in North Africa have a 5% higher resource potential. The impact on the cost is almost linear as can be seen in Figure 5.1.

The analysis presented in Table 5.1 gives a cost figure for CSP electricity within the range given in the studies mentioned above (IEA 2010b; Turchi 2010b; Kost and Schlegl 2010). It also enables a comparison of the CSP generating cost to other conventional and renewable options under similar boundary conditions.

Table 5.1 Illustrative costs of generating technologies in 2010 (currency conversion 2010 $/€ = 0.755)

Technology	LEC €c/kWh$_e$	Capacity MW	EPC cost €/kW$_e$	Cap factor (—)	Fuel costs €c/kWh$_e$	O&M$_{fix}$ €/kW/y	O&M$_{var}$ €c/kWh$_e$
CSP: 100 MW no storage (Arizona)	17.9	100	3542	0.28	0	48	0
Pulverised coal: 650 MW: base-load	6.9	650	2391	0.90	2.9	27	0.3
Pulverised coal: 650 MW: mid-load	9.0	650	2391	0.57	2.9	27	0.3
Gas combined cycle mid-load	6.1	540	738	0.40	3.2	11	0.3
Wind onshore: 100MW	8.5	100	1841	0.30	0	21	0
Wind offshore: 400 MW	15.3	400	4511	0.40	0	40	0
Photovoltaic: 150 MW (Arizona):	21.2	150	3590	0.22	0	13	0

Figure 5.1 Impact of the quality of the solar resource (DNI) on the relative LEC (from AT Kearney and ESTELA, 2010).



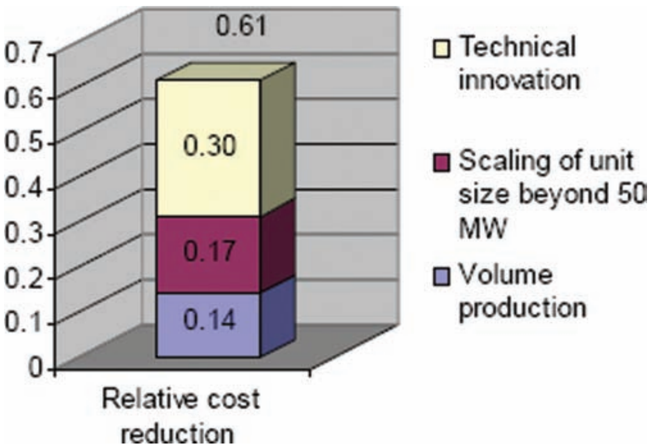
From the US Department of Energy study, it can be concluded that, when the solar resource is good, CSP had slightly lower costs than large-scale PV systems in 2010. (In 2011, the costs of PV systems were significantly reduced so that they are currently slightly lower than those of CSP systems.) CSP costs in 2010 were about twice those of onshore wind farms, and slightly higher than estimates for offshore wind energy. CSP can provide services similar to fossil fuel power plants in respect of dispatchable power and grid services as discussed later in this chapter, but as can be seen from Table 5.1, its electricity generation cost is today a factor 2–3 higher than for new fossil-fired power plants based on gas or coal. CO_2 emissions of CSP plants are negligible compared with fossil-fired plants, and CSP would currently be cost competitive with coal if CO_2 emissions were priced at about 80 to 120 €/t. However, CO_2 emissions certificates are currently traded in Europe at a rate of around 15 €/t, estimates of the social costs of carbon vary widely but are typically lower than this 80–120 €/t range (Tol, 2009), and there are other technical options that can avoid CO_2 emissions at significantly lower costs than 80–120 €/t (see, for example, McKinsey, 2009).

The implementation of CSP systems therefore currently depends on market incentives established by governments. However, changes in fuel prices, higher CO_2 penalties and, in particular, cost reduction of CSP are expected to change this situation over time as discussed in the following sections of this chapter.

5.2 Cost reduction potential

Three main drivers for cost reduction are: scaling up, volume production and technology innovations. As an example, one of the first comprehensive studies of the potential for cost reduction of CSP was undertaken

Figure 5.2 Potential relative reduction of LEC by innovations, scaling and volume production through 2020 for the parabolic trough/HTF system compared with today's LEC (after Pitz-Paal et al., 2005).



in the framework of the European 'ECOSTAR' project (Pitz-Paal et al., 2005). The study proposed the potential relative reduction of the LEC of parabolic trough plants shown in Figure 5.2. Further details of the cost breakdowns for Figure 5.2 and the other cost information presented in this section are given in the listed references.

Scaling up

CSP technology favours big power plant configurations because (Pitz-Paal et al., 2005):

- procurement of large amounts of solar field components can lead to discounts;
- engineering, planning and project development costs are essentially independent of the scale of the plant;
- operation and maintenance costs reduce with plant size; and
- large power blocks have higher efficiency than small ones and cost less per kilowatt.

The impact of scaling up on CSP electricity cost is still under discussion. The Kearney report (AT Kearney and ESTELA, 2010) indicates a 24% reduction of capital expenditure for an increase of parabolic trough plant size from 50 to 500 MW, and Lipman (2010) estimates a 30% reduction of LEC for an increase of turbine power from 50 MW to 250 MW. Finally, the Sargent and Lundy (2003) study points to a 14% cost reduction for a 400 MW power block.

Volume production

For parabolic trough plants, the Sargent and Lundy (2003) study estimates a cost reduction of 17% due to volume production effects when installing 600 MW per year. Cost decreases in the range 5–40%, depending on components, are expected in AT Kearney and ESTELA (2010).

Technology innovations

According to Pitz-Paal et al (2005), technology innovations will:

- increase power generation efficiency, mainly through increasing operating temperature;
- reduce solar field costs by minimising component costs and optimising optical design; and
- reduce operational consumption of water and parasitic power.

Table 5.2 Anticipated technology innovations (adapted from Pitz-Paal et al., 2005)

Subsystems	Concentrating system	Solar receiver	Storage	Power block
Technology				
Parabolic troughs	Mirror materials, size and accuracy Support structure design	Thermal performance (mainly optical efficiency) Higher operating temperature	Alternative storage media System design	Turbine efficiency
Linear Fresnel systems	Mirrors and mirror assembly Support structure design	Thermal performance (mainly optical efficiency) Higher operating temperatures	Storage development for direct steam generation	Turbine efficiency
Towers (central receiver systems)	Field and heliostat size optimisation Tracking system Support structure design	Higher operating temperature Receiver design for reducing losses and thermal stresses	High-temperature storage media and heat exchangers	Turbine efficiency New turbine
Parabolic dishes	Support structure design Concentrator size for various solar resources	Receiver design for reducing losses and increasing lifetime	Storage and hybridisation development	Engine reliability New engines

Table 5.2 gives a list of anticipated technology innovations for the four CSP technology families.

Expected cost reductions and plant efficiency improvements associated with technology innovations are listed in Table 5.3.

Horizontal technological improvements are anticipated, potentially providing benefits across the families of CSP technologies. For mirrors these improvements include increasing reflectivity to 95% (by developing thinner front glass), anti-soiling and hydrophobic coatings on glass (to prevent dust deposition and reduce cleaning requirements), front surface aluminised reflectors, and polymer reflectors. Reflectance can be increased by 2.5% if the reflective surface is not covered by a glass layer. This results in an increase in the collected power while the thermal losses that diminish it stay constant. The relative gain of the output power, which is the difference between collected power and heat losses, is about 3.5%. Replacing glass as a carrier of the reflective surface by other materials also offers a potential in a 25% cost reduction of the reflector. Interrelated technology breakthroughs are expected in heat transfer fluids, storage media and thermodynamic cycles, as follows:

- **Heat transfer fluids**: superheated steam, new molten salts (with low melting temperature and higher working temperatures), nano-fluids, pressurised air (mainly development of new solar receivers), and circulating particles.
- **Storage**: phase change materials for direct steam generation, high-temperature storage for gas cycles, compact heat storage (chemical reactions), and heat transfer concepts (discussed in Chapter 4).
- **Thermodynamic cycles:** supercritical steam or carbon dioxide cycles, air Brayton cycles and combined cycles (for tower technology).

Examples of the consequent, expected efficiency improvements for each of the technology families are summarised in Table 5.4.

To realise these technology breaktroughs and associated cost and efficiency improvements, it is essential to coordinate the different research, development and demonstration efforts with a market incentivation that favours cost reduction by innovation over cost reduction by mass production of state of the art technology options. Research without the chance to implement the technology in the market, and to improve and adapt it over a couple of technology generations, has a high risk of failure in a competitive market.

Increased research funding and a stronger integration of fundamental and applied research, together with demonstration programmes and market incentives, are required to speed up the innovation cycle. Fundamental research on new materials, heat transfer fluids, and coatings is needed, and integrated programmes should enable smooth progression of promising technologies from laboratory-scale prototype systems to pilot plants and demonstrations units. Results of the individual phases should be independently evaluated and benchmarked with respect to their impact on system cost targets before starting on the next phase.

Table 5.3 Expected cost reduction (of the components or LEC) or plant efficiency improvement associated with technology innovations (after Pitz-Paal et al., 2005 and AT Kearney and ESTELA, 2010). (Where no values are given for cost reduction or efficiency improvement they are as yet not quantified.)

Subsystems	Concentrating system	Solar receiver	Storage and heat exchangers
Technology			
Parabolic troughs Data from AT Kearney and ESTELA (2010) except if specified	Mirror reflectivity (93% today) and new materials: 25% cost reduction by 2020 Size and accuracy: 7.5% cost reduction by 2012, 13% by 2020 Support structure:12% by 2015, 33% by 2025	Thermal performance (mainly optical): +4% efficiency Glass-metal seal: 2–5% cost reduction Higher operating temperature: molten salt, 20% cost reduction (including effect on storage), +6% efficiency DSG: 5% cost reduction, +7% efficiency	Heat exchanger: 10% cost reduction Steam generator: 15% cost reduction New materials and design: reduction 16–18% of LEC (Pitz-Paal et al., 2005)
Linear Fresnel systems Data from AT Kearney and ESTELA (2010)	Mirrors and mirror assembly: 17% cost reduction Support structure: 10% cost reduction by 2015	Thermal performances (mainly optical) Higher operating temperatures: +17% efficiency (increase from 270 °C to 500 °C)	Storage development for direct steam generation
Towers (central receiver systems) Data from AT Kearney and ESTELA (2010) except if specified	Thin glass mirrors: 1–4% LEC reduction (Pitz-Paal, et al., 2005) Heliostat size optimisation: 7–16% cost reduction Field optimisation: cost reduction 10%, efficiency +3% Tracking system: cost reduction 40% Support structure design	Tower (multi-tower): 25% cost reduction, +5% efficiency Higher operating temperature: 40–60% efficiency increase	Thermocline tank (molten salt): 25–30% cost reduction, 1% LEC reduction (Pitz-Paal et al., 2005) Advanced storage (DSG): 5–7.5% LEC reduction (Pitz-Paal et al., 2005)
Parabolic dishes Data from Pitz-Paal et al (2005)	Concentrator: 43–47% LEC reduction	Receiver design for reducing losses and increasing lifetime: 39–40% LEC reduction	**Engine** Stirling engine: 41–45% LEC reduction Brayton cycle: 44–51% LEC reduction

Table 5.4 Examples of expected efficiency improvements from technology breakthroughs

Performances	Innovation	Current plant efficiency (%)	Plant efficiency with innovation (%)	Relative increase of efficiency (%)
Technology Parabolic troughs	Molten salt as heat transfer fluid	15–16	18	20
Linear Fresnel systems	Superheated direct steam generation	8–10	12	25
Towers (central receiver systems)	Combined cycle	15–17	25–28	40–65
Parabolic dishes	System improvement	20–25	30	25

5.3 Competition with other technologies

In summary, it can be stated that different in-depth analyses of near- and mid-term technological options to reduce CSP costs have come to similar conclusions. They identify the potential for 25–35% reductions in CSP generating costs by capital cost and efficiency improvements based on technology developments already underway, and a further 20–30% reduction in costs through scaling up and volume production effects.

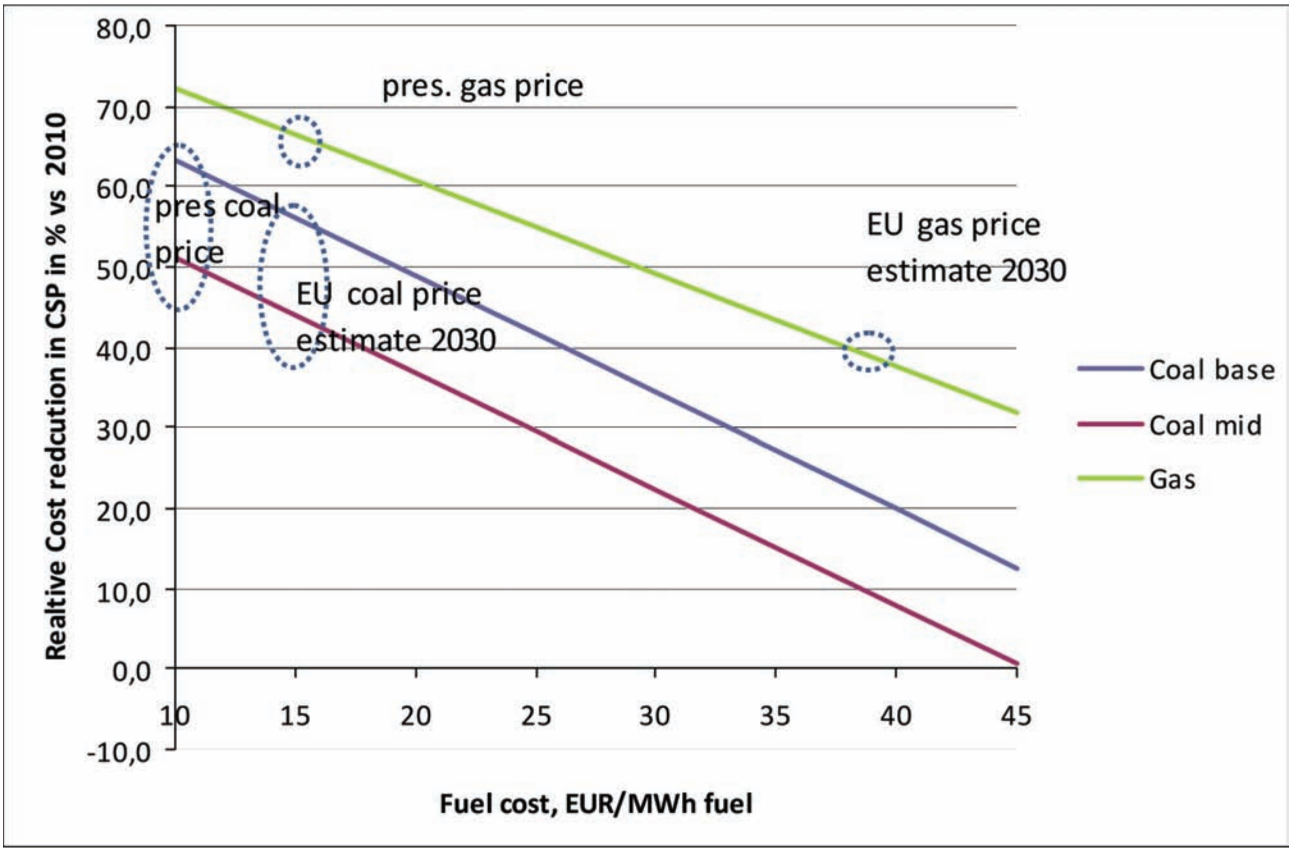
Operation and maintenance costs are also expected to decrease with CSP technology development and exploitation. For example, they dropped about 40%, from 4 $ cents/kWh (25% of the electricity cost in 1999) to 2.5 $ cents/kWh, at the Kramer Junction plant in the US between 1992 and 1998 (Cohen et al., 1999). Operation and maintenance costs also reduce sharply as plant size increases.

To estimate whether the anticipated cost reduction may enable CSP to break even with the LEC of the fossil-fired alternatives presented in Table 5.1, Figure 5.3 plots the percentage changes in investment cost required for CSP plants to break even with coal- and gas-fired plants as a function of fuel price. At today's fuel prices, a reduction of 50–70% in the investment cost of CSP is needed to compete.

Prices of CO_2 certificates will influence the point at which cost competitiveness is achieved as they can be considered as equivalent to surcharges on the fuel price. For coal, each additional euro per tonne CO_2 on the certificate price has a similar effect on the competitiveness as a CSP cost reduction of 0.5% (for gas it is 0.3%). Assuming, for example, a coal price of 15 €/MWh and a CO_2 certificate price of 30 €/ton in the future, a 30% cost reduction of the CSP plant corresponds to break-even on LEC with mid-load coal-fired plants. The analyses discussed above consistently point to the potential for significantly greater CSP cost reductions.

The competition is also strongly determined by the cost of money as the cost per megawatt of capacity of CSP systems is larger than that of fossil fuel fired power plants. The overall global market situation, as well as the perceived risk of the investment, strongly influence the cost of money for a project. However, typically the loan conditions are known and fixed at the beginning for the pay-back time of the project, whereas fossil fuel price change represents a continuous risk.

Figure 5.3 Cost reduction of CSP needed at variable fuel price to break even with fossil-fired power plants based on the data from Table 5.1.



The competition with other renewable technologies, in particular with solar PV (including concentrating solar PV) which uses the same solar resource, is more complex. Decentralised application of solar PV competes at the level of consumer prices, which are significantly higher than the market prices for bulk electricity. In Europe, grid parity for domestic solar PV systems is expected to be achieved within the next few years. The market growth of solar PV in this segment will reduce the amount of electricity taken from the grid, but will force the grid to react more quickly to the changes provided by this variable resource. The flexibility of CSP can be one option to help the grid accommodate such variable sources.

If solar PV is used to provide bulk electricity, its average value is lower than CSP as it cannot provide dispatchable electricity, and cannot provide other grid services (stable frequency, spinning reserve, etc.). On the other hand, the cost-reduction curve for PV has to date been very steep, the PV market and PV research capacity are currently much larger than for CSP, and PV power plants can be implemented more quickly than CSP systems.

Recent aggressive competition, in particular from Asia, has resulted in a further price drop of PV systems and has led to a situation where in some markets, where time of delivery and capacity aspects are not reflected in the revenues, project developers have preferred large-scale PV over CSP technology options. However, the potential future cost reductions of both CSP and PV are high, and only time will tell which will have the steeper learning curve.

The difference in value between the technologies depends on the overall energy system and, in particular, on the share of variable renewable electricity as discussed later in this chapter, and hence needs to be evaluated for each market. The future cost evolution of solar PV and CSP systems, and the price difference between dispatchable and non-dispatchable electricity, will be decisive in determining the relative sizes of the contributions of solar PV and CSP in the market. Given the challenge that society faces in transforming quickly to a low carbon economy, and taking into account the high resource potential that solar energy has in the world, it would be inappropriate to drop one or the other option too early based on short-term price differences. CSP's ability to support the system integration of variable renewable sources, as discussed later in this chapter, also suggests that its further support should not be determined solely by its short-term competitiveness with PV systems.

5.4 Time-frames for cost competitiveness

An alternative approach to estimating future potential for cost reduction is to use well-established 'learning curve' effects, which are based on observations for technologies more generally that their cost reduces by a characteristic percentage for each doubling of installed capacity (hence, the 'learning rate' is defined as the percentage reduction in costs for each doubling of installed capacity). Although this concept was originally applied to a product of a single entrepreneurial entity it has been found to work for many mass produced components on the global scale.

If the concept is applied to a system that consists of different components like a CSP plant, the overall learning curve for the system will be, at least in part, an amalgamation of the learning curves of individual components. While solar collectors or thermal storage systems do not yet have the status of being mass-produced, the conventional power block is. Further implementation of solar power plants will therefore only marginally impact its general future cost reduction, although there may be potential cost reduction for CSP associated with its adaptation to the specific needs of CSP applications.

Trieb (2004) has suggested an approach that combines different learning rates of components and the effects of scaling to larger plants for CSP, and calculated a CSP system learning rate of 14%. The uncertainty in this figure is high as it is not based on empirical data. The following analysis, which examines cost reductions up to 50%, therefore considers a range of 10–20% as potentially achievable for CSP. The impact of installed capacity on costs for this range of learning rates is illustrated in Figure 5.4.

Starting from an actual installed capacity of 1 GW, a 20% learning rate would require an installed capacity of around 9 GW to halve costs, whereas 100 GW would be required in the case of a 10% learning rate.

Figure 5.5 illustrates the potential implications of a learning rate of 15%, i.e. in the middle of this range, for when CSP may reach a 50% cost reduction. Starting from a current CSP installation rate of around 500 MW per year, and assuming a growth rate in CSP installations of 15% (low) and 30% (high) per year, results in CSP achieving a 50% cost reduction between 2021 and 2031.

The learning rate and the growth rate of installed CSP capacity are key determinants of when CSP will be cost competitive with other technologies. The ranges of figures selected in this analysis are based on expert estimates and opinion, and have not been verified by actual data (which are not available). It is therefore strongly recommended that mechanisms are put in place that enforce a transparent monitoring of installation costs, and the rate of CSP technology capacity increases, to enable estimates of the learning rate to be refined.

The growth rate of the CSP market is currently constrained by market opportunities rather than production capacity. Additional incentives, and the creation of new market opportunities in other countries, will help to speed up the cost reduction process according to this model.

Figure 5.4 Relative cost of CSP technology as a function of the cumulative installed capacity for learning rates of 10 and 20%.

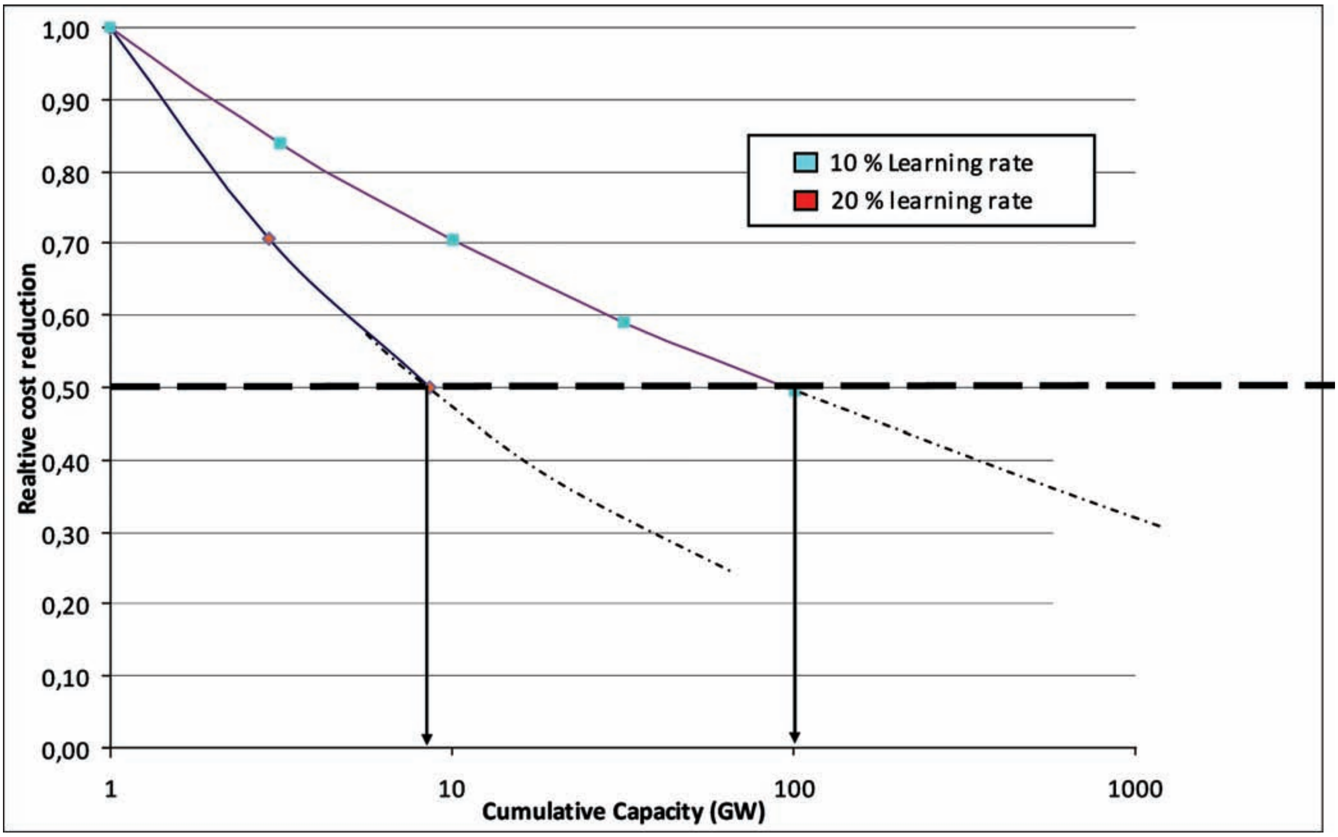
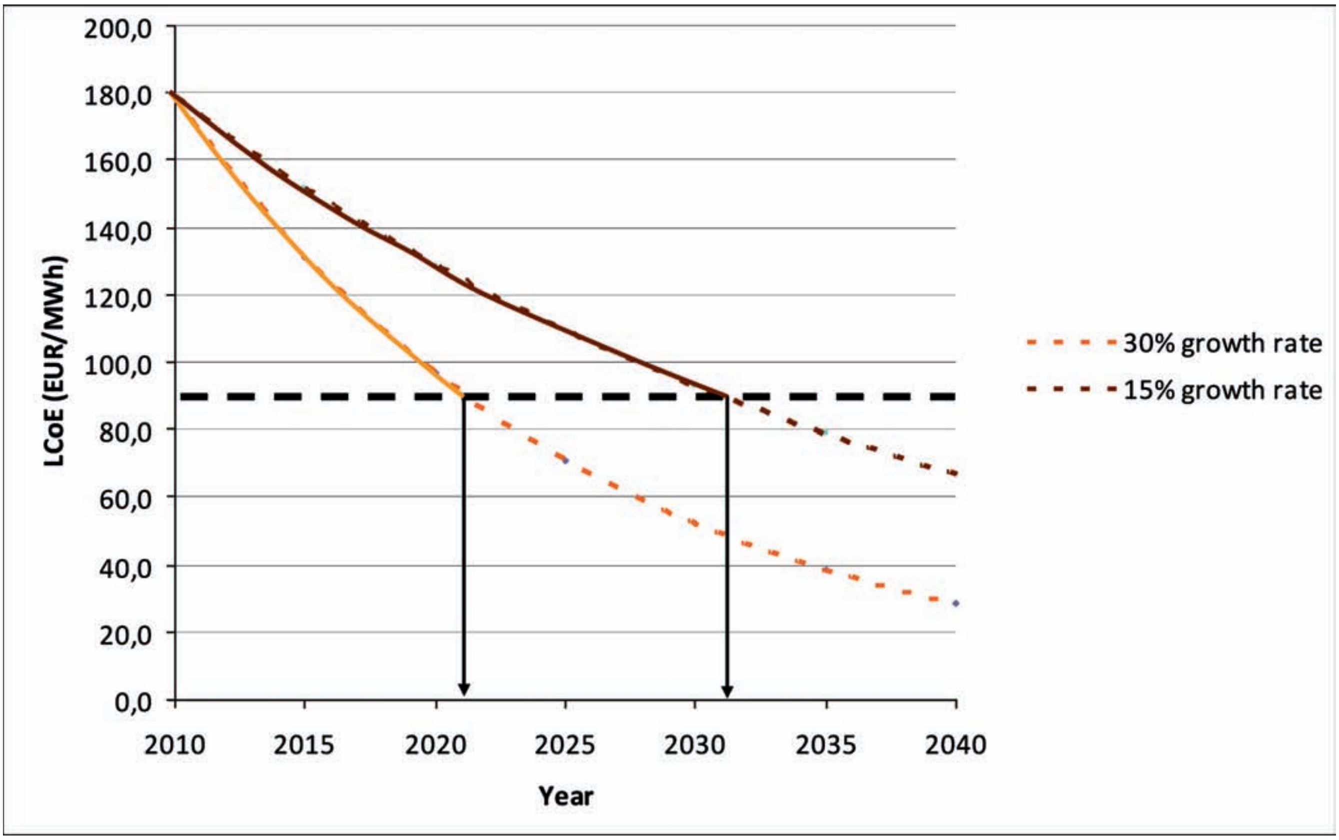


Figure 5.5 Development of LEC over time for CSP systems installed at 15% (low) and 30% (high) growth rates per year (based on a learning rate of 15%).



5.5 The value of CSP with storage in electricity markets

The electricity system can be considered in two parts: generation/supply of electricity, and networks (transmission and distribution). In the EU, as a result of EU directives, generation and sale of electricity to end users are balanced in a competitive market, while transmission and distribution systems are operated under the supervision of national regulatory authorities.

Thermal energy storage can be beneficial for integrating CSP into an electricity system in both these spheres. Inclusion of a storage system in a CSP plant can therefore have a significant impact on its value, which comprises three main components:

- the value of the kilowatt-hours of **electrical energy** generated by the plant, which will vary over time in a competitive electricity market, reflecting the availability and cost of electricity from other sources;
- the contribution that the CSP plant makes to ensuring that generating **capacity** is available to meet peak electricity system demand; and
- the '**services**' provided by the plant in helping the electricity transmission system operator to balance supply and demand in the short term (typically, on timescales of seconds and minutes).

Considering the **first component** of value, optimisation of the relative sizes of a CSP plant's collector field, turbine and thermal energy store will depend crucially on the structure of the price curve (the hourly variation of electricity price through the year), which in turn depends on the supply demand-pattern of the electricity system into which the CSP plant feeds.

Generally, the value of a kilowatt-hour of electrical energy is higher at times of higher demand. Even without storage, the profile of output from a CSP plant in Southern Europe and the MENA region is reasonably well matched to demand, which often peaks in the middle of the day when the sun's strength, and hence CSP generation, is highest. Demand often remains strong into the evening, and storage enables some proportion of the daily generating capacity of the CSP plant to be shifted to the evening to contribute to meeting this demand and so enabling the CSP plant to benefit from the associated revenues. The ability of a CSP plant with storage to match the pattern of diurnal demand has been well received by the power grid operator in Spain, Red Eléctrica de España (REE). This demand pattern is typical for Europe more generally, with electricity prices generally peaking at midday and in the early evening, although this varies between week-days and week-ends, by season, and by country.

Although renewable systems without storage or back-up firing will be able to match the demand curve statistically quite well, there is still a need for 'shadow' capacity to ensure security of supply. CSP systems (in particular when equipped with fossil co-firing) can avoid this need. This 'capacity' value is discussed later in this section.

Given the coincidence of the energy generated by CSP (as by any other solar technology) and the price peaks in the middle of the day, storing solar energy as thermal energy rather than supplying electricity to the grid immediately at the time of solar irradiation would regularly be associated with an opportunity cost at the system level. Energy losses associated with storing and retrieving heat exacerbate this opportunity cost although, in practice, the large volume to surface ratio of the storage containers and their good insulation means that energy losses are low. 'Round trip efficiencies' of 93% have been routinely achieved by commercial plants in Spain, even when energy is stored for 24 hours. Scale-up of plant sizes should further reduce heat losses as the surface area of storage tanks will reduce in relation to the stored volume.

The economic value of thermal energy storage for a CSP plant cannot therefore be calculated at the plant level, but only at the system level: the overall configuration of the electricity system determines the price curve and hence the value of shifting the timing of generation through the day. Generally speaking, the higher the share of solar power within the system, the less pronounced the diurnal price curve will be, reflecting a need to use solar power at times other than the middle of the day peak. This implies that thermal energy storage is less relevant today (at low solar shares), but may rise over time (with increasing solar shares).

A recent simulation by the Institute of Energy Economics at the University of Cologne confirms this effect (Nagl et al., 2011). It involved a least cost optimisation for the (stylised) development of the power markets of the Iberian Peninsula (i.e. Spain and Portugal) until 2050. Allowing a choice between CSP systems with different thermal energy storage sizes, the model indicated that the cost optimal solution only involves significant amounts of CSP with thermal energy storage in the long-term. In the short to medium-term, electricity prices in the model are sufficiently high during the day (and low at night) that it is best for CSP plants to sell electricity as it is generated. In the longer term, the model includes substantial capacities of variable renewable energy sources, especially PV and CSP without storage. This has the effect of lowering, and in some cases reversing, the differential in electricity prices between day and night, making it economic to include thermal energy storage in CSP plants so that they can take advantage of the better prices when the sun is not shining.

Two key insights into the value of thermal energy storage in CSP plants in Europe emerge from this simulation exercise:

- The opportunity cost of thermal energy storage at the system level (i.e. the cost of transferring electricity from a time of high prices to a time of lower prices) can in fact exceed the benefits of thermal energy storage at the plant level.

- Whether or not this is the case largely depends on the share of variable renewable energy supplies in the overall electricity system. Depending on the overall configuration of an electricity system (i.e. the mix of power plants, availability of pumped storage, demand level and demand structure), the amount of variable renewable energy supplies has to reach a specific threshold before the price differences between hours with high solar radiation and hours with low or no solar radiation decline or even reverse.

On the issue of seasonal patterns of electricity supply and demand, CSP storage is unable to overcome potential variations in the price curve which might arise from seasonal patterns of generation by renewable sources. For example, CSP plant generation in Southern Europe on a typical sunny day in winter will only be around half that on a sunny day in the summer. Again, the appropriate response will depend on the properties of the electricity system overall, i.e. on the seasonal pattern of demand and the other sources of generation in the system. It is noted that seasonal fluctuations of electricity from CSP plants located in the MENA region are lower than those in Europe, and hence for Europe, importing CSP electricity from MENA countries may be able to make some contribution to addressing seasonality.

Other storage technologies (besides pumped-hydro), i.e. 'unconventional' storage systems (e.g. compressed air energy storage), are not cost-efficient for use as seasonal storage, because the investment is only used for a limited time during the year and not every day, even taking into account the planned expansion of variable renewables (see for example Gatzen, 2008). However, like CSP they may find application in daily and weekly electricity storage. In practice, the combination of regional variation in renewable energy supplies, fossil back-up generation, and sufficient grid interconnection typically prevents the prolonged, substantial price peaks which would be required to make such 'unconventional' seasonal storage systems cost efficient from the system perspective. This is especially so when other potential options for added flexibility are taken into account such as the use of biomass, conversion of electricity to gas and the use of the gas grid, or the use of demand side options especially in the industrial sector (Dena, 2010).

However, in the absence of a well integrated electricity system, supplementary firing with natural gas or biomass may, in some circumstances, have value for the electricity system in helping to balance seasonal variations in generation and demand. It should be noted, however, that the use of local biomass for this purpose would rely on a good annual rainfall (to enable the growth of the plants and trees providing the biomass) combined with high direct solar radiation.

With regard to the **second component** of value, the provision of generating capacity to meet peak electricity system demand, CSP with storage can contribute to meeting peak system loads and can provide backup capacity to cover variable renewable sources. Incorporation of supplementary firing will further increase the capability of the CSP plant to provide capacity at the system peak, although the efficiency of fossil-fuel use for such supplementary firing is likely to be significantly lower than if it is used in a combined cycle power plant. The value of providing capacity to meet the system peak demand will depend on the system, so its quantification needs to be informed by system models.

The electricity system operator needs to know the profile of electricity generation it can expect from its connected plants over the next day or two. Although further improvements could be made, weather forecasts are already sufficiently good that the output from CSP plants over such time periods can be predicted with high confidence. For example, in Spain, CSP plant operators must predict their electricity production 24 hours in advance with a maximum deviation of 10%, and 6 hours in advance with only a 5% deviation. These tight requirements imposed by the Spanish grid operator, REE, are regularly fulfilled by operational CSP plants. In contrast, deviations greater than 25% are usual in the predictions made by the Spanish wind farms.

Turning to the **third component**, the value of thermal energy storage in enabling the CSP plant to deliver grid services, such services may be differentiated according to response timescales: 'regulation' services requiring response time measured in seconds, 'spinning reserves' being available on timescales of up to 30–60 minutes, and 'non-spinning reserves' capable of being started up and brought on line within 30–60 minutes.

A CSP plant, with or without storage, is considered to be unlikely to make a significant contribution to regulation or non-spinning reserves services (Sioshansi and Denholm, 2010). In the case of regulation services, this is because the inherent storage in the steam generator is small (in conventional plants it is the steam drum which is the initial source for energy ramps on timescales of seconds), and the inertia of other plant components prevents a sufficiently fast response. In the case of the longer-term non-spinning reserves, this is because either the CSP plant will be running and delivering electricity, and not kept in reserve, or if shut-down may not be able to be started up quickly enough, though this depends on the specific technology.

CSP with storage can provide spinning reserves, being able to ramp up power if operating at part-load in less than 30 minutes by drawing on the stored heat (the rate of ramping is limited by the thermal inertia of the equipment). Ramping down is quicker: on timescales of around 15 minutes by diverting heat to storage. This is used in Spain to deliver, on demand, 30% power ramps in less than an hour, enabling the plant to be considered dispatchable by the grid operator REE.

In discussing the services provided by a CSP plant in helping the electricity system operator to address short-term supply demand imbalances, consideration must be given to the potential 'negative value' arising from transients during partly cloudy days. Inclusion of at least three hours storage in the CSP plant enables the substantial thermal inertia provided by the storage medium to be used to dampen any resulting steam temperature/pressure gradients at the power block inlet on such days.

CSP plants may also be able to contribute to grid services by providing 'reactive power' which is needed to achieve local balance on the system. Small payments are made to CSP plant operators in Spain for supplying reactive power. However, CSP plants located remote from demands are unlikely to be able to make a substantial contribution to meeting system operational needs for reactive power.

Whether or not thermal energy storage is the cheapest and/or simplest way of delivering such grid services merits further investigation. It can be assumed, however, that the value of grid services provided by thermal energy storage increases as the concentration of solar power plants (CSP and PV) in a particular region increases.

Sioshansi and Denholm (2010) have undertaken system modelling studies to evaluate incorporation of thermal energy storage in CSP plants in four locations in the southwest USA, which confirm the system dependence of the value of storage discussed above. In all four cases, for the modelling assumptions used in the study, reductions in the cost of storage are needed to make storage economic if just the energy value of kilowatt-hours sold is considered. However, in this study, inclusion of calculated values of providing system services and capacity substantially increases the value of storage, making it economic in all but one of the 16 site and parameter variations considered.

5.6 The value of auxiliary firing

A CSP plant with storage and auxiliary firing can reproduce many of the operating characteristics of fossil-fired plants or dispatchable hydro plants (the match becoming closer as the auxiliary firing capacity of the CSP plant is increased). In this way it is more readily integrated into normal power system operations than other renewable electricity sources such as wind or PV. Its output can be scheduled to suit its host power system, or where plant scheduling is based on a market, to run during the time of day when prices are highest. Wind and PV can be linked with pumped storage hydro to deliver some of these benefits, but the round trip losses are very much greater than the losses in thermal storage associated with CSP. Supplementary firing, if installed, can also be used to smooth power block operation on cloudy days, and thereby deliver system services.

Again, however, the economic value of auxiliary firing at the CSP plant level has to be carefully compared with the alternative options within the power system, for example, high-efficiency thermal power plants located closer to the demand centres. Most of today's CSP plants operate at significantly lower fuel-to-electricity efficiencies than conventional power plants, so auxiliary firing can have a negative impact on CO_2 emissions. However special designs optimised for hybrid operation can go some way towards overcoming this problem.

The value of supplementary firing (and storage) will tend to be higher when the accessible electricity system is smaller. For many countries in the MENA region, the size of the electricity system into which power plants feed is limited. This factor, and the cost advantages of natural gas firing, may go some way to explaining why supplementary firing and hybrid schemes (in which a CSP facility is used to augment the efficiency of a larger fossil-fired plant), have previously been adopted in this region. As fossil-fuel costs increase there may be a shift to thermal storage as the preferred mechanism for addressing the isolation issue. Also, CSP may be deployed along with other renewable technologies such as wind power and solar PV which may contribute to increasing the reliability of supply in the absence of good grid connections.

When auxiliary firing is incorporated, a CSP plant may be able to help the system operator in a 'black start' situation, i.e. to supply electricity to the system when it is not energised in order to restore electricity supplies. This capability would have to be designed into the plant.

6 Environmental impacts of CSP

As for other energy technologies, CSP has distinctive environmental impacts. They are reviewed in this chapter under the following headings:

- water issues;
- land use and visual impact;
- energy and materials use;
- emissions; and
- impacts on flora and fauna.

A final section draws together the findings to provide an overview of the environmental impacts of CSP compared with other energy technologies. Annex 4 provides supporting details.

6.1 Water issues

CSP plants require large amounts of direct sunlight and hence are best constructed in arid or semi-arid regions, globally known as the Sun Belt. However, CSP plants are often designed to use water for cooling at the back-end of the thermal cycle, typically in a wet cooling tower. These water requirements can result in difficulties in arid areas, particularly in the MENA region, being the region in the world experiencing the hardest water stress (World Bank, 2007). Large-scale implementation of CSP in Europe and the MENA region requires that additional water needs can be effectively met, or technologies with lower water use must be implemented.

A typical 50 MW parabolic trough plant uses 0.4–0.5 million m^3 of water per year for cooling: roughly the same as agricultural irrigation of an area corresponding to that occupied by the CSP plant in a semi-arid climate (and less than half that used for irrigating food crops in Andalucia in Spain). In the MENA region, withdrawal of renewable water resources is already above 70%, i.e. close to exhaustion. Water could possibly be diverted from its massive, in some cases inefficient, use in irrigation. The water withdrawal for agriculture in the MENA region was 188.3 billion m^3 in 2002, while the corresponding figure for the entire MENA region's industrial sector was only 7.9 billion m^3 in the same year (World Bank, 2007). But the prospect of withdrawing large amounts of fresh water for CSP cooling is not appealing, particularly when the MENA region water demand is conservatively expected to almost double in the period 2000–2050 (DLR, 2007).

Water is also used for cleaning the mirrors to maintain their high reflectivity, although water use for cleaning is typically a factor of a hundred lower than that used for water cooling. It may be more significant in desert areas where dust storms may require more frequent cleaning, and the associated water consumption is relatively higher when compared with precipitation. Experience with CSP plants in Spain is that soiling rates and hence washing requirements are a little higher than initially expected.

Water use can be decreased by cooling with air instead, but this lowers the efficiency of the system. A study conducted by the US National Renewable Energy Laboratory (Burkhardt et al., 2011) indicates that the switch from wet to dry cooling in a 100 MW parabolic trough CSP plant can decrease the water requirement from 3.6 l/kWh to 0.25 l/kWh. As stated in Chapter 3, using dry instead of wet cooling increases investment costs and lowers efficiency, adding 3–7.5% to the LEC. For areas with high irradiation and available land close to the sea, such as the Egyptian north coast, using salt water for cooling could be an attractive option. It also opens up the possibility of integrating desalination with the CSP plants (see Fact Box on next page). Finally, there are some CSP plant designs that have inherently low fresh water requirements, such as gas turbine towers and parabolic dishes with Stirling engines.

6.2 Land use and visual impact

To compare CSP land use to that associated with other energy conversion technologies, a basic estimate of land use has been made in this study (see Annex 4), and is presented in Table 6.1. Land use refers to the area directly occupied by a power plant structure (in a CSP plant the collector/heliostat fields dominate), by extraction of fuel, or by plantations for biomass. It is presented in relation to the energy generated annually by each plant, and hence is expressed in units of m^2/(MWh/y). The 'visual impact' gives the area over which a power plant disturbs the view, divided by the energy generated annually by the plant (and hence is also expressed in units of m^2/(MWh/y)). Table 6.1 presents data for CSP technologies and, for comparison, for wind power. Visual effects are most noticeable in tower CSP plants where very bright points appear in the rural landscape. However, due to contemporary social attitudes the signal has been interpreted by the population as a technical novelty and a sign of progress, not causing rejection (so far).

One advantage of CSP plants is that they are often located in areas with limited amenity or aesthetic value. Using desert land for solar plants could in many ways be seen as better than, for instance, agricultural land for biomass energy. The placement of power plants or fuel extraction (such as lignite) close to highly populated areas can be almost completely avoided. As described in Chapter 7, the areas available globally for CSP development far exceed present needs.

Nevertheless, arid regions do have environmental value, and contain some biotopes or species that are threatened. The harshness of the desert climate also makes it take longer for an arid biotope community to recover from the effects of disturbance. Massive establishment of solar plants in an area may affect regional animal or plant populations by cutting dispersion routes and partially isolating populations from each other. This is hardly unique for CSP plants, but calls for some caution.

Fact Box: Desalination

CSP plants can be used to produce fresh water from salt water, either by using heat from the plant for distillation processes, or the produced power for mechanical processes (reverse osmosis, mechanical vapour compression). Heat for distillation can be taken directly from the collectors or from the exhaust steam of the turbines. The energy cost of solar desalination is equivalent to 5–15 kWh of electricity for 1 m^3 of water, either directly by reverse osmosis or indirectly as pump losses and decreased efficiency in backpressure turbines (Fiorenza et al., 2003).

In MENA countries, desalination typically accounts for less than 1/1000 of the fresh water supply (Deane, 2003). Hence, a change in the markets for water, such as a large price increase due to scarcity, may be needed for desalination to become widespread. Even then, desalination using fossil-fired plants is cheaper given current fossil-fuel prices, and incentive schemes would be required to stimulate CSP-based desalination.

Figure 6.1 Water desalination plant in Dubai.

It is expected that water scarcity in the MENA region due to growth in the economy and population will become a major challenge in the MENA region in the next 40 years. Low cost CSP technology driving desalination processes is expected to be one of the most attractive options in the future to address this challenge. Details can be found in DLR (2007).

Table 6.1 Land use and visual impact for solar, wind, biomass and lignite power plants

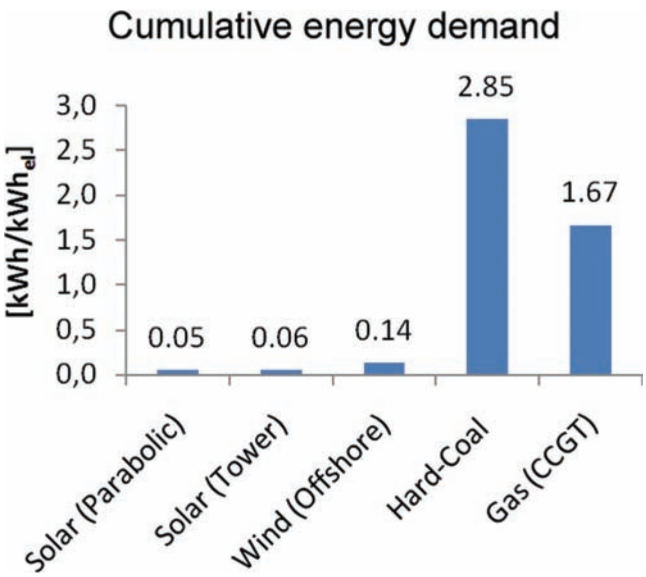
	Land use (m^2/(MWh/y))	Visual impact (m^2/MWh/y))
Parabolic solar power, Spain	11	15
Solar tower power, Spain	17	1100
Photovoltaic power plant, Germany	56*	
Wind power	<5	8600
Biomass plantation, France	550	
Open-cast mining (lignite), Germany	60	
High-voltage power transmission line across Europe	0.4	

*Photovoltaic power can also be placed on rooftops, in which case land use is essentially zero.

6.3 Energy and materials use

In evaluating the sustainability of CSP plants it is useful to compare their energy balance and material use over their life cycle to other power generation technologies. The life cycle assessment methodology used is described in Annex 4. A life cycle assessment of CSP power shows that the cumulative (non-renewable) primary energy invested in construction and operation of a plant over its lifetime is gained back as renewable power in less than one year of the assumed 30-year life. This gives an energy return on investment (EROI) of about 30. The cumulative (non-renewable) primary energy needed to produce 1 kWh of electricity is comparable to that of wind power and orders of magnitude lower than for fossil-fired power plants, as illustrated in Figure 6.2.

Figure 6.2 The cumulative (non-renewable) primary energy over the lifetime of the plant needed to produce a unit of electricity from different power plants: parabolic CSP plant (May, 2005), CSP tower plant (Weinrebe, 1999), offshore wind farm (Wagner et al., 2010), hard coal- (GaBi, 2007) and gas combined cycle gas turbine (CCGT) power plant (Ecoinvent-Database, 2007).



CSP plants are more material intensive than conventional fossil-fired plants as illustrated in Figure 6.3. The main materials used are commonplace commodities such as steel, glass and concrete whose recycling rates are high: typically over 95% is achievable for glass, steel and other metals. Materials that cannot be recycled are mostly inert and can be used as filling materials (e.g. in road building) or can be land-filled safely. There are few toxic substances used in CSP plants: the synthetic organic heat transfer fluids used in parabolic troughs, a mix of biphenyl and biphenyl-ether, are the most significant. They can potentially catch fire, can contaminate soils and create other environmental problems, and have to be treated as hazardous waste. One aim of current research activities is to replace the toxic heat transfer fluid with water or molten salts. As mentioned in Chapter 3, these also have the benefit of being able to be used at higher temperatures, giving better efficiencies and hence decreased specific emissions.

Figure 6.3 Material intensity for different power plants: parabolic trough CSP plant with storage (May, 2005), tower CSP plant without storage (Weinrebe, 1999), offshore wind farm (Wagner et al., 2010), hard-coal power plant (Köhler et al., 1996) and CCGT power plant (Hoffmayer et al., 1996).

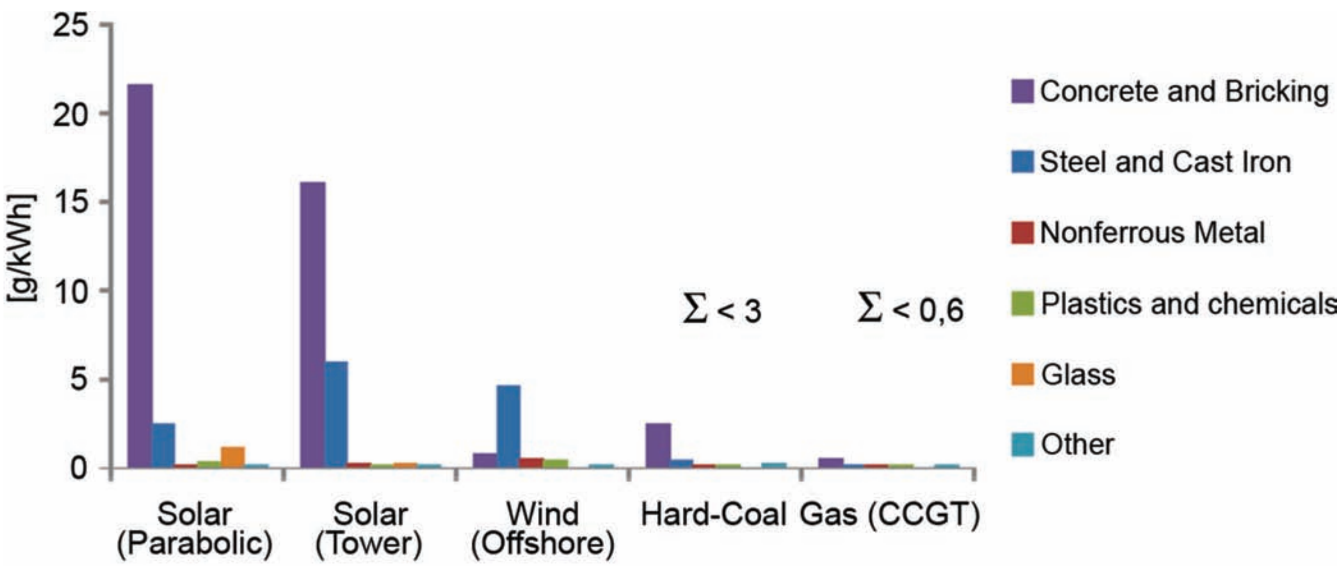


Figure 6.4 Global warming and acidification potentials from selected studies of the different power plant systems: parabolic CSP plant (May, 2005), tower CSP plant (Weinrebe, 1999), offshore wind farm (Wagner et al., 2010), hard coal (GaBi, 2007), and gas CCGT power plant (Ecoinvent-Database, 2007).

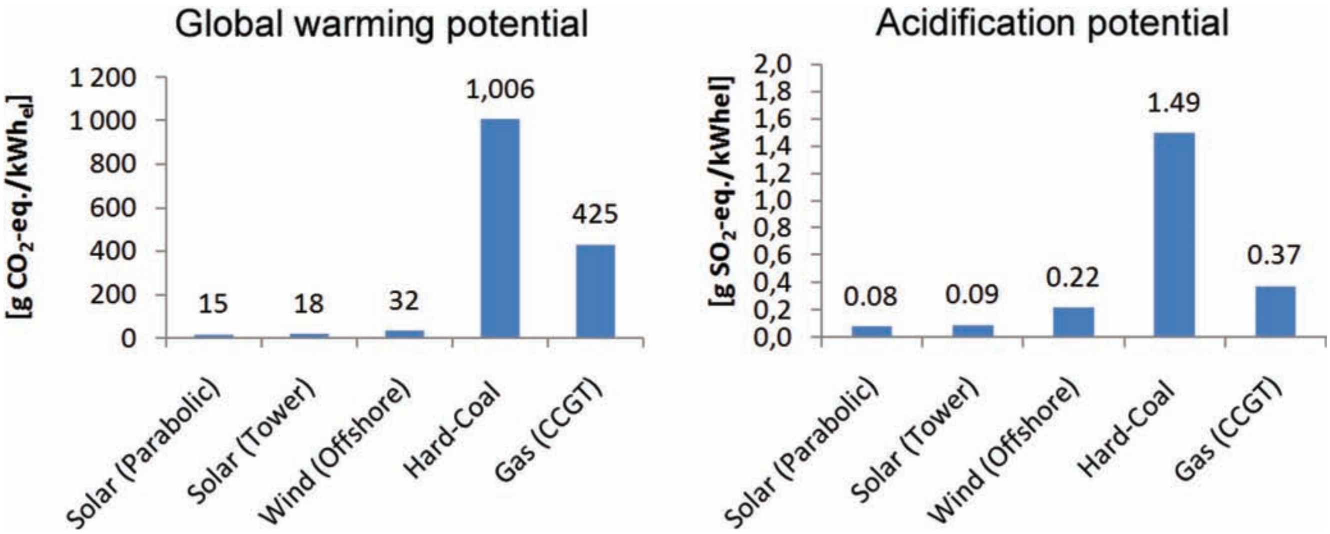
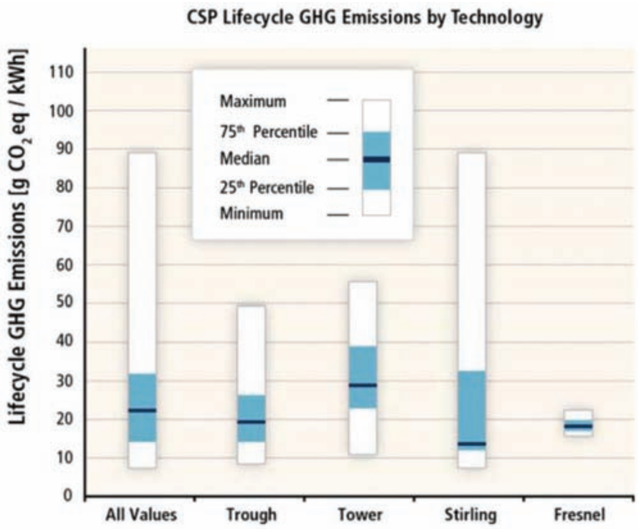


Figure 6.5 Greenhouse gas emissions of CSP technologies, including confidence intervals (IPCC, 2011).



	All Values	Trough	Tower	Stirling	Fresnel
Estimates:	42	20	14	4	4
References:	13	7	5	3	1

6.4 Emissions

The emissions of greenhouse gases are strongly linked to the cumulative (non-renewable) primary energy demand shown in Figure 6.2. As illustrated in Figure 6.4 (but with the reservation that the numbers are taken from different sources), greenhouse gas emissions for CSP plants are estimated to be in the range 15–20 grams CO_2-equivalent/kWh, much lower than CO_2 emissions from fossil-fired plants which are 400–1000 g/kWh. Figure 6.5 presents data for a wider range of CSP technologies and drawing on a larger number of studies (IPCC, 2011) indicating greenhouse gas emissions of about 9–55 g CO_2-eq/kWh for large-scale CSP technologies.

Figure 6.4 compares plants without salt storage (though the solar parabolic trough plant on which this figure is based includes a concrete thermal storage system). Using nitrous salts as heat transfer fluid and/or storage medium creates life cycle emissions of nitrous oxide (N_2O). Although the amounts are roughly 500–1000 times smaller than the carbon dioxide emissions associated with a coal plant (Viebahn et al., 2008), they are not negligible as N_2O is about 300 times stronger than CO_2 as a greenhouse gas.

Comparative emissions of acid gases are also shown in Figure 6.4. Again, coal-fired plants have the highest emissions, but in this case, natural gas-fired plants have values not much higher than the renewable technologies.

6.5 Impacts on flora and fauna

Local impacts of CSP plants on the environment may be associated with traffic, building works, ecosystem disturbance, and loss of ecosystem functions. Traffic, plant construction and surface treatment of parking plots cause indirect mortalities to local fauna at a level depending on the surface area of the facility and the land use type before plant construction.

Mortalities caused to vertebrates are the main concern in respect of the local environmental impact of CSP plants. Direct mortalities take place under two main circumstances: collision with top mirrors and buildings (the tower in particular), and heat shock or burning damage in the concentrated light beams. Birds rarely collide with CSP plants when visibility is good, but when vision is impaired casualties have been documented. A poorly illuminated solar tower can be hit by birds at night, but this is rare. Birds may mistake the reflecting surfaces for air or water and collide with them, for instance when taking flight from the ground. Insects can also mistake the glass surfaces for water and be killed, or lose eggs they are carrying, in attempts to enter the surfaces.

If a plant is built on former agricultural land, available nutrients in the soil may facilitate growth of vegetation up to 1 m in height below and between solar collectors. Under Mediterranean climates the vegetation can dry up and contribute to fire risk. Herbicides can be used to prevent plant growth, but they typically have toxic effects at some scale, persist in the soil profile, and may be exported with runoff. Alternative treatments of soil surface that impair seedling establishment include compacting the ground, enabling the development of a surface crust, or adding gravel.

The water used in mirror cleaning drips onto a narrow 'wet band' at the base of the collectors whose area is around 15–25% that of the collectors' surface. This cleaning water supply to the wet band may range from 10 to 20 mm/year, which can be a significant amount during dry summer months (particularly in desert areas), stimulating and/or maintaining plant growth.

As mentioned earlier, CSP plants may indirectly harm local animal or plant populations by cutting off migration routes. Another impact related to plant construction and operation is the introduction of species previously alien to the area. Gardening, goods and equipment, and public works machinery all contribute to introductions. Some other species actively follow contractors and colonise their area of activity, gaining from the removal of local species from the disturbed land.

Although CSP plants can have several effects on the local environment, compared with other technologies, particularly fossil-fired plants, they are relatively benign. The direct damage from solar plants is low: a monitored CSP tower plant operating since 2007 in Spain has so far (2011) only recorded two bird deaths. Even with a much larger implementation, environmental impacts will not be on the same scale of direct and indirect effects from fossil fuels, like the Deepwater Horizon oil disaster in the Mexican Gulf in 2010.

6.6 Overview

All power generation has some effects on the environment but it is evident that CSP plants on the whole have much better environmental performance than today's fossil-fired technologies. Not using extractable fuels means that CSP is free of the impacts from coal mining, spills from oil rigs, leakage of methane from gas extraction, etc. On the other hand, use of commodities such as steel, glass and concrete is relatively high, although most of these materials are readily available and have high recycling-potential. Issues that need to be addressed are water requirements in arid areas, use of toxic synthetic oils as heat transfer fluids, and use of pesticides to restrict vegetation growth in heliostat fields. For all of these issues, technical solutions are available or under development.

Environmental impacts vary between technologies and over time. Although some CSP technologies today are proven and commercialised, they are less mature than conventional fossil-fired power stations. This means that they can be expected to progress faster with innovation and improvements of efficiency, and hence the environmental impact of CSP technologies, relative to fossil-fired power, is likely to get (even) better over time.

7 Future contribution

Following an initial review of the present position of CSP deployment, this chapter summarises the EU and international policy goals relevant to CSP and then evaluates the key factors influencing the future contribution of CSP. Section 7.4 discusses the issues associated with development of CSP in the MENA region before a final section reflects on the prospects of CSP towards 2050.

7.1 The present position

An overview of CSP deployment across the world in 2011 is given in Figure 7.1. The underpinning data (derived from: California Energy Commission, 2010; CSP Today, 2011b; Greentechmedia, 2011; Protermosolar, 2011; US Bureau of Land Management, 2011) indicate that 1.3 GW of CSP were operational worldwide, 2.3 GW under construction, and 31.7 GW planned. Europe, and in particular Spain, has played an important role in the development of the early CSP market, with the benefit that most of the companies involved in CSP are based in Europe.

Current deployment of CSP (and PV) has exploited only a tiny fraction of the available solar resource, which is estimated to be capable of supporting an annual CSP output of 1800 TWh in Europe, mainly in Spain, Italy, Greece, Cyprus and Malta (Eck et al., 2007). This figure only considers unused, unprotected flat land area with no hydrographical or geomorphologic exclusion criteria and a direct annual solar radiation above 1800 kWh/m^2.

The 1800 TWh/y above corresponds to around half the EU's electricity consumption of 3400 TWh in 2008 (Eurostat, 2011), is around three times the potential of hydropower, and is similar to Europe's wind energy potential (on-shore and off-shore). But it is dwarfed by the solar resource available in neighbouring countries in North Africa and the Middle East (see Figure 7.2) which, as observed in Chapter 1, could support CSP capacity generating 100 times present electricity consumption in Europe and the MENA region (Knies, 2006).

Subsequent sections will explore the factors that will determine how much of this resource is exploited over the period to 2050.

Figure 7.1 Worldwide distribution of CSP plants that are operational, under construction and planned.

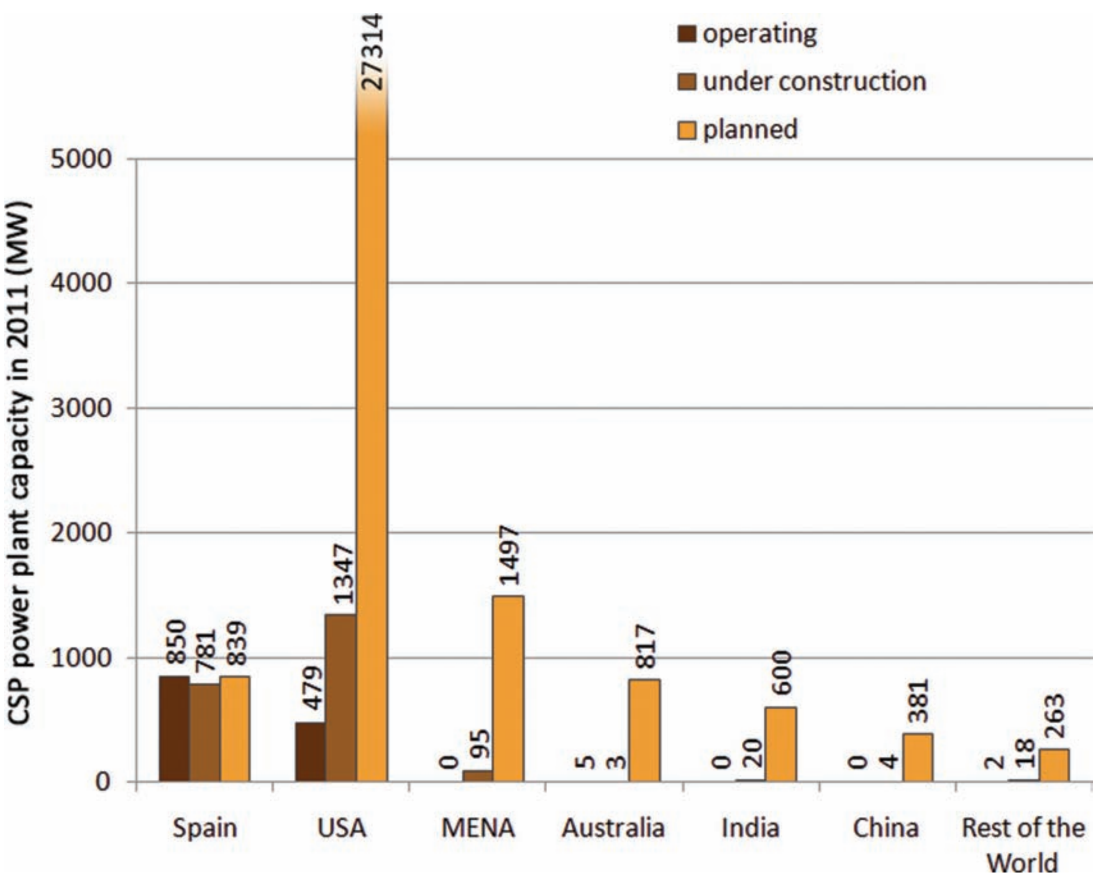
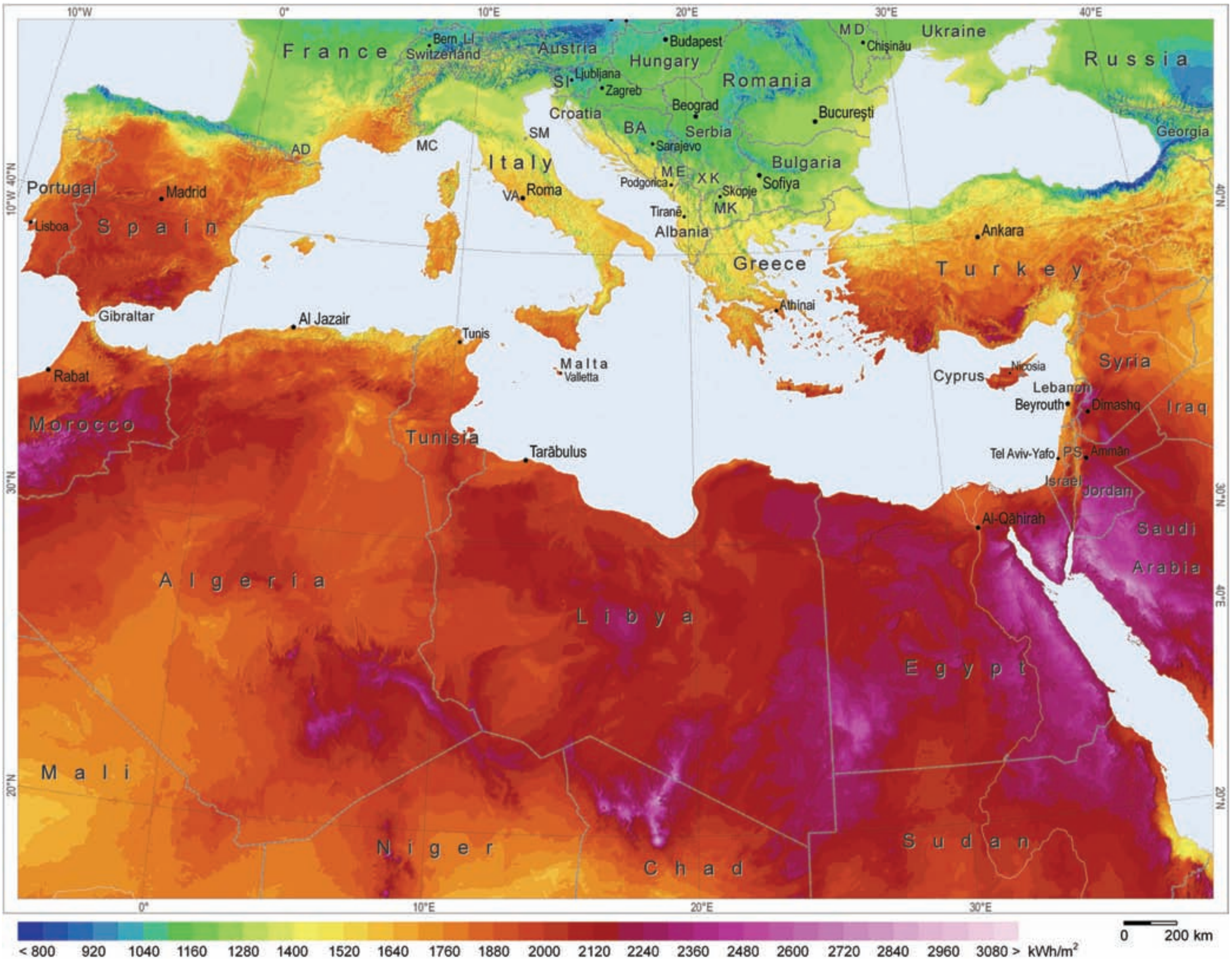


Figure 7.2 Direct normal irradiation potential (kWh/m²) for the Mediterranean area (http://solargis.info).



7.2 Policy goals

In considering the potential role of CSP in Europe towards 2050, the EU's objective of reducing greenhouse gas emissions by 80–95% by 2050 is a key parameter. Re-affirmed by the European Council in February 2011, this objective requires the EU's electricity system to achieve essentially zero emissions of greenhouse gases by 2050 (European Commission, 2011).

The 2050 generating mix may include nuclear power and fossil-fired power stations incorporating carbon capture and storage. But ongoing public concerns about nuclear power, exacerbated by the Fukushima accident in Japan in March 2011, have led some countries such as Germany to exclude it from consideration. Carbon capture and storage on fossil-fired power stations remains essentially unproven at commercial scale, with questions remaining as to whether sufficient safe storage sites, acceptable to the public and regulators, can be found. And it locks in Europe's exposure to fossil fuel price escalation and volatility.

Variable renewable sources such as wind, solar PV and marine energy will be required to play a major role in Europe's 2050 electricity system, but their variability will bring challenges of balancing supply and demand. An integrated European grid and market, together with demand management may go some way to meeting these challenges, but additional system storage capacity may be needed, and controllable renewable sources will be at a premium. Such sources include hydro and geothermal energy – but in both cases natural resources in Europe are limited – and CSP with storage, for which natural resources far outstrip anticipated electricity demand when account is taken of CSP potential in the neighbouring MENA region.

Whereas many forecasts anticipate limited, or no, growth in European electricity demand to 2050, in the MENA region population growth and economic development are expected to result in a rapid increase in electricity demand, potentially reaching similar overall levels to the EU by 2050 (for example, DLR 2005). International initiatives to limit global warming emphasise that such development should follow a sustainable path, putting an onus on maximising the use of indigenous renewable resources: the solar resource, of course, being dominant in the MENA region. However, as such renewable capacity is currently significantly more expensive than the fossil alternative, and given their economic starting point, MENA countries will require foreign assistance to follow such a low-carbon path.

The final piece of the policy jigsaw derives from the proximity of countries in the MENA region to Europe which brings them within the ambit of the EU's Neighbourhood Policy. This commits Europe to deepening relationships with neighbouring countries to strengthen security, stability and prosperity for all. EU policies already state the intention to better integrate energy markets with neighbouring countries (European Commission, 2010, 2011d), and to step up energy relationships with North Africa (European Commission, 2008, 2011c, 2011d). Initiatives such as the 'Union for the Mediterranean', and its associated 'Mediterranean Solar Plan', have recently been augmented by the G8 led 'Deauville Partnership' aimed at supporting democratic reforms in MENA countries, and developing an economic framework for sustainable and inclusive growth, as discussed in Chapter 2.

7.3 Key factors influencing the future contribution of CSP

As discussed above, it is not a shortage of sunshine in Southern Europe and the MENA region which will constrain CSP's contribution but other factors, particularly the following:

- CSP's **generating costs** in relation to alternative technologies, and the **values** of CO_2 mitigation and of CSP generation compared with alternatives;
- **physical constraints** on the installation of CSP generating capacity due to the availability of land, water, manufacturing capacity, skilled labour, etc.;
- physical and operational constraints on the **transmission** of electricity across Europe and the MENA region to balance supply and demand; and
- considerations of **security of supply**, particularly the comparative vulnerabilities inherent in different energy vectors when imported from other countries.

Other factors beyond the scope of this report include the political issues associated with the provision of subsidies, and legal aspects concerning, for example, conditions and guarantees for foreign investments, particularly in MENA countries.

Chapter 5 has discussed anticipated reductions in CSP **generating costs** and reflected on the expectation that they may be competitive with fossil-fired power generation somewhere between 2020 and 2030, depending on the slope of the learning curve for CSP, the value placed on CO_2 mitigation, and future fossil fuel prices. In specific locations with good solar resources this point may be reached earlier. Also as discussed in Chapter 5, CSP with thermal storage may carry a premium in **value** in the bulk electricity market compared with variable renewable sources such as wind and PV owing to its ability to provide dispatchable electricity and other grid services.

To reach cost competitiveness, incentives and subsidies will be required to trigger project development activities, construction of plants and the erection of additional manufacturing facilities for key-components, as well as to drive cost-targeted R&D. Other renewable technologies face a similar situation. Demonstration plants are a key stage in achieving the necessary scale-up and commercialisation of new technologies, and subsidy schemes need to ensure that they are funded.

CSP Today (2011) describes feed-in tariffs available in eight countries around the world, and Table 7.1 summarises the incentive schemes for CSP currently in place in Greece, Italy, Portugal and Spain.

The total amount of incentives that will be required is sensitive to the rate at which CSP costs reduce as installed capacity increases due to cost reductions from scaling up, volume production and technological innovation (amalgamated, as discussed in Chapter 5, in a simple 'learning rate'). For example, if today 60% of the CSP capital cost needs to be subsidised (assumed for simplicity as a grant) but only a 10% subsidy is needed when CSP generating costs are halved, then the cumulative subsidy to achieve a halving of costs is €6.5 billion for a learning rate of 20% (corresponding to an installed capacity of 9 GW), and €61 billion if it is only 10% (corresponding to an installed capacity of 100 GW). Two recent estimates of the total incentive payments needed to achieve cost parity fall within this range of cumulative subsidies: Ummel and Wheeler (2008) estimate it at US$ 20 billion (corresponding to 20 GW of CSP), Williges et al (2010) at €43 billion for their baseline case (corresponding to 157 GW of CSP).

Although investments in this range are substantial, they are small compared with those required to be made in energy systems worldwide over coming years (IEA, 2010) and the €1 trillion investment estimated to be required in the EU's energy system by 2020 (European Commission, 2010). And they would establish a cost competitive renewable option with favourable operating characteristics and essentially unlimited natural resources.

Incentive schemes need to send the right price signals and appropriately reflect the time varying value of

Table 7.1 Present CSP incentive schemes in Greece, Italy, Portugal and Spain

Country	Incentive scheme
Greece	Feed-in tariff of 26.5 € cents/kWh, rising to 28.5 € cents/kWh if at least 2 hours storage is incorporated. Payable for 20 years.
Italy	Feed-in tariffs in Italy, valid up to the end of 2012, for 25 years after start-up of the plant are: • 28 € cents/kWh for integration with other energy sources which provide up to 15% of the energy input; • 25 € cents/kWh for integration with other energy sources over 15% up to 50%; and • 22 € cents/kWh for integration with other energy sources over 50%. A reduction of 2% per year after 2012 is foreseen for start-up during 2013 or 2014. Incentives are limited to CSP plants with less than 1.5 million m^2 of installed solar collectors (mirrors).
Portugal	Average indicative tariff for CSP installations <10MW: 26.3–27.3 €cents/kWh (valid for 15 years)
Spain	Promoters can chose between two different schemes: • a fixed price of about 28.5 € cents/kWh with small yearly variations due to the inflation index; • a premium that adds to the pool price, but the sum of pool price plus premium has a guaranteed minimum of 26.9 € cents/kWh and a maximum of 36.4 € cents/kWh. These prices are granted for 25 years. For new plants to be installed after 2013 the total power will be limited every year and the premium will be substantially smaller.

electricity. If they do, then the commercial optimisation of the CSP investor will lead to a configuration which is also optimal from the perspective of the entire electricity system. Some current subsidy schemes do not, resulting in inappropriately designed plants. For example, in Spain the feed-in tariff varies by no more than 20% between peak and off-peak hours resulting in CSP plants incorporating an inefficiently high level of storage.

The evaluation of alternative investment opportunities needs to be informed by the marginal system cost. The best proxy for this marginal system cost is the competitive cost of energy, and the design of markets, policies and subsidies to promote CSP generation should support the effective operation of the competitive pricing system.

Given its influence on the total amount of incentive payments that will be required for CSP to achieve cost parity with fossil-fired generation, it will be important to establish, and monitor, the learning rate of CSP. Subsidy schemes should ensure that the required cost data are made publicly available, but without compromising commercial incentives to innovate and reduce costs.

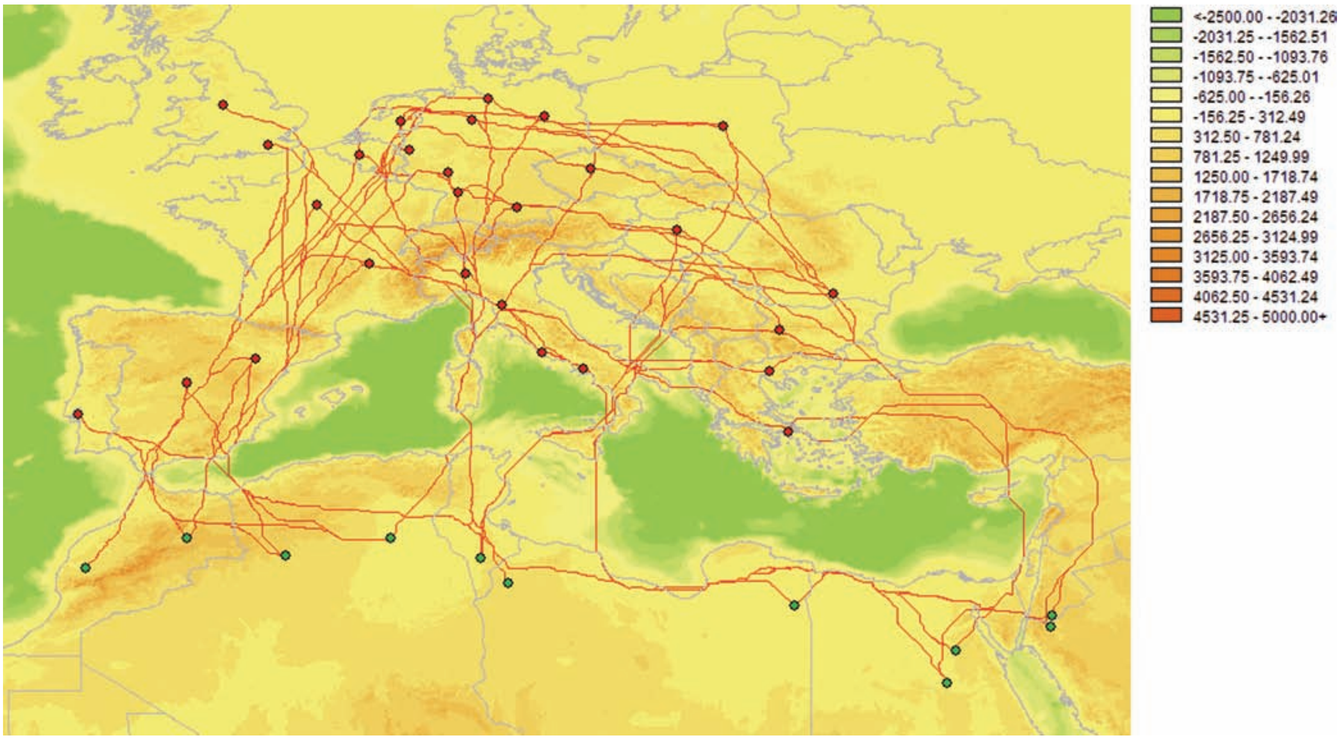
With regard to **physical constraints**, Chapter 6 has discussed the issues of water availability for CSP, particularly in desert regions, and pointed to the need for further development of dry cooling systems which minimise the associated generating efficiency penalty. As discussed earlier, plenty of potentially suitable land exists, particularly in the MENA region, but land acquisition, planning permissions, etc. take time and might at some points constrain high rates of development of CSP, particularly in Southern Europe.

Achieving an essentially zero carbon electricity system in Europe by 2050, will require the replacement of much of the existing generating capacity over the intervening period. Similarly, meeting the MENA region's anticipated expansion in electricity supply will require large and sustained investments in new generating capacity. The availability of the required manufacturing capacity for a major expansion of CSP is appropriately considered in this context, particularly as many of the plant components such as turbines, heat exchangers, piping, etc. are common to many of the candidate technologies. Significant increases in, and shifts of, manufacturing capacity will be required whichever generating mix is chosen.

The analysis presented in Chapter 6 has indicated that CSP is more material intensive in its construction that fossil-fired plants, primarily in commonplace materials such as steel, glass and concrete. Given the levels of production of these materials in the economy more generally, it seems unlikely that their availability will prove to be an insurmountable constraint on CSP expansion. However, costs of these materials are rising and there is burgeoning demand in rapidly developing economies such as China and India. Further studies could usefully therefore be undertaken to examine potential manufacturing constraints to a major expansion of CSP which should look, in particular, at possible bottlenecks, for example manufacturing capacity for receivers and the availability of salts for thermal storage.

Growth of CSP will require the development of an associated workforce with the skills necessary to support equipment manufacture, plant design and construction, and plant operation. For example, a typical 50 MW trough CSP plant in Spain employs 40 people as permanent staff, and several hundred on the site over more than one year in the construction phase. In addition, an increased workforce is needed in the component supplier industry. In a high-growth

Figure 7.3 Exploration of potential transmission routes for HVDC lines connecting CSP plants in the MENA region to demand centres in Europe (DLR, 2009). The background map shows the elevation in metres above/below sea level.



(60% per annum) scenario examined by the World Bank (2011) 14.5 GW of installed CSP capacity in 2025 in the MENA region is estimated to correspond to 65,000–79,000 permanent jobs in the region (around 75% in manufacturing and construction and 25% to support operation).

Although a sustained and rapid growth of CSP in Europe and the MENA region would require co-ordinated efforts to enable the associated re-deployment and re-skilling of a substantial workforce, it is instructive to note that in a five-year period the renewable energy industry in Europe increased its workforce from 230,000 to 550,000 (European Commission, 2011). More generally, in countries with favourable policies towards wind and PV, annual growth rates of 60% have been sustained over a decade until growth has slowed as markets have matured (World Bank, 2011).

In the scenario where the EU's demand for renewable electricity remains strong, CSP capacity may be built in the MENA region which exports electricity to Europe. Grid connections will need to be built between Europe and the MENA region to enable the **transmission** of the CSP electricity. At present, active connections between the MENA region and Europe are limited to two undersea cables between Morocco and Spain (each 700 MVA, 400kV AC lines) (Resources and Logistics, 2010). Interconnections between MENA countries are generally rather limited, the area comprising Morocco, Algeria and Tunisia being the main interconnected area.

In a scenario for 2050 in which Europe imports 750 TWh per annum of CSP electricity from North Africa (around 20% of current EU electricity use), PriceWaterhouseCoopers (2010) emphasise the need to construct a large number of cross-Mediterranean HVDC links, each fully integrated into the overlay grid, ensuring redundancy of import/export lines and reducing vulnerability to interruptions in supply. Similarly, DLR 2006 consider a scenario for 2050 in which 15% of EU electricity demand is met by solar inputs from the MENA region transmitted by 20 power lines each of 5 GW. Figure 7.3 illustrates the outcome of an exploration of potential transmission routes for HVDC lines connecting CSP generation in 11 sites in the MENA region with 27 European demand centres (DLR, 2009).

It is generally considered that a high-voltage direct current (HVDC) grid needs to be built as a 'back bone' or 'super-highway' across Europe and the MENA region to augment existing high voltage alternating current (HVAC) transmission and distribution systems. Modern HVDC lines can limit transmission losses over 3000 km to around 10%. Transfer of electrical power over such distances is an impractical proposition for HVAC lines where the losses would be nearer to 50% (DLR, 2006). In addition, HVAC grids will need to be reinforced and 'smart' grid technologies will be widely deployed.

The current limitations of Europe's electricity grid, and developments needed to meet the EU's policy aims for a reliable and well-integrated electricity market supporting a substantially increased share of renewable energy sources, have been discussed in a previous EASAC report on the European grid which also considered potential technological developments in transmission technologies (EASAC, 2009). These transmission limitations are well-recognised in the EU's energy strategy which aims to secure the grid reinforcements necessary for the effective functioning of the EU market and the trans-national transfers of bulk electricity associated with geographical diversity as a mechanism for matching supply and demand for renewable energy sources (European Commission, 2010).

Transmission enhancement projects in Europe face long delays: the time from the start of planning to the issuing of the building permit for a Trans-European Energy Networks (TEN-E) priority electricity transmission project is on average seven years, with 25% of projects requiring more than twice this time (MVV consulting, 2007). The EU's energy strategy (European Commission, 2010) aims to address this problem, streamlining permit procedures for projects of 'European interest' through rationalising regulatory arrangements and enhancing public acceptance through better engagement processes.

Increasing **security of supply** of energy is a key concern of EU energy policy. To the extent that CSP capacity is located in Southern Europe, it contributes positively to increasing supply security as it reduces the need for energy imports (currently standing at over 50% of the EU's energy use, mainly for fossil fuels). The security of supply issues associated with Europe importing CSP electricity from the MENA region are not so clear cut, and political upheaval in some countries in the MENA region during this study has provided a challenging backdrop to any consideration of security issues. The next section provides some reflections on the potential role of CSP deployment as a component of international initiatives to support the development of stable and prosperous democracies in the MENA region.

More generally, security considerations arising from the import of CSP electricity from the MENA region include the following:

- Interruptions of power supplies can cause significant economic harm (PriceWaterhouseCoopers (2010) present a figure of 8 €/kWh lost) and a short power disruption causes major disturbance, whereas a short interruption to gas or oil supplies can easily be managed. However, diversification of supply sources and routes can help to mitigate the risks of supply interruptions due to terrorism or political interference, and currently there is a substantial reserve of fossil-fired capacity.
- Unlike fossil fuels and uranium, an interruption in the supply of electricity would represent an unrecoverable loss of revenue for supply countries, because electricity cannot be stored, and would likely harm exporting countries more than the supply interruption would harm Europe (IIASA, 2009).
- Import of CSP electricity would enable reduction of the imports of fossil fuels which constitute a major risk to Europe due to the possibility of supply interruptions, and the economic consequences of price volatility and potential sustained future price rises if the world does not take co-ordinated action to reduce fossil fuel dependence (European Commission, 2011).

Integration of energy markets with neighbouring countries is a particular EU initiative which should help to mitigate risks from CSP imports (European Commission, 2010 and 2011d). Also, in a scenario in which there is a lot of excess CSP capacity in the MENA region, some of it may be used to generate hydrogen or syngas for export to Europe so helping to mitigate the immediacy of supply disruptions if just electricity were exported. However, there may be significant energy losses associated with this option (DLR, 2006).

7.4 Development of CSP in the MENA region

The MENA region is particularly well-suited to the development of CSP, not just because of the size and quality of its solar resource, its rapidly increasing indigenous electricity demand and its proximity to Europe with its appetite for 'CO_2-free' power. CSP technologies (unlike some other renewable energy technologies) lend themselves to high levels of local-deliverables, well-matched to the capabilities of the workforce and industries in the region. A recent review of the value chain of CSP technologies by the World Bank (2011) concluded that a high proportion of the value (up to 60% by 2020) could be created locally, including the manufacture of most CSP plant components, as well as in construction, civil works and plant operation.

The MENA region is already shifting from having mainly low-cost contracting industries, to a greater proportion of more skilled and high-tech production (World Bank, 2011), meaning that it can increasingly capture value at the high-tech end of the CSP technology spectrum. There is a growing foundation for a local CSP industry, with strength in lower labour costs, close proximity to deployment and strongly growing economies. To realise it, a focused effort is needed from public bodies at all levels, with emphasis on international co-operation, education and training, and removal of administrative barriers.

Although there is well established co-operation between industries in the MENA region and western countries, intra-regional co-operation is limited, and needs to be developed further (World Bank 2011). Investment conditions need to be created that are attractive to international companies (a key factor here being the existence of a predictable and stable market: World Bank, 2011), and also provide for ownership arrangements that allow the people of the concerned countries to take a share in the profits. An important message is the need for continuity of initiatives to support the development of CSP in order to create the right conditions for local and international business, and to enable the success of key supporting measures such as skills development.

Rapidly growing indigenous demand, enhanced opportunities for CO_2 displacement compared with Europe, and losses of up to 10% incurred in transporting CSP electricity to major demand centres in Northern Europe, point to the prioritisation of domestic use of MENA-generated CSP electricity over its export to Europe. The balance available for export to Europe will depend on the rate of installation of CSP capacity in the MENA region, the value ascribed to export revenues by MENA countries, and the motivations of the EU in supporting the development of CSP in the MENA region. Some portion of CSP generation would need to flow into Europe if its financing is motivated, at least in part, with achieving the EU's policy goal of a zero-carbon electricity system by 2050.

However, the large investments needed for new CSP power plants are not profitable in today's markets (particularly as investors currently price-in high risk premiums due to unstable political and regulatory conditions), and Government subsidies through feed-in tariffs in the MENA countries are unlikely. Feeding into European networks, where customers could pay higher prices for renewable energy, is inhibited by the lack of energy-efficient HVDC transmission networks. In turn, no investments in such networks can be expected while little desert power is produced.

The challenge is to take a co-ordinated approach, simultaneously addressing the different bottlenecks (investment protection, energy policy incentives, R&D, etc.), and to identify options which lower the barriers to entry for other actors. For this purpose, a transformation process needs to be designed and supported scientifically over a long period. This will require financial incentives from the EU. The Desertec Foundation (www.desertec.org), and associated Desertec Industrial Initiative (www.dii-eumena.com), are important initiatives that aim to realise the potential contribution of renewable energy from desert areas.

7.5 Looking towards 2050

Viewed as a 'project' undertaken over the 40 year period to 2050, CSP development in Europe and the MENA region has an initial investment phase lasting 10 to 20 years involving incentive payments measured in billions of euros or tens of billions of euros (depending on whether the learning rate in practice is at the high or low end of the range of possibilities), resulting in a pay-back over the subsequent period to 2050 and beyond, the returns depending on the value ascribed to avoiding CO_2 emissions and future fossil fuel prices. Additional motivations to undertake the project include establishing a sustainable energy system, reducing dependence on imported fossil fuels, job creation and supporting the development of prosperous democracies in MENA region countries.

In embarking on this project a phased approach is appropriate, where progress to subsequent phases is contingent on the emerging picture of the merits of CSP compared with other options. Learning mechanisms need to be built in which allow early feedback on the learning rate of CSP compared with other renewable technologies, particularly PV, and the value of the dispatchability of CSP with storage as the generating mix develops.

Given these considerations, it would be inappropriate to say at this time what the size of the project should eventually be in terms of the CSP capacity installed in Europe and the MENA region. Suffice to say that CSP has the potential to make a major contribution to achieving a zero- or close to zero-carbon electricity supply in Europe and the MENA region in 2050. The CSP 'project' therefore merits strong support from the EU, and from national governments in Europe and the MENA region, particularly as there is a limited range of alternatives, each of which has associated challenges.

Others have explored particular scenarios for CSP in Europe in 2050. For example:

- DLR (2006) considers CSP electricity imports into Europe from the MENA region in 2050, of 700 TWh (around 20% of current EU electricity consumption).
- European Climate Foundation (2010) looks to MENA-based CSP to provide 15% of Europe's electricity in a 2050 scenario in which renewable energy sources provide all of Europe's energy.
- In the 2050 scenario explored by Wenzel and Nitsch (2010), 12% (812 TWh) of electricity demand in Europe and the MENA region is provided by CSP.
- The IEA CSP Technology Roadmap (IEA, 2010b) projects an annual consumption of CSP electricity by the EU and Turkey in 2050 of around 700 TWh, of which around 600 TWh is generated in the MENA region.

8 Conclusions

1. CSP is a reliable, proven renewable technology for generating electricity. Based in the sunny regions of the World, and in Southern Europe and the MENA region in particular, it can potentially make a substantial contribution to mitigating greenhouse gas emissions and establishing a sustainable energy system. There are various CSP technologies with different advantages and disadvantages, and no clear 'winner', though the relative maturity of parabolic troughs have to date made them the preferred choice for most commercial plants. CSP plants need to be designed to optimally meet local and regional conditions.

2. Currently, electricity generated by CSP plants located where there are good solar resources costs 2–3 times that of electricity from existing fossil-based technologies without carbon capture and storage. This is mainly due to the costs of the solar field installation which are still relatively high. Considering other renewable electricity sources, CSP generation costs are on a par with offshore wind, but are significantly more expensive than onshore wind. In 2010, the average cost per kilowatt-hour for CSP and large-scale PV systems were broadly comparable. But currently, intensive competition, particularly from Asia, has depressed PV prices giving them the edge over CSP systems. Future competition will depend on the speed of cost reduction of both technologies as well as on the question of how additional services provided by CSP (dispatch, capacity, etc., as discussed below) will be valued.

3. Provided that commercial deployments of CSP plants continue to grow, and that these deployments are associated with sustained research, development and demonstration programmes, CSP generating cost reductions of 50–60% may reasonably be expected over the next 10 to 15 years. Allowing for some escalation in fossil fuel prices and incorporation of the costs of CO_2 emissions in fossil generation costs (through carbon pricing mechanisms and/or requirements to install carbon capture and storage), it is anticipated that CSP should become cost competitive with fossil-based generation at some point between 2020 and 2030. In specific locations with particularly good solar resources this point may be reached earlier.

4. CSP plants that incorporate thermal storage offer additional potential benefits beyond the value of the kilowatt-hours that they generate, as they can provide dispatchable power, helping the grid operator to reliably match supply and demand. The value of this capability is context specific, but increases as the proportion of electricity generated by variable renewable sources such as wind and PV increases. As long as no cheap electric storage system is available, wind and PV alone are unlikely to be a solution for a carbon free electric generation system. CSP with storage may therefore, in future, offer a cost-effective way of enabling the incorporation of substantial contributions of variable renewable sources in electricity systems. System simulation studies are needed to develop a better appreciation of the circumstances in which CSP with storage is the preferred choice to fulfil this role (including scenarios in which electric car usage is substantially increased). And CSP subsidy schemes need to reflect the price signals from competitive electricity markets in order that CSP investors make appropriate decisions on storage.

5. Supplementary firing with fossil fuel or biomass further enhances the ability of CSP plants to provide grid services and may reduce generating costs. Alternatively, CSP may be used to augment the efficiency of conventional fossil fuel fired plants. These may prove to be useful bridging technologies en route to achieving low/zero-carbon electricity systems by 2050 by enabling the replacement of fossil capacity.

6. Environmental impacts of CSP plants are generally low, and may be expected to further improve compared with fossil-fired technologies over time given the relatively early stage of development of CSP. While the construction of CSP plants is more material intensive than fossil-fired plants, the required materials are mainly commonly available, and readily recyclable, materials such as steel, concrete and glass. Given the likely positioning of CSP plants in arid areas, their use of water, particularly for cooling, is an issue pointing to the need to improve the performance of air cooling systems. CSP may play a role in sea water desalination in the MENA region, but water prices will need to be higher, and subsidies will initially be needed to overcome the current cost differential compared with fossil-fired desalination, before CSP-based desalination can make a significant contribution to meeting the MENA region's freshwater needs.

7. The solar resource in Southern Europe is such that CSP could provide a useful contribution to achieving Europe's aim of a zero-carbon electricity system by 2050. Solar resources in the MENA region are even better, and far larger. Once CSP achieves cost parity with fossil-fired generation, these resources have the potential to transform the system of electricity generation in Europe and the MENA region. However, substantial **challenges** will need to be overcome if this transformation is to be achieved.

8. The **first challenge** is to move towards, and in time to achieve, cost parity of CSP and fossil-fired generation. Around half of the anticipated reductions in CSP generating costs are expected to come from technology developments, and the other half from economies of scale and volume production. The study has identified the most promising areas of scientific and technological development to realise cost reductions. Well-designed incentive schemes will be needed, which reflect the real, time-varying value of generation so that CSP plants are appropriately designed, and which effectively drive research and development activities. Schemes need to ensure that new CSP technology innovations can progress rapidly from the laboratory to pilot and demonstration scales, and to commercial application.

9. Incentive schemes may be specific to particular technologies (for example, differentiating between CSP and PV), or may give more generic support to increasing the installed capacity of low-carbon technologies while also supporting technology specific research, development and demonstration. In either case, the total amount of subsidy that will be needed to achieve cost parity will depend crucially on how quickly costs reduce as installed capacity increases. Incentive schemes need to ensure that cost data are made available so that the learning rate, and its underlying drivers, can be established and monitored, and consequently energy strategies and incentive schemes can be adjusted as appropriate.

10. In the medium term, CSP's ability to support the system integration of variable renewable sources suggests that its further support should not be determined solely by its short-term competitiveness with PV systems. CSP and PV may prove to be complementary technologies in harnessing the solar resource, and it is appropriate to continue to support both technologies at the present time.

11. CSP technologies are consistent with a high share of local value creation, which with appropriate investments in skills and manufacturing facilities may be expected to increase over time. This local benefit is more pronounced than for other renewable technologies such as PV, and supports economic development, particularly in countries with increasing industrialisation, creating local jobs, wealth and expertise.

12. The **second challenge** is to establish the grid connections and market mechanisms that will enable the integration of solar power in Europe and in the MENA region. If substantial amounts of CSP electricity are to be exported from the MENA region to Europe, then large investments will need to be made in grid connections between MENA countries and Europe, and in HVDC lines in Europe to transport electricity to demand centres.

13. The **third challenge** relates to the development of CSP in the MENA region as a potentially significant component of initiatives to support low-carbon economic development and political progress in the region, while addressing security of supply concerns if Europe were to rely heavily on solar power from the MENA region. Given the rapidly increasing demand for electricity in MENA countries, much of the electricity generated by CSP plants in the MENA region over the short to medium timescale may, and should, be expected to be used locally rather than exported to Europe, thus avoiding the construction of fossil-fired capacity in the MENA region. Financing schemes, and associated political agreements between the EU and MENA countries, will be needed to enable these short to medium timescale developments. Without financial commitments in the order of billions of euros from Europe, renewable energy technologies, including CSP, are unlikely to develop quickly in the MENA region.

14. Looking towards 2050, if investments in CSP capacity in the MENA region are sufficient, there is the potential for major exports of electricity to Europe. It is possible that solar-generated hydrogen and syngas exports may also play a role. The closer economic and social integration of the EU and MENA region anticipated by the Barcelona Process, the Deauville Partnership, etc. will be critical in ensuring that security of supply concerns can be allayed. Imports of solar electricity from the MENA region would lower dependence on imports of fossil fuels from that region, and other regions too.

15. The rationale for Europe to support CSP deployment in the MENA region derives in part from its commitments to support sustainable economic development in the region as discussed in Chapter 2, and is twofold. Firstly, CSP is an attractive and easily integrated option to limit CO_2 emissions resulting from the increased energy consumption associated with population growth and economic development in this region. Secondly, local suppliers can undertake a substantial portion of the activities needed to design, build and operate CSP plants, bringing regional development and employment benefits, and consequently contributing to the development of stable societies.

16. A co-ordinated approach is needed, simultaneously addressing the different bottlenecks (investment protection, energy policy incentives, R&D, etc.), and identifying options which lower the barriers to entry for other actors. For this purpose, a transformation process needs to be designed and supported scientifically over a long period. Scientific academies in Europe and the MENA region can play a useful role in supporting this process.

9 Recommendations

The following recommendations arise from the study and are aimed at policy-makers in the European institutions – in particular the European Commission and Parliament – and in the EU Member States.

1. Over the interim period until CSP achieves cost parity with fossil-fired generation, incentive schemes to subsidise renewable energy generation should be extended and harmonised, and designed to:
    - reflect the true value of electricity to the grid;
    - effectively drive research and development, and enable the market entry of technology breakthroughs;
    - ensure transparency of cost data; and
    - be progressively reduced over time.
2. R&D should be funded at EU and national levels to complement commercially funded research. Funding schemes should ensure that market realities are strong drivers of R&D, and should ensure that new technologies can progress rapidly from the laboratory, through pilot and demonstration scales, to commercial application. They should cover:
    - fundamental research on high-temperature materials, optical coatings, radiative heat transfer modelling, etc.;
    - potential technology breakthroughs in solar collectors, heat transfer fluids, and thermodynamic cycles; and
    - improving the performance, and reducing the cost, of storage systems through new storage media and designs.
3. Further system simulation studies should be undertaken, including the use of high resolution and (ideally) stochastic power system models, to look at interaction effects for different shares of renewable energy sources at EU, MENA and EU–MENA levels of power system integration. Understanding from these studies, together with data on the learning rates of CSP and PV technologies, should be used to guide the development of the optimal mix to harness solar resources.
4. A transformation process should be defined that addresses the technical, political and socio-economic factors necessary to achieve integration of EU and MENA energy systems and to strengthen the implementation of renewable options in the MENA region. Co-funding and co-financing options for CSP in the MENA region should be developed by the EU at a substantial scale as part of its neighbourhood policy, and potentially through the proposed 'EU-Southern Mediterranean Energy Partnership' (European Commission 2011c, 2011d).
5. Transmission capacity should be installed in Europe and the MENA region as necessary to enable the system integration of CSP electricity. To the extent that substantial exports of CSP electricity from the MENA region to Europe are anticipated, or there is a strategic intent to enable that option, then high-voltage direct current links between MENA countries and Europe should be created.
6. Capacity building initiatives should be put in place to support sustainable growth of the necessary technological skills in the relevant countries and regions. Such initiatives may include developing international networks of universities and industrial companies, and programmes for technology transfer from research to industry.

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Annex 1 Working group membership, meetings and presentations

Working group membership

Professor Amr Amin, Helwan University, Egypt

Professor Marc Bettzüge, Cologne University, Germany

Professor Philip Eames, Loughborough University, UK

Dr Gilles Flamant, CNRS, France

Dr Fabrizio Fabrizi, ENEA, Italy

Professor Avi Kribus, Tel Aviv University, Israel

Professor Harry van der Laan, Universities of Leiden and Utrecht, Netherlands

Professor Cayetano Lopez Martinez, CIEMAT, Spain

Professor Fransisco Garcia Novo, University of Seville, Spain

Professor Panos Papagiannakopoulos, University of Crete, Greece

Mr Erik Pihl, Chalmers University of Technology, Sweden

Professor Robert Pitz-Paal (Chair), DLR, Germany

Mr Paul Smith, University College Dublin, Ireland

Professor Hermann-Josef Wagner, Ruhr-Universitat Bochum, Germany

EASAC Secretariat

Dr Christiane Diehl, EASAC Executive Director

Dr John Holmes, Secretary to the EASAC Energy Programme

Meetings and presentations

Meeting 1

ENEA Casaccia Facility, Rome: 26–27 August, 2010

Presentations from:

Dr Luis Crespo, Protermo Solar: 'Overview of CSP technologies and current developments in Spain'

Dr Rainer Tamme, DLR: 'Storage issues'

Dr Fabrizio Fabrizi on the ENEA Casaccia facility

Professor Mark O'Malley, University College, Dublin: 'Electricity system integration'

Dr Nikolaus Benz, ESTELA/Schott CSP: 'Economics of concentrating solar power'

Meeting 2

CIEMAT's Plataforma Solar Facility, the Andasol CSP plant, and DLR Office, Almeria: 29–30 November, 2010

Presentations from:

Ms Lucia Doyle on the Andasol plant

Dr Francisco Martin on the Plataforma Solar facility

Mr Antonio Hernandez, Spanish Ministry of Industry: 'The Spanish experience of tariffs to incentivise concentrating solar power'

Mr JuanMa Rodriguez Garcia, RED Electrica de Espana: 'The experience of integrating CSP in the Spanish grid'

Meeting 3

Seligenstadt, Germany: 10–11 March 2011

Meeting 4

DLR solar facility, Cologne, Germany: 14 June 2011

Presentation from:

Dr Michaela Fürsch, Institute of Energy Economics at the University of Cologne, on the Iberian Peninsula simulation

Annex 2 Glossary

Annual capacity factor: the ratio of the actual output of a power plant over a year and its potential output if it had operated at full nameplate capacity the entire time

Black start: a black start is the process of restoring a power system to operation without relying on the power system itself to be energised.

Brayton cycle: the thermodynamic cycle converting heat into power using gas turbines.

Concentration ratio: ratio between energy density at the exit aperture of a concentrator to the energy density at the aperture entry.

Cosine effect: the energy density on a plane that is not perpendicular to the direction of the radiation is reduced by the cosine of the angle of incidence.

CO2-equivalent: used to compare the climate impact of emissions of different kinds of greenhouse gases: the amount of carbon dioxide with the same climate forcing potential.

Direct normal irradiation/insolation (DNI): direct irradiance on an area perpendicular to the sun rays,

Energy Return on Investment: the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource

kW/MW/GW: units of power. The basic unit is the watt = 1 joule (unit of energy) flowing per second. kW is the symbol for a thousand watts, MW the symbol for a million watts, and GW the symbol for a billion watts.

kWh/MWh/GWh: measures of energy corresponding to the measures of power listed above. So, for example, 1 kWh is the amount of energy resulting from the flow of a kW of power for an hour.

Levelised electricity cost: the cost of generating a unit of electricity taking account of all costs – capital, fuel, operation and maintenance, etc. – over the lifetime of a generating plant.

Marginal system cost: the cost of the last unit of electricity generated at a particular point in time.

Nominal power: power output under design point conditions.

Opportunity cost: the cost of any activity measured in terms of the best alternative forgone.

Optical efficiency: energy fraction that is transferred through an optical system.

Price curve: the varying price of electricity in a market over the year, typically hour by hour.

Rankine cycle: the thermodynamic cycle converting heat into power using steam turbines.

Reactive power: in alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power. On the other hand, the portion of power flow due to short-term (less than a quarter of the period of the fundamental frequency) stored energy, is known as reactive power. The associated currents are called reactive currents.

Smart grid technologies: technologies which enable an electrical grid to predict and intelligently respond to the behaviour and actions of all electric power users connected to it - suppliers, consumers and those that do both – in order to efficiently deliver reliable, economic, and sustainable electricity services.

Solar multiple: the ratio of the actual size of a CSP plant's solar field compared with the field size needed to feed the turbine at design capacity at reference solar conditions.

Solar to electricity efficiency: fraction of electric energy produced by a solar system to the solar radiation energy collected by the optical aperture of the system.

SO_2-equivalent: used to compare the acidification potential of emissions of different kinds of acid gases: the amount of SO_2 with the acidification potential.

Stirling cycle: is the reversible thermodynamic cycle, driven by an external heat source, used in Stirling engines.

Syngas: is a gas mixture that contains varying amounts of carbon monoxide and hydrogen.

Thermocline: is a thin but distinct layer in a large body of fluid in which temperature changes more rapidly with depth than it does in the layers above or below.

Annex 3 Cost calculation methodology

The levelised electricity cost (LEC) in € cents/kWh presented in Table 5.1 is calculated as:

$LEC = (Annuity*EPC + O\&M_{fix})/(8760 \times CF) + O\&M_{var} + Fuel$
where:

EPC = Engineering, procurement and construction cost (€cents/kW_e)
Annuity = Fraction of EPC cost charged annually against generating costs, taken as 0.11 = 11% (10% discount rate over 25 years)
$O\&M_{fix}$ = Fixed O&M costs, taken as fraction of EPC cost (€cents/kW_e)
CF = Capacity Factor
$O\&M_{var}$ = Variable O&M costs (€cents/kWh_e)
Fuel = Annual fuel costs (€cents/kWh_e)

In addition, the following assumptions have been made:

Currency conversion: 1 US \$ = 0.755 €
For coal plants, fuel costs are chosen to be 85 €/ton (as received) giving 11.3 €/MWh_{fuel}.
Fuel cost for gas power plants is chosen to be 15.4 €/MWh_{fuel}.
Power generation efficiencies have been assumed as 38.8% for coal (mid and base) and 48.4% for gas.

For Figures 5.4 and 5.5:

Growth rate
The cumulative installed capacity, CAP(y) at a given year, y is given as:

$$CAP(y) = CAP(0) \cdot (1 + r_c)^y$$

where CAP(0) is cumulated installed capacity at present and r_c is growth rate factor (-).

Cost reduction
The electricity cost at a given installed capacity, LEC(CAP), reduces by learning rate factor r_l (-) per doubling of CAP;

$$LEC\,(CAP) = LEC(0) \cdot (1 - r_l)^{2\log[CAP / CAP(0)]}$$

Annex 4 Supporting information on environmental impacts

A4.1 Land use and visual impact

Limited data are available on land use by CSP plants and there are different methodologies for calculating it. A first estimation for trough plants has been made based on data in Solar Millennium (2011) and NREL (2011). The calculation takes the duration of land occupation and the amount of power generated by the plant into account, and hence is expressed in units of $m^2/(MWh/y)$. It proceeded as follows:

- These sources indicate that the area of Andasol 1 is 1.95 million m^2.
- The electricity generated is 174.7 GWh/y for Andasol 1 (Solar Millennium, 2011).
- Taking an assumed lifetime of 30 years into account, a 'land use' of 11 $m^2/(MWh/y)$ is consequently estimated.

Following a similar approach, land use for tower plants based on information on the PS20 and Gemasolar plants in Spain is estimated to be around 17 $m^2/(MWh/y)$ for a tower of 20 MW nominal power and the irradiation conditions of southern Spain.

Comparative figures have been estimated on the basis of data from others sources as follows:

- Data on land occupied by photovoltaic power plants presented by Petrovic and Wagner (2005) corresponds to a land use of 56 $m^2/(MWh/y)$. This figure corresponds to centralized PV plants (as distinct from PV placed on roof tops whose additional land use is essentially zero) in Northern Europe.
- For open-cast mining to extract lignite, a land use figure of 60 $m^2/(MWh/y)$ has been derived from Hirtz (1997), based on an assumed useful life of 60 years.
- For biomass, a land use of 550 $m^2/(MWh/y)$ has been calculated based on a yield of 220 GJ/ha/y (from Ericsson and Nilsson, 2006) for short-rotation energy crops. This only gives the area used for the plantation, excluding infrastructure and boilers (a small land use compared to the plantations). A conversion factor of 0.3 for power production from biomass was assumed.

This illustrative comparison does not take the different qualities of land into account. Land that is occupied by biomass plantations or open-cast lignite mining is often fertile land, while places that are suitable for CSP plants are less populated arid or desert areas.

Although also rarely calculated in life cycle analyses, an indicator that may usefully be combined with land use is the visual impact. A first estimate has been made based on a methodology which calculates the area over which the power plant or fuel extraction process is visible, and which takes into account decreasing visibility with distance. The calculation of the visual impact following this methodology is based on the highest component of the plant under consideration (Petrovic and Wagner, 2005).

For parabolic CSP plants, the visual impact is calculated using this methodology to be 15 $m^2/(MWh/y)$ (the parabolic mirrors have been taken to be the highest component because their visual impact exceeds that of other plant components). For solar tower CSP plants it is calculated to be 1100 $m^2/(MWh/y)$. Following the same methodology the visual impact of wind energy has been estimated to 8600 $m^2/(MWh/y)$.

A4.2 Life cycle assessments

The data on specific emissions and materials use given in Chapter 6 are based on studies using life cycle assessment (LCA) methodology. This is a common and proven method to investigate environmental impacts of goods or services, such as the production of power. The methodology is internationally standardised by the International Organization for Standardization within ISO 14040 and 14044 (DIN-EN-ISO-14040, 2006; DIN-EN-ISO-14044, 2006). A *functional unit* is defined, in this case a kilowatt-hour of electricity. The resources used and emissions produced during the full life cycle are allocated in *impact category indicators*, the contribution to respectively acidification, global warming, metal extraction, etc.

The depicted results below refer to LCA studies, conducted by the German Aerospace Center (DLR) (parabolic CSP plant), Stuttgart University (tower CSP plant), the Ruhr-University Bochum (offshore wind farm), LBP University Stuttgart

Table A4.1 Power plant specifications

	CSP (parabolic)	CSP (tower)	Wind (offshore)	Hard coal	Gas (CCGT)
Installed capacity (MW)	80	30	60	See notes	400
Life time (years)	30	30	20	See notes	35
Capacity factor	0.88	0.22	0.45	See notes	0.59

and PE International GmbH (coal-fired power plant) and the Swiss Centre of Life Cycle Inventories (CCGT plant). The specifications of the different power plants are shown in Table A4.1.

Notes:

- CSP (parabolic):
    - Source: May, 2005.
    - Includes storage (based on concrete storage technology).
- CSP (tower):
    - Source: Weinrebe, 1999.
    - Excludes storage.
- Wind (offshore):
    - Source: Wagner et al., 2010.
    - Includes grid connection.
- Hard coal:
- Source: GaBi, 2007: the calculations of the cumulative energy demand and emissions taken from GaBi are not based on a concrete plant, but on a German average for hard coal-power plants.
- Gas (combined cycle gas turbine: CCGT):
    - Source: Ecoinvent Database, 2007.

A4.3 Impacts on flora and fauna

In support of the information presented in Chapter 6, the following paragraphs provide some further elaboration on the impacts of CSP plants on flora and fauna.

Thermal impact: may occur to birds in flight crossing the concentration of beams at the 'standby point' of CSP tower plants (the point of focus for the beams away from the tower when the plant is not generating power), or when they are pointed at the tower. Damage may occur to eyes (impairing navigation), to feathers (compromising flight), or to the whole body. Light/heat injuries will easily cause death. Corpses are charred and may be difficult to identify at species level.

The CSP plant at Solucar, PS10, in Spain, has been operating for 1100 hours since 2007 and monitoring only revealed two bird casualties giving a figure of 2×10^{-4} birds per operating hour and 1.8×10^{-5} birds per megawatt-hour, in the lower estimates of the literature. It cannot be ruled out that small birds entering the high-temperature area may disintegrate, leaving no evidence which can be recovered at ground level. Direct observation has not recorded direct flight trajectories towards the beams. Local birds in agricultural land and shrubbery do not fly high when commuting short distances, thus avoiding the dangerous zone. It is birds flying longer distances which may enter the risky 100–150m height interval. It is suggested that birds avoid the brilliant concentration of light beams in stand by and the strongly illuminated tower target.

Collisions. During favourable seasons (winter, spring) when biological productivity peaks, birds may be attracted to solar tower plants by seeds, grains or insects, and they will use heliostats as perches, but collisions rarely occur. In the Solucar PS10 plant, cattle egrets were observed preying on western spadefoot toads which gathered in shallow temporary ponds among heliostats. The hurried flights of numerous birds were not hampered by heliostats and no collision with mirrors was observed.

Polarised light effect. Some insect orders, namely Ephemeroptera, Diptera, Homoptera and Coleoptera, are sensitive to polarised light. This trait favours the finding of water surfaces which are used for mating or egg-laying. Most reflecting surfaces, such as glass, glossy surfaces of plastic containers and cars, induce light polarisation. Windows, glass houses and vehicles all attract sensitive insects which try to enter the surface or lay eggs on them, and are killed or losing their eggs in the attempt. In the same way, heliostats and parabolic troughs act as insect attractors, reducing the populations of insects sensitive to polarised light.

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