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The potential role of concentrated solar power (CSP) in Africa and Europe—A dynamic assessment of technology development, cost development and life cycle inventories until 2050

Peter Viebahn [a,*,1], Yolanda Lechon [b], Franz Trieb [c]

[a] Wuppertal Institute for Climate, Environment and Energy, Research Group on Future Energy and Mobility Structures, P.O.B. 100480, 42004 Wuppertal, Germany
[b] CIEMAT (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas), Energy Systems Analysis Unit, Avda Complutense 22, 28040 Madrid, Spain
[c] DLR (German Aerospace Center), Institute of Technical Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

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ABSTRACT

Concentrated solar power (CSP) plants are one of several renewable energy technologies with significant potential to meet a part of future energy demand. An integrated technology assessment shows that CSP plants could play a promising role in Africa and Europe, helping to reach ambitious climate protection goals. Based on the analysis of driving forces and barriers, at first three future envisaged technology scenarios are developed. Depending on the underlying assumptions, an installed capacity of 120 GW_{el}, 405 GW_{el} or even 1,000 GW_{el} could be reached globally in 2050. In the latter case, CSP would then meet 13–15% of global electricity demand. Depending on these scenarios, cost reduction curves for North Africa and Europe are derived. The cost assessment conducted for two virtual sites in Algeria and in Spain shows a long-term reduction of electricity generating costs to figures between 4 and 6 ct/kWh_{el} in 2050. The paper concludes with an ecological analysis based on life cycle assessment. Although the greenhouse gas emissions of current (solar only operated) CSP systems show a good performance (31 g CO_2-equivalents/kWh_{el}) compared with advanced fossil-fired systems (130–900 CO_2-eq./kWh_{el}), they could further be reduced to 18 g CO_2-eq./kWh_{el} in 2050, including transmission from North Africa to Europe.

1. Introduction

Concentrated solar power (CSP) is one of the promising, future-oriented renewable energy technologies. In the last five years, CSP attracted more and more interest from energy utilities all over Europe and in the United States. Private initiatives like the Desertec Foundation (Desertec, 2010) and political roadmaps like the Mediterranean Union's Solarplan (Euromed, 2010) call for a strong deployment in the mid- and long-term. To assess the sustainability of these concepts, a holistic view into the future is necessary: what are the drivers of CSP; why should CSP be brought forward as soon as possible? Which individual technologies within CSP could develop in the long term? How much capacity could be installed and how much electricity could be generated over the next decades, at what economic and ecological cost? All in all, what could be the potential role of CSP technology in the future?

These questions were analysed in the EU-funded project NEEDS (New Energy Externalities Developments for Sustainability), together with similar analysis of other future electricity generating systems (Viebahn et al., 2008; NEEDS, 2009). This paper gives insights into the basic results. It is structured as follows: First, a short introduction into CSP technology is given (Section 2). Based on an analysis of drivers, general aims and supporting instruments (Section 3), three long-term development scenarios are explored (Section 4). These scenarios and expectations of technological breakthroughs are the basis for the specification of future technology configurations (Section 5). Applying the learning curve approach, future electricity generation cost is modelled depending on the development scenarios (Section 6). To assess the ecological impacts, a dynamic life cycle inventory (LCI) analysis is carried out for the current systems and updated to the assumed characteristics of the future technologies (Section 7). Following the discussion in Section 8, the main conclusions are drawn in Section 9.

It should be noted that both, the technical development scenarios and the cost assessment consider CSP technology in general, whereas the life cycle analysis differentiates between different technology configurations.

2. Solar thermal power plants

CSP plants capture energy from solar radiation, transform it into heat and generate electricity by using steam turbines, gas turbines

* Corresponding author. Tel.: +49 202 2492 306; fax: +49 202 2492 198.
E-mail addresses: peter.viebahn@wupperinst.org (P. Viebahn), yolanda.lechon@ciemat.es (Y. Lechon), franz.trieb@dlr.de (F. Trieb).
[1] Formerly with the DLR.

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or Stirling engines. Therefore, they consist of both a solar part and a conventional power block. Since they concentrate the sunlight to achieve higher temperature in the power cycle, their primary energy source is the direct normal irradiance (DNI), perpendicular to a surface that is continuously tracking the sun. CSP plants have their highest potential in the "sun belt" of the earth, which is between the 20th and the 40th degree of latitude south and north.

Three main types of CSP plant technology developed and commercialised so far, can be identified:

- Parabolic trough and Fresnel trough technology.
- Central receiver (also called power tower or solar tower).
- Dish–Stirling systems.

Troughs and central receivers usually use a steam turbine to convert the heat, produced by the solar irradiation, into electricity. Different heat transfer fluids can be used for this process: thermo oil, molten salt, air or water. While parabolic troughs using thermo-oil or direct steam operate with steam temperatures up to 400 or 500 °C, respectively, central receivers can achieve temperatures of more than 1000 °C. This enables them to produce hot air for gas turbines operation combined with downstream steam turbine operation, resulting in high conversion efficiencies. Dish systems either use a Stirling engine at the focus of each dish or they transport heat from an array of dishes to a single central power generating block. Since dish systems will most likely be used as decentralised applications (EUREC, 2004), they are not included in this study.

Thermodynamic power cycles can be operated by fossil and renewable fuels like oil, gas, coal and biomass, combined with solar energy. This so-called hybrid operation has the potential to increase the value of CSP technology by increasing its power availability and decreasing its cost by making more effective use of the power block.

The solar operation time of all types of CSP technology can be expanded to run on a "power on demand mode" using thermal energy storage combined with larger collector fields. Solar heat collected during daytime can be stored in storage systems based on concrete, molten salt, ceramics or phase change materials. At night (or during the day, if needed), the heat is extracted from the storage to run the power block continuously (base load) or on demand (balancing power). Base load operation is also an important feature for coupling with desalination processes, as they usually prefer steady-state operation and are not easily operated with fluctuating energy input.

Furthermore, high-temperature concentrated solar energy can be used for co-generation of electricity and process heat. In this case, the primary energy input is used with efficiencies of up to 85%. Possible applications cover the combined production of industrial heat, district cooling and brine desalination (DLR, 2007).

In the year 2009, 604 MW_{el} of CSP plant capacity was in operation globally, 761 MW_{el} were in construction and 5780 MW_{el} were in the planning phase (Vallentin and Viebahn, 2009). Since parabolic troughs are the most mature CSP technology, they dominate these figures with a share of 75% (planned) and nearly 100% (in operation and in construction).

3. Main drivers and general aims of development

3.1. Main drivers influencing future technology development

Whereas climate protection is one of the major drivers for renewable energy technologies in general, we identified several drivers influencing specifically the development of CSP plants.

- *Objective of security of supply*: From the technical perspective, the objective of security of supply is a pushing factor for solar thermal technologies. In Southern European countries which are highly dependent on fossil fuel imports like Spain or Portugal, CSP generation is a high potential source for diversifying energy sources and increasing the share of domestic sources in energy supply.
- *Direct market support for renewable energies (feed-in laws)*: We also see the establishment of preferential market conditions for renewable energies in several countries (e.g. feed-in laws in Germany, Spain, Portugal and Algeria) and the resulting success stories like the wind energy expansion in Germany and Spain as an important driver for CSP plants. In Spain and Algeria, CSP technologies were explicitly included in the support scheme. As a result, the first (modern) parabolic trough plants have been set up in Spain.
- *Preference for non-intermittent electricity generation*: Energy sources with low intermittency have an economic advantage over energy sources with high intermittency. CSP will be able to offer balancing power at a competitive price level. By incorporating thermal storage and co-firing options, CSP plants can internalise the costs of compensating the intermittency of the solar energy resource.
- *Advanced side applications and side products*: CSP technologies can be used for co-generation. The joint production of electricity and heat for operating adsorption cooling and water desalination facilities is the most interesting application. Both cooling and fresh water provision meet pressing demands in sun-rich, arid countries. Demand for those services usually appears at the same time when the power plant is operated at full capacity and in the same region which is suited for a reasonable economic solar thermal performance. Other processes are solar reforming of natural gas and other organics, or thermo-chemical hydrogen production. These options, which have partly been demonstrated successfully may open up high potential markets. Sargent & Lundy state that CSP could thus potentially get a major source of energy in the fuels and chemical sector (S&L, 2003).
- *Increasing demand for local added value*: Many developing and transitional countries put more and more emphasis on local added value in investment decisions. They wish to realise the associated employment benefits, support the accumulation of local expertise and reach a high share of national content as a value for development. Moreover, local added value also promotes socio-economic stability. Solar thermal power stations are considered to be one of the technologies with a high potential for local added value. High-tech components constitute only a small fraction in these plants and nearly 50% of the investment is spent on steel, concrete, mirrors and labour (Pitz-Paal, 2007), which have high potentials to be provided locally (Lorych, 2006).
- *Aiming at conflict neutral technologies*: The fossil fuel based energy supply system and nuclear energy technologies are increasingly involved in military conflicts and instable political environments. The discussion is concentrated on the possible transition from peaceful nuclear energy use to the production of weapon relevant material (Iran). Moreover, proliferation of weapons-grade plutonium is a latent threat. CSP technologies do not incorporate conflict relevant materials. Even more important, the solar resource is abundant and inexhaustible, and thus will likely not give rise to conflicts over the right to use it. This may turn out to be an important pushing factor for CSP technologies, even more as CSP addresses the same market segment as fossil and nuclear power plants.