Energy Policy 39 (2011) 4420–4430

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# 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

ARTICLE INFO

*Article history:*
Received 10 May 2010
Accepted 16 September 2010
Available online 14 October 2010

*Keywords:*
Concentrated solar thermal power
Integrated assessment
Scenario analysis

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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doi:10.1016/j.enpol.2010.09.026

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.

### 3.2. General aims of development and supporting instruments

The overall future solar thermal development situation can be characterised as an *activation energy* model. We identified two main phases: The *first one* is the time until commercial competitiveness is reached. The *second phase* is the phase of participating in the electricity market at competitive conditions. Concerning the likeliness how these two phases will develop, both phases have very different characteristics. The *second phase* will presumably be a "self-runner". Once economic competitiveness is gained, commercial investors will have a strong incentive to invest into CSP plants and the dynamics become self-reinforcing: The more power plant capacity is installed, the cheaper the technology will become.

The tipping points are found in the *first phase*. To achieve a development as described above, an active push for CSP technologies is necessary. Therein a critical mass and concentration of supporting factors is necessary. The most important supporting instruments that could contribute to CSP plants reaching the second phase are those which directly address the economics of power plant projects:

- *Regulative framework conditions* with preferential market conditions for CSP as they are meanwhile established in Spain, Algeria, France, Israel and Italy have to be expanded to more countries adequate for CSP-based electricity generation. Through reliable feed-in laws for example, the pay back of the investment, including an adequate return, can be guaranteed.
- In countries with national power companies a feed-in law is not necessarily needed. In these cases, the required revenues can be provided in form of long-term *power purchase agreements*, preferably backed by an international guarantee (Trieb and Müller-Steinhagen, 2007). This would be the case in most Middle East and North African (MENA) countries that could deliver most of the CSP-based electricity worldwide.
- Furthermore, not only in the countries generating CSP electricity, but also in countries that could purchase CSP-based electricity via transmission lines, feed-in-laws should include an incentive for importing solar thermal electricity. This would push the investment in power plants located in countries outside of the where the electricity is used. A first step towards this option has recently been made by the European Union, which allows its Member States to import "electricity from renewable energy sources" from third countries for the purposes of complying with the requirements of national renewable energy targets (EU, 2009).
- An indirect support of CSP is the reduction of *subsidies* granted for fossil and nuclear power plants and to enable an electricity market under competitive conditions.
- The effects of such support schemes will be strengthened by an *increase in fossil fuel prices* expected by many experts to occur within the next decades. The more these prices increase, the earlier CSP technologies will become competitive.
- In the optimal case, a worldwide and ambitious long-term oriented *climate protection regime* is implemented. Such a regime would internalise the costs of $CO_2$ emissions and would thus be beneficial for solar thermal power stations, which have no $CO_2$ emissions during operation.
- Last but not least, we see increasing *research and development* spending for CSP technologies which are near to commercialisation (demo-types) as an important instrument during the activation phase. In the next 15 years a significant increase in R&D efforts is required if the cost reductions, which are possible by applying technical innovations, are to be realised (Pitz-Paal et al., 2005).

## 4. Three future envisaged solar thermal technology development scenarios

The different market development conditions outlined lead to three future envisaged technology development scenarios. We distinguish between an "optimistic-realistic" scenario and two extreme developments, a "very optimistic" view on the one hand and a "pessimistic" view on the other hand. The "optimistic-realistic" perspective is considered to be the most likely pathway of development. The scenarios follow the two-main-phases approach explained in Section 3.2 by differing in how strong especially the activation phase will be implemented (Table 1).

Fig. 1 illustrates the worldwide installed capacity resulting from our scenarios that are based on a review of ten studies, published between 2003 and 2008. Almost all studies refer to CSP in general and differ neither between trough and tower technologies, nor between heat-transfer fluids or storage systems. Each of the scenarios starts in the year 2007 with an already installed capacity of 405 MW (composed of 354 MW of "older" plants in the United States and 50 MW of the newly erected plant "Nevada Solar 1") and reach between 120 and 1000 $GW_{el}$ in 2050 (Table 2).

The "*very optimistic*" diffusion scenario is based on the assumption that both phases, the activating phase as well as the competing phase, can fully be explored. Especially in the first phase a maximum deployment needs to be realized with the help of all instruments discussed above to enable an early and strong increase of solar thermal power plant capacity. Until 2040, the scenario follows an ambitious long-term pathway developed in (Greenpeace and Estia, 2005), which is supplemented by a 2050 target value taken from the United Nations Development Programme's world energy assessment (Goldemberg, 2000). To reach the ambitious goal of 1000 $GW_{el}$ of installed capacity in 2050, growth rates similar to those realized in recent years by wind power plants are necessary (we calculated 35%/yr between 2010 and 2020, 18%/yr between 2020 and 2030 and further decreasing rates between 2030 and 2050).

**Table 1**
Supporting instruments defining the diffusion scenarios.

| Instrument | Scenario | | |
|---|---|---|---|
| | "Very optimistic" | "Optimistic-realistic" | "Pessimistic" |
| Feed-in law | ****** | ****** | *** |
| Power purchase agreements | ****** | ****** | *** |
| Reducing subsidies for fossil and nuclear power plants | ****** | *** | * |
| Increasing fossil fuel prices | ****** | ****** | *** |
| Internalisation of the costs of $CO_2$ emissions | ****** | *** | * |
| Research and development spending | ****** | *** | *** |

*Remark*: The number of stars represents the intensity of a measure.

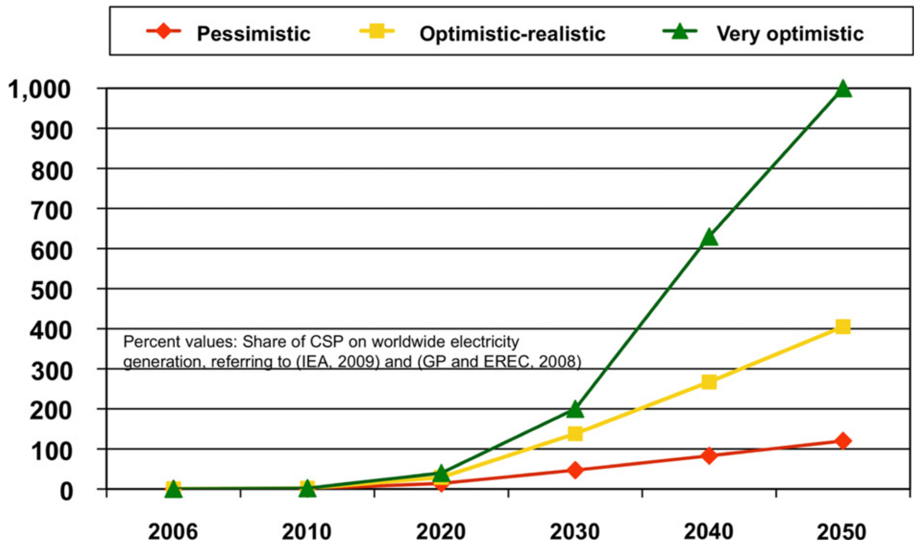


**Fig. 1.** Installed capacity in different CSP technology development scenarios and their share on the worldwide electricity generation as outlined in energy scenarios of IEA (2009) (lower value) and Greenpeace and EREC (2008) (higher value).

**Table 2**
Installed CSP capacity, generated electricity from CSP and its share in meeting global electricity demand.
*Sources*: IEA=IEA 2009 and own update to 2040 and 2050; GP&EREC=Greenpeace and EREC 2008 ("2 °C scenario").

| Scenario | Electricity generation | 2007 | 2010 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|---|
| *NEEDS scenarios of worldwide CSP electricity supply* | | | | | | | | |
| "Very optimistic" | GW | 0.4 | 2 | 40 | 89 | 200 | 630 | 1000 |
| | TWh | 1 | 8 | 220 | 492 | 1100 | 3465 | 5500 |
| | % (IEA) | 0 | 0 | 0.8 | 1.6 | 3.2 | 9.5 | 13.1 |
| | % (GP&EREC) | 0 | 0 | 0.9 | 1.8 | 3.8 | 10.5 | 14.8 |
| "Optimistic-realistic" | GW | 0.4 | 2 | 29 | 63 | 138 | 267 | 405 |
| | TWh | 1 | 8 | 160 | 348 | 759 | 1469 | 2228 |
| | % (IEA) | 0 | 0 | 0.6 | 1.1 | 2.2 | 4.0 | 5.3 |
| | % (GP&EREC) | 0 | 0 | 0.6 | 1.3 | 2.6 | 4.5 | 6.0 |
| "Pessimistic" | GW | 0.4 | 0.8 | 14 | 26 | 47 | 83 | 120 |
| | TWh | 1 | 3 | 77 | 141 | 259 | 457 | 660 |
| | % (IEA) | 0 | 0 | 0.3 | 0.5 | 0.8 | 1.3 | 1.6 |
| | % (GP&EREC) | 0 | 0 | 0.3 | 0.5 | 0.9 | 1.4 | 1.8 |
| All scenarios: Solar full load hours | H | 3312 | 3974 | 5500 | 5500 | 5500 | 5500 | 5500 |
| *For comparison: scenarios of worldwide electricity demand* | | | | | | | | |
| IEA | TWh | 19,756 | 21,780 | 27,232 | 30,670 | 34,292 | 36,500 | 42,000 |
| GP&EREC | TWh | 19,440 | 21,523 | 25,743 | 27,434 | 29,124 | 32,916 | 37,116 |

The "*optimistic-realistic*" scenario illustrates the progressive targets to be reached in the next decades if most of the instruments are strong enough to activate the market development. Especially the feed-in laws and the power purchase agreements will enable an increasing diffusion of solar thermal electricity into the market that leads to a total installed capacity of 405 $MW_{el}$ in 2050. In this scenario we expect a worldwide capacity development as it is described in the "2 °C scenario" provided by Greenpeace and EREC (2008). After a deployment of 160 GW until 2020 a strong increase during the next decades determines the development path until 2050 (resulting in a growth rate of 31%/yr between 2010 and 2020, 17%/yr between 2020 and 2030, decreasing rates between 2030 and 2050).

Finally, for the "*pessimistic*" scenario we assume that the driving forces will push CSP development in the next decade, but they will be too weak to enable a significant diffusion. CSP will not be swept out of the renewables' portfolio, but its deployment will only increase on a constrained development path reaching 120 $GW_{el}$ in 2050. The target figures of this scenario are similar to the DLR study "TRANS-CSP", using those capacities calculated for Europe and for the export from MENA to Europe (DLR, 2006).

In order to assess the possible contribution of CSP to meeting the global electricity demand, the electricity generation resulting from the outlined scenarios are compared with two energy scenarios: on the one hand IEA's World Energy Outlook reference scenario (IEA, 2009) and on the other hand the more ambitious Energy[R]evolution "2 °C scenario" outlined by Greenpeace and EREC (2008) and Krewitt et al. (2009). While the latter covers a period until 2050, IEA's electricity demand curve ends in 2030 and is extended to 2050, extrapolating the trend of the previous decades.

The electricity generation of CSP plants is calculated conservatively by assuming 6400 solar full load hours (sflh) per year achievable in Spain (see Section 6), which are about 20% less than what is possible in average North African sites (8000 slfh/yr). Furthermore, only base-load generation is considered, which reduces full load hours to 5500 sflh/yr from 2020 on. Between 2007 and 2020, the number of solar full load hours reached by current installed systems is increased slowly until it reaches 5500 sflh/yr in 2020.

Table 2 illustrates the installed capacity, the generated electricity from CSP plants as well as its share in meeting global electricity demand. It shows that CSP electricity generated in our scenarios could cover between 1.6% and 13.1% of the electricity demand outlined by IEA and between 1.8% and 14.8% of the envisaged electricity demand in the Greenpeace/EREC scenario. The higher values in the latter case result from a lower increase of the energy demand as assumed in the Greenpeace/EREC scenario.

## 5. Specification of future technology configurations

To achieve the development targets of CSP technologies outlined above, substantial technological improvements are a precondition. Expectations on key technological breakthroughs and key factors influencing the implementation of technological change are described in the ECOSTAR study (Pitz-Paal et al., 2005) and the study of Sargent & Lundy (S&L, 2003). Whereas the latter only considers scaling up and volume effects, the ECOSTAR study carried out a detailed analysis on innovation and cost reduction potentials until 2020 considering three major categories: "concentrators (including mirrors)", "thermal energy storage" and "receivers, absorbers and cycles (including heat collection elements and power block)". The key findings of ECOSTAR are the basis for specifying future technology configurations assumed for the diffusion scenarios illustrated in Fig. 1.

In the three deployment scenarios, the technological characteristics and the relative success of the considered CSP technologies will develop differently. The overview given in Table 3 describes which of these technologies will dominate the market and will therefore realise the most significant cost reduction potential from our point of view. Those technologies are selected which seem to be the most cost effective ones in the different scenarios. Nevertheless, we acknowledge that there are some other new and promising developments (for example the utilisation of molten salts as primary fluid, Forsberg et al., 2007) that could lead to technologies capable to supplement or possibly outperform the technologies selected here.

The *current situation* is characterised by a CSP market, which is dominated by commercially available parabolic trough technologies. CSP plants with trough technologies are currently under construction and some are already in operation in Spain (CSP plants with trough technology are also being built in some modifications in the United States). Solar tower technologies are currently in the demonstration phase. Typical current CSP plant characteristics are as follows:

a) *Parabolic trough* (50 MW) using thermo oil as heat transfer fluid (HTF) and a 7.5 h molten salt storage running in a quasi-hybrid mode (a small amount of natural gas is allowed by the Spanish renewable act to maintain the thermal storage temperature during periods with no solar generation). A 7.5 h storage system means that an additional solar field must be erected—one solar field is driving the installed turbine while the second one is filling the storage for operation at night. The number of solar fields, each of them large enough for nominal turbine capacity, is called solar multiple (SM)—in this case SM=2. This enables around 3820 full load hours of operation, which corresponds to a capacity of 44%.
b) *Central receiver* (solar tower, 15 MW) planned to be built as a demonstration project based on the experiences gained from previous solar tower and molten salt receiver experiments. It is based on molten salt for both, the HTF and the (16 h) storage systems (SM=3), enabling 6230 full load hours or a capacity of 71%. As in the case of the trough technology, a small natural gas backup is allowed.

Solar-only operation reaches an efficiency of 14.7% as proved by the parabolic trough power plant Andasol I, and 15.5%, which still has to be demonstrated by the central receiver power plants Solar Tres (in this paper, efficiency means "solar-to-electricity" efficiency). The assumed share between trough and tower is taken from (Caldés et al., 2005) where a scenario is used assuming that 80% of the solar thermal capacity planned within the Spanish Renewable Energy Plan 2005–2010 (PER, 2005) would be met with parabolic troughs, while 20% would be installed as central receivers.

In the "*pessimistic*" scenario development we assume that CSP will not have the "activation energy" to establish beyond the proven technology, which is the parabolic trough technology as described above. The technical innovations feasible for these plants will be realised; the storage system will be supplemented by a concrete storage currently under development which has a better ecological performance (Laing et al., 2010). Although feed-in laws or similar instruments are weak, co-firing will decrease and solar-only operation will be enabled by the use of efficient 16-h storage system from 2020 on (SM=3). The plants' efficiency will slightly increase to 16.2%, the highest efficiency possible for thermo oil based troughs. The size is enlarged to units of 200 $MW_{el}$ in 2025 and 400 $MW_{el}$ in 2050.

**Table 3**
Future technology configurations depending on the three technology development scenarios.

| Development scenario | Base technology | Share | Electrical efficiency | HTF | Storage type/capacity |
|---|---|---|---|---|---|
| Current situation | 50 MW trough[a] | 80% | 14.7% (p) | Thermo-oil | 7.5 h MS |
| | 15 MW tower[b] | 20% | 15.5% (d) | Molten salt | 16 h MS |
| "Pessimistic" | 200/400 MW trough | 100% | 16.2% | Thermo-oil | 16 h MS |
| | | | | | 16 h CON |
| "Optimistic-realistic" | 200/400 MW trough | 40% | 19% | Steam | 16 h PCM |
| | 200/400 MW Fresnel | 40% | 11.9% | Steam | 16 h PCM |
| | 180 MW tower | 20% | 18% | Molten salt | 16 h MS |
| "Very optimistic" | 200/400 MW Fresnel cogeneration (cooling) | 50% | 7.1%[c] | Steam | 16 h PCM |
| | 200/400 MW Fresnel cogeneration (desalination) | 50% | 9.2%[c] | Steam | 16 h PCM |

HTF=heat transfer fluid; MS=molten salt; CON=concrete; PCM=phase change material p=proven; d=to be demonstrated.

[a] Trough type Andasol I.
[b] Tower type SolarTres.
[c] Thermal efficiency=22.1%.

Along the "*optimistic-realistic*" scenario development we see direct steam generation (DSG) instead of thermo oil as the state-of-the-art HTF from 2025 on. DSG plants have a lot of advantages because the thermo oil as well as the pumps and tanks used for operation are no longer needed; the HTF/steam exchanger drops and the efficiency increases to a maximum of 19% due to three issues: Operating with higher HTF temperatures, reducing the need for pumping power and avoiding the heat exchanger losses. DSG will be used both in conventional parabolic trough systems and in upcoming Fresnel trough technology.

The Fresnel structure allows for a very light design and thus – even if the efficiency of 11.9% is only two thirds of the parabolic trough – a decrease of the specific material consumption. Furthermore, land use is reduced which is a significant advantage in highly populated areas: Since a Fresnel trough needs only one third of the area required by a parabolic trough of the same installed power, and considering the lower efficiency of 66%, a land use reduction of 50% per produced kWh can be reached. The size of troughs is enlarged to units of 200 $MW_{el}$ in 2025 and to 400 $MW_{el}$ in 2050.

Central receivers will play only a minor role because the proposed cost reductions will not reach generation costs lower than those of parabolic troughs. Due to feed-in laws or equivalent instruments co-firing will also decrease. Solar-only operation will be enabled from 2020 on by developing an efficient 16 h high-pressure steam storage system based on phase change materials (PCM) to meet the demand resulting from the use of steam as HTF. The plant's efficiency will increase to 18%; the size is enlarged to units of 180 $MW_{el}$ from 2025 on. This size is already theoretically optimal due to the need for a round adjustment of the mirrors in relation to the tower.

Considering the "*very optimistic*" scenario development we think that in an early stage (until 2025), solar steam power plants will be displaced by solar combined cycle troughs. They use the waste heat, which is currently not used, for cooling or desalination processes. Although the electrical efficiency will decrease from 11.9% to 7.1% in case of cooling or 9.2% in case of desalination, the total efficiency will be quite higher due to a thermal efficiency of 22%. Cooling and especially desalting brine will become more and more important in the future due to the combined effects of an increasing population and shrinking fresh water resources in many North African regions (DLR, 2007; WWF, 2007). At the same time these countries are excellently suited for solar thermal power plants. As the basic CSP plant we assume the Fresnel technology already described within the "optimistic-realistic" scenario.

Central receivers operating with pressurised air enable combined gas and steam turbine cycles which increase the efficiency more than it would be possible with any other solar steam technology (Buck et al., 2002). Although electrical efficiencies of 23–25% are believed to be achievable, we do not consider them as a main technology within this scenario. To enable temperatures of up to 1,400 °C which are required by the subsequent gas turbine process, a continuous co-firing with natural gas is necessary. This would increase the emissions per kWh electricity much more than using solar-only operated power plants.

## 6. Cost assessment using the learning curve approach

Based on the technology development scenarios illustrated in chapter 4, future electricity generation costs (EGC) are derived. Given the investment costs at the beginning of the technology development and taking into account the capacities to be installed according to the scenarios, for each of the three scenarios a learning curve is derived. This is done by applying learning factors which define the decrease in costs occurring for each doubling of capacity. The derived learning curve is a generic curve, not differing between troughs and towers.

For the future cost assessment, a learning rate (LR) of 12% is taken from (Neij, 2008), who analysed the cost development and the learning effects of the nine SEGS ("Solar Electricity Generation System") power plants which were the first solar thermal power plants commercially operated in California and built between 1984 and 1990, and several cost reduction studies. Although the total installed capacity of 354 MW (SEGS) is quite low for deriving a learning rate (only three doublings have taken place), we use this figure in default of similar technologies from which learning rates could be adopted. To decrease the uncertainty in this value, we make two assumptions.

First of all, we split up the learning rate into the main parts of a CSP plant (Table 4). While the power block represents a conventional and almost mature technology, the innovative parts are the solar field and, more and more of importance in the future, the thermal storage system. Therefore, we decrease the learning rate for the power block to LR = 5% and, additionally, define floor cost since a cost development below this threshold does not seem to be realistic due to least costs for the material production.

Secondly, for the initial cost we do not take the updated cost development of SEGS power plants, but use the investment cost of Andasol 1, a recently built Spanish 50 $MW_{el}$ trough power plant. Since this power plant includes a 7.5 h molten salt thermal storage system, which increases the investment cost significantly, we "restart" the learning process at a much higher cost level (which sums up to 5300 €/$kW_{el}$) than the previously occurred learning effects of the SEGS plants would let expect.

To be able to deliver balancing power in the future, the storage capacity is increased from currently 7.5 to 16 h in 2020 (SM = 3). This development results in a slower decrease of total investment cost since the increasing storage cost (per $kW_{el}$) partly cancel out the decrease caused by learning effects.

Furthermore, to take into account the different irradiation conditions between Southern Europe and North Africa two different sites are chosen: a site in Spain with an irradiation of 2000 kWh/($m^2$, yr), enabling 6400 sflh/yr (case A) and a site in Algeria with an irradiation of 2500 kWh/($m^2$, yr), enabling 8000 sflh/yr (case B). Such a difference influences the investment cost since the lower the irradiation, the larger the collector field has to be configured to gain the same electricity output. Algeria was chosen arbitrarily as one of North African countries providing good solar irradiation conditions—several other countries could have been taken in consideration as well. Fig. 2 shows the development of both the total and of each component's investment costs in case of the "optimistic-realistic" scenario (only for case A).

**Table 4**
Learning rates defined for the main parts of solar thermal power plants.

| Component | Initial cost | Learning rate | Referring to | Floor costs |
|---|---|---|---|---|
| Storage system | 115 €/kWh | 12% | $kWh_{th}$ storage capacity | — |
| Collector field | 300 €/$m^2$ | 12% | $m^2$ aperture | — |
| Power block, BoP | 1350 €/kW | 5% | $kW_{el}$ load | 800 €/$kW_{el}$ |

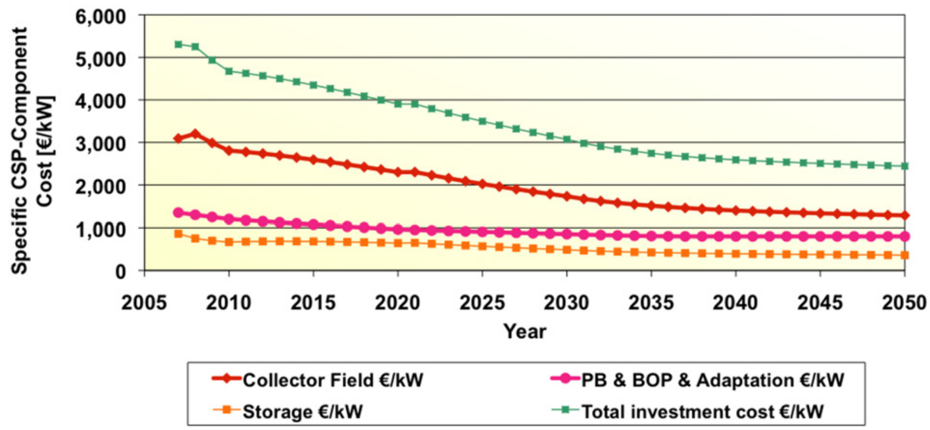


**Fig. 2.** Overall learning curve and the contributions of the main parts (''optimistic-realistic scenario'', case A=Spain).

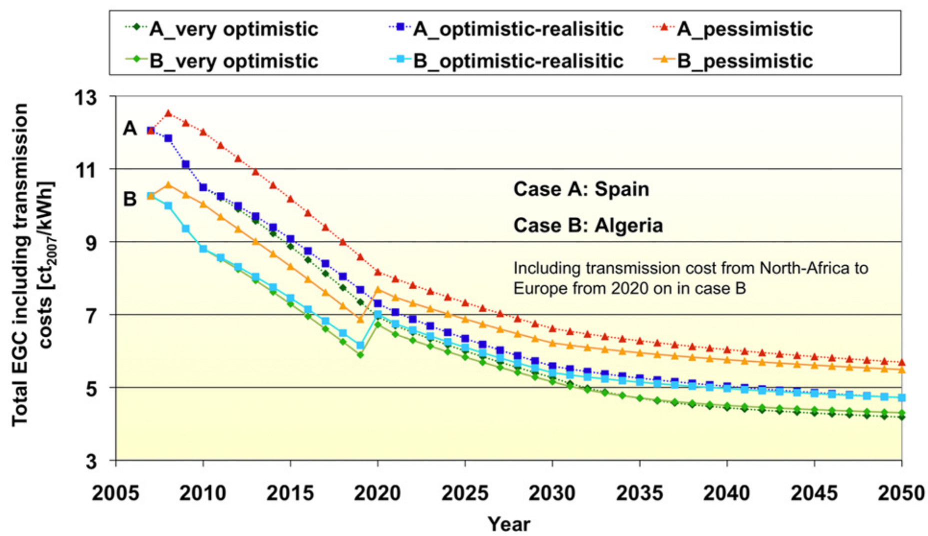


**Fig. 3.** Total electricity generation costs (all scenarios), hybrid-operation until 2020, including transmission costs in case B=Algeria (baseline eliminated).

In the next step the future EGC for each of the development scenarios are derived. The calculation is based on the following assumptions:

- Project discount rate of 6%.
- Annual O&M rate of investment 2.5%.
- Annual insurance rate of investment 0.5%.
- Specific demolition cost 1% of investment.
- Depreciation time 25 years.
- Fuel cost for co-firing of natural gas (only required until 2020) starting at 25 €/barrel of oil equivalent in 2007 and increasing between 2010 and 2020 by 0.8%/yr.
- Furthermore, transmission costs for high voltage direct current (HVDC) lines from Algeria to Germany are added from 2020 on. They raise the EGC by 1.2 $ct/kWh_{el}$ in 2020, 1.1 $ct/kWh_{el}$ in 2025 and 1 $ct/kWh_{el}$ from 2030 (DLR, 2006).

Fig. 3 gives an overview of the EGC for all scenarios considered under these conditions. In the year 2050 they result in a range of 4.2–5.7 $ct/kWh_{el}$ for electricity generated in Spain and of 4.3–5.5 $ct/kWh_{el}$ in case of Algeria. While the highest cost decrease takes place in the *first phase* (of strongly increasing investments), in the *second phase* (from 2025 on) the cost curve slabs. It should be kept in mind that the development illustrated until 2020 is characterised by changes in technology starting with hybrid power plants, including only small storage capacity, to solar-only plants using 16 h storage capacity. The jump of EGC in 2020 is caused by the start of electricity transmissions from Algeria to Germany via HVDC lines.

## 7. Dynamic life cycle inventory analysis

In a third step, individual life cycle inventories (LCI) are calculated for the present situation as well as for 2025 and 2050. In an LCI the material and energy flows of the whole life cycle chain of a product are investigated, cumulated and related to the functional unit. In this context, it is distinguished between direct and indirect flows: *Direct flows*, also referred to as foreground or first order processes, represent material consumption and emissions related to the final production process of a product, its use and its disposal. *Indirect flows* describe the interventions that contribute to the product in the background—production and transport of materials and energy (carriers) (second-order processes) as well as providing the infrastructure for them (third-order processes).

In our case, the life cycle considers the construction of the CSP plant, the plant's operation and its dismantling. For all products involved, their sub-processes beginning from the exploration and extraction of raw materials from the earth and ending with the transport to the power plant's site, are included. For example, alloyed steel needed for the power block is divided into unalloyed steel and alloying materials for which the direct production process as well as their pre-processes are modelled. For analysing the main contributors to the emissions' and materials' balance, the CSP plant is divided into seven main parts: solar field (including mirrors, their basement, absorbers, pipes and cables), tower (in case of central receiver), buildings and urbanization, power block, cooling tower, power equipment and thermal storage.

The functional unit, to which the inventory is scaled to make material and emission flows comparable to other power plants, is one kilowatt-hour of electricity leaving the power plant's site. In case that electricity consumption far away from the power plant's site should be considered, the transmission line from the source to the consumer must be included.

While usually "static" LCI of existing products are carried out, our aim is to present the results of a "dynamic" LCI analysis based on the future power plant configurations specified in Table 3. Considering our three envisaged technology development scenarios outlined in Section 4 enables us to assess the dynamic evolution of CSP plants. The approach is as follows: first, complete new LCI of the power plants currently in operation (Andasol I trough) or in the planning status (Solar Tres tower) are carried out. Second, these LCI are updated to a possible situation in 2025 and 2050 taking into account the following six development steps:

(1). *Increase of lifetime* from currently 30 years, assumed for the solar field and the power block, and from 25 years, assumed for the storage system, to 35 and 30 years in 2025 and to 40 and 35 years in 2050, respectively. The lifetime of the buildings (60 years) is not changed. This approach seems justified, since more experience will enable a longer durability. As a result, material consumption and resulting emissions per kilowatt-hour decrease.

(2). *Up-scaling* the trough's electrical load from currently 50 $MW_{el}$ to 200 $MW_{el}$ (2025) and to 400 $MW_{el}$ (2050) and the tower's load from 15 $MW_{el}$ to 180 $MW_{el}$ (2025), the expected target values for CSP plants (S&L, 2003; DLR, 2004). Solar field and storage system are scaled linearly (scaling factor 1), which means each doubling of the load requires doubling these components resulting in the same material demand per MW load. For the other components scaling factors between 0.1 and 0.9 are applied which means a specific material reduction.

(3). *Increase of storage time* to 16 h from 2020 on, enabling a solar-only operation over nearly 24 h (SM=3). Similar to the investment cost, the material and therefore the emissions inventory increases. While the environmental expense of the additional solar field is cancelled out by an equivalent additional electricity generation, the burdens of the storage field increase the specific emissions (per kWh electricity). In the same way as the price of power increases, which can be used for peak-load and which is therefore characterised by a higher "quality", the environmental burdens increase, too.

(4). *Applying higher efficiencies* as illustrated in Table 3 decreases the specific material consumption and resulting emissions accordingly.

(5). *Reduction of material use* by applying a new developed "material learning curve": The material consumption for the production of the power plants is reduced according to the innovation potential provided by the ECOSTAR study (Pitz-Paal et al., 2005). To find the relevant materials where a reduction seems to be achievable, a new approach was developed. It combines the learning curve approach used to calculate *cost* reduction potentials (learning rate of 12%) with the *mass* of the most cost intensive components and derives a "material learning rate" $LR_m$ of 3%. This learning rate is applied to the most cost intensive materials, which are flat glass and steel in case of solar field and aluminium and steel in case of storage systems.

(6). *Adapting background processes* (*third order processes*): Usually, the background processes used for the production of materials (for example the electricity mix, the steel production or the share of secondary use of aluminium) change over time. By applying "dynamic" background processes for 2025 as well as for 2050 the general influence of an assumed material and energy reduced ("low carbon") economy can be considered (Pehnt, 2005). For example, an electricity mix with an increasing share of renewable energies decreases the greenhouse gas emissions of electricity-intensive aluminium production processes as well. The calculations shown below are based on an energy supply scenario that limits the rise of the concentration of greenhouse gases in the atmosphere to 440 ppm ($CO_2$-equivalent) until 2050, which is roughly in line with the 2 °C target. It is one of several scenarios developed in other parts of the NEEDS project (NEEDS, 2009).

Where necessary, we modelled new life cycle inventories to include the advanced technologies listed in Table 3. This leads to six power plant concepts included in the overall assessment:

- Parabolic trough operating with thermo oil and molten salt (MS) storage.
- Parabolic trough operating with thermo oil and advanced concrete storage.
- Parabolic trough operating with direct steam and phase change material (PCM) storage.
- Fresnel trough operating with direct steam and PCM storage.
- Central receiver operating with MS and MS storage.
- Fresnel trough combined heat and power (CHP) operating with direct steam and PCM storage.

Fig. 4 illustrates the influence of each development step for the "pessimistic" scenario and the appropriate parabolic trough technology development from the current situation to 2025. As an example, the greenhouse gas (GHG) emissions as an indicator for the environmental impact category "global warming" are selected. Although in this study no full impact analysis is carried out, the global warming potential as one of the most important indicators for the assessment of energy systems, is determined. The GHG emissions are calculated by weighting the most relevant GHG $CO_2$, $CH_4$ (methane) and $N_2O$ (dinitrogen oxide) using the weighting factors 1, 25 and 298, respectively (IPCC, 2007). The result is given in g $CO_2$-equivalents/$kWh_{el}$.

Increasing lifetime (step 1) and up-scaling (step 2) lead to a 15% and 7% decrease of GHG emissions, respectively. In contrast, increasing storage capacity from 7.5 to 16 h (step 3) leads to a GHG increase of 13%. As expected, the next three steps improve the GHG balance (8% by increasing efficiency, 3% by reducing material use and 4% by adapting background processes). In total, the considered development path enables a 23% decrease of emissions until 2025.

In a similar way, the step-by-step approach is applied to all considered development pathways. Fig. 5 illustrates this by way of the global warming potential of current and future CSP systems for the two regions (case A=Spain, case B=Algeria). The GHG emissions range from 33.4 g $CO_2$-equivalents/$kWh_{el}$ for current

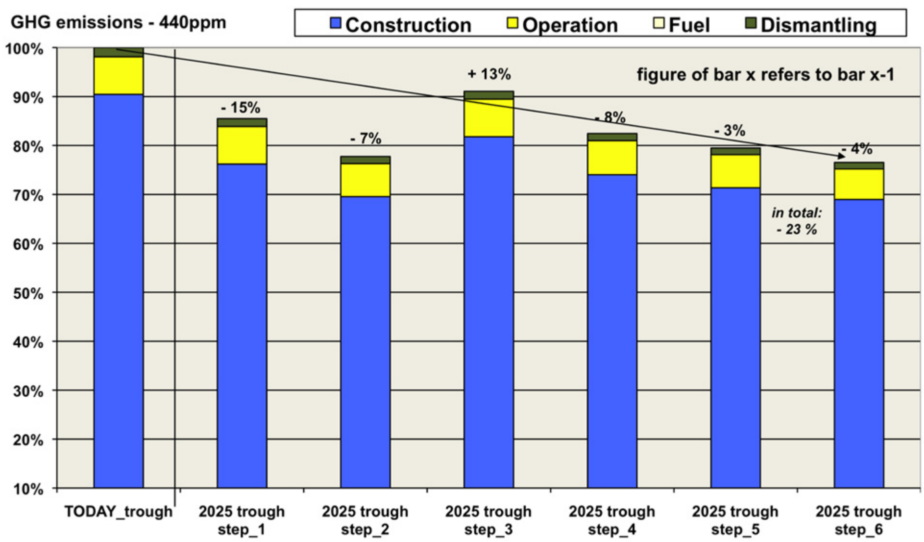


**Fig. 4.** Impacts of the "pessimistic scenario" development steps on the greenhouse gas emissions of a 2025 thermo oil based parabolic trough power plant with molten salt storage (440 ppm scenario).

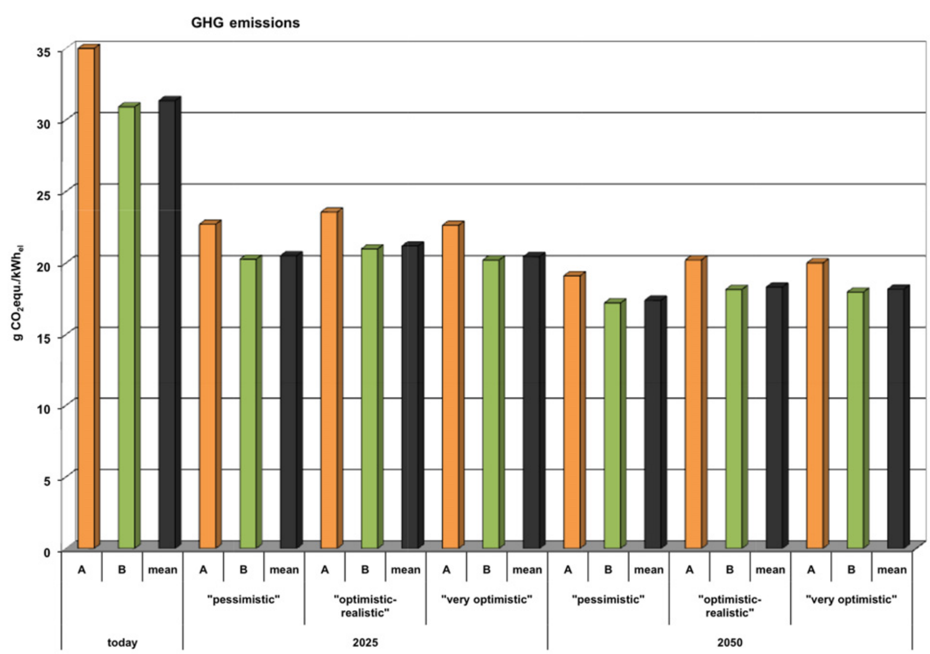


**Fig. 5.** Development of solar thermal GHG emissions from present to 2050 (case A=Spain, case B=Algeria).

systems (solar-only operation) to 20 g $CO_2$-eq./kWh$_{el}$ in 2050 (case A) and from 30.9 g $CO_2$-eq./kWh$_{el}$ to 18 g $CO_2$-eq./kWh$_{el}$ (case B). The difference between A and B results from a decrease in emissions due to better solar irradiation conditions in Algeria, diminished by the higher burden resulting from the need to transmit the electricity to Europe. The mean is formed by the assumption that 10% of future CSP production originates from Spain and 90% from Algeria (DLR, 2006).

## 8. Discussion

Provided that an active pushing of CSP technologies will take place and that especially the "activating phase" will fully be explored, the "very optimistic" case as illustrated within our future envisaged technology development scenarios could reach an installed capacity of 1000 GW$_{el}$ in 2050. In this case, CSP could meet 13% of global electricity demand in 2050 based on the IEA's reference development or even 15% based on Greenpeace and EREC's "2 °C scenario". New energy scenarios published by Greenpeace and EREC after the finalisation of the NEEDS project show that even this scenario may be outperformed when taking more optimistic assumptions. (Greenpeace and EREC, 2010) published both an update of the 2008 Energy[R]evolution scenario as well as a more ambitious "Advanced Energy[R]evolution" scenario which assumes a shorter lifetime of existing coal-fired power plants and further increases in the growth rates of renewable energy technologies. These two scenarios illustrate an increase of installed CSP capacity to 1012 and 1643 GW as well as an increase of electricity generated by CSP to 5917 and 9012 TWh in 2050, respectively. A precondition for such a strong deployment is that all supporting instruments listed in Table 1 are completely and rapidly activated.

Our analysis shows that in the “very optimistic” case (1000 GW installed in 2050) CSP electricity generation costs of 4.2 ct/kWh$_{el}$ may be reached in 2050. A comparison of the “top-down” approach applied here with the “bottom-up” method used in ECOSTAR (Pitz-Paal et al., 2005) shows quite similar results in case of our two more progressive development scenarios for Spain until 2020. The ECOSTAR study is based on initial EGC of 17.2 ct/kWh for sites similar to case A (Seville, irradiation of 2000 kWh/(m$^2$, yr)) and 12.7 ct/kWh for a site with higher irradiation as chosen for case B (desert climate, 2700 kWh/(m$^2$, yr)). Adjusting the last one to a site with an irradiation as used in case B (Algeria, 2500 kWh/m$^2$, yr) yields the figures shown in Table 5.

As Table 5 illustrates, the ECOSTAR cost data for the current situation is nearly the same as our data and in 2020 our best case (”very optimistic” scenario) is also similar to the case of ECOSTAR (even if considering that our data is based on 2007 values, whereas ECOSTAR cost data is based on 2005 values). The ECOSTAR cost data given for 2020 is reached in our ”optimistic-realistic” scenario in 2023 and in our ”pessimistic” scenario around the year 2029. These results indicate that plausible learning rates were assumed if one compares our results to the cost reduction potential provided by ECOSTAR’s investigation of the innovation potential.

As recommended by Neij (2008), a sensitivity analysis considering different learning rates was carried out. By way of the scenario “optimistic-realistic” we varied the learning rates using a range 6–16%. Whereas the base case (LR=12%) yields EGC of 4.72 ct/kWh$_{el}$ in 2050, the sensitivity cases, assuming LR=16% and LR=6%, result in a range 3.27–8.87 ct/kWh$_{el}$ (Case A) and 3.58–8.04 ct/kWh$_{el}$ (Case B), respectively. These results show how elastic the EGC are with respect to the learning rate. This requires cautious assumptions on the innovations that could be reached especially in the next 10–15 years, when cost reduction by learning effects will likely have the strongest impact.

**Table 5**
Comparison of CSP electricity generation costs between this study and the ECOSTAR study (solar only-operation, transmission costs not included).

| Scenario | 2007 | | 2020 | |
|---|---|---|---|---|
| | Case A | Case B | Case A | Case B |
| ECOSTAR study | 17.2 | 13.7 | 6.7 | 5.4 |
| NEEDS—”very optimistic” | 17.32 | 13.86 | 6.94 | 5.47 |
| NEEDS—”realistic-optimistic” | 17.32 | 13.86 | 7.31 | 5.76 |
| NEEDS—”pessimistic” | 17.32 | 13.86 | 8.21 | 6.47 |

All figures given in ct/kWh$_{el}$ (ECOSTAR based on 2005 values, NEEDS based on 2007 values).

Similar to the cost development, the highest reduction of materials and emissions takes place during the *first phase* until 2025 (minus 30% on average). In the *second phase* until 2050 only minor improvements are possible which lead to a further decrease of emissions by 10–15% points. Unlike one might assume, these results do not differ very much between the three technology development scenarios due to several trade-offs: new power plant concepts introduced in the scenarios with higher deployment do not necessarily show better performance due to novel materials partly increasing the emissions balance.

Nevertheless, one should realise that even the current CSP systems show quite a good performance in comparison to advanced fossil fired power plants which emit between 400 and 900 $CO_2$-eq./kWh$_{el}$ and to future CCS-based power plants (equipped with carbon capture and storage) which will emit 130–260 $CO_2$-eq./kWh$_{el}$ (Viebahn et al., 2007; WI, 2010). Fig. 6 illustrates these relations, taking into account mean CSP emission values from Fig. 5.

## 9. Conclusion

Our integrated assessment of CSP plants shows significant potential for a strong and long-term CSP deployment. The energy policy of the near future will decide whether this ambitious but (in order to be able to meet the 2 °C goal) necessary development pathway can be realised or whether a continued fossil fuel based supporting scheme will enable only a “pessimistic” CSP diffusion. As the cost assessment shows, the pathway pursued in the next years will also decide about the reduction of electricity generating costs—whether they can reach about 4 ct/kWh$_{el}$, as modelled for the “very optimistic” case, or only 6 ct/kWh$_{el}$, as in the “pessimistic” case. Although greenhouse gases and other emissions from CSP plants are already quite low if the current systems – operated in solar-only mode – are compared with advanced fossil fired systems,

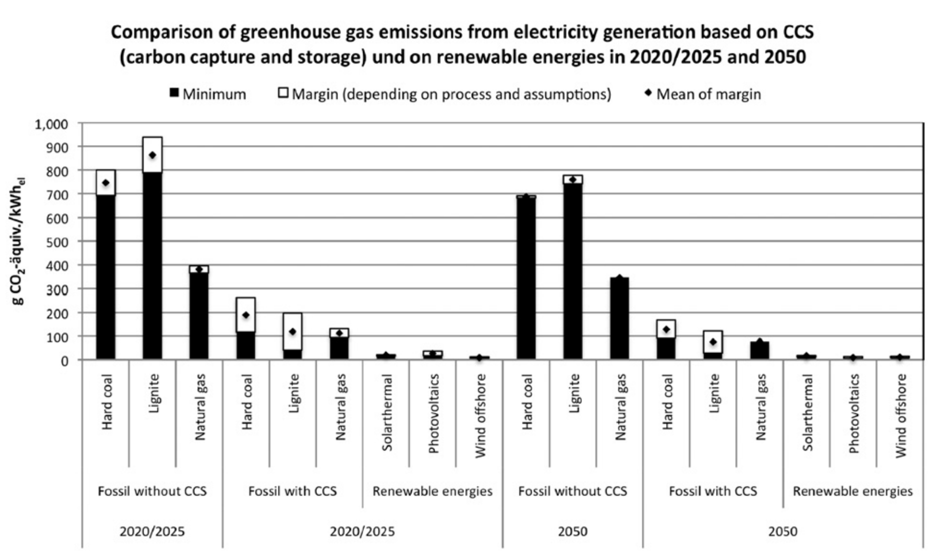


**Fig. 6.** Comparison of greenhouse gas emissions for different renewable and advanced fossil fired power plants (based on WI, 2010).

life-cycle emissions of CSP plants can further be reduced in the future. Altogether, CSP plants could play a promising role helping to reach the climate protection goals aimed for in the next decades.

## Acknowledgements

The work this paper is based on (project NEEDS) was financially supported by the European Commission within the Sixth Framework Programme (2002–2006), sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy. We would like to thank three anonymous reviewers for their comments and suggestions.

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