E.ON Energy Research Center
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FCN Working Paper No. 1/2009

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November 2009
Revised September 2010

Institute for Future Energy Consumer Needs and Behavior (FCN)

Faculty of Business and Economics / E.ON ERC

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Publisher: Prof. Dr. Reinhard Madlener
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Development Trends and Economics of Innovative Solar Power Generation Technologies: A Comparative Analysis

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November 2009

Revised September 2010

Abstract:

In this paper we compare development trends, economics and financial risks of alternative large-scale solar power generation technologies (parabolic trough, solar tower, and three different photovoltaic technologies). In particular, a number of European countries, Algeria and the US promote solar power generation. In oure study, we investigate the economic viability of the solar trough projects Andasol-I (Spain), Nevada Solar One (US), the solar tower projects PS-10 and Solar Tres (Spain), and the three PV projects Solarpark Waldpolenz (Germany), Parque Solar Beneixama (Spain) and Nellis Solar Power Plant (US). To this end, we employ a battery of economic indicators, such as net present value (NPV), return on investment (ROI), alternative discount rate (ADR), and amortization time (T_a), and also perform a detailed sensitivity analysis. We find that, in the absence of subsidization, current solar technologies cannot compete with conventional power plant technologies. Overall, we conclude that for realizing the Europe-Middle East-North Africa (EUMENA) Mediterranean ring connection, more research and development is needed on solar power generation technologies for making them sufficiently attractive on economic grounds.

Keywords: Concentrating solar power; CSP; profitability;

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1. Introduction

In discussions about environmental protection, the current and future energy mix plays an important role. Electricity produced in fossil-fueled power plants, especially coal-fired ones, is an important contributor to anthropogenic CO_2 emissions, and thus adds to the problem of climate change. In combination with a phase-out of nuclear power aimed at by many countries, the need to replace fossil fuels, and the enormous appetite for energy in countries like India and China, in the long run renewable energy sources will have to be used widely. Renewable energy can be grouped into solar energy, hydropower, wind energy, bioenergy and geothermal energy, all of which can in principle be harnessed in commercially operated plants, although not all of them are economically viable today. In a Trans-Mediterranean renewable energy cooperation of the "EUMENA" region – i.e. Europe (EU), the Middle East (ME) and Northern Africa (NA) – all of these sources would be used. Within that scenario solar power could play an overwhelming role, given the enormous potential for solar power in the countries that are located in the so-called 'Sunbelt' (Trieb, 2006).

This paper, which is based on Mathar (2008), takes an investor's perspective at different solar power plants that are currently being built or planned. The organization of this paper is as follows. In section 2 we provide an overview of the different technologies and projects studied. In section 3 we summarize the political and regulatory framework conditions in the countries or regions investigated. In section 4 we undertake an economic analysis and a sensitivity check. Section 5 concludes.

2. Technologies and power plants considered

2.1. Parabolic trough solar power plants

Parabolic troughs are concentrating systems. They convert solar irradiation into heat that is stored in a circulating heat exchange medium (e.g. thermo-oils or molten salt), which is located in a vacuum absorber tube in the focal line of a parabolic trough. Via a range of heat exchangers the hot exchange medium (ca. 400 ºC) is cooled down outside of the solar field and the freed energy used to produce steam. Total conversion efficiency, on average, is about 15%. The size of parabolic trough power stations can range from a few Megawatts (MW) to several hundred MW.

2.1.1. Market overview

Currently, about ten parabolic trough solar power plants are in commercial operation worldwide. Dozens of new projects are currently either planned or under construction. Table 1 summarizes the characteristics of the power plants scrutinized in our study.

The “Solar Energy Generation Systems” (SEGS) in the U.S. comprise nine individual power plants at different locations in the Californian Mojave desert (Daggett, Kramer Junction, and Harper Lake), with installed capacities of 14 MW (SEGS-1), 30 MW (SEGS-2 to SEGS-7) and 80 MW (SEGS-8 and SEGS-9). Apart from SEGS-1 all power plants are equipped for using additional gas-fired steam generation (limited by law to max. 25% of total heat production), so that they can also operate on cloudy days and in the evenings (NREL, 2007). The SEGS plants were consecutively erected on a yearly basis, starting in 1984, and were the first commercially operated solar power plants worldwide. Specific investment costs decreased continuously and were at 5979 $/kW for SEGS-1 to 3011 $/kW for SEGS-9 (total investment volume $1.2 billion) (EIA, 1995).

2.2. Solar tower power plants

Solar tower power plants are also concentrating systems. A heliostatic field reflects incoming sunlight to a receiver unit mounted on a tower, in which a circulating fluid is heated up (up to 600 ºC). The heat energy is then used via several heat exchangers for steam generation and the powering of a steam turbine. The height of the tower and the size of the heliostatic field vary, while installed capacity typically amounts to a few MW. The heliostats are adjusted such that they trace the sun during the day. Conversion efficiencies reach up to 18% and are therefore higher than those of parabolic trough solar power plants. Currently, PS-10 is the only such plant in operation worldwide. Table 1 also summarizes the characteristics of the solar tower power plants investigated in our study (columns 5-7).

Table 1: Basic characteristics of the technologies studied

Technology	Parabolic trough			Solar tower			Photovoltaic		
Project	SEGS 1-9	NSO	Andasol-1	Solar Tres	PS-10	PS-20	Solarpark Waldpolenz	PSB	NSP
Location	California, USA	Nevada, USA	Andalusia, Spain	Andalusia, Spain	Andalusia, Spain	Andalusia, Spain	Leipzig, Germany	Alicante, Spain	Nevada, USA
Installed capacity (MW)	354	64	50	17	11	20	40	20	14.2
Power produced (GWh/a)	1132.8	130	179.45	110.6	24.3	44.2	40	30	30
Full load hours (h/a)	3200	2031	3589	6504	2209	2209	1000	1500	2113
Collector area (m^2)	ca. 2.3 mill.	357,000	510,000	298,000	75,000	151,000	400,000	160,000	N/A
Investment cost	US$1.2 bn (ca. €1.278 bn)[1]	€220 mill.	€260 mill.	€196 mill.[2]	€36 mill.[3]	Unknown	€130 mill.	€120 mill.	ca. US$100 mill.
Putting into operation	1985-1991	Jun 2007	Summer 2008	At the earliest 2009	Mar 2007	Anticipated end of 2008	Since Aug 2007	Sep 2007	Dec 2007
Special characteristics	Add’l gas firing	Short-term accumulator	Thermic accum.	Add’l gas firing, thermic accum.	Short-term accum.	Short-term accum.			
Solar radiation (kWh/m^2 a)							ca. 1050	1934	ca. 2000

Source: Own compilation

[1] In 1984-1991 prices.

[*] Estimate.

[2] Estimate provided by Solar Paces (2005a).

[3] Estimate provided by Müller-Steinhagen (2006).

A forerunner of today's solar tower power generation plants is the pilot plant "Solar One" (not to be confused with "Nevada Solar One"), which was installed in the Mojave desert in the early 1980s, with an installed capacity of 10 MW. It was in operation between 1982-1986. In 1995, a number of heliostats were added and the plant was renamed "Solar Two". In this second project stage, molten salt was used instead of direct conversion of water into steam (SolarPaces, 1997; Herrmann et al., 2004). The project was abandoned in 1999 and the plant converted for other research purposes (Müller-Steinhagen, 2006). Based on the experience gained from the pilot projects Solar One and Solar Two, construction of the first solar tower power plants has been under way in Spain since 2004. Thanks to grants from the European Union and guaranteed feed-in tariffs, these are expected to be commercially operated and profitable for the investors. In March 2007, the first of them, PS-10, located on the Plataforma Solar near Seville, was brought online, and is expected to eventually have a total installed capacity of 300 MW. The owner and operator of PS-10 is the Spanish company Abengoa. Also involved are Inabensa S.A. from Spain, Fichtner GmbH from Germany, as well as two state-owned institutions, CIEMAT and DLR. PS-10 has a short-term storage system that enables to run the plant for some 50 minutes at half capacity even during cloudy weather conditions. There are 2209 full-load hours p.a., which is somewhat lower than for plants with full thermal storage systems at comparable sites. The annual yield is expected to be around 24.3 GWh. The nearby PS-20, under construction since 2007, is a larger unit with a higher tower, more mirrors and a more powerful 20 MW receiver, expected to provide some 44 GWh of electrical energy per year (Abengoa Solar, 2007). No detailed data are yet available for PS-10 and PS-20, as these are still treated confidentially. Total investment costs for PS-10 have been estimated at €36 million (Müller-Steinhagen, 2006), of which €5 million were contributed by the European Union and €1.5 million by the Spanish authorities. The level of subsidies granted to PS-20 are not known yet (CEC, 2007a; Pitz-Paal, 2008). In contrast to Andasol-I, green electricity from the PS power plants is not fed into the grid at a guaranteed fixed tariff, but at a price that is determined from a variable reference price and a mark-up granted over 25 years. Currently, the remuneration is about 21 ct/kWh (SolarPaces, 2005a), varying in line with the general electricity price development. Due to the uncertainty in the investment cost and the revenues, the sensitivity analysis of these parameters is of particular importance for these two plants.

Solar Tres is a solar tower project still in the test and development phase, to be realized most likely also in the Seville area not before the end of 2009 (Pitz-Paal, 2008). In contrast to PS-

10 and PS-20, Solar Tres will have a full-blown thermal storage device, which enables to deliver electricity also during times of little sunshine and during the night for up to 15 hours, albeit at a somewhat reduced load. As a consequence, and in contrast to systems without storage or other volatile regenerative energy sources (e.g. wind), Solar Tres can deliver dispatchable electricity and be used in the regular load dispatch. The expected annual yield of more than 100 GWh and the correspondingly higher full-load hours of 6500 hours p.a. are thus considerably higher than for PS-10 and PS-20, which otherwise have similar turbine sizes. Owner and operator of Solar Tres will be Gemasolar2006 S.A., a 100% subsidiary company of the Spanish company Sener.[4] Solar Tres is analyzed in this study despite its early project phase, in order to investigate the impact of a thermal storage device on the economic viability of such a plant. It can be assumed that investment costs are higher than for the PS plants used for comparison, but that, on the other hand, higher revenues will actually over-compensate the additional costs. In the empirical part further below, we show at what assumptions this effect actually materializes. More specifically, for the base case calculations, we use the estimated revenues of €196 million, provided by SolarPaces (2005a), as our best estimate available.

2.3. Photovoltaic power plants

In contrast to the previously described technologies, photovoltaic (PV) power plants do not concentrate solar irradiation (i.e. heat generation is not needed). Solar cells, grouped as solar modules, absorb the sunlight and convert it directly into electric energy. Usually, the modules do not trace the sunlight (and if they do, then only on one axis). In Germany, PV systems have become popular because they can be mounted as small units on the roofs of residential buildings and according to the German Renewable Energies Act 2004 receive guaranteed feed-in tariffs of up to 57.4 ct/kWh, depending on the start of operation (EEG 2004). Investment costs, depending on the location and other influencing factors, can be amortized typically in 10-15 years. Technical lifetime is expected to be some 20 years, so that the owner of a PV installation has no or negligible costs after that and substantial revenues.

[4] Sener joined the project team in 2001, which at that time consisted of the Spanish company Ghersa as well as Nexant and Boeing (two U.S. firms). Both Nexant and Boeing have left the consortium for different reasons, so that currently, apart from the governmental support via CIEMAT and DLR, Siemens (Germany) and Saint Gobain (France) are newly involved partners (Martin, 2007). Solar Tres components are currently tested on the Plataforma Solar in Almeria, Spain.

There are many different types of solar cells, and classification can be done by different criteria. For our analysis the distinction between thick-film and thin-film technology is useful. Thick-film technology is subdivided into mono-crystalline and poly-crystalline cells. Both consist of silicon but differ with regard to the production process and also the purity of the silicon used (and hence in price and conversion efficiency, the latter of which in the case of mono-crystalline cells is at around 17% and for poly-crystalline cells at around 12%). Thin-film cells consist either of amorphous silicon, cadmium-telluride (CdTe modules) or of copper, indium and selen (so-called ‘CIS modules’). Characteristic features of thin-film cells are their simplified production processes and lower material input needs, since the photoactive layer, which can be applied directly on some carrier material (e.g. glass) by means of vapor deposition, is about 10 times thinner than for thick-film cells. Conversion efficiencies of thin-film cells vary between 6-10%, depending on the technology, and are thus lower than for thick-film cells.

Even in Germany, where solar irradiation is relatively low and greenfield plants only subsidized moderately, economic viability can be achieved due to economies of scale and economies of scope. The commercial availability of the less costly thin-film technology facilitates the use of PV at low solar radiation sites. An interesting aspect is that, despite of the lower theoretical conversion efficiencies of thin-film solar cells, it has been claimed that in reality they can gain higher energy yields for the same capacity than poly-crystalline solar cells, due to the lower temperature dependence of the conversion efficiency (FirstSolar, undated).

Currently, a large number of large-scale PV projects is realized, with capacities of up to 40 MW_e. For the future, it can be expected that, due to the modular set-up, several hundred MW_e of plant capacity will also be feasible. In contrast to solar thermal power systems, PV technology has been available for decades and for niche applications (e.g. space, insular systems) continuously developed further. Since large-scale power plants are not totally different in design from smaller insular systems, not much additional research had to be undertaken since the introduction of feed-in tariff systems in various countries of the

EUMENA network.[5] For that reason the number of the newly installed, commercially operated large-scale PV systems of more than 10 MW of installed capacity (at the time of writing this article eleven) is much higher than the number of newly installed solar thermal power plants (apart from Andasol-1 only two such plants have so far been connected to the grid). Likewise, the number of large-scale PV systems planned is much higher than the number of planned solar thermal power plant projects.

When analyzing the market of the solar module manufacturers, it is interesting to note that there are many players in different countries, which is in contrast to the manufacturers of components for solar thermal power plants (usually less than half a dozen of enterprises). Measured by the 2007 annual PV module production (in MW), the top-10 ranking is (cf. Solar Verlag, 2008): (1) Suntech (China, 354); (2) Sharp (Japan, 363); (3) Kyocera (Japan, 207); (4) First Solar (US, 200); (5) Sanyo (Japan, 165); (6) Yingli (China, 150); (7) Solarworld (Germany, 135); (8) Mitsubishi Electric (Japan, 121); (9) BP Solar (UK, 120); and (10) Solon (Germany, 118). As can be seen from this ranking, Germany – the country with the highest demand for PV modules worldwide, has to meet this demand mainly by imports from Asia, so one of the desired effects of the act on granting priority to renewable energies (Erneuerbare Energien Gesetz, EEG), i.e. to foster the domestic PV industry, did not materialize sufficiently, at least in the field of PV module manufacturing.

Table 3 summarizes the characteristics of the three largest PV power plants worldwide used for the comparative analysis in our study, and compares them with the other technologies and plants investigated. The "Solarpark Waldpolenz" in Brandis near Leipzig, Germany, has been put into operation sequentially since August 2007, with planned incremental installations of 10, 20 and 10 MW in 2007, 2008 and 2009, respectively, a timetable which could largely be realized (Falck, 2008). Given the anticipated number of full-load hours (1000 hours p.a.), the expected annual energy yield is 40 GWh (Juwi, 2007a). Total investment costs are €130 million, financed entirely by the Sachsen Fonds GmbH as project owner, without grants from the federal or regional governments or other institutions. Juwi GmbH, the project developer, uses CdTe thin-film solar cells of the U.S.-based firm First Solar, manufactured by its

[5] In 2003, the Club of Rome introduced their vision of a EUMENA-wide renewable energy cooperation (Trans-Mediterranean Renewable Energy Cooperation – TREC) that uses the best locations in the EUMENA region to produce energy by means of different kinds of sustainable energy technologies.

subsidiary First Solar Manufacturing GmbH in Frankfurt/Oder, Germany. An interesting feature of the project is that the power plant is erected on a former military site and leased by the project operator, which has important economic implications (cf. section 3).

The Parque Solar Beneixama near Alicante, Spain, was already put into operation at the end of 2007. Given an installed capacity of 20 MW and some 1500 full-load hours it produces around 30 GWh of electricity per year. Total investment costs of ca. €120 million were borne by a pool of investors. The German company City Solar AG, which produces poly-crystalline solar modules (Model PQ200), was the project developer. The company uses its own modules manufactured by Tenesol, Aleo and Solon, with cells provided by the German manufacturer Q-cells. Auxiliary technology was mainly provided by the German multi-national enterprise Siemens, while the installations were carried out almost exclusively by the Spanish companies Enersolar and PowerSol (City Solar 2007; Hug, 2007). If the main features of Solarpark Waldpolenz are compared with those of the Parque Solar Beneixama, one can see that due to the technology characteristics, and despite of the 50% lower solar irradiation levels in Bandis, full-load hours are only one third lower. Note that these performance characteristics are still theoretical, and can only be verified after a few years of operation. Hence it has to be questioned whether the expected yield of the Solarpark Waldpolenz can actually be achieved, which makes full-load hours an important parameter in the sensitivity analysis reported in Section 4.

The third project considered in our study is the Nellis Solar Power Plant in Nevada, U.S., which was put into operation at an Airforce Base (Nellis) in December 2007. Installed capacity of the plant, which consists of mono-crystalline silicon cells, is about 14 MW, and the amount of solar power produced at 2113 full-load hours is around 30 GWh per year. The plant was built and is operated by Sun Power Corp., and the owner of the plant is MMA Renewable Ventures. In contrast to the case of the two European PV power plants, there is no guaranteed feed-in tariff offered by a governmental scheme, but the military base purchases the electricity at 2.2 ct/kWh over a contracted duration of 20 years from MMA. MMA in turn receives from the State of Nevada for each kWh of green power generated pollution permits (credits) sold to the local utility Nevada Power, which due to the state-level RPS (Renewable Portfolio Standard) has to purchase a certain quota of electricity production from renewables. The Airforce Base has to pay 6.8 ct/kWh less than it paid before the installation of the PV plant, but provides the (previously unused) site for free. MMA expects to gain revenues from the sales of green electricity to the military base and the revenues from selling the pollution permits to Nevada Power total revenues that pay for the US$100 million investment (O'Connor, 2007). Nevada Power fulfills part of its obligations under the RPS and hedges its certificate price risk, without having to invest in green power self-generation capacity (or any other options). Therefore, the certificate price level is an important parameter in the economic analysis of the Nellis power plant, since no information was available to us about the contents of the contract between MMA and Nevada Power.

3. Political frameworks

In this section, we provide an overview of the political framework conditions in selected EUMENA countries and the U.S. Our main interest is in guaranteed feed-in tariffs for solar power and direct or indirect investment grants, for example, in the form of subsidies or tax grants. Moreover, we also consider RPS that oblige the electric utilities to achieve certain portfolios of renewables. But first of all, we scrutinize the investment climate in the countries concerned, evaluated by means of six independent rankings, as shown in Table 2.

Table 2: Investment climate rankings

Country	CCR 08	CPI 07	IEF 08	WBDB 07	GCI 08 Infrastructure	GCI 08 Higher Education
Germany	7	16	Mostly free	Easy	1	20
US	13	20	Free	Easy	6	5
Spain	19	25	Moderately free	Easy	19	31
UAE	28	34	Moderately free	Moderate	17	58
Saudi Arabia	40	79	Moderately free	Easy	45	63
Morocco	66	72	Mostly unfree	Difficult	68	83
Algeria	67	99	Mostly unfree	Difficult	82	94
Egypt	73	105	Mostly unfree	Difficult	62	80

Sources: CCR08: Institutional Investor (2008), CPI: Transparency International (2008), IEF: Wall Street Journal (2008), WBDB: World Bank (2007), GCI: WEF (2008); own compilation

The indicators are as follows: The Country Credit Rating (CCR 08), published since 1979 by the Institutional Investor Magazine, measures the creditworthiness of 174 countries on a semi-annual basis (Institutional Investor, 2008). The Corruption Perceptions Index (CPI 07) by Transparency International measures the perceived degree of corruption in a country

(Transparency International, 2008). In contrast, the Index of Economic Freedom (IEF 08) published by the Wall Street Journal and also the World Bank Doing Business Index (WBDB 07) are measures of how easy it is for foreign firms to do business in the country concerned (Wall Street Journal, 2008; World Bank, 2007). Finally, the Global Competitiveness Index (GPI) issued by the World Economic Forum sorts countries by their competitiveness according to various criteria (in our analysis, we chose “infrastructure” and “higher education”) (WEF, 2008). All six indicators exhibit a clear trend, in that the Western European countries and the U.S. rank first in attractiveness for investments. Middle East countries, led by UAE, follow suit. Far less attractive, according to these rankings, are the North African countries, which often feature only in the lower third of the ranks.

Investments in the higher ranked countries are preferred to those in lower ranked countries, if the totality of the rankings with their clear trend is interpreted as part of the investment risk. Ultimately, a higher risk related to an investment in a lower ranked country can be compensated by other factors, especially if a risk premium is paid in the form of a higher expected profit. Factors leading to higher profits are introduced next. We concentrate on cross-country guidelines before introducing country-specific conditions.

In the Fifth and Sixth Framework Programme of the EU (FP5 and FP6, 1998-2007), research on solar thermal power plants was financially supported with €25 million (CEC, 2007b). Within the currently operational Seventh Framework Programme (FP7, 2007-2013) concrete power plant projects are supported, on the one hand, by the newly introduced “Risk Sharing Finance Facility” (RSFF) and, on the other hand, by direct subsidies amounting to €15 million (€5 million each for Andasol-1, PS-10 and Solar Tres). The goal of RFSS is to facilitate access for enterprises and public entities engaged in research, technological development, demonstration and innovation projects, and the access to financing, since the search for private funds is often difficult (EIB, undated). For Andasol-1, for instance, a long-term credit of €120 million and for Solarpark Solucar a credit of €50 million was granted (EIB, 2007).

Power plant projects in Developing Countries can hope for support through the Global Environment Facility (GEF), which is jointly funded by the World Bank and the United Nations. Currently, the GEF funds ISCC projects in Ain Beni Mathar (Morocco) and in Kuraymat (Egypt), with approximately US$ 50 million each (SolarPaces, 2005b, 2005c).

Moreover, projects in Africa can obtain funds from the African Development Bank (AfDB). The above-mentioned ISCC power plant in Morocco is co-funded by AfDB with a credit of about €135 million (AfDB, 2004). While electricity markets in Europe have been liberalized over several years, in MENA countries often state-owned utilities, which are candidates as co-investors for solar power plants due to their not purely market-oriented focus. The state-owned Moroccan energy supplier ONE (Office Nationale d'Electricité) supports the ISCC power plant in Ain Beni Mathar with about €34 million (AfDB, 2004).

3.1. Germany

In Germany, PV systems for private households and SMEs have been supported since the early 1990s, mainly within the 1000 roofs and the 100,000 roofs program by means of low interest loans, i.e. investment subsidies. Since the reform of the Renewable Energies Act (EEG) in 2004, solar power production is promoted by means of guaranteed feed-in tariffs, which are funded by a levy on all electricity consumers. The goal of the EEG is to raise the share of renewables in overall electricity production in Germany to at least 12.5% until 2010 and at least 20% by 2020. The long-term goal of the German Federal Ministry of the Environment (BMU) is a share of 50% by 2050 (Trieb et al., 2003). The feed-in tariff is held constant for the duration of 20 years. Its level is dependent on the date of putting the plant into operation and its technical characteristics. For large-scale PV systems considered in this study, the base rate for greenfield plants applies, which is lower than the base rate for roof and façade constructions. The base rate currently decreases by 6.5% per year (previously 5%). Electricity produced by plants put into operation in 2004 is remunerated at 45.7 ct/kWh, whereas such from a plant from 2008 is only granted 35.49 ct/kWh (EEG, 2004). Beyond the feed-in tariff, large projects cannot expect to receive further subsidies. As already mentioned above, the solar park Brandis for instance, with an investment volume of more than €130 million, is funded completely by the park operator, the Sachsen Fonds GmbH, by means of equity and debt capital (Juwi, 2007a).

Table 2 shows that Germany and the U.S. are leaders in all categories of the general investment climate considered here. Overall, we find that Germany, at least concerning the framework conditions considered up to now, has an investment-friendly climate. However, a decisive factor has been ignored so far. Due to the relatively low direct solar irradiation levels in Germany, only such plants can be operated economically that also make use of diffuse light (e.g. light reflected by clouds), i.e. *de facto* only PV power plants. Solar tower (Solar Tower Jülich) and parabolic trough (DLR Cologne) power plants only exist as demonstration plants, i.e. there is no intent to produce electricity commercially at competitive prices. Global solar irradiation values (i.e. direct and diffuse irradiation) range from 950 to 2550 kWh/(m^2 a) (cf. Table 3). Note that for comparison between concentrating systems direct irradiation would suffice, whereas for PV systems global irradiation has to be considered, as these can also make use of diffuse light. Obviously, locations in Germany have the lowest irradiation values, but the values differ only by a factor of two from the most favorable sites worldwide, and by a factor of 1.5 compared to the most favorable locations in much sunnier Spain. Compared to locations in Germany, the advantage of Southern (and thus much warmer) locations is actually reduced, as the efficiency of PV plants is reciprocally dependent on the temperature.

Finally, the nuclear power phase-out plan of Germany can be seen as a further advantage of solar enterprises, since up to the year 2022 about 40 GW of capacity have to be replaced, and in order to achieve Kyoto and EEG goals, this can only be achieved by further promotion of renewables.

3.2. US

The first solar thermal power plants worldwide were built during the 1980s in the Californian Mojave desert. Governmental policy at that time foresaw a tax exemption for investments (investment tax credits, ITC) in power plants and an accelerated depreciation of the investment costs (NREL, 2007). Power plants were only allowed to use additional gas-firing up to 25% of the totally produced electricity (Solel, 2007).

Current framework conditions in the US are characterized by the RPS. RPS in many states stipulate a fixed portfolio of renewable energy sources, which in California and Nevada can be covered to a large extent by solar thermal and photovoltaic power production. In California, the RPS stipulates that a renewables share of 20% has to be achieved by 2010. In Nevada, the regulation is slightly less stringent at 20% until 2015. Moreover, many States have set independent but nonetheless very ambitious renewable energy targets. California, for example, aims at requiring a minimum share of 33% of renewables in the power suppliers' portfolio (DoE, 2008).

The state-level and the governmental promotion schemes are restricted to ITCs, just like in the 1980s and 1990s, which are at 30% for the projects considered in this study. Additional feed-in tariffs are not foreseen. In the Southwestern US States the use of solar thermal and photovoltaic power plants is promising even in the absence of feed-in tariffs, since in the last years brownouts and blackouts increased in occurrence during summertime, and led to peak power costs of between 10 and 18 ct/kWh (Solar Paces, 2005d). Since solar thermal and photovoltaic plants produce their highest output exactly during those peak-load times, they can, on the one hand, increase supply security, while covering peak loads (e.g. due to air conditioning at lunchtime in summer) yields the highest revenues. Since in the US electricity is sold from power plant owners to electric utilities via Power Purchase Agreements (PPA), it is not possible to state a single price at which green power from solar thermal and PV plants in the US are remunerated. Generally speaking, power prices in the PPAs are split into a fixed base price and a time-of-use (TOU) rate, whose level is dependent on the timing of the delivered energy. Across contracts the TOU factor varies only marginally. And while TOU rates, with which electric utilities compete at power plant operators for a PPA, are public, the decisive base price of the remuneration is – like the determination of the TOU rates – the result of negotiations between power plant operators and power suppliers (Wittmann, 2007).

3.3. Spain

Until a few years ago, it seemed that no other country would miss the Kyoto target more than Spain. In 2003, for instance, greenhouse gas emissions were 41% higher compared to 1990 reference levels instead of the targeted 15% (BpB, 2006). In order to achieve the target, Spain has started promoting solar power a few years ago. Since 2004, the feed-in tariffs are raised from 12 ct/kWh to 21 ct/kWh for the first 200 MW of installed electric capacity, and 18 ct/kWh for further installations. In 2007, the feed-in tariff scheme was revised again and is now dependent on technology and design, and decoupled from the oil price. Moreover, green power producers have a choice to either receive a guaranteed feed-in tariff or to sell the green power in the free market and to receive a fixed grant from government. The subsidies are granted for a period of 25 years, and are increased by the inflation rate minus one percent (in order to account for technological progress). So plants put into operation in 2008 receive 26 ct/kWh if they are solar thermal and 44.0381 ct/kWh if they are PV systems (Hurt, 2008; Holler-Bruckner, 2007).

Spain is among the European countries with the highest solar radiation levels, which makes it very well suited for solar energy production. As shown in Table 3, Spain lags only slightly behind Germany and the U.S. regarding the investment climate. Due to often poor transport and grid infrastructure, difficult terrain and a lack of accommodation for workers, however, it is often difficult to exploit good sites. Nevertheless, it is possible to find favorable locations, as the example of Andasol-1 shows, where access to both road and rail infrastructure and feed-in of the electricity generated into a nearby 400 kV line is possible.

3.4. Northern Africa and Middle East

North-African and Middle East countries have very high solar irradiation levels, but lose attractiveness for investors in solar power projects due to political, economic and socio-cultural boundary conditions (cf. Table 3). Moreover, these countries often have considerable oil and natural gas resources, so that they do not only have excellent solar energy potentials but also enjoy low cost fossil fuel production compared to, say, Western European countries. Hence interest in solar power production, which is still not profitable without subsidies, is moderate and in direct competition with oil- and gas-fired power plants. Only Algeria so far has a feed-in law, in which the natural gas resources were accounted for by allowing ISCC power plants a grant, the level of which depends on the level of the solar share.

If in the longer-term future the EUMENA ring becomes a reality, solar power generation in North Africa and the Near East will play an overarching role.

Table 3: Summary of the political framework conditions

Country	Global radiation (kWh/m2a)	Feed-in tariffs	Subsidies	General investment climate
Germany	950-1150	For free-standing plants put into operation in 2008 35.49 ct/kWh, guaranteed for 20 yrs	Not foreseen, possible via 7th EU Framework Programme	Upper third
US (NV, CA)	1750-2000*	-	30% ITC	Upper third
Spain	1650-1950		Not foreseen, possible via 7th EU Framework Programme	Upper third

UAE	1550-2150	-	-	Midfield
Saudi Arabia	1950-2550*	-	Possible via GEF	Midfield
Marocco	1950-2250	-	Possible via GEF and AfDB	Lower third
Algeria	1950-2450	Décret Exécutive 04/90 (also for ISCC)	Possible via GEF and AfDB	Lower third
Egypt	1950-2550*	-	Possible via GEF and AfDB	Lower third

Source: own compilation

* and beyond

4. Profitability considerations and sensitivity analysis

4.1. Influencing factors

Apart from the technology costs themselves, a number of additional factors influence the profitability of solar thermal and PV power plants, including (1) solar irradiation intensity, temperature and full-load hours; (2) infrastructure and grid infrastructure; (3) wage levels; (4) feed-in tariffs and investment grants; (5) fuel prices and material prices; and (6) the discount rate applied. In the following, we will discuss these factors in turn.

4.1.1. Intensity of solar irradiation, temperature and full-load hours

Solar irradiation intensity for the different locations was presented in section 3. Those values can be used to compute the amount of full-load hours for each type of technology and specific location using the performance ratio. Projects with additional gas-firing or a thermal storage unit will exhibit a higher amount of full-load hours. The annual amount of energy produced is given by the installed capacity, multiplied by the amount of full-load hours. As it is the produced energy which generates income for the plant owners, in the end it is the intensity of solar irradiation and the amount of full-load hours per year that influence the profitability of the project. Hence the amount of full-load hours per annum will be one of the variables in our sensitivity analysis. For the calculation of PV projects it is important to know that the full-load hours are reciprocally dependent on temperature, i.e. the higher the temperature, the lower the amount of full-load hours, *ceteris paribus*. Therefore, PV power production works best on sunny but cold days.

4.1.2. Infrastructure and grid infrastructure

For their solar collectors, solar thermal power plants as well as PV power plants need vast undeveloped areas that is easily accessible. Such locations can mostly be found in rural, non-forested areas. In this respect, PV plants could use e.g. former military zones in Central European countries, whereas solar thermal plants can be built on arid or semi-arid land of the countries in the Sunbelt not needed for other purposes. Those areas in many cases lack a certain standard in infrastructure as well as (access to the) grid infrastructure. Hence it may be possible that, before building a solar power plant, additional roads, railroad lines or electric grid connections need to be built first. In the end, all these investments have to be taken into consideration in the total investment costs of a solar power plant. Obviously, the higher the infrastructure investment costs are, the lower is the profitability of the solar power plant. Nonetheless, in the sensitivity analysis we will only consider total investment costs of the plant itself, leaving it to a potential investor which additional site-specific cost components to include when constructing a particular solar power plant.

4.1.3. Wage levels

Wage levels affect investment costs as well as the operating costs of a plant and thus its profitability. Both low- and high-skilled workers are needed in the construction phase (depending on the technology type between 50 and 500 limited jobs) and in the operational phase (dependent on the technology type between 10 and 50 permanent jobs) of a plant (cf. Stoddard et al., 2006; Juwi, 2007b; Solar Millenium, undated). High-skilled workers, for instance, have planning and monitoring responsibilities in the construction phase of a plant as well as monitoring duties in the operational time. Lesser qualified employees are needed for the assembly of the solar field, or later for its cleaning during operation. Just like in the case of the costs for establishing a proper infrastructure, the site-specific wage levels will also not be directly taken into account in our sensitivity analysis. It will only be considered indirectly through the variables “investment costs” and “operating costs”, respectively, which themselves consist of several factors.

4.1.4. Feed-in tariffs and investment subsidies

Possible feed-in tariffs and investment subsidies play an important role in the profitability calculations for a new power generation plant done by its investors. The feed-in tariffs and subsidies for the projects mentioned in this paper were presented in section 3 above. The base rate of the compensation in most cases is lowered over time, but then for existing plants remains constant over a period of some 20 to 25 years. Therefore, the construction phase has to be extremely precise, so that a possible delay in the building process will not force the plant into a lower feed-in tariff over a period of up to 25 years, which would result in considerable changes in cost accounting. The example of Luz International, on the other hand, shows the devastating consequences that might result from a hasty planning or construction phase. In the sensitivity analysis that follows, the feed-in tariffs and investment subsidies are used as variables to show the profitability of a plant in view of the prevailing energy policy framework.

4.1.5. Price of fuel and materials

Fuel prices, such as the prices of oil, brown coal, lignite, or uranium influence the profitability of a solar power plant in various ways. On the one hand, they are an indirect part of the investment cost. As during construction of a solar power plant many components are shipped over long distances via boat, airplane or truck. Moreover, the costs of the components themselves are influenced by the fuel and other resource prices. On the other hand, input fuel prices also have an impact on electricity prices and, therefore, the revenues of a solar power plant. High fuel prices and thus a high electricity price level, *ceteris paribus*, make a solar power plant more profitable. This connection between fuel prices and revenues is only effective in countries that link their feed-in tariffs to the energy price level. Fuel and resource prices will not be used explicitly as variables in our sensitivity analysis, but instead integrated into the variables “investment cost” and “feed-in tariff”.

4.1.5. Discount rate

The discount rate can be interpreted as the rate of time preference of an investor and it directly influences the annuity factor. A higher discount rate symbolizes a stronger preference for the presence, i.e. future payments (in our case: revenues from selling the produced energy (positive value) and the operating costs (negative value)) have a lower impact on the NPV than payments that are made at the beginning of a plant's lifetime (in our case: investment costs (negative value) and subsidies (positive value)). The annuity factor can be seen as the number of years over which the profits are added to the NPV without any discounting. At a discount rate of 8% and a lifetime of 25 years the annual profits are not multiplied by a factor of 25, but "only" by the annuity factor, which in this case is 10.6748. Instead of discounting the annual profits for the 25 year' lifetime period, the same NPV is calculated by multiplying the undiscounted profits by 10.6748. With this interpretation, it is clear that a lower discount rate and hence a higher annuity factor (i.e. a higher number of years in which the profits are added to the NPV without discounting), *ceteris paribus*, makes a plant more profitable regarding its NPV. The discount rate can also be seen as the overall interest rate for investment, i.e. it contains a compensation for inflation and it reflects the investment risk. It is impossible to come up with one single discount rate for all plants considered in our study. Hence the discount rate will be a variable in our sensitivity analysis.

In the following, we present our profitability calculations for the different technologies. Whenever possible, we took data from plants that are currently in operation or in the state of being built, so that investment decisions are being portrayed as realistically as possible. Every subsection closes with a sensitivity analysis, where we vary the variables named above in a way that critical values for the profitability parameters are achieved. In doing so, we can see in which combinations an investment is profitable and in which it is not.

4.2. Parabolic trough power plants

4.2.1. Profitability considerations

In the following, we compute the profitability indicators for Andasol-1 and Nevada Solar One. For the case of Andasol-1 the values used are based on Hurt (2008a), CEC (2007a), Schiel (2007) and Solar Millennium (undated). The investment costs of Andasol-1 are €260 million (excl. capital cost), of which €5 million are borne by the European Commission. Assuming an average of 3589 full-load hours per annum, an expected 179.45 GWh of electrical energy p.a. results. The feed-in tariff amounts to 26 ct/kWh. Operating costs vary between 2-4 ct/kWh (in the base case, computed at 3 ct/kWh, to amount to €5.38 million p.a.). The discount rate applied is 8%, the lifetime of the project is assumed to be the same as the duration of the guaranteed feed-in tariff. The oldest plant still in operation, SEGS-1, has been in operation for 24 years. Table 4 (2nd column) depicts the results for Andasol-1 for the base case.

Table 4: Profitability calculations, Base Case

Technology	Parabolic trough		Solar tower		Photovoltaics		
Project	Andasol-1	Nevada Solar One	PS-10	Solar Tres	Solarpark Waldpolenz	Parque Solar Beneixama	Nellis Solar Power Plant
Installed capacity (MW)	50	64	11	17	40	20	14.2
Lifetime (years)	25	25	25	25	20	25	25
Full-load hours (h/a)	3589	2031	2209	6504	1000	1500	2113
Investment cost (million €)	260	220	36	196	130	120	64.82
Subsidies (million €)	5	66	6.5	5	0	0	19.45
Feed-in tariff (ct/kWh)	26	14	21	26	35.35	44.0381	19
Operating cost (ct/kWh)	3	2	2	3	4.5	2.5	4
Discount rate (%)	8	8	8	8	8	8	8
Annuity	10.67	10.67	10.67	10.67	9.82	10.67	10.67
NPV (million €)	185.59	12.51	19.78	80.47	-8.14	13.02	2.67
ROI (%)	172.78	108.12	167.06	142.13	93.74	110.85	105.88
ROI_a (%)	6.91	4.32	6.68	5.69	4.69	4.43	4.24
ADR (%)	12.19	6.13	11.65	9.31	4.55	6.38	5.92
T_a (a)	6.66	11.11	6.90	8.22	11.87	10.80	11.37

Source: own calculations

Notation: NPV … net present value; ROI … return on investment; ADR… alternative investment rate of interest; T_a … amortization period.

The second plant studied is Nevada Solar One. Investment costs were about €220 million (Acciona Energy, undated). The investment tax credit granted is 30%, which can be converted into €66 million at the time of construction (NREL, 2007; Pitz-Paal, 2008). The average annual full-load hours of 2031 are lower than for Andasol-1, despite higher solar irradiation values, due to an incomplete energy storage unit and the lack of gas firing. The expected energy production is thus 130 GWh/a (Acciona Energy, undated). There is no fixed feed-in tariff in Nevada, and the price paid is unknown. For peak power, we assume 14 ct/kWh in the base case, and operating costs to be less favorable than for Andasol-1 (lack of energy storage units) at 2 ct/kWh. This results in the profitability indicators reported in Table 4 (3rd column).

It can be seen that the capital value is positive at an 8% discount rate, but also that the NPV and the ROI (ROI_a) are lower (and thus the amortization time longer) than in the case of Andasol-1. The ADR of 6.13% is lower than interest rates that can be obtained for alternative investments in the same risk and size category. Possible explanations why the investment was effected are that the revenues of 14 ct/kWh are maybe too low and that the below-average interest was accepted for strategic reasons (i.e. in the hope that future projects will be more profitable).

As can be seen the investment is profitable: the capital value at an 8% discount rate is highly positive, and 73% beyond the capital value are obtained as discounted profits. The ADR is 12.19% (i.e. Andasol-1 is as profitable as a bond with 12.19% annual interest payment). The amortization time is 6.66 years.

4.2.2. Learning curves

Specific investment costs account for the largest part of the levelized energy costs (LEC). The specific investment costs of NSO (3438 €/kW) and Andasol-I (5200 €/kW) are above the costs of the last SEGS plant erected in California (SEGS-9 at 2488 €/kW at 1990 prices, and 3421 €/kW if an annual 1.5% inflation rate is accounted for). A reason is that since the early 1990s no continuous development and innovation cycle has taken place (Hurt, 2008b). While the two plants benefitted from the experience gained with the SEGS plants, it does not manifest itself in the cost curves (both plants are on one of the peaks of the jagged-ratchet learning curve). In case of Andasol-I the maximum is somewhat higher, since a further component is added (thermal storage device). It needs to be seen whether or not the higher investment and operating costs can be overcompensated by higher revenues.

Another relevant study on cost development of parabolic trough power plants is Sargent and Lundy (2003), who have done a comparative analysis with solar tower power plants, and then compared their findings with those of SunLab (2002). Both studies have adopted a time horizon 2020 and assume that all newly constructed plants have a thermal storage device. In line with Trieb et al. (2003), the two studies assume a too rapid (i.e. overly optimistic) market diffusion of the CSP technology, so that already in 2004 new 50 MW power plants are built and in 2010 such with 150 MW of installed electric capacity. For the purpose of our study, it thus seems reasonable to shift the learning cost curves by 3-4 years into the future, given that the first 50 MW plant with a thermal storage unit (Andasol-I) only went online in late summer 2008, and given that no 150 MW power plant is in sight to be completed by 2010. Regarding the specific investment costs and the corresponding LEC the values assumed in the study are way too low compared to the real existing plants: both Sargent and Lundy and SunLab assume 4300 €/kW for plants with thermal storage, compared to Andasol-I, which features specific investment costs of 5000 €/kW, and for plants without storage Sargent and Lundy assume 2172 €/kW, while the costs reported for NSO are at 3438 €/kW. In other words, LEC are also assumed too low. While the values for NSO and Andasol-I in the Base Case are at 17.9 ct/kWh and 16.6 ct/kWh, respectively, Sargent and Lundy forecasted 10.63 ct/kWh and 9.81 ct/kWh. In the light of these underestimates compared to our base case computations, the other values provided by Sargent and Lundy for 2020 should also be treated with caution.

By means of improving the design of receivers and collectors, by increasing the working temperature, by advances in the operation and maintenance of the plants, by higher installed capacities (and related economies of scope) as well as by mass production of the required components, continuous cost reductions can be achieved in the medium term (Schott, 2005). Long-term technology advancements can be expected due to a different arrangement of the mirrors (Fresnel collectors) and direct vapor deposition. Whereas direct vapor deposition can lead to efficiency increases in the case of higher working temperatures, the Fresnel arrangement ‘only’ leads to cost reductions by the use of less expensive, non-bended mirrors, which, however, lead to a reduced conversion efficiency of the plant. It should be noted that both technologies have not reached commercial maturity yet.

4.2.3. Sensitivity analysis

In the sensitivity analysis for the parabolic trough power plants reported in the following, we varied the parameters full-load hours, plant lifetime, and operating costs. For the case of Solar One we also varied the electricity price, in order to check how sensitive the return on investment reacts. We further varied some parameters that can be considered as given, such as investment costs and capital grants, in order to check the extent to which learning curve effects may affect the profitability of a plant over time. Cost decreases over time can allow the establishing of plants at formerly unprofitable locations.

For Andasol-1 we considered five different scenarios. In the Base Case (Scenario 1), the plant is highly profitable. From Scenario 2 it can be learned that the EU capital grant only has a minor impact on profitability. In contrast, a reduction of the feed-in tariff to 7 ct/kWh (Scenario 3) would lead to a negative NPV. Over the duration of 25 years, only 30% of the investment can be recouped. The negative ADR shows that even at zero discounting, 1.19% of the investment would be lost each year. Scenario 4 shows that the minimum feed-in tariff for a zero NPV is 16.32 ct/kWh. Since the intra-day spot market price at the Spanish power exchange OMEL ranges between 4-9 ct/kWh, it becomes clear that even if energy prices rise, investment subsidies, capital grants or some other internalization of external costs are required. Finally, Scenario 5 shows that at least 2078 full-load hours per annum are required for profitability.

For Nevada Solar One we considered three scenarios besides the Base Case (Scenario 1). Scenario 2 shows that without tax credits the project would be clearly negative, which is not surprising given the 30% level of the capital grants (compared to only 1.92% in Spain). Scenario 3 shows that 13.1 ct/kWh feed-in tariff is required at a minimum for a positive NPV. Without subsidies, Nevada Solar One becomes profitable beyond a market price of 17.9 ct/kWh, compared to 16.6 ct/kWh for Andasol-1. In other words, without subsidies thermal storage technology enables higher revenues that in turn allow for an overcompensation of the higher investment costs even at a less favorable location. Finally, Scenario 4 shows that solar irradiation has a lower impact than the other parameters considered in the sensitivity analysis.

4.3. Solar tower power plants

4.3.1. Profitability considerations

Our profitability considerations for the solar tower technology address the PS-10 and Solar Tres projects. PS-10 is connected to the electric grid since 2007; hence all input data for our analysis is known, except for the exact amount of the investment costs. Given its turbine output of 11 MW and 2209 full-load hours p.a., PS-10 delivers some 24.3 GWh/a of green electricity, which is refunded by law at 21 ct/kWh (Abengoa Solar, 2007). Operating costs are estimated at 2 ct/kWh. The European Union bears some €5 million of total investment costs, which are estimated at €36 million in the Base Case (Müller-Steinhagen, 2006). Table 4 depicts the results for PS-10.

The NPV, being positive at an 8% discount rate, indicates the profitability of the PS-10 project for the base case assumptions. 167% of the own investment is paid back at the end of the lifecycle, which corresponds to a bond with 11.65% annual interest payment. The amortization time is 6.9 years. In contrast to PS-10, Solar Tres is still in its planning stage and input data has to be deducted from estimations of the project partners involved. The turbine output is 17 MW, which – at an assumed 6504 full-load hours p.a. – leads to an expected electricity generation output of 110 GWh/a (Martin, 2007). Just like Andasol-1 and PS-10, Solar Tres is also supported by the European Union with €5 million (CEC, 2007). SolarPACES (2005a) estimates total investment costs at €196 million. The feed-in tariff amounts to 26 ct/kWh in the Base Case, but its applicability depends on the actual connection of Solar Tres to the grid. Operating costs are estimated somewhat higher than in the Base Case for PS-10, because of the energy storage unit. Table 4 depicts the results for Solar Tres.

4.3.2. Learning curves

In contrast to parabolic trough power plants, which have a track record of almost 25 years, the experience with solar tower power plants is limited to Solar One and Solar Two (N.B. the latter of which was only an upgrade of Solar One) and a few smaller demonstration plants (e.g. Plataforma Solar in Almeria, Spain) operated over a relatively short period of time only. Hence it is not possible to use actual data about specific investment costs or LEC. However, for individual components sometimes learning curves do exist, such as for the tracking systems of the heliostats (Domingo, 2005). Current research, for example on the optimal size of the heliostats and direct vaporization and alternate receiver designs, promise further cost reductions. A detailed study on expected learning curves has again been undertaken by Sargent and Lundy (2003). According to their long-run estimates, LEC for solar tower power plants will decrease to 5.5 ct_{US}/kWh (in 2003 prices: 4.87 $ct_{€}$/kWh). Note, however, that the authors assume rapid market diffusion, so that their estimates have to be shifted by at least three years backwards. Medium- and long-term projections depend very much on the speed of market development. In contrast to Sargent and Lundy, it remains doubtful that 1000 MW plants will already be in operation by 2010, given that Solar Tres and PS-20 only went on line in 2009, with comparably modest 20 MW each. Regarding the LEC for 2007 the study by Sargent and Lundy is again overly optimistic: for PS-10 in the Base Case scenario at 15.9 ct/kWh and for Solar Tres 19.7 ct/kWh (in contrast to the projected 12.67 ct/kWh). Time will tell how accurate the projections of Sargent and Lundy have been; the Luz International case has shown that sudden regulatory changes can bust entire businesses in very short periods of time. Sargent and Lundy assume that 49% of the cost reductions are achieved through economies of scale, 28% by mass production of the components, and 23% of the reductions by technical development.

4.3.3 Sensitivity analysis

For the sensitivity analysis of PS-10, we again considered three scenarios besides the Base Case (Scenario 1). Scenario 2 shows that capital grants, due to their modest size relative to total project costs (18%) and feed-in tariffs only play a moderate role with regard to the profitability of the plant in absolute terms (note, however, that the ADR drops below 9%). Scenario 3 assumes higher investment costs for PS-10, which yields a value of €49 million (based on an estimate derived from the investment costs of Solar Tres) and a reduced NPV of €6.78 million. Hence without subsidies the project runs some danger to become unprofitable. The last scenario again focuses on the minimal required number of full-load hours. We find that *ceteris paribus* full-load hours would have to drop to 1614 h/a (-27%).

The sensitivity analysis of Solar Tres also comprises three scenarios besides the Base Case (Scenario 1). In Scenario 2, investment costs are varied relative to those of PS-10, such that a 75% reduction in cost would lead to the same costs as for PS-10 (€36 million). The profitability indicators show that for this situation, *ceteris paribus*, Solar Tres would be the most profitable of all projects considered. Discounted equity capital over the duration of the project would nearly double, and the ADR amounts to 14.3%, while the amortization period would be less than six years. Scenario 3 shows the dependence of Solar Tres with respect to the framework conditions in Spain. For the former feed-in tariff regulation, according to which solar thermal power plants only received 18 ct/kWh, the project would be unprofitable at an 8% discount rate, and only about 93% of the equity capital could be recouped over the project's lifetime. The final scenario again addresses full-load hours. These have to be at least 4577 h/a for making the project profitable. Relatively speaking, therefore, full-load hours must only be 28% lower than expected.

4.4. Photovoltaic power plants

4.4.1. Profitability considerations

In this section, we study the economic viability of large-scale PV systems by analyzing three distinct projects at three very different locations (Solarpark Waldpolenz, Parque Solar Beneixama and Nellis Solar Power Plant). Investment cost for the Solarpark Waldpolenz have been stated at €130 million (Juwi, 2007a). Construction, which has been planned to be realized over a period of three years (2007-2009) and in three stages (10/20/10 MW), is progressing according to plan (Falck, 2008). This leads to an average feed-in tariff of 35.53 ct/kWh over the duration of 20 years, without any additional subsidies by the federal or state government. Operating costs at 4.5 ct/kWh are somewhat higher, compared to concentrating solar thermal systems (Falck, 2008). We assume the number of full-load hours to be 1000 h/a in the Base Case, which is in line with the data made public (Juwi, 2007a). The results of our Base Case calculations are shown in Table 4. As can be seen, for the assumptions made, the project is unprofitable (negative NPV). Only 94% of the (discounted) equity capital would be recouped over the duration of the project. Hence, on economic grounds, there is little leeway for interpretations why the plant should be built.

Investment and operating costs used in our calculations are adopted from current statements of the leading construction company, Juwi GmbH, e.g. they have to be valued as the best estimates available. The number of full-load hours and the annual power output, respectively, are also variables in our calculations. But as both are already set optimistically high, in our opinion a higher annual power output should not be expected. Hence the discount rate will play an important role in the sensitivity analysis. Changes in the level of the average feed-in tariff can only be made according to the apportionment of the installed capacity in 2008 and 2009, as the values for 2007 have been proven right. The shorter economic lifetime of the Solarpark Brandis compared to other projects mentioned in this paper could be equalized by including the last five years of its technical lifetime in our calculations, without assuming a fixed feed-in tariff for those years. However, this variation does not change the overall result, because the accumulated revenues for the five years enhance the NPV by only €0.5 million.

The second PV system analyzed is the Parque Solar Beneixama. For its Base Case we made use of the data provided by the leading constructor City Solar AG. The installed capacity is 20 MW. Given its 1500 full-load hours p.a., the energy output is some 30 GWh/a (City Solar, 2007). The energy is remunerated at 44.0381 ct/kWh over a period of 25 years. Compared to the Solarpark Waldpolenz and considering its 60% smaller collector area, and the fact that during wintertime no additional costs caused by snow and ice will occur in Spain, operating costs in Beneixama are estimated at 3 ct/kWh. The results for our Base Case calculations are shown in Table 4.

In contrast to the PV system in Brandis, the NPV for the Beneixama project is positive, making the investment not only relatively more profitable than Brandis, but also achieving absolute profitability. As with Nevada Solar One, also the Parque Solar Beneixama only has a low ADR of 6.5%. In the sensitivity analysis we will see how higher operating costs and a lower feed-in tariff affect profitability.

The third PV system analyzed is the Nellis Solar Power Plant. As with the other plants for the Base Case, we used the data provided in official statements by the project partners. Given 2113 full-load hours p.a. and an installed capacity of 14.2 MW, the annual energy output is 30 GWh (MMA, 2007). The green power is bought by the Air Force Base at 2.2 US$-ct/kWh (1.43 €-ct/kWh). Moreover, MMA generates indirect earnings by selling the renewables credits to Nevada Power (O'Connor, 2007). It is not known to us at which price those credits are sold. For our Base Case calculations, we assume the price to be 27.10 US$-ct/kWh (17.57 €-ct/kWh), which results in a total compensation of 19 €-ct/kWh generated. Due to the sun tracking mechanism, operating costs are estimated slightly higher than at the Parque Solar Beneixama, viz. at 4 ct/kWh. Investment costs are not known precisely, but according to

O'Connor (2007) they amount to some $100 million (€64.82 million). The results for our Base Case calculations are shown in Table 4.

Besides the Solarpark Waldpolenz, which was not profitable in our Base Case scenario, the Nellis Solar Power Plant exhibits the second-worst profitability indicators. The AIZ is less than 6%, hence relatively low for an investment of that duration and risk. In the sensitivity analysis, we later have a closer look at the sum of the refund for the generated energy and the investment costs, as those values are uncertain.

4.4.2. Learning curves

The historical learning curves for PV systems are, according to CEC (2005), approximated by the real price development of the major components of a PV power plant, i.e. the PV modules. In contrast to concentrating systems, the price development path exhibits a much less jagged-ratcheted shape, because innovation cycles were much more continuous due to the continued private and government-driven demand for components. A complete new start of production, as in the case of the solar thermal plants, did not take place in the case of PV technology. Moreover, on the component markets there are more competing companies, as compared to the component market for solar thermal power plants, yielding fiercer price competition and taking care of a more rapid price adjustment for new products. Finally, the CEC study is only for classic silicon solar ('first generation') modules, i.e. the learning curve derived by the CEC does not account for second generation modules, such as CdTE-thin film modules, as used in the case of the Waldpolenz plant. The maxima of the learning curve can be found in the years after 2001, as in Europe and in particular in Germany the PV boom has led to a continuously high level of demand. Higher prices are also due to the shortages in (refined) silicon and too slow adjustments of the feed-in tariffs (and less so due to technical innovations). In the long run, both economies of scale and product innovations concerning the first- and second-generation modules, as well as the diffusion of innovative (third-generation) modules, such as tandem cells or modules made of organic or color-sensitive materials, enable further cost reductions.

4.4.3 Sensitivity analysis

As already mentioned above for the profitability calculations of the Solarpark Waldpolenz, we varied the discount rate and the feed-in tariffs in the sensitivity analysis for PV plants. In principle, the discount rate is chosen arbitrarily for each individual project considered, based on the capital structure and the desired ROI. Obviously, a project does not become more profitable by reducing the discount rate, but it can serve as an explanation why a project such as Solarpark Waldpolenz is realized despite its apparent non-profitability. Besides the Base Case (Scenario 1), we also considered three other scenarios. Scenario 2 shows clearly that at a discount rate of 7% the (discount-rate-dependent) profitability indicators become positive. Even if the sequential 10/20/10 MW installation over the years 2007-2009 is realized as planned, Scenario 3 assumes that the 30 MW are put into operation in 2008 *en bloc*, so that the average feed-in tariff would rise to 36.11 ct/kWh. It can be seen that even this early realization does not lead to a positive NPV at a discount rate of 8%. Finally, Scenario 4 makes clear that the feed-in tariffs guaranteed would have to be at least 37.61 ct/kWh for making the project profitable at the standard discount rate of 8%.

Sensitivity analysis for the Parque Solar Beneixama (PSB) again contains three scenarios besides the Base Case (Scenario 1). Scenario 2 looks at how increased operating costs affect profitability. Whereas we derived operating costs of the PSB in the Base Case from the operating costs of Solarpark Waldpolenz relative to the collector area, Scenario 2 assumes a less direct coupling between the operating costs and the collector area. However, as the profitability indicators show, the project remains profitable even at operating costs of 3.5 ct/kWh. Scenario 3 takes account of the new feed-in tariff regulation in Spain. Whereas the eligibility of PV systems for subsidies were limited to 100 kW of installed capacity (so that PSB was not considered as a 20 MW plant, but rather as an accumulation of a series of 100 kW plants), economies of scope, leading to cost reductions, could only be gained partly, since the plants also technically had to comprise of fully-fledged and independent 100 kW plants. Since the new regulation foresees higher feed-in tariffs for plants with more than 100 kW of capacity, it might be more profitable to actually give up this previously ‘enforced’ modularization to 100 kW units. Scenario 3 assumes the new feed-in tariffs for plants of more than 100 kW of installed capacity and, consequently, assumes lower investment costs due to economies of scope. The results confirm that the lower investment costs actually overcompensate the lower feed-in tariffs, so that the 20 MW plant is more profitable than an aggregation of 100 kW plants. It needs to be confirmed in reality, however, whether the assumed 20% investment cost reduction can actually be achieved. The final scenario considered for PSB shows that the minimum number of full-load hours for making the project profitable is 1354 h/a. Hence the predicted value must not drop by more than 9%.

The sensitivity analysis for the Nellis Solar Power plant comprises of two scenarios besides the Base Case (Scenario 1). Scenario 2 shows that the minimum sum of the direct compensation for green electricity paid by the Airforce Base and the purchase price of electricity certificates by Nevada Power has to be at least at 18.17 ct/kWh for making the project profitable. Scenario 3 again focuses on a variation of the full-load hours. It turns out that for safeguarding a positive NPV full-load hours have to be at least 1996 h/a. Hence full-load hours must deviate negatively by no more than 5%, which is critical given that in years with low solar radiation (and higher than usual foreseen or unforeseen outages) a larger downturn is not unlikely.

4.5. Comparative analysis

In this section, we compare the results for the different technologies studied in terms of their relative economic viability. As Table 5 shows, none of the technologies is absolutely superior compared to the others, which confirms current market analysis. Solar thermal plants seem to be generally advantageous in contrast to PV systems in terms of their profitability, since LEC is lower throughout, requiring higher feed-in tariffs to maintain economic viability. It should be kept in mind, however, that solar thermal plants have higher total investment costs due to a much lower degree of modularity, whereas PV systems can even be financed by private individuals (at almost the same relative economic viability as large plants). Contrary to expectations, for the group of solar thermal power plants, we do not find evidence for a clear dominance of projects with thermal storage units. One reason might be the poor database due to the low number of real plants and the not exactly known investment costs of solar tower power plants in Spain. In the longer run, we believe that plants with storage facilities will have a certain advantage due to learning and scale effects with respect to their LEC, compared to plants without storage.

Table 5: Comparison of the different technologies studied, Base Case

Technology	Parabolic trough		Solar tower		Photovoltaics		
Project	Andasol-1	Nevada Solar One	PS-10	Solar Tres	Solarpark Waldpolenz	Parque Solar Beneixama	Nellis Solar Power Plant
Technology	Parabolic tube power plant, with full-value thermic storage unit	Parabolic tube	Solar power tower	Solar power tower, with full-value thermic storage unit	Photo-voltaic power plant -CdTe thin film	Photo-voltaic power plant - poly-crystalline	Photo-voltaic power plant - mono-crystalline
Investment cost (*C*)	260	220	ca. 36*	Ca. 196*	130	120	64.82
NPV	185.59	12.51	19.78	80.47	-8.18	13.02	2.67
ROI	172.78	108.12	167.06	142.13	93.74	110.85	105.88
ADR	12.19	6.13	11.65	9.31	4.55	6.38	5.92
T_a	6.66	11.11	6.9	8.22	11.87	10.80	11.37
LEC	16.6	17.9	15.9	19.7	34.95	39.97	24.24

Source: own calculations

Table 6 summarizes the sensitivity of the NPV in reaction to a 10% change of the input data. It can be seen that the NPVs for most projects is very sensitive with regard to changes in the feed-in tariff. Exceptional are U.S. projects, where the feed-in compensation is replaced by direct investment subsidies, and where the investment costs have a higher influence than the feed-in tariffs. Interestingly, full-load hours (and thus location) of the projects have the lowest influence on the capital value. This observation explains why the investors consider the guaranteed feed-in tariffs as being more important for their locational choice compared to solar irradiation intensities.

Table 6: Sensitivity analysis for NPV, expressed in million € (parameter variation by +/-10%)

Technology	Parabolic trough		Solar tower		Photovoltaics		
Project	Andasol-1	Nevada Solar One	PS-10	Solar Tres	Solarpark Wald-polenz	Parque Solar Beneixama	Nellis Solar Power
Full-load hours (hrs)	44.05 +/- 23.7%	16.65 +/- 132.9%	4.93 +/- 25.1%	27.14 +/- 34.1%	12.19 -	13.31 +/- 102.2%	4.80 +/- 179.8%
Investment cost	26.00 +/-14%	22.00 +/- 175.9%	3.60 +/- 18.2%	19.60 +/- 24.4%	13.00 -	12.00 +/- 92.2%	6.48 +/- 242.7%
Feed-in tariff	49.8 +/-26.8%	19.42 +/- 155.2%	5.45 +/- 27.5%	30.68 +/- 38.1%	13.96 -	14.11 +/- 108.4%	6.09 +/- 228.1%

5. Discussion and conclusion

In this paper, we investigated the economics of innovative centralized solar power generation technologies. We reviewed the various existing technologies and some promising future technologies. For real projects, we investigated the economic viability of different plant types at different locations. We identified development trends and cost reduction potentials, and scrutinized learning curves. For each of the plants considered, we did a sensitivity analysis. We have shown that current solar technologies cannot compete with conventional power plants without subsidization. The results also show that sustainable energy production is hardly possible without the willingness to pay more. Apart from Germany, which has a leading role in promoting renewables, Spain, Portugal, France, Italy and many other European countries promote solar power generation. In North Africa, Algeria has made a first inroad in this respect by introducing a feed-in tariff law. The U.S. has been a leader worldwide for decades where solar thermal power plants were operated commercially, and it is still today the country with the highest installed solar thermal power generation capacity. For realizing the completion of the EUMENA ring connection, and thus the synergies of coupling the southern solar potentials with the wind, biomass, geothermal and hydro power potentials of the north, much more work is needed.

Glossary/Nomenclature:		
AIZ	…	Alternative investment rate of interest
CEC	…	Commission of the European Communities
CSP	…	Concentrating solar power
DS	…	Dish-Stirling
EEG	…	Erneuerbare Energien Gesetz (Renewable Energies Act)
EU	…	European Union
EUMENA	…	Europe (EU) – Middle East (ME) – North Africa (NA) region
GEF	…	Global Environment Facility
IGCC	…	Integrated Gasification Combined Cycle
ISCC	…	Integrated Solar Combined Cycle
ITC	…	Investment tax credit
LEC	…	Levelized energy cost
NPV	…	Net present value
NSO	…	Nevada Solar One
NSP	…	Nellis Solar Power
OMEL	…	Operador del Mercado Ibérico de Energía – Polo Español S.A. (= Spanish power exchange)
PPA	...	Power Purchase Agreement
PSB	…	Parque Solar Beneixama
PV	…	Photovoltaics
ROI	…	Return on Investment
RPS	…	Renewable Portfolio Standard
SEGS	…	Solar Energy Generation Systems
TOU	…	Time-of-Use
TREC	…	Trans-Mediterranean Renewable Energy Cooperation

Acknowledgements

The authors gratefully acknowledge helpful comments received from Lars Falck of Juwi GmbH, Nikolaus Hurt of SolarMillennium, and Robert Pitz-Paal of DLR.

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