Title:

Concentrating solar power plant investment and operation decisions under different price and support mechanisms

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Abstract

The dispatch opportunities provided by storage-enhanced Concentrating Solar Power (CSP) plants have direct implications on the investment decisions as not only nameplate capacity but also the storage capacity and the solar multiple play a crucial role for the viability of the plant investment. By integrating additional technical aspects and operation strategies, this paper extends the optimization model proposed by *Madaeni et al, How Thermal Energy Storage Enhances the Economic Viability of Concentrating Solar Power*. Using a mixed integer maximization approach the paper yields both the optimal layout decision and the operation of CSP plants.

Subsequently, the economic value of CSP storage is analyzed via energy modeling of a Spanish plant location under the respective wholesale market prices as well as the local feed-in tariff. The analysis shows that investment incentives for CSP plants with storage need to appropriately account for the interdependency between the price incentives and the plant operating strategy. As the resulting revenue characteristics influence the optimal size of solar field and storage differing operating strategies also give rise to differing optimal plant layouts. Most noteworthy, the current Spanish support scheme offers only limited incentives for larger thermal storage capacity.

Key words:

- Concentrated solar power

- Storage operation

- Optimization model

Research Highlight:

- Dispatch opportunities of CSP have direct implications on both investment and operational decisions

- Valuation approach with a single mixed integer maximization problem

- Profitability of CSP plants under the premium feed-in tariff in Spain was assessed

- Layout decision and storage size are influenced by remuneration scheme

- Discuss alternative remuneration schemes for "dispatchable" RE technologies

1. Introduction

Increasing shares of electricity generation from renewables in European countries raise new technical and economic questions about the operation and valuation of technologies in these new energy systems. Storage solutions are one key factor for the integration of fluctuating generation of wind and solar technologies (Acre, 2011, Denholm and Hand, 2011, Sioshansi et al., 2012). Among the new generation technologies Concentrating Solar Power (CSP) has the advantage of producing thermal energy that can be stored in thermal energy storages (TES). Using this storage during hours without radiation offers the possibility to provide dispatchable electricity.

In Europe only Mediterranean countries have a sufficiently high direct radiation potential for CSP plant operation with most of the CSP projects being based in Spain. By end of 2012, Spain had installed a total CSP generation capacity of about 1800 MW. This makes Spain by far Europe's largest market for CSP. Therefore, this analysis focuses on the Spanish electricity market. However, the model can easily be adapted to other electricity markets like Italy or North Africa. In future super grid scenarios one could even consider Northern demand market locations like Germany that could be supplied through electricity trading. The first commercial CSP plant with storage Andasol One (50 MW peak output, 7.5 hours of thermal storage) was commissioned at the end of 2008 close to the city Guadix in Andalusia. Today, about half of the Spanish CSP plants are equipped with thermal storage. Current plans indicate that by 2020 a total CSP capacity of over 5000 MW will be connected to the grid. A major reason behind this development is the

implementation of a favorable regulatory support scheme for CSP plants through a feed-in tariff (Griffiths, 2012). This has created a stable and constant market environment since 2007. The arrangements of this scheme give investors incentives to invest in CSP plants including thermal energy storage.

A marked difference between classic renewable energy (RE) technologies (wind turbines, photovoltaic (PV) installations) and CSP plants with storage is the type of operation. While the former are "passive" (non-dispatchable) systems offering no control opportunities (except for generation shedding), the latter are "active" (dispatchable) in the sense that operators can deliberately steer energy flows within the plant and access energy stored in the thermal storage. Given the limited control structure of non-dispatchable or passive systems, investment decisions are a simple question of efficient scale, energy yield and total capacity. Consequently, establishing investment incentives for these plants only requires setting a remuneration scheme for each unit of capacity provided, respectively for each unit of energy generated over a given time horizon. On the other hand, the control opportunities provided by storage-enhanced CSP plants have direct implications on the investment decisions as not only nameplate capacity but also interdependencies between turbine capacity, solar field size and thermal energy storage play a crucial role for the viability of the plant investment.

The current legal framework and support mechanism in European countries are highly influencing design and operation of CSP power plants. In the US, a quota system and tax reductions yield different effects on CSP investments. Due to higher electricity demand during daylight hours, CSP projects are often constructed without thermal storage, e.g., Nevada One (Nevada) or Martin (Florida).

In Southern Europe, some countries with high direct solar irradiance (Spain, Portugal, Italy) have decided to support CSP power plants through feed-in tariffs. One important goal of the energy planners was to support CSP power plants with storage to provide a market environment for flexible dispatch power plants based on solar power. In Portugal, small CSP plants (<10 MW) can operate under a fixed FIT of 260-270 Euro/MWh which is seen as a support for small pilot power plants. In Italy, the FIT for CSP ranges from 220 to 280 Euro/MWh reflecting the use of natural gas back-up in the CSP plant (CSPtoday, 2011). Feed-in tariffs in these countries do not couple the production of the CSP with the electricity market price but rather offer a fixed tariff for each kWh generated. Under this support scheme, thermal storage is only included to increase overall production per installed turbine capacity.

In Spain, the regulatory framework of the RD 661/2007 established a FIT for CSP investments. The RD 661/2007 had the largest impact on market creation of CSP in Europe due to its stable conditions reducing investor risk for renewable energy technologies (Ciarreta et al, 2011; Burgos-Payán et al., 2013). The regulatory body offers two different FIT options for CSP plants: a fixed and a premium FIT (P-FIT). Other generation technologies like wind can apply for similar premium FIT but with different remuneration. Schallenberg (2012) reports a strong increase of projects applying for premium FIT over all technologies, e.g. 96% of all wind projects and all CSP projects opted for the premium FIT in 2009. The standard FIT, similar to the ones offered in Portugal and Italy, guarantees a fixed rate of $\alpha = 270$ €/MWh over 25 years for each produced kWh (ϕ_t, electricity produced in time t over time period T). The second option uses the current pool price p_t from the Spanish electricity exchange plus a premium of $\alpha^p = 254$ €/MWh.

Total remuneration is capped at $\overline{\alpha_t}$ = 334 €/MWh. These FITs were established in

2007 and can be formalized as follows:

$$\text{FIT revenue} = \sum_{t=1}^{T} \phi_t \cdot \alpha \tag{1}$$

$$\text{P-FIT revenue} = \sum_{t=1}^{T} \phi_t \cdot min\{(p_t + \alpha^p), \overline{\alpha_t}\} \tag{2}$$

The revenue from a fixed FIT is lower than the P-FIT if the market price is above

16 €/MWh (see Figure 1). The P-FIT therefore encourages a preferred supply from

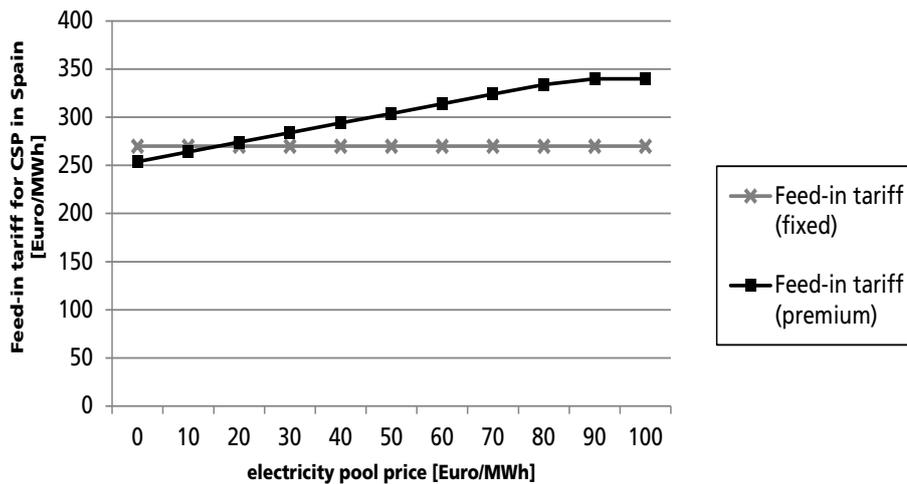CSP power plants during times of high electricity pool prices (Couture 2009).

Figure 1:   Two options of CSP feed-in tariff in Spain: A fixed and a premium tariff

Quantitative analyses of the P-FIT in the literature have been limited. P-FIT is

regarded as more risky for investors and therefore may lead to negative results for

market growth of RE technologies (Klein et al., 2008). Gonzales (2008) highlights

the minimization of windfall profits with the implementation of a cap price. From

an economic point of view, it has to be assumed that non-dispatchable generation

technologies like wind and PV opt for the premium tariff only in case of an

expected higher average remuneration. On the other hand, dispatchable generation technology can be operated in accordance with the P-FIT. Therefore, the valuation of dispatchable generator investments needs to account for the dependency between operational choices and the remuneration scheme.

This paper links an optimization model for the investment decision of the plant layout and the operations strategy of CSP plants with an analysis of the influence of different tariffs on these choices. Section 2 reviews the related work on economic analysis of CSP technology with storage. The optimization model for investment and operation is presented in Section 3. Subsequently, storage operation and economic evaluation are carried in the context of a Spanish case study using comparable layout and cost assumptions of the Andasol plants. In Section 5, different remunerations scenarios for CSP plants are analyzed to illustrate their effect on both operation and investment decisions. The final section concludes and provides an outlook on future research opportunities.

2. Concentrated solar power plants

Unlike PV solar plants which rely on the photoelectric effect, CSP power plants convert the energy of direct solar radiation into electric power via a thermal process. In the solar field, solar radiation is concentrated using reflective optics and captured in a focal point. Focused radiation is absorbed by receiver tubes which transport the thermal energy through a piping system to the central power block. Here, thermal energy is converted to electricity by means of a heat engine (turbine) driving an electric generator connected to the electrical grid. The system can be coupled with thermal storage tanks via heat exchangers. These storage tanks can store thermal energy for several hours or days.

Generally, CSP storage plants are operated by direct use of thermal power from the solar field in the turbine. Surplus thermal energy can be stored in the thermal tanks and is discharged from the storage at a later time, e.g., after sunset. Relloso and Delgado (2010) describe the technical experiences with commissioning and operation of the first CSP storage plant (Andasol1). As most of the CSP plants in Spain are based on parabolic trough technology, this technology is also assessed in this paper. Technical layout and design of the power plant can be optimized along many different parameters like material and component choice, plant size, process temperatures, operation modes or pressure levels (see Morin, 2011). Substantial research has been done to increase the efficiency and the energy output of these plants and to reduce construction costs.

This paper focuses on the optimal choice of two major components in relation to a fixed turbine size of 100 MW: the solar field size and the storage capacity. In Spain, the CSP plants are typically constructed as 50 MW plants due to a cap in the national support scheme which does not allow larger turbine sizes. The solar field size (aperture area of the used mirrors and receivers) determines the amount of captured solar energy from the sun. It is characterized relative to the turbine size via the solar multiple (SM), see Isquierdo et al. (2010). A solar multiple of 1 offers enough peak energy to run the turbine with full capacity on a typical solstice day at noon (Montes et al., 2009). The storage tanks are characterized by their thermal capacity which is expressed in terms of turbine energy for one hour. For each "storage hour", the turbine can be run at full capacity for one hour. Therefore, the storage volume (in MWh_{th}) required for one storage hour is equal to the turbine capacity (MW_{el}) multiplied by one hour and divided by the efficiency of the turbine and the heat transmission to the turbine. In Spain most CSP plants are designed

with identical storage size of about 1,000 MWh thermal energy capacity, equivalent to 7 – 8 hours of full-load turbine capacity (Relloso and Delgado, 2010). One example of a large storage is given by the Gemasolar tower near Servile which includes a storage tank with a capacity of 15 hours of turbine full-load (Burgaleta, 2011).

Another important technological option for CSP plants is to complement solar power by burning natural gas. This gas burning activity (hybridization) ranges from small amounts of natural gas for anti-freeze protection to an electricity output which is based on natural gas use by 15% (share of electricity output produced by natural gas) in Spain (Caldés et al. , 2009) or up to 25% in the US (IEA, 2010). In the future, innovative technology and operation strategies may arise due to new market opportunities. One future option for CSP plants could be storing electrically generated heat in the thermal storage tanks. Lizzaraga-Garcia et al. (2013) describe a technical solution by adding small electric heater of 4 kW each on internal vertical walls in the hot storage tank. The storage medium has to be heated uniformly and under steady conditions to avoid overheating of the salt. The presented model includes this option by assuming the availability of an electric heater to store electricity from the grid as thermal energy in the storage tank. This may be an interesting operational choice if electricity prices reach low levels, e.g., during hours of high wind generation. Therefore, the economic viability is detailed for a Spanish business case in chapter 4 of this paper. Due to the inherent high uncertainty of the cost realization and the small share compared to the overall power plant costs, additional costs for the electric heater system were not explicitly included in the analysis. However, an investment analysis for the electric heater is provided. A further detailed economic assessment is shown by Lizzaraga-Garcia et al. (2013).

The economic valuation of CSP plants with storage has been discussed more frequently in recent years. From a technical point, Garcia et al. (2011) develop a detailed model to show the technical flows of energy and to facilitate the prediction of the electrical output of a CSP storage plant. Morin (2011) develops an optimization tool for CSP plants based on the levelized cost of electricity (LCOE). The disadvantage of the LCOE method is the equalization of each kWh generated in the denominator. The point of time at which the electricity is generated is not considered in this formula. Therefore, the value of dispatchable power plants like CSP storage plants is underestimated as their potential to react to current market price conditions is ignored. Sioshansi and Denholm (2010) develop a mixed integer program to account for electricity market prices in the valuation of CSP storage plants. This model determines the optimal operation of a CSP under market prices. Consequently, it closes a modelling gap of the SAM (System Advisor Model, 2012) which does not facilitate a market-based evaluation of CSP plants. The model of Sioshansi and Denholm uses SAM's energetic model for the solar field while operating the plant according to the MIP model. CSP plant operation reflects several parameters like ramping cost, efficiencies, maximum and minimum loads. Madaeni and Sioshansi (2011) expand the approach and analyse the CSP power plants in the US. They find that plants with storage of two to four hours feature the lowest break-even level.

Aga et al. (2012) compare the net present value (NPV) of CSP plants with and without storage under the Spanish system. They underline the importance of cost decreases for TES for CSP plants to achieve competitiveness with conventional power plants. Nagl et al. (2011) present a scenario outlook for Spain with different shares of renewable energies. They conclude that CSP plants are not competitive

under current investment costs. However, they also note that CSP value will increase in future energy scenarios due to their energy storage capacity. A similar result is presented by Brand et al. (2012). They describe renewable energy scenarios for North Africa and find that CSP dispatchability becomes more valuable if the share of renewable energies increases.

3. Optimization of operation and investment decision

The optimal thermal storage size of a CSP plant needs to account for the subsequent dispatch decisions based on the plant's revenue stream (hourly electricity market prices, fixed FIT, P-FIT). Therefore, an hourly dispatch model can be used to evaluate different investment alternatives. A two-step approach for the plant valuation process was proposed by Madaeni and Sioshansi (2011). First, an appropriate plant set with over 100 different plant layouts specifying a solar multiple and storage size for each plant is generated. Thereafter, the optimal operation policy for each plant in the set is derived and the net present values are compared.

This paper extends the approach along multiple dimensions. Firstly, additional technical options – usage of natural gas for hybridization and storage of electricity from the grid by means of an electric heater – are included to better reflect CSP plant operations and shed light on the viability of alternative operation modes. Secondly, the decision model was refined: Instead of a two-steps approach (for operation and investment), the plant design choices are integrated as integer decision variables in the dispatch optimization model. The generation of a set of power plants is incorporated in additional constraints. These constraints are created by considering the relevant investment constraints. Following Madaeni and

Sioshansi (2011), the set of plants is spanned by considering different combinations of solar multiple and storage size. Furthermore, investors could also consider the plant location if there are multiple potential sites. Input profiles for the solar thermal output from different solar fields are generated by the energetic model of SAM to determine limitations of the thermal output of the solar field of each plant design (Figure 2). The variables and parameters in the optimization are given in Table 1.
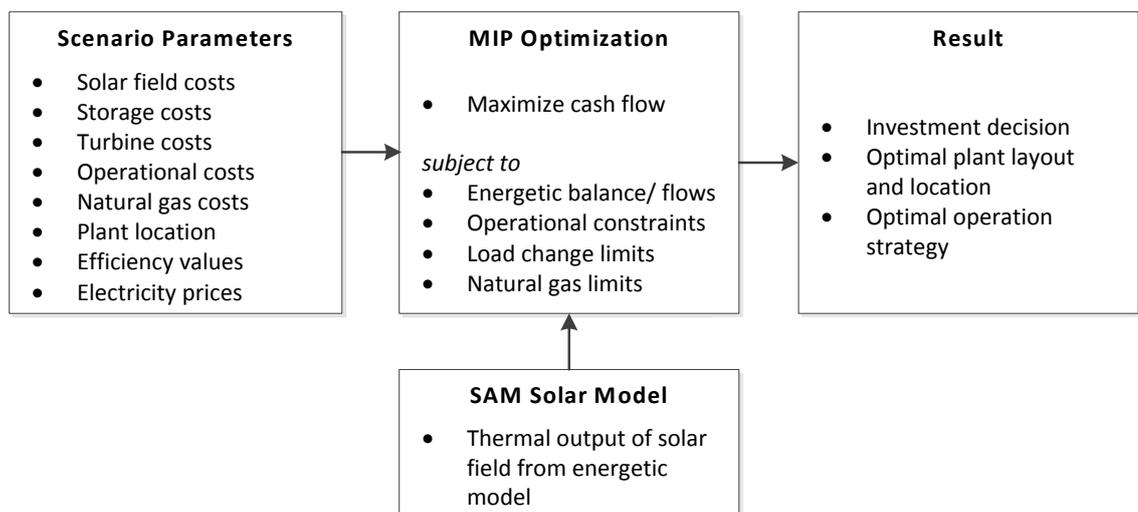
Scenario Parameters	**MIP Optimization**	**Result**
• Solar field costs • Storage costs • Turbine costs • Operational costs • Natural gas costs • Plant location • Efficiency values • Electricity prices	• Maximize cash flow *subject to* • Energetic balance/ flows • Operational constraints • Load change limits • Natural gas limits	• Investment decision • Optimal plant layout and location • Optimal operation strategy

SAM Solar Model
- Thermal output of solar field from energetic model

Figure 2: **MIP plant valuation framework**

Table 1:   Variables and constants in storage optimization problem

Constants		Decision variables	
p_t	Market price of providing 1MWh of electrical energy to the grid at time t	$\phi_t \geq 0$	Amount of electricity fed into grid at time t
k^v	Variable costs of turbine operation		
k^g	Cost of burning 1 MWh of natural gas	$\phi_t^g \geq 0$	Amount of gas burned at time t
k^w	Cost of dumping 1 MWh of electrical energy (waste)	$\phi_t^w \geq 0$	Amount of energy electricity? dumped at time t
k^f	Fixed operation costs		
pi	Purchase fee for buying 1 MWh from grid	$\phi_t^p \geq 0$	Electricity purchased from grid at time t
c_{sm}	Specific cost of solar field	ϕ_{sm}^c	Factor for Solar Multiple (discrete values)
c_{st}	Specific cost of storage	ϕ_{st}^c	Factor for storage size (discrete values)
C_{Pb}	Base cost (power block and others) independent of storage and solar field size		
v	Terminal value		
y	Lifetime of power plant (years).		
T	Planning horizon T consists of all hours t which are optimized (e.g. 8760).		
$a(i,y)$	Annuity depending on interest rate (i) and lifetime (y)		
k^Δ	Cost of load adjustment per MW change	Δ_t	Load change in time t
e_t^{SF}	Energy from solar field at time t		
e^{su}	Power block start-up energy	τ_t^{dpb}	Energy from solar field that is directly used in power block
$f(°)$	Power block heat rate function	τ_t^{intoPB}	Thermal energy to power block at time t
$P_h(°)$	Parasitic function of heat process		
$P_b(°)$	Parasitic function of storage process	γ_t	Storage level at time t
$self_t$	Self-consumption of power block at time t	σ_t	Energy to TES at time t

hl	Hourly losses in TES	δ_t	Energy from TES at time t
eff_{tur}	Maximum efficiency of the turbine (only necessary to calculate the maximum use of natural gas)		
eff_{dc}	Efficiency of discharging and charging process		
eff_{el}	Efficiency of thermal energy generation from electricity		
g	Maximum of hourly gas consumption		
ep_{max}	Maximum of hourly electricity purchase		
gas_{max}	Maximum share of annual gas consumption		

The objective function (3) of the mixed integer problem maximizes the plant's cash flow (operational profit and investment annuity) over the planning horizon *T*:

$$\max_{\phi_t, \phi_t^g, \phi_t^w, \phi_t^p, \phi_{sm}^C, \phi_{st}^C} \sum_{t=1}^{T} \left[(p_t - k^v)\phi_t - \left(k^g \phi_t^g + k^w \phi_t^w + (pf + p_t)\phi_t^p + k^\Delta \Delta_t \right) \right]$$

(3)

$$- \left(c_{Pb} + c_{sm} \cdot \phi_{sm}^C + c_{st} \cdot \phi_{st}^C + \frac{v}{(1+i)^y} \right) \cdot a(i, y) - k^f$$

To simplify the financial evaluation, annual optimized cash flows were considered to remain constant over time. An underlying assumption for this being that both solar and market conditions remain stable over time. The model operates with perfect foresight of the electricity pool price and the solar radiation over the whole year. This is a reasonable simplification as short-term forecasts are continuously improved. The simple cash flow structure of the objective function contains annual optimized cash flows of operational profit, terminal value by *v*, fixed operation costs *f_c* and the annuity of the investment.

CSP power plants are optimally dispatched in accordance with the current market and solar conditions. The objective function includes both the operation revenues and the investment costs in a single formulation. The optimization is subject to several constraints that reflect, among others, storage carry-over, efficiency and ramping conditions. These constraints follow the general approach described by Madaeni and Sioshansi (2011), but the original model was extended by additional constraints reflecting new operation modes. The constraints are:

Solar Multiple (SM):
$$sm = 0.1 * \phi_{sm}^C; \quad \phi_{sm}^C \in Z^n, \phi_{sm}^C \geq 0; \phi_{sm}^C \leq 32 \tag{4}$$

Storage Size:
$$st = 1 hour * \phi_{st}^C; \quad \phi_{st}^C \in Z^n; \phi_{st}^C \geq 0; \phi_{st}^C \leq 12 \tag{5}$$

Total thermal energy (flux):
$$e_t^{SF} + \phi_t^p * eff_{el} = \tau_t^{dpb} + \sigma_t + \phi_t^w \tag{6}$$

Total production:
$$\tau_t^{intoPB} = \tau_t^{dpb} + \delta_t + \phi_t^g - e^{SU} \tag{7}$$

Net generation:
$$\phi_t = f(\tau_t^{intoPB}) - P_h(\delta_t) - P_b(\tau_t^{intoPB}) - self_t \tag{8}$$

Storage level:
$$\gamma_l = (1 - hl) * \gamma_{t-1} + \sigma_t - \delta_t(1 + eff_{dc}) \tag{9}$$

Maximal gas consumption:
$$\phi_t^g \leq g \tag{10}$$

Maximal annual gas consumption:
$$\sum_1^r \phi_t^g / eff_{tur} \leq \sum_1^r \phi_t * gas_{max} \tag{11}$$

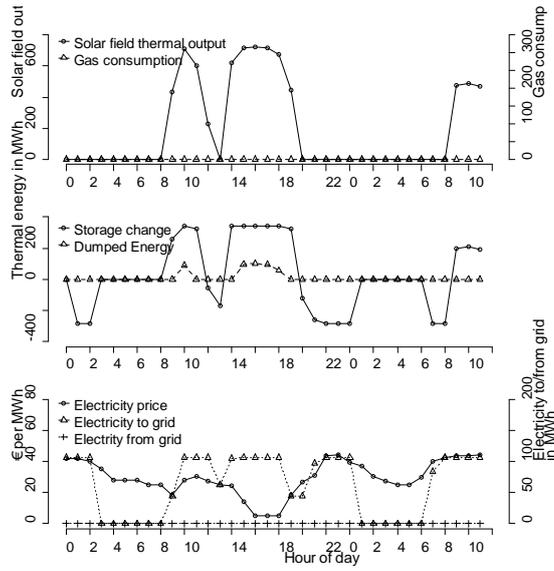Maximum purchase of electricity:
$$\phi_t^p \leq ep_{max} \tag{12}$$

Load change of power block:
$$\Delta_t = \phi_t - \phi_{t-1} \tag{13}$$

Constraints (4) and (5) limit the size of solar field and storage which are covered by the model. The integer decision variables for the storage size and solar multiple are exemplarily chosen here, but the ranges need to be adapted according to the investment situation at hand. Constraints (6), (7) and (8) reflect additional operational constraints covering the use of natural gas, storing of electricity from the grid and plant self-consumption. The technical and regulatory implications of using natural gas as hybrid operation mode are covered by constraints (10) and (11). In constraint (12), the maximum operation capacity of the electric heater is limited to its maximum technical capacity of 50 MW$_{el}$, which is also the maximum value of electricity purchase from the grid. Self-evident, if the electricity purchase for the heater ep$_{max}$ is defined as zero this setting corresponds to removing the electric heater from the plant design. Constraint (13) indicates the load change between two time units.
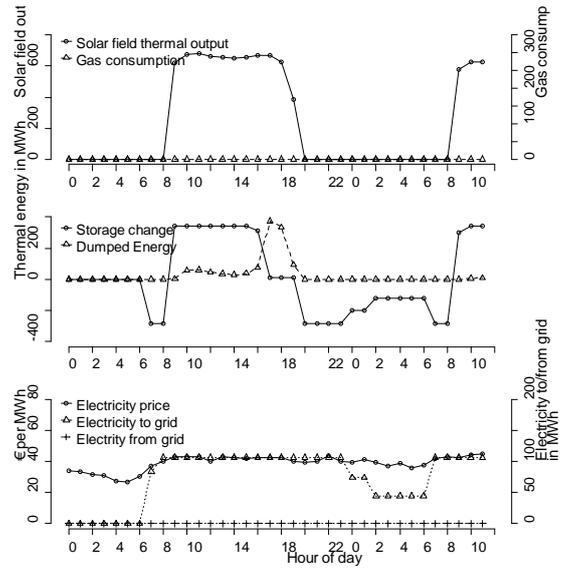
Figure 3 illustrates the optimal operation policy of a CSP plant with storage obtained from the optimization model under electricity pool prices for a few selected days. The figure exemplarily shows how the optimization model selects the operation strategy to maximize plant profitability. The optimal plant operation is clearly driven by *both,* the market price and the solar conditions. During the day the plant's power block generates electricity and surplus solar thermal energy is transferred to the energy storage. If the price is high in hours without sunlight the power plant operates the power block using energy from the storage. Figure 4a explains a down-ramping in the late afternoon to store more energy until 9pm to feed-in electricity at higher prices. During perfectly sunny days (4b) the CSP plant operates at full capacity from 8am in the morning to 1am the next day while a small share of energy cannot be stored in the storage (full tank) and has to be dumped.

Figure 4c presents the case of natural gas use during the night to avoid shutdown during night. This also improves ramping in the morning to full capacity after sunrise. During nights with very low electricity prices (close to 0 Euro/MWh) the plant stores electricity from the grid (e.g., from wind power plants) through electric heaters in the storage from 3 to 5am (see Figure 4d). These examples indicate that CSP plants with thermal storage offer additional potential to shift electricity generation to times without solar radiation. Furthermore, both natural gas feed-in as well as direct electricity storage are viable and relevant operation modes in certain situations.
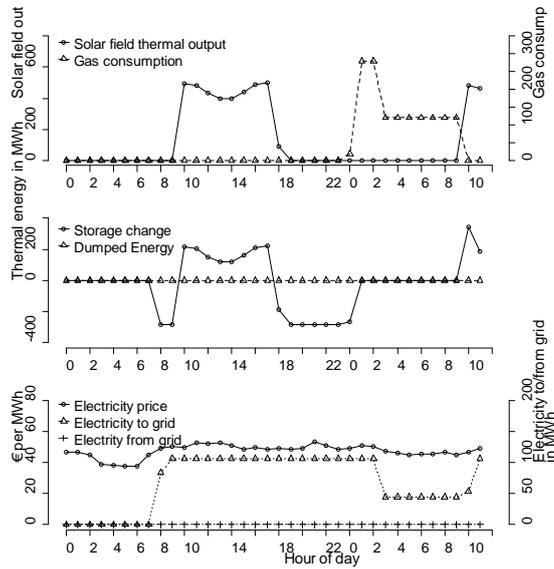
Figure 3:   Optimal operation strategy for 4 different time periods (36 hours)
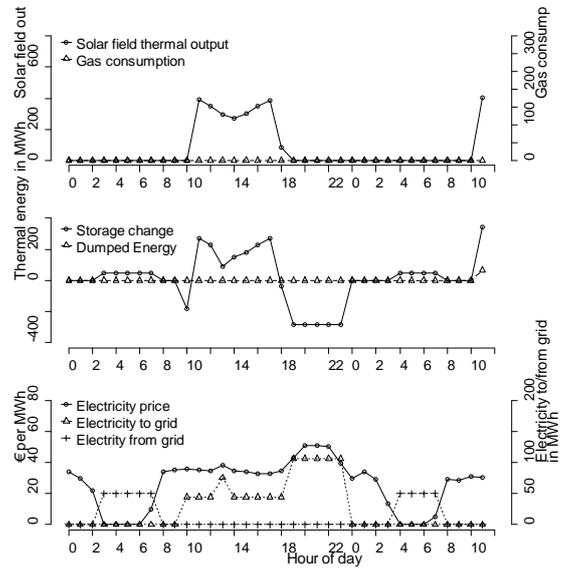

(a) 08.05.: Power block ramped down during the day to facilitate evening production

(b) 05.05.: Stable price and high solar intake lead to dumping during the day and generation throughout the night

(c) 21.10.: Gas burnt avoid overnight generation shutdown

(d) 25.01.: Low night-time electricity price facilitates buy and store strategy

4. Storage operation and evaluation – A Spanish case study

The MIP model for CSP plant operation and investment decisions was evaluated by analysing a CSP parabolic trough plant in the Spanish market, similar to Andasol One. The energetic output from the solar field is modelled with SAM using a typical meteorological year (TMY file) from Meteonorm for the area close to Guadix (Spain) with a direct normal irradiance (DNI) of 2,182 kWh/(m²*year) (Meteonorm, 2011). Cost assumptions by Kost et al. (2012) for a 50 MW are included in the analysis by scaling these numbers up to a 100 MW power plants by using a reduction scale-up factor (Kistner et al., 2009). In table 2, the cost items for the solar field, power block and thermal storage are presented. For the electric heater, Lizzaraga-Garcia et al. (2013) assume costs of 0.75 Mio Euro per 20 MW_{el} (capacity of the electric heater unit) which would be a share of 1.5% of the power block costs but which are not explicitly considered here (see following economic analysis of electric heater). For example, the total costs of a CSP plant with SM=2.8 and 8 hours of storage are 557.4 Mio Euro. The thermal storage tank accounts for a significant share (15%) of the total investment costs of this plant. From the SAM model fixed operation costs for a 100 MW were obtained as 5.3 Mio Euro per year.

Table 2: **Cost components of a CSP plant with a turbine capacity of 100 MW and variable solar field and storage size, based on Kost et al. (2012) and Kistner et al. (2009)**

Component	Cost [million €]	
Cost of solar field (c_{sm})	120.7	per 1.0 SM
Cost of power block (c_{Pb})	1.18	per 1 MW
Cost of thermal storage (c_{st})	12.5	per 1 hour storage

The Net Present Value of CSP different storage plants is analyzed under different remuneration schemes (market prices, feed-in tariffs) over the financial lifetime of a power plant. Due to high investment cost, no CSP plant is competitive at an electricity prices between 20 and 60 Euro/MWh (the Spanish average market price was 37.4 Euro/MWh in 2010, OMIE, 2010). Currently, CSP plants would require electricity prices that are 3 to 5 times higher than market prices as the technology is still at the beginning of its learning curve where significant cost reductions have not yet been realized (see Estela /AT Kearney 2010).

A generic goal for any support scheme would be to reach a reasonable return on equity for investors while inducing plant operation in accordance with residual load patterns. For CSP storage plants, the scheme has to especially take into account the potential to store energy and use it at a later point of time.

The model determines the best plant configuration out of 100 different SM and storage size combinations. Using 2010 market price, this economic valuation yields negative values for all plant configurations. On the other hand, under the current CSP support scheme (P-FIT), CSP plant investments are viable depending on the

interest rate. Figure 4 shows these results calculation is shown for interest rates of 10% and 20%. With lower interest rates all SM / storage size combinations have a positive NPV. Naturally, this result strongly depends on the cost assumptions and the turbine size. The analysis shows that the valuation differences between the storage tank with a capacity of 6 and 11 equivalent full load hours are not too pronounced, if solar field size is chosen appropriately. This suggests that technical constraints (tank volume, radius, height, thermal losses, and thermal stress on material) may be the reason that most Spanish CSP plants are equipped with eight hours of thermal storage capacity.
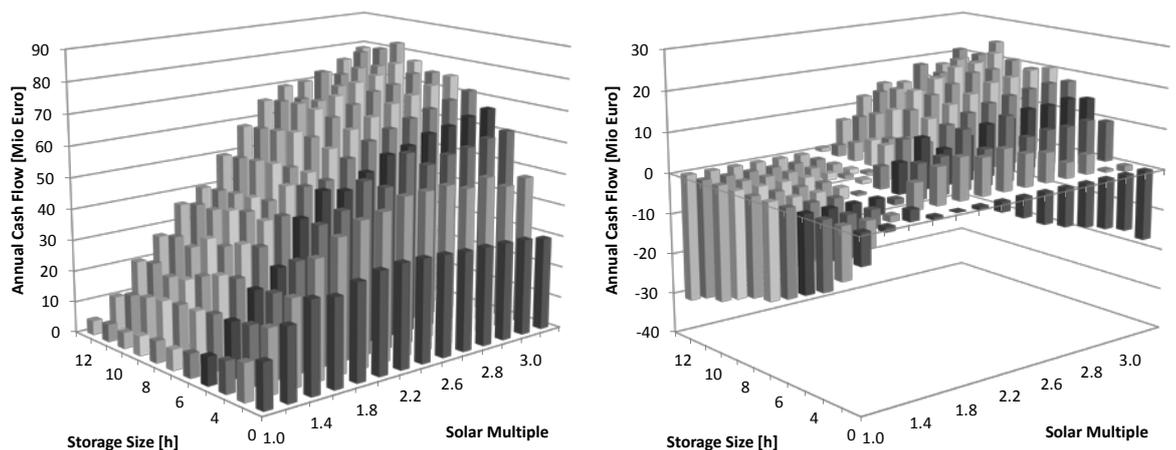

Figure 4:   Cash Flow analysis of a 100 MW CSP plant under the premium FIT in Spain with electricity prices of 2010 with an interest rate of 10% (left) and 20% (right).

The economic viability of an electric heater clearly depends on two issues: the cost for the electric heater and the electricity price for which the electricity can be bought at the electricity market. Assuming the electricity price of Spain 2010, the operating profits with five different layouts the annual profit difference with and without electric heater were compared. The heater generates around 0.2 Million of extra profits annually. However, under the assumed cost structure and discount rate this

yields a negative present value (see Table 3). Still, given the much larger total plant costs this cost element has only a very limited impact on overall plant profitability. Furthermore, more volatile price could in the future further improve the business case for the use of electric heaters.[1] From a system-perspective the heater increases the versatility of CSP storage systems. Therefore, to evaluate the utilization of highly flexible CSP plants in different market scenarios, the electric heater is included in the analysis regimes presented in the following chapter despite the slightly negative net present value.

Table 3: Profitability analysis of electric heater for different plant layouts

SM	Storage	Annual cash flow from heater unit	NPV of heater investment (10% interest, 1.9M € invest)
2.2	4	176,884 €	-422,330 €
2.4	6	201,702 €	-215,003 €
2.8	8	201,534 €	-216,407 €
3.0	10	184,370 €	-359,793 €
3.2	12	182,835 €	-372,616 €

5. Market scenarios and their effect on operation and layout

Investment incentives for CSP plants with thermal storage need to appropriately account for the interdependency between subsidy scheme, plant design and the optimal plant operation policy. Therefore, an ill-designed scheme can give rise to

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[1] In a similar vein, there has been a tendency in Germany to equip CHP systems with immersion heaters to take advantage of low (or negative) electricity prices.

two inefficient outcomes arising from optimal behaviour of plant investors or operators:

(1) Inefficient storage-sizing by strategically leveraging the incentive scheme (plant design)

(2) Operation mode selection not aligned with general market conditions (plant operation)

Clearly, inefficiency in plant design is fundamentally driven by an inefficient operation scheme. In the following the effect of the Spanish feed-in tariff on optimal CSP plant operation is compared to the case of a plant operated only reflecting the electricity pool price (market condition) by using the MIP model for storage operation and investment decision. Subsequently, it is investigated whether the two regimes give rise to different optimal plant design choices.

The results are calculated for the Spanish market using electricity pool prices of 2008 and 2010. Furthermore, German and Italy electricity exchange prices were used to investigate the robustness with respect to alternative price scenarios. See Figure 5 for an overview of the price duration curves of each price vector. To maintain comparability, the cap and floor values of the premium feed-in tariffs used for the German and Italian scenario were adjusted by the annual average of these prices in relation to the Spanish market price of 2010.
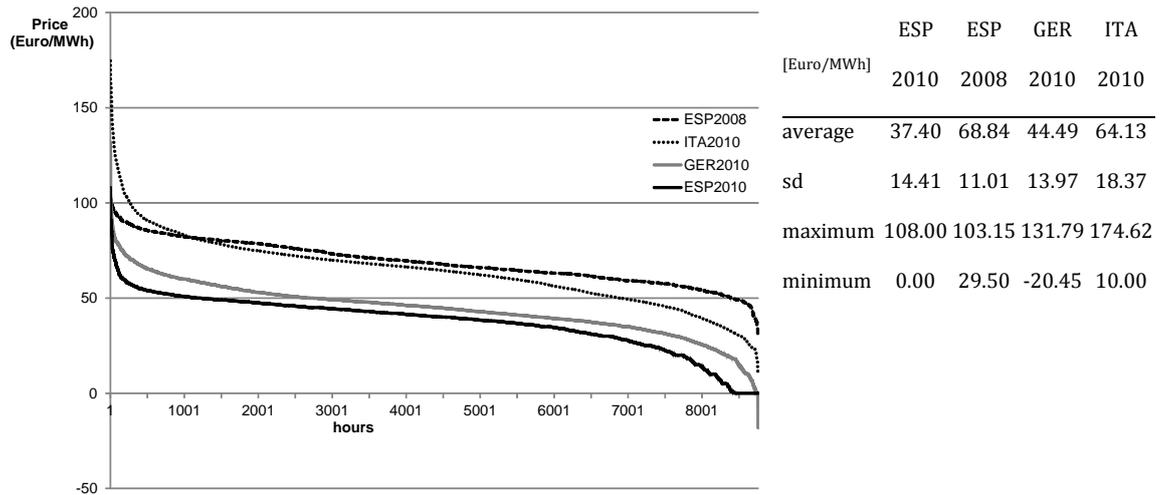
[Euro/MWh]	ESP 2010	ESP 2008	GER 2010	ITA 2010
average	37.40	68.84	44.49	64.13
sd	14.41	11.01	13.97	18.37
maximum	108.00	103.15	131.79	174.62
minimum	0.00	29.50	-20.45	10.00

Figure 5: **Price duration curve of Spain (2008 and 2010), Germany (2010) and Italy (2010)**

The problems of a premium FIT can be highlighted when considering the optimal use of the storage and the optimal electricity production related to the hourly demand obtained in a pure market setting and in a PFIT setting. Both settings are compared in the following with respect to differences in operation and optimal plant design. We characterize the dispatch disparity by looking at the daily generation differential $DailyGen_{market} - DailyGen_{P\text{-}FIT}$. This differential is positive if

the daily output to the grid is higher under the market regime than under the P-FIT regime while it is negative in the opposite case. A zero-differential indicates days where the total output is identical under both regimes. Figure 6 illustrates that there are significant differences between the two scenarios over the year. This is especially true for the beginning and end of a year. This seasonal effect is due to more volatile electricity prices in the winter season. While a plant in the market regime is fully exposed to this price volatility, a plant under the P-FIT subsidy is mostly protected through the high price floor. Clearly, storage is more valuable in a volatile than in a non-volatile market.
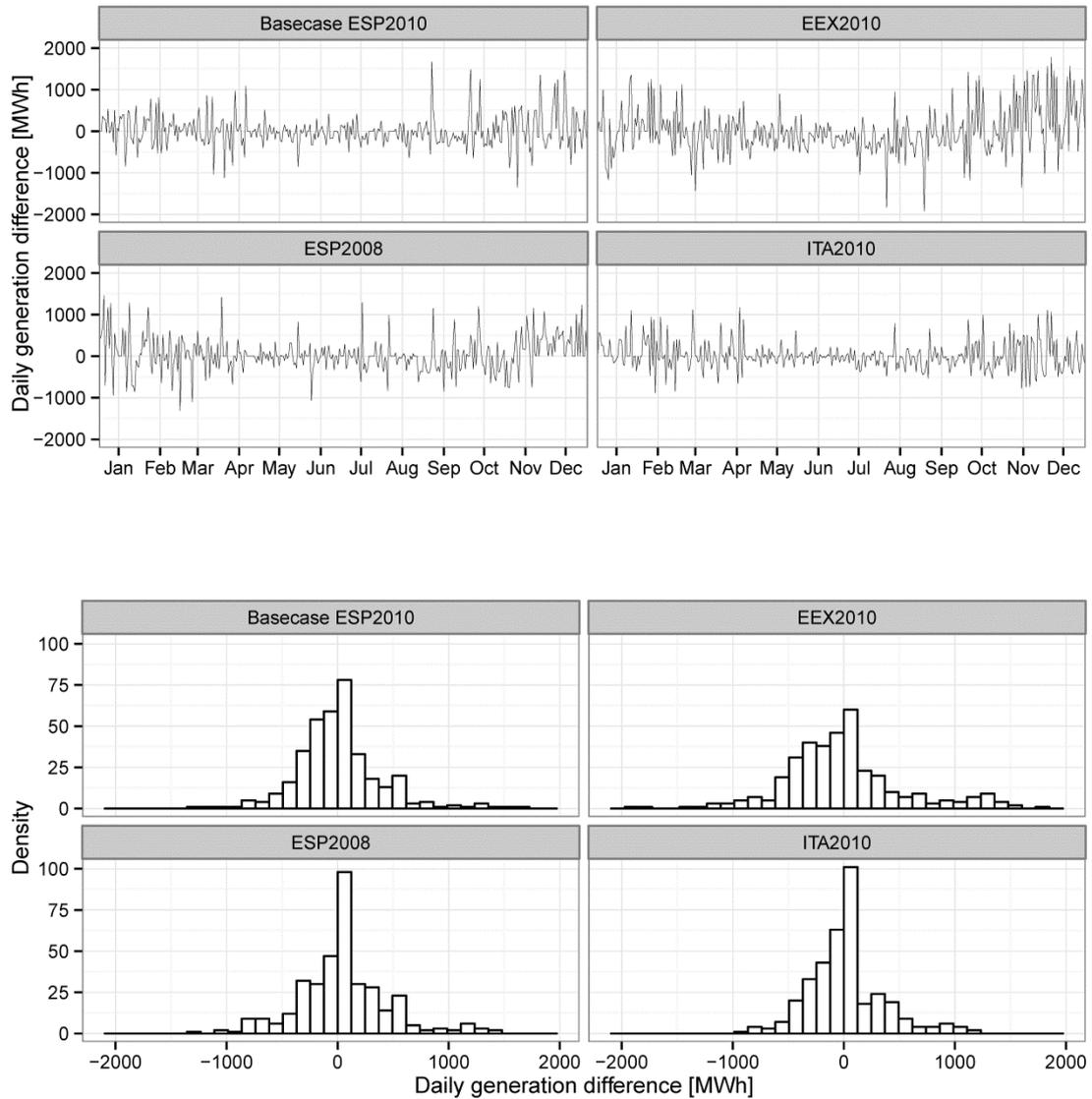
Figure 6: **Comparison of daily production of a CSP storage plant under Pure Market setting and Premium Feed-in Tariff (100 MW CSP, solar multiple of 2.8, 8 hours of storage)**

The hourly operation patterns (Figure 7) confirm this observation. Under the P-FIT regime plant shut-down is more often avoided than under the market regime – clearly visible in the central bar in both histograms. Yet the "binary" plant operation pattern under market remuneration is very similar to the way a typical storage plant is operated with either zero output in times of low prices and maximum output in times of high prices.
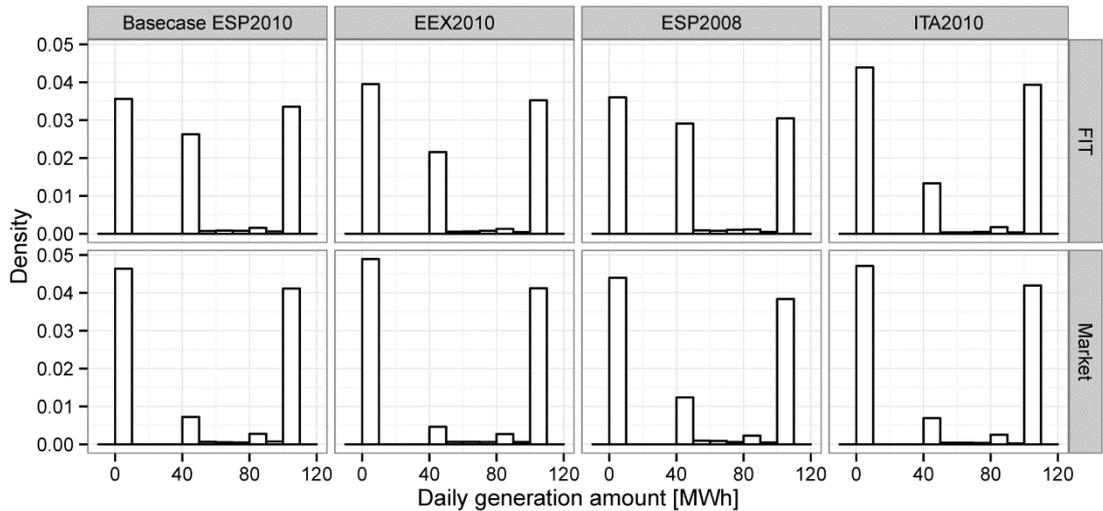
Figure 7: **Distribution of hourly production of a CSP storage plant under Pure Market setting and Premium Feed-in Tariff (100 MW CSP, solar multiple of 2.8, 8 hours of storage)**

This difference between the two regimes is driven by the energetic start-up costs of the turbine and the thermal energy losses in the storage tanks. Under a market regime these energy losses have limited value given a low market price. However, under P-FIT support the energy losses are significantly more costly due to the high guaranteed floor value. Therefore, under the market regime the plant is much more sensitive to the market price. P-FIT results in significantly less storage usage and generation shut-downs than would be optimal under market conditions. As storage and balancing capabilities are often put forward as central advantages of CSP technology these effects may be of special concern.

Having determined optimal operation strategy, one can now subsequently address optimal investment decisions of CSP plant layouts. During the planning phase of a CSP project, an investor evaluates different plant layout options by doing an economic and technical assessment of feasible and profitable configurations. This analysis needs to account for the interdependency between plant operation and plant layout (storage and solar field size) choices. The model captures 100 different

power plant layout options. The optimal plant layout is determined within the optimization model by using the investment framework described above, assuming Spanish market prices from 2010, a useful investment life of 25 years, a terminal value of 10% of the initial investment and an interest rate of 6%. As noted before NPVs are always negative in the case without a feed-in tariff. Therefore, the optimal choice would be not building a power plant at all or choosing the smallest (which would have the least negative NPV due to lower investment costs) possible power plant. To be able to still analyze optimal plant investment decisions under market based vs. P-FIT based remuneration an alternative approach was applied: We specify a set of fixed investment sums (ranging from 434 to 606 million Euros) that each has to be fully invested in a corresponding CSP storage plant. To ensure non-singular investment sets a tolerance band of +/- 2 Mio Euro is applied and two additional constraints are introduced for the optimization problem:

$$C_{Pb} + c_{sm} * \phi_{sm}^C + c_{st} * \phi_{st}^C \geq \textit{fixed investment sum} - 2M\text{\euro} \tag{14}$$

$$C_{Pb} + c_{sm} * \phi_{sm}^C + c_{st} * \phi_{st}^C \leq \textit{fixed investment sum} + 2M\text{\euro} \tag{15}$$

Then, the most valuable (highest NPV, i.e. least negative NPV) plant layout matching the given investment sum is determined (for illustration of this approach see Figure 8). By fixing the total investment sum, different layout with equivalent costs can be compared (see also Figure 9 in the appendix).
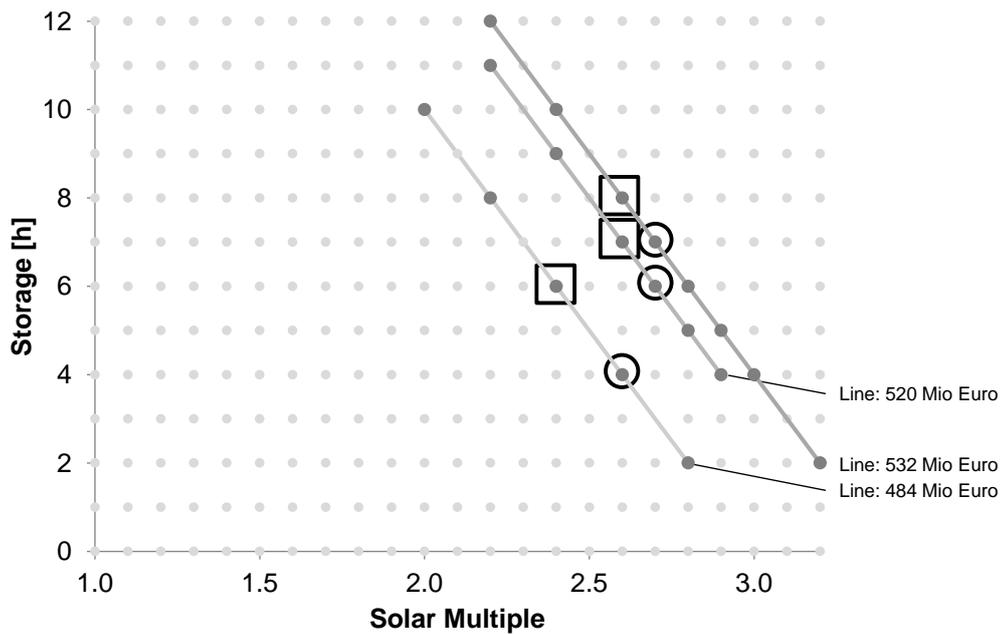
Figure 8: **Three exemplary fixed investment sums give specific solar field and storage size combinations (examples with 484, 520 and 532 Mio Euro). Optimum under P-Fit is market with a circle, optimum of market based operation with square.**

The final results are shown in Table 3. In Table 3 a pure market case with electricity exchange market prices of 2010 (*Market case*) can be compared to the premium feed-in tariff based also on electricity exchange market prices of 2010 in Spain, Germany and Italy (*P-FIT case*). For Spain, also the prices of 2008 can be compared for both cases.

Given Spanish electricity prices of 2010, the P-FIT does indeed influence the optimal investment decision in four of the eight cases (shown in grey). Similar effects can be seen when electricity prices of Germany and Italy or the prices of 2008 (Spain) are used. A more granular discretization of solar field and storage size would result in even more mismatches. Under P-FIT investors choose smaller storage sizes in exchange for increasing the solar field. This confirms the observation of storage under-utilization in the P-FIT regime. Hence, the P-FIT

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subsidy scheme influences both optimal plant operations *and* optimal plant design in comparison to the market case. This result is also robust to changes of the storage and solar costs (see Table 5 in the Appendix).

Table 4: **Optimal plant design choices under market and P-FIT regime for different investment volumes**

Investment sum (million Euro) # *of Layouts*	434 3		460 4		484 5		508 7		520 6		532 8		556 6		606 4	
Configuration	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS
Market case (ESP, 2010)	2.2	4h	2.2	6h	2.4	6h	2.6	6h	2.6	7h	2.6	8h	2.8	8h	3.0	10h
Premium FIT (ESP, 2010)	2.2	4h	2.2	6h	2.6	4h	2.6	6h	2.7	6h	2.7	7h	2.8	8h	3.2	8h
Market case (ESP, 2008)	2.2	4h	2.2	6h	2.4	6h	2.6	6h	2.6	7h	2.6	8h	2.8	8h	3.0	10h
Premium FIT (ESP, 2008)	2.2	4h	2.4	4h	2.6	4h	2.6	6h	2.6	7h	2.8	6h	2.8	8h	3.0	10h
Market case (EEX, 2010)	2.2	4h	2.2	6h	2.4	6h	2.6	6h	2.6	7h	2.6	8h	2.8	8h	3.0	10h
Premium FIT (EEX, 2010)	2.2	4h	2.4	4h	2.4	6h	2.6	6h	2.6	7h	2.8	6h	2.8	8h	3.0	10h
Market case (ITA, 2010)	2.2	4h	2.2	6h	2.4	6h	2.6	6h	2.6	7h	2.6	8h	2.8	8h	3.0	10h
Premium FIT (ITA, 2010)	2.2	4h	2.4	4h	2.4	6h	2.7	5h	2.6	7h	2.6	8h	2.8	8h	3.0	10h

SM = Solar Multiple
SS = Storage Size (in hours equivalent to energy amount to operate the turbine with full load)

The question is what can be done to incentivize CSP plant investments that are better aligned with market requirements? CSP plant investments are currently not viable without any subsidy. At the same time the P-FIT support scheme distorts plant design and operation choices compared to a purely market based operation.

This raises the question whether another support scheme can guarantee both sufficient investment incentives and economic plant design and operation decisions. Maintaining a generation-based reward structure, one could similarly imagine dropping the base remuneration in exchange for increased market participation. The market price obtained by selling electricity at the electricity exchange could be multiplied with a fixed parameter to guarantee reasonable revenues to the investors. The greater variance of revenues enhances the value of storage and incentivizes market-oriented dispatch. This comes at the cost of increased market price volatility which renders CSP investments more risky and will likely increase the return required by investors. Furthermore, the subsidy payments would also be very volatile which is highly unattractive to investors and would rise with increasing market prices which is highly unattractive to regulators. Generation-based remuneration schemes can thus not ensure market-oriented dispatch as well as layout choices on the one hand and stable investment conditions on the other at the same time. However, other classic investment subsidy schemes may also distort the layout and operation choices for CSP storage plants. An investment subsidy (direct subsidy or tax credit) lowers the investment cost for an investor and can lead to a positive NPV of CSP plants. However, in the Spanish market investors would currently need a direct subsidy of 60 to 80 % of the plant investment. Such a high subsidy share could easily yield further market distortions.

Given these troubles with the various simple support schemes, it hast to be acknowledged that there is no silver bullet for improved market integration of CSP storage plants. Better suited support schemes should therefore include indirect remuneration for the provision of dispatchable capacity for ancillary or backup services. This notion resonates well with current discussions that aim to better

reflect the negative externality imposed by intermittent generation within the electricity market design (Varaiya et al 2011). The stipulated solutions include the establishment of capacity markets (Creti & Fabra 2007) to better compensate dispatchable power plants or the requirement of binding market commitments by all market participants including renewable generators. The latter would need to acquire sufficient storage capacity or enter appropriate hedging agreements to achieve these commitments (Kim & Powell 2011). In contrast to other forms of renewable generation, CSP storage plants are able to directly participate in capacity markets. Similarly, they would incur lower costs to serve binding market commitments due to storage availability. In summary, the dispatchability of CSP storage plants renders generation-based feed-in tariffs inadequate to ensure market-oriented investment and operation behavior. Future support schemes should thus also include an indirect remuneration for guaranteed availability and capacity provision levels.

6. Conclusion and outlook

The operation of CSP plants with thermal storage opens the potential to provide dispatchable power to the electricity system. To reflect additional operational settings, the CSP plant optimization model proposed by Madaeni and Sioshansi (2011) was extended. These extensions facilitate the valuation of CSP storage plant valuations in additional application scenarios. Using a Spanish case study, the relevance of the additional operation modes is demonstrated. This analysis yields helpful insights for plant investors, grid operators as well as regulators. Firstly, the profitability of CSP plants under the premium feed-in tariff in Spain was assessed by analyzing 100 potential plant layouts at a location in Spain. The results indicate

that several different plant layouts are economically viable, while in reality only a few layouts are chosen. Thus with increasing technology and market capacity, different sizes of storage capacities are expected to be constructed. Secondly, the comparison of operational patterns under a premium FIT and the electricity market price exhibit a different utilization of the storage capacity during many operation hours. Finally, investors will furthermore choose different plant layouts depending on the remuneration scheme. These results signify that it would be beneficial to establish a remuneration scheme which distinguishes between "dispatchable" and "non-dispatchable" renewable energy technologies if the amount of energy from renewable sources should be further increased.

To give an outlook on further research questions the current developments in the energy sector are highly interesting: More volatile electricity prices will increase the dispatch operation of CSP plants by using their storage efficiently. On the other hand a decrease of prices could appear during peak hours between 1 and 3 pm due to large feed-in of solar photovoltaics (see, e.g., Germany in summer 2012). A consequence for CSP storage plants could be to store more thermal energy of CSP plants for the evening. Additionally, demand patterns could be changed to locations with higher average electricity pool prices to reflect power export scenarios. Uncertainties of the investment decisions could also be covered in further work. The model itself can be extended by including stochastic parameters for prices and solar resources. Other papers have also shown the potential to provide reserve power which was not included in this paper.

Acknowledgement

Appendix

Table 5: CSP model parameters (own research, Sioshansi and Denholm (2010))

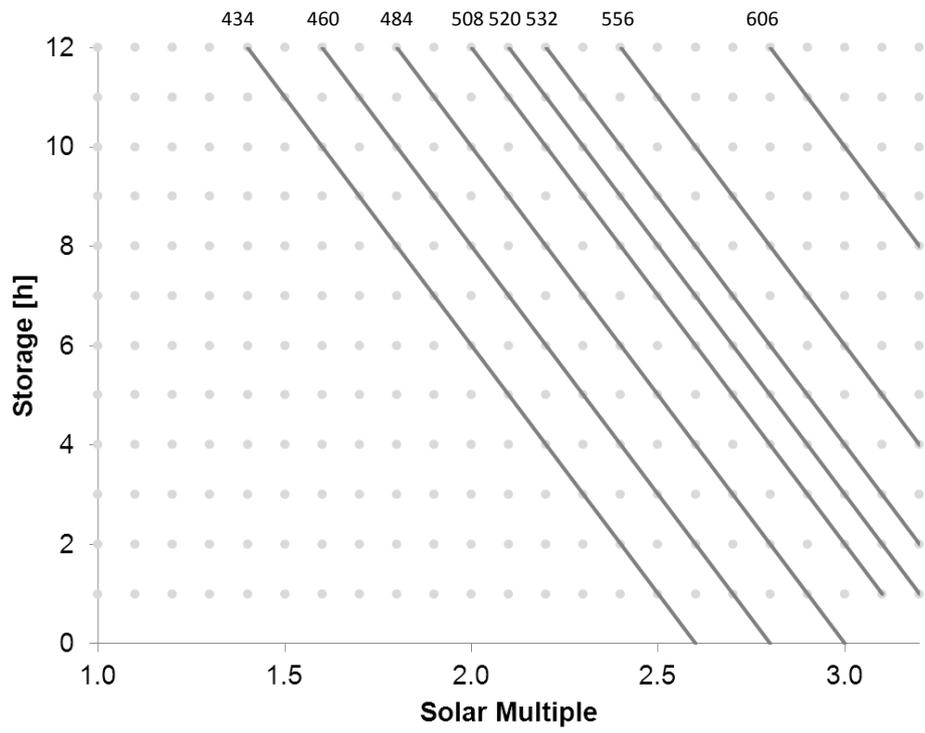|		
eff_{tur}	Maximum efficiency of the turbine	40%
eff_{dc}	Efficiency of discharging and charging process	1.5%
eff_{el}	Efficiency of thermal energy generation from electricity	90%
g	Maximum of hourly gas consumption	300 MWh$_{th}$
ep_{max}	Maximum of hourly electricity purchase	50 MW$_{el}$
gas_{max}	Maximum share of annual gas consumption	10%
$self_t$	Self-consumption of power block at time t	1.6 MWh
hl	Hourly losses in TES	0.031%
k^A	Cost of load adjustment per MW change	1 Euro/MW
e^{SU}	Power block start-up energy	58.3 MWh
k^V	Variable costs of turbine operation	2 Euro/MWh
k^g	Cost of burning 1 MWh of natural gas	3.85 Euro/MMBTU
k^w	Cost of dumping 1 MWh of electrical energy	1 Euro/MWh
pi	Purchase fee for buying 1 MWh from grid	1 Euro/MWh

Figure 9: **Potential layouts under a fixed investment volume**

Table 6:   **Sensitivity analysis of investment assumptions for solar field and storage system**

Investment (million Euro)		434		460		484		508		520		532		556		606	
Components	Revenue	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS	SM	SS
Solar field costs +25%	**ESP**	-o-	-o-	-o-	-o-	2.0	5h	2.2	5h	2.2	6h	2.4	4h	2.4	6h	2.7	6h
	ESP-PFIT	1.6	6h	1.8	6h	2.0	5h	2.2*	5h*	2.2	6h	2.4	4h	2.4	6h	2.7*	6h*
Solar field costs -25%	**ESP**	2.6	6h	2.6	8h	3.0	7h	3.0	9h	3.0	10h	3.0	11h	3.2	12h	-o-	-o-
	ESP-PFIT	2.8	5h	2.8	7h	3.0*	7h*	3.0	9h	3.2	9h	3.2	10h	3.2	12h	-o-	-o-
Storage costs +25%	**ESP**	2.0	5h	2.2	5h	2.2	6h	2.4	6h	2.4	7h	2.6	6h	2.8	6h	2.7	10h
	ESP-PFIT	2.0	5h	2.6	2h	2.4	5h	2.6	5h	2.7	5h	2.8	5h	3.0	5h	3.0	8h
Storage costs -25%	**ESP**	2.2	5h	2.4	5h	2.4	8h	2.6	8h	2.6	9h	2.6	10h	2.8	10h	3.2	11h
	ESP-PFIT	2.2	5h	2.4*	5h*	2.4	8h	2.7	7h	2.8	7h	2.8	8h	3.0	8h	3.2	11h

Remark: Tolerance band of 6 Mio Euro, in a few cases (*) only 2 Mio euro.

"-o-": no layout combination in the tolerance band (+/- 6 Mio Euro)

References

Aga, V., Boschek, E., Simiano, M. (2011). The value of dispatchability for CSP plants under different market scenarios. 17th International SolarPACES Symposium on Solar Thermal Concentrating Technologies, Granada, Spain.

Arce, P., Medrano, M., Gil, A., Oró, E., and Cabeza L.F., (2011). "Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe." Applied Energy 88(8): 2764-2774.

Brand, B., A. Boudghene Stambouli, et al. (2012). "The value of dispatchability of CSP plants in the electricity systems of Morocco and Algeria." Energy Policy 47(0): 321-331.

Burgaleta, J. I., Arias, S., Ramirez, D. (2011). Gemasolar, the first tower thermosolar commercial plant with molten salt storage. Solarpaces 2011, Granada Spain.

Burgos-Payán M., J.M. Roldán-Fernández, Á.L. Trigo-García, J.M. Bermúdez-Ríos, J.M. Riquelme-Santos (2013). Costs and benefits of the renewable production of electricity in Spain. Energy Policy 56: 259-270.

Caldés, N., Varela, M. Santamaría, R. Sáez (2009). Economic impact of solar thermal electricity deployment in Spain. Energy Policy 37: 1628-1636.

Ciarreta, A., C. Gutiérrez-Hita, Nasirov, S. (2011). "Renewable energy sources in the Spanish electricity market: Instruments and effects." Renewable and Sustainable Energy Reviews 15(5): 2510-2519.

Cossent, R., T. Gómez, Olmos, L. (2011). "Large-scale integration of renewable and distributed generation of electricity in Spain: Current situation and future needs." Energy Policy 39(12): 8078-8087.

Creti, A., & Fabra, N. (2007). Supply security and short-run capacity markets for electricity. Energy Economics, 29(2), 259-276.

Denholm, P. and M. Hand (2011). "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity." Energy Policy 39(3): 1817-1830.

Gharbi, N. E., Derbal, H., Bouaichaoui, S. and Said, N. (2011). "A comparative study between parabolic trough collector and linear Fresnel reflector technologies." Energy Procedia 6: 565-572.

del Río González, P. (2008). "Ten years of renewable electricity policies in Spain: An analysis of successive feed-in tariff reforms." Energy Policy, 36 (8): 2917-2929.

Griffiths, S. (2012). Strategic considerations for deployment of solar photovoltaics in the Middle East and North Africa. Energy Strategy Reviews, Available online 27 November 2012, In Press, Corrected Proof, http://dx.doi.org/10.1016/j.esr.2012.11.001.

IEA, International Energy Agency (2010). Technology Roadmap - Concentrating Solar Power. Paris. Accessed at
http://www.iea.org/publications/freepublications/publication/csp_roadmap.pdf.

Izquierdo, S., Montañés, C., Dopazo, C. and Fueyo, N. (2010). "Analysis of CSP plants for the definition of energy policies: The influence on electricity cost of solar multiples, capacity factors and energy storage." Energy Policy 38(10): 6215-6221.

Kim, J. H., & Powell, W. B. (2011). Optimal energy commitments with storage and intermittent supply. Operations research, 59(6), 1347-1360.

Kistner, R., T. Keitel, B. Felten, T. Rzepczyk (2009). Analysis of the potential for cost decrease and competitiveness of parabolic trough plants. SolarPACES 2009, Berlin.

Klein, A., A. Held, et al. (2007). "Evaluation of different feed-in tariff design options: Best practice paper for the International Feed-in Cooperation, 3rd edition, update by December 2010." A research project funded by the Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Kost, C., Pfluger, B., Eichhammer, W. and Ragwitz, M. (2011). "Fruitful symbiosis: Why an export bundled with wind energy is the most feasible option for North African concentrated solar power." Energy Policy 39(11): 7136-7145.

Kost, C., M. Engelken, T. Schlegl (2012). Value generation of future CSP projects in North Africa. Energy Policy 46: 88-99.

E. Lizarraga-Garcia, A. Ghobeity, M. Totten, A. Mitsos (2013). Optimal operation of a solar-thermal power plant with energy storage and electricity buy-back from grid. Energy. In Press, corrected proof. http://dx.doi.org/10.1016/j.energy.2013.01.024

Madaeni, S. H., Sioshansi, R. (2011). "How Thermal Energy Storage Enhances the Economic Viability of Concentrating Solar Power." Proceedings of the IEEE.

Meteonorm (2011). Software and data base of Meteotest. http://meteonorm.com/.

Ministerio de industriea, tourismo y comercio (2007). REAL DECRETO 661/2007.

Morin, G. (2011). Techno-economic design optimization of solar thermal power plants, Dissertation, University of Braunschweig, Fraunhofer Verlag.

Nagl, S., M. Fürsch, et al. (2011). "The economic value of storage in renewable power systems - the case of thermal energy storage in concentrating solar plants." EWI Working Paper, No 11/08, Institute of Energy Economics at the University of Cologne (EWI).

OMIE (2012). Market Results of 2010 (Precio marginal espagnol). Access via http://www.omie.es/.

Relloso, S., Delgado, E. (2010). Experience with molten salt thermal storage in a commercial parabolic trough plant. Andasol-1 commissioning and operation. Solarpaces 2010, Perpignan, France.

SAM (2012). System Advisor Model of NREL. https://sam.nrel.gov/

Schallenberg-Rodriguez, J. and R. Haas (2012). "Fixed feed-in tariff versus premium: A review of

the current Spanish system." Renewable and Sustainable Energy Reviews 16(1): 293-305.

Sioshansi, R., Denholm, P., (2010). The value of concentrating solar power and thermal energy storage. NREL Technical report NREL-TP-6A2-45833. Golden, Colorado.

Sioshansi, R., Denholm, P., Jenkin, T. (2012). "Market and Policy Barriers to Deployment of Energy Storage." Economics of Energy & Environmental Policy 1(2).

Varaiya, P. P., Wu, F. F., & Bialek, J. W. (2011). Smart operation of smart grid: Risk-limiting dispatch. Proceedings of the IEEE, 99(1), 40-57.

Wittmann, M., Eck, M., Pitz-Paal, R. and Müller-Steinhagen, H. (2011). "Methodology for optimized operation strategies of solar thermal power plants with integrated heat storage." Solar Energy 85(4): 653-659.