THEORETICAL ECONOMIC POTENTIAL OF THE SPANISH PREMIUM TARIFF FOR SOLAR THERMAL POWER PLANTS

Michael Wittmann, Markus Eck, Tobias Hirsch, Robert Pitz-Paal

DLR, Institute of Technical Thermodynamics, Solar Research, Dipl.-Ing.,
DLR, Institute of Technical Thermodynamics, Solar Research, Dr.-Ing.,
DLR, Institute of Technical Thermodynamics, Solar Research, Dr.-Ing.,
DLR, Institute of Technical Thermodynamics, Solar Research, Univ.-Prof. Dr.-Ing.
DLR German Aerospace Center, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
+49 711 6862 730 (phone), +49 711 6862 747 (fax), michael.wittmann@dlr.de,

Abstract

The Spanish Royal Decree 661/2007 for the regulation of renewable energy allows the plant operators – beside a flat-rate price – to participate directly on the electricity market. This option is called the premium tariff (PT). The motivation of the PT is that the plant operators of renewable energies should act more and more like operators of conventional plants. This means that they sell their electricity at the electricity stock exchange or in bilateral contracts. As a normal market participant, the operator needs to place his bids in advance on the day-ahead market and is obliged to fulfill his bids. Deviations between fed-in energy and contracted energy lead to contract fines reducing the daily profit.

The levelized electricity costs of renewables are significantly higher than the market electricity price; therefore the operator gets a premium per kWh additionally. In sum the PT has the potential to exceed the flat-rate price. In order to participate economically in the PT a thermal storage is needed. It allows shifting the harvested energy over the time axis towards high price times and increases flexibility for fulfilling the production schedule. The operation strategy of the storage needs therefore to be based on forecast: price and weather forecast, respectively.

The paper will present the theoretical potentials of the premium tariff in comparison to the flat feed-in tariff. The Andasol-1 power plant with 50 MW of electric power serves a reference plant. The influence of the storage size on the yearly revenue is assessed.

Keywords: solar thermal power, operation strategy, electricity market, Spain, economic potential, optimization

1 Introduction

The Spanish Legal Foundation[1] offers the renewable energy operators two possibilities to sell their electricity production: the tariff- and the premium-model. The tariff model offers one fixed price (26.9375 €-ct/kWh) independently when the electricity is fed in. The operator is allowed to feed-in his renewable electricity with priority over any other conventional electricity generator.

The premium model has been introduced in order to motivate the operators of renewable energy to act on the liberalized market like the conventional electricity producers have to. The conventional producers must place their energy bids in a day-ahead market. The bids contain at least the hour of energy production, energy amount and the price. Depending on the market situation and the bid price, the operator may be capable of getting his bids confirmed. If these bids are confirmed by the market operator OMEL[2] in a matching procedure of power purchase and sale bids, the suppliers are obliged to fulfill their bids. Hence, for the system operator REE[3] a reliable basis for secure grid operation is being set up for the next day. Any operator, who does not fulfill his delivery schedule, will be charged deviation costs per kWh of deviation.

The premium model enables the operators of renewable energy plants to participate on the market like the conventional players. In addition to the market price, they get a premium per kWh from the National Energy Commission CNE (25.4 €-ct/kWh) in order to balance out competition disadvantages. The premium is lower than the fixed tariff. To be economically advantageous the operator has to act on the market in a manner to gain in yearly sum of premium and market price (minus deviation fines) more profit than in the fixed tariff model. Like conventional producers the renewable producers have only the right to feed in their sold electricity. Deviations lead to deviation fines.

In this paper, the theoretical potential of the participation in the premium tariff is assessed. This is done for two different years 2002 and 2005. The year 2002 has the yearly sum of irradiance of a typical year. The year 2005 represents an extraordinary good year in terms of solar irradiation and prices. In the first paragraph, the models and their assumptions are explained and the operation strategies are described. In order to asses the theoretical potential of the premium model all significant influences which reduce the potential are idealized. Here three candidates are selected, which affect the economic potential mostly: weather forecast, electricity price forecast and storage efficiency. The results are shown in the last chapter.

2 Simulation Environment, Model Assumptions

2.1 Datasets

Two different years are assessed in this paper, 2002 and 2005. The year 2002 represents a typical year of solar irradiation at the Andasol site in Spain with 2,141 kWh/m² a. Whereas 2005 features a year with extraordinary high solar irradiation (2,415 kWh/m² a) and increased electricity price volatility on a high level. The weather conditions have been very stable with an above average number of clear sky days. The metering location of the meteorological dataset is 37°2’N, 3°4’W.

The electricity price time series represent the prices in the day-ahead market of the Spanish market operator OMEL. In Spain the electricity prices have a resolution of 1h in the day-ahead market. The mean price paid in 2002 is 3.74 ct/kWh with a standard deviation of 1.62 ct/kWh. In 2005 volatility and price was superior with 5.37 ct/kWh and 1.93 ct/kWh, respectively.

In real operation of the power plant, to fix the schedule for the next day is based on forecast of both electricity price and meteorological conditions. In the assessment of the theoretical economic potential it is assumed, that exact information on the next day’s conditions are available, i.e. a perfect forecast of 100% accuracy is given.

2.2 Power Plant Model

For this study Andasol-1 is used as the reference plant. The Andasol-I power plant is actually the only one which has a significant storage capacity in order to be able to transfer significant amounts of solar energy towards periods with high stock prices. The power block consists of a 49.9 MW turbine with live steam parameters of 100 bar and 371 °C[3]. After the high pressure turbine the steam will be reheated to 370 °C at 16.5 bar[4]. The design gross efficiency of the power block reaches 38 %.

During simulation it is assumed that live steam parameters and superheating temperature is held constant. The energy flow to the power block needs to exceed a threshold of 20 % in order to provide sufficient mass flow for turbine operation. Also the feed-water temperature was assumed to be constant. The part load behavior of the turbines has been taken into account and auxiliary power was considered.

2.3 Solar Field

The Andasol-1 solar field was used as a reference for the simulation models. Even though, the Andasol-1 solar field is equipped with SKAL-ET collectors, the public available efficiency models of LS-2 collector[6] have been used in this study. The collector surface is set to 510,000 m². The mean temperature of the ambient was held constant at 25 °C and for the absorbers at 300 °C. The average optical efficiency was assumed to be 73.2 %.

2.4 Thermal Energy Storage

In this paper the thermal energy storage is assumed to be ideal, due to reasons for assessing the theoretical economic potential as mentioned before. This means, it does neither loose energy nor exergy. Due to imperfect insulation a real thermal energy storage looses energy by heat transfer to the ambient. Also, indirect storage, as realized in the Andasol-1 project, has exergetic losses due to heat exchange from solar field HTF to the storage fluid during charging and discharging. The storage capacity of Andasol-1 is 1010 MWh_{th} this corresponds to about 7.5 h at design electricity production.

Further assumption of a perfect storage model is that the charging rate is not restricted by any technical component, i.e. basically the entire current energy offer from the solar field can be charged into the storage. Obviously the restriction of the storage capacity needs to be considered when reaching maximum storage load. The discharge rate is limited by the ability of the power block to convert thermal energy into electricity. Regarding 49.9 MW_{el} of electric power with an efficiency of 38 % this maximum discharge rate is calculated to 131.3 MW_{th}.

2.5 System Model

In the simulation environment the single components of the solar thermal power plant are connected via energy fluxes. Additionally, the solar thermal power plant is connected to meteorological conditions via the solar field and to the electricity market via the generator. The system is depicted in figure 1.

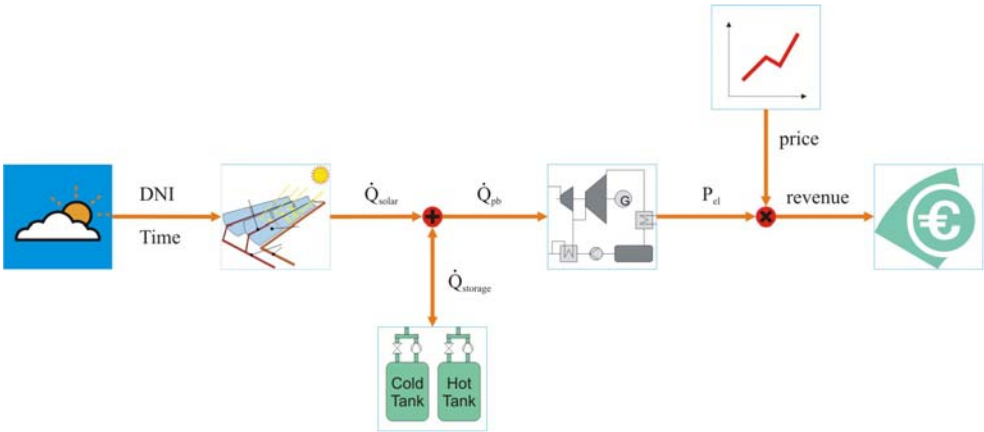

Figure 1. Flows and interconnections of the system model

3 Definition of Operation Strategies

3.1 Reference Operation Strategy

The reference operation strategy prioritizes the direct solar operation. While producing heat, the solar field feeds directly into the power block in order to produce electricity. The surplus of heat which cannot be converted in the power block is used for charging the storage. When the heat production of the solar field drops below the design heat consumption of the power block, storage energy will be used to compensate the lack of energy. After sunset the storage energy will be used to prolong the electricity production into the night until the storage is depleted and the whole daily irradiation is completely converted into electricity.

The solar field will be defocused, when thermal solar field power exceeds the sum of maximum storage charging due to storage capacity limits and design heat consumption of the power block.

3.2 Optimized Operation Strategy

The aim of the optimized operation strategy is to maximize the daily revenue at the electricity stock exchange. The strategy is pursued to sell the electricity preferably at high price times rather than at low price times. The storage is used to adapt the electricity production to the electricity price characteristic. It allows shifting the collected energy in the solar field towards the high price periods. The schedule is basically defined by the daily price course. An adequate storage capacity is necessary in order to get the flexibility needed for shifting the energy over the time axis.

In order to set up the optimized operation strategy an optimization problem needs to be solved. For the optimization a problem adopted solver was developed. The objective function to be maximized is the daily revenue:

$$\int P_{el}(t) \times price(t)\, dt \overset{!}{=} \max$$

With limitations

$$\begin{aligned}
&0 \le Q_{\text{storage}} \le Q_{\text{storage capacity}} \\
&-\dot{Q}_{\text{discharge,max}} \le \dot{Q}_{\text{storage}} \le \dot{Q}_{\text{charge,max}} \\
&\dot{Q}_{\text{charge,max}} = f_1(DNI) \\
&\dot{Q}_{\text{discharge,max}} = f_2(DNI).
\end{aligned}$$

Function f_1 describes the upper limit of the charging rate which is restricted by the current amount of solar radiation. The solar radiation also influences the maximum discharge rate f_2 because of the maximal possible heat load of the power block. Both energy fluxes from the solar field and storage may not exceed the design heat load. Certain requirements for the adopted optimizer are needed: use of steady-state models and ideal storage. Additionally, no energy consumption due to start-up is considered.

4 Results

4.1 Dependency of forecast horizon for Operation Strategy

Since trading electricity on a day-ahead market at least one day of forecast is necessary. This chapter assesses the question how the revenue of the optimized operation strategy alters when using a different time period as forecast and data basis for the optimization. It is clear, that using more days of forecast will allow increasing revenue by raising possibility of the optimization in a longer time period.

In figure 2 the interrelation of forecast horizon and yearly stock exchange revenue of 2002 is shown. Due to the fact, that at least one day is necessary to set up a day-ahead schedule, this forecast period also serves as a reference case. Thus, the yearly theoretical revenue at the stock exchange in the reference case is 7.44 M€. An additional day of forecasting permits a rise in revenue of 3.0 % to 7.67 M€. Expanding the forecasting horizon to three or more days has only a minor effect on the yearly revenue and optimized operation strategy, respectively.

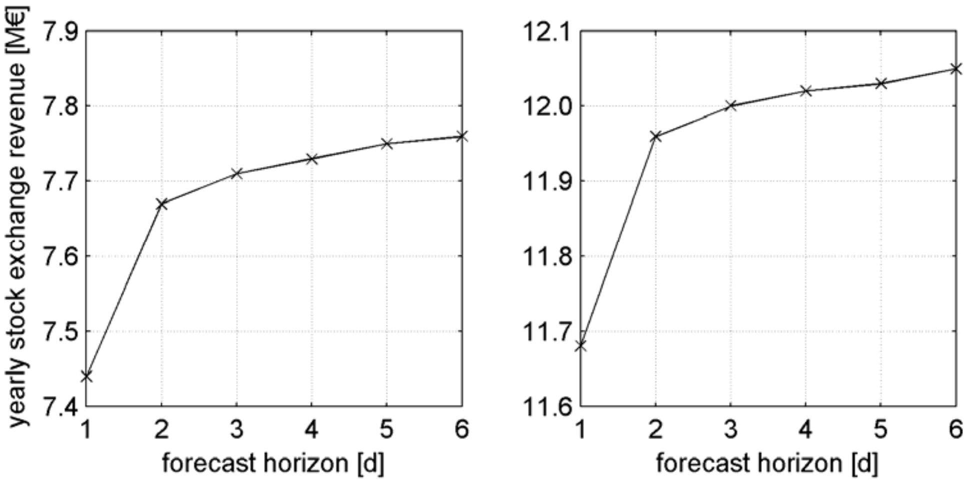

Figure 2. Dependency of data basis on yearly profit in 2002 (left) and in 2005 (right)

The optimized schedule benefits from the information of the second day of forecast most. Further days do not significantly increase the daily profit, due to storage capacity limitations. The storage capacity limitation prevents the optimizer shifting greater amounts of energy from low price to high price times. The limitation has a greater impact during summer time because of a higher daily insolation in comparison to lower irradiance in winter. In figure 3 the cumulative improvement due to extended forecast data basis is shown. It can be seen that higher increases in winter seasons is achieved than in summer.

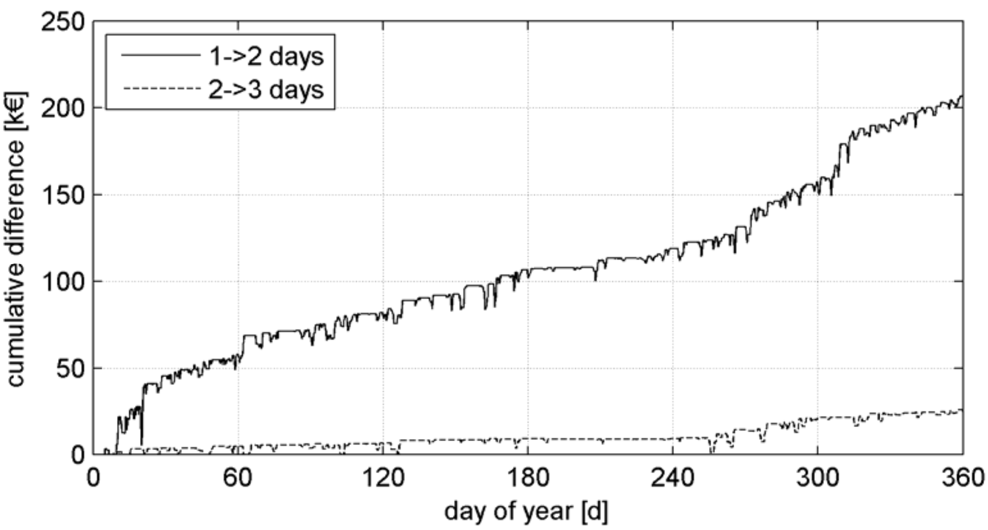

Figure 3. Yearly distribution of profit increase in 2002

Beside the effect of storage capacity limitations it can also be seen that providing the information of weather changes permits a potential of profit increase. Using data basis of one day only allows basing the next day's schedule on the actual forecasted irradiation. Whereas using two days of weather forecast allows determining weather changes. Consider two subsequent days as example: the first as a clear sky day with no clouds or aerosol pollution and therefore maximum solar irradiation, the second as a cloudy day with no direct insolation. Due to the information of the second day the optimizer is able to see that a shift of adequate solar energy to high price periods of the second day promises a greater profit and therefore uses the storage accordingly. A forecast horizon of just one day does not allow this scheduling. This coherence can also be seen in figure 3. The biggest increases happen during the winter seasons where weather changes occur with a higher probability. The benefit of the third days forecast is very limited since it is not likely that two distinct weather changes occur within three days.

The daily price characteristics are very similar for weekdays and differ for weekend days, namely the electricity price is higher on weekdays. Also these different characteristics offer an optimization of daily profit particularly on the days from Sunday to Monday. Here also at least a two day forecast is necessary in order to be able to use this information by the optimizer.

The assessment is repeated for year 2005. It can also be seen that the early saturation also takes place on the second day of forecast data basis. The relative increase turns out to be more moderate (+2.4 %). Whereas, in terms of absolute values the daily profit at the electricity stock exchange rises from 11.68 M€ to 11.96 M€.

The assessment of data basis is not necessary for the reference operation strategy because it converts the solar energy when it is available, so no information of further days is included into this strategy. Thus it is independent from the forecast horizon.

4.2 Energetic Comparison of Reference and Optimized Operation Strategy

In this paragraph the two operation strategies are compared with respect to their energy fluxes and electricity production. For the optimized operation strategy it is also distinguished between one and two days of forecast on which the day-ahead schedule is set up. The simulation is based on the year 2002.

4.2.1 Reference Operation Strategy

Within the reference strategy the collected energy is converted preferably directly in the power block. Only the surplus of energy is charged into the storage and is used to balance solar irradiation dips and prolongation of daily electricity production, respectively. Hence, the energy fluxes through the storage are minimized. Since defocusing of collectors only becomes necessary when having a completely loaded storage and a solar surplus this operation strategy also minimizes the need of defocusing.

In this configuration the solar field looses 2.6 % of the energy by defocusing. The thermal energy produced by the field (525.0 GWh) is used preferentially in the power block. The fraction which is passed through the storage into the power block is 27.1 %. A yearly net electricity production of 168.6 GWh is achieved. In figure 4 all energy fluxes are depicted.

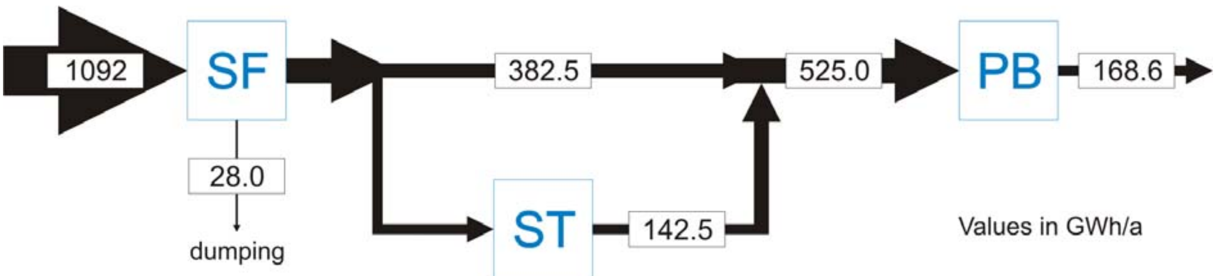

Figure 4. Energy fluxes of the reference operation strategy 2002
(solar field (SF), storage (ST), power block (PB))

4.2.2 Optimized Operation Strategy

In comparison to the reference strategy a significantly higher use of storage is noticed, see figure 5. The energy turnover increases from 53.9 % to 219.3 GWh for the same solar yield. With the assumption of a perfect storage no losses due to storage use is observed. On the contrary, due to the bundling of energy on high price hours the power plant is mainly operated at design load; but due to higher storage turnover auxiliary power use also increases. Overall, the mean annual net efficiency is increased by this operation strategy, so a slightly higher yearly electricity yield of 169.0 GWh is achieved.

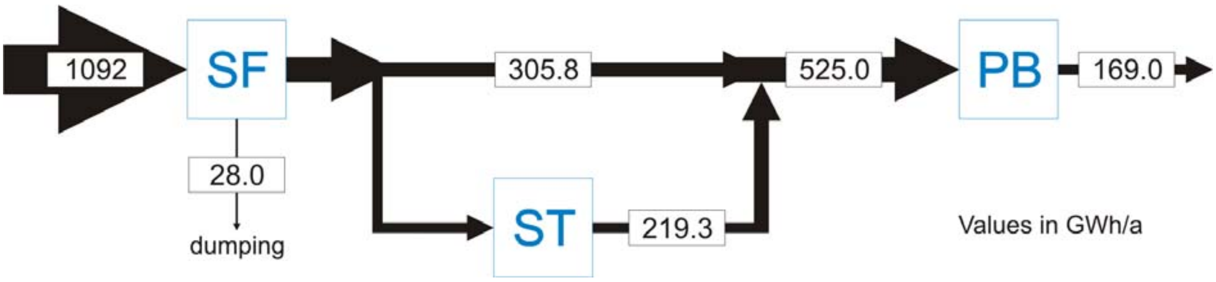

Figure 5. Energy fluxes of optimized operation strategy based on one day in 2002 (solar field (SF), storage (ST), power block (PB))

In figure 5 and 6 the energy fluxes of the yearly simulation based on one and two forecast day are shown, respectively. Both figures show that no further energy needs to be defocused when scheduling the operation with an optimized strategy. Hence the optimized operation strategy uses the solar resource more efficiently.

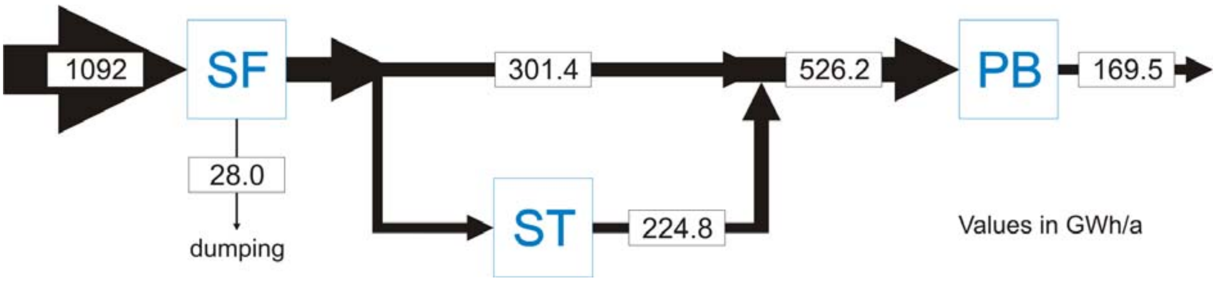

Figure 6. Energy fluxes of optimized operation strategy based on two day in 2002 (solar field (SF), storage (ST), power block (PB))

Figure 6 shows that due to an additional day of information for the basis of the operation strategy the storage turnover will be further augmented and reaches a value of 224.8 GWh. This means 42.7 % of the harvested solar energy is passed through the storage.

4.2.3 Conclusions

Although the electricity production is nearly independent of the operation strategy significant impact is observed for financial revenues. By a storage operation that bundles the solar energy on high price hours, the power plant is able to operate most of the time at its design load. The yearly mean thermal gross efficiency of the power block is 37.7 % for the optimized operation strategies and 37.4 % for the reference operation strategy.

Due to the active utilization of the storage when setting up the schedule the energetic turnover rises significantly. In comparison to the reference the energy stored and discharged rises from 50.0 to 53.7 % in the optimized operation strategies. It can be seen that the choice of the storage type will have significant influence on the electricity production. In this study the storage was treated as an ideal storage (no energetic or exergetic losses).

4.3 Monetary Comparison of Reference and Optimized Operation Strategy

The main monetary advantage is achieved by acting in the premium model due to higher mean energy prices compared to the difference of fixed tariff and premium. Further increase in yearly profit is achieved by the optimization of the operation strategy.

The yearly profit of the premium model is calculated as

$$P_{premium} = \sum_{i=1}^{8760} E_i \cdot (price_i + premium - deviation\ fines_i)$$

and the equation of the tariff model is

$$P_{tariff} = feedintariff \sum_{i=1}^{8760} E_i \ .$$

For this study the deviation fines are always zero in the premium model equation because of perfect forecasts in solar irradiation assumed.

The higher electricity output can directly be seen in the increase of paid premium. Due to optimization on the stock market a higher profit at the stock exchange can be obtained. In 2002 the rise of the yearly profit is equal to 2005 up to 1.0 M€ per year for the optimized compared to the reference strategy. The essentials of this paragraph are summarized in table 1.

	2002				2005			
	T/R	P/R	P/O1	P/O2	T/R	P/R	P/O1	P/O2
Premium / Fixed Tariff [M€]	45.4	42.7	42.9	43.1	51.3	48.2	48.3	48.4
Stock Exchange [M€]	-	7.02	7.44	7.67	-	11.1	11.7	12.0
Yearly Profit [M€]	45.4	49.7	50.4	50.7	51.3	59.4	60.0	60.4

Table 1. Summary of yearly profit for 2002 and 2005 (tariff model (T), premium model (P), reference operation (R), optimized operation based on one day (O1), based on two days (O2))

The change from the tariff model to the premium model gives a significant rise in profit, whereas further improving the operation strategy by one or two day forecasts give a minor additional profit.

This theoretic potential is reduced by two main factors. The forecast quality of the solar resource is directly related to the deviation fees an operator has to pay when differences of scheduled and fed-in power are observed. So a certain quality is necessary to have economic advantages when changing the market model to the premium tariff. The storage type and its efficiency reduces the potential of the optimized operation strategy because of the increased energy turnover in the storage system.

4.4 Influence of Storage Capacity on the Revenue

The participation at the electricity market influences the design of the storage, because the size is fundamental for the yearly profit of a solar thermal power plant. It was described earlier how the capacity limits the operation due to the need of defocusing and limitation of flexibility when scheduling.

Figure 7 depicts the dependency of yearly profit on storage size. The general potential of the premium model can be seen, independently on the choice of the operation strategy. In the premium model the optimization of the strategy requires an integrated storage. Therefore figure 7 shows an equal result for both operation strategies at storage capacity 0. While increasing the storage also the flexibility of the optimized operation strategy increases and thus the potential of the premium model. The saturation of the curves is caused by reducing the amount of lost energy due to defocused collectors during the year. No changes of yearly revenue can be seen with a storage capacity above 2000 MWh_{th}. Here maximal difference of both optimized operation strategies is 1.2 M€/a, for the reference plant with a storage of 1010 MWh_{th} this difference is 1.0 M€/a.

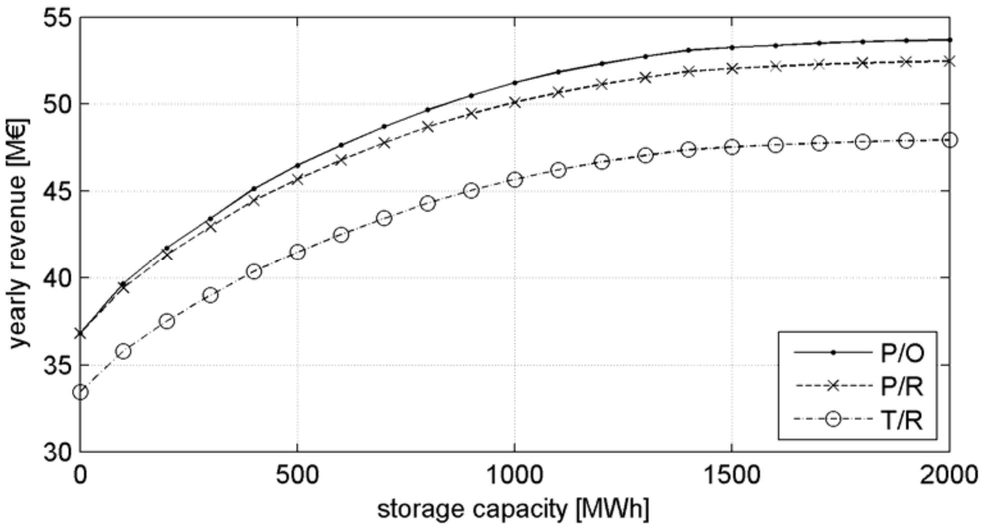

Figure 7. Yearly Revenues of different operation strategies and market models (premium model (P), tariff model (T), optimized strategy (O), reference strategy (R))

5 Conclusions

The Spanish legal foundation, that motivates the operators of renewable energy plants to participate on the electricity market like the conventional power producers, offers potential of economic improvement of the plant. In this paper this potential is quantitatively assessed using an Andasol-1-like solar thermal power plant with two different operation strategies as reference. In order to determine the maximum theoretical economic potential certain assumptions are made. First, perfect forecasts for either weather and electricity price is assumed. Furthermore, the storage which has an essential impact on the operation strategies was modelled to be energetically and exergetically ideal. Two different operation strategies have been defined: a solar-driven operation strategy as reference that prioritizes the direct conversion of the solar energy in the power block instead of charging the storage; and an optimized price-driven operation strategy which adapts the storage operation on the electricity price on the stock market and is based on forecasts for weather and market prices.

It was shown that a forecast-based operation strategy with two days of forecast offers an increase in the economic potential compared to an operation strategy with one day forecast. Any further extension of the forecast horizon will improve the economic potential only marginally. In reality the suppliers must rely on forecast which quality decreases with time. Thus for real applications the small increase of economic potential seems not to satisfy the extensions to more than two days.

An energetic comparison of the two operation strategies shows that by using an operation strategy that bundles the solar energy in order to operate the power block preferably in design point the annual thermal gross efficiency can be increased. The reference operation strategy reaches values of 37.4 % and the optimized strategy of 37.7 %. In the optimized strategy the higher conversion amount will partly be reduced due to higher auxiliary power used by the storage system. The net electricity production will thereby rise only marginally from 168.6 to 169.0 and 169.5 GWh. It was also shown that the storage energy turnover is significantly increased when using a price-driven set up of the operation strategy. The turnover increases from 142.5 GWh in the reference case to at least 219.3 GWh with optimized operation strategies. This shows the high sensibility of the choice of storage for the optimized operation strategies.

The change of the market model to the premium option shows under current Spanish legal foundation a huge potential of economic advantage. In the reference case the change of the market model increases the yearly revenue by 9.7 %. Further optimization of the operation strategy can raise this increase to 11.7 %. In the extraordinary year 2005 characterized by over-average solar irradiation and high price volatility the increase of the potential may rise to 17.7 %.

With participation on the market the capacity of the storage has an important influence on yearly revenue. The influence is assessed for 2002. The minimum difference between premium and tariff model of 3.4 M€ was observed when no storage was used. The maximum of theoretic potential of the yearly revenue is seen when the storage has no limiting effect that provokes defocusing of the absorbers. The maximum yearly revenue in the tariff model is 47.9 M€, in the premium model with reference operation 52.5 M€ and 53.7 M€ with optimized operation strategies. Thus, having a maximum difference of 5.8 M€. The potential of the optimized operation strategy compared to the reference strategy for storage capacity of 7.5 h @ 49.9 MW for the premium tariff was determined by 1.0 M€ for the reference year 2002.

This significant theoretic potential of the operation strategy on the yearly earnings encourages investigating optimized operation strategies in more detail. Currently real storage performance characteristics and realistic uncertainties for weather as well as for price forecasts are being implemented in the model required for more detailed system analysis. In the future this tool might serve as a valuable decision criterion for operators of solar thermal power plants.

Acknowledgements

Thanks to Solar Millennium AG for providing meteorological data for 2002 and 2005.

References and Notes

[1] Royal Decree 661/2007 of 25th may, 2007, to be found at www.cne.es
[2] Operador del Mercado de Electricidad, to be found at www.omel.es
[3] Flagsol, to be found at www.flagsol.com
[4] Herrmann, Ulf et al. – “The Andasol Project” at Workshop on Thermal Storage for Trough Power Systems, NREL, 2003
[5] Gomez Zamorra, Antonio – “Centro Thermosolar Andasol-1”, Jornada Annual 2005 – Energía Solar: Estado Actual y perspectiva inmediata, May, 2005
[6] Dudley, Vernon et al. – “Test Results - SEGS LS-2 Solar Collector”, SAND94-1884, 1994