# System Advisor Model (SAM) Case Study:

# Andasol-1

Aldeire, Spain

The SAM team is compiling a series of case studies to provide specific examples with the view to guide users in constructing their own SAM analyses. These case studies describe the process of acquiring data, generating a SAM file with explicit inputs, and analyzing the salient results. Each case study is accompanied by the SAM file (v2012.11.30) that has been used to model the case.

**Abstract**

Andasol-1 is a parabolic trough concentrating solar power (CSP) plant in Aldeire, Spain about 40 km east of Granada. This was the first parabolic trough power plant built in Europe as well as the first trough plant in the world to incorporate thermal storage [1]. The plant has a nominal capacity of 50 MWe and covers slightly less than 500 acres. It is owned and operated by ACS-Cobra Energy, who invested around €310 million to build the plant. The feed-in tariff in Spain was set by Royal decree 661/2007 and offers a guaranteed power purchase agreement (PPA) for 25 years at a tariff rate of €0.27/kWh. Performance data from the plant is proprietary but even without a very accurate weather file the SAM model predicts an annual energy output and a PPA proportional to the values reported in the media [2,3].

Figure 1: South-facing view of Andasol-1 solar field [4]

## System Description

Andasol-1 has a solar field aperture of 510,120 m², consisting of 624 Skal-ET parabolic trough collectors, including 156 parallel loops of four collectors in serial connection. The plant uses proprietary technology to track the sun's location in order to maximize the collection of thermal energy. The solar collectors are made up of more than 200,000 mirrors that concentrate the sun rays on 22,464 tube receivers. The receivers are both Schott PTR-70 and Solel UVAC models. The heat transfer fluid (HTF) in the receivers is Dowtherm A. This synthetic oil is heated to 393ºC and flows through the tubes in order to boil water in the heat exchangers. The steam produced from this process drives a 50 MW (net) Siemens SST-700 reheat steam turbine, which is connected to a generator that produces electricity. The plant uses a wet-cooling system to condense the steam back to liquid. The Andasol-1 power plant has a thermal storage system which stores part of the heat produced in the solar field during the day in a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate. A full storage tank can be used to operate the turbine for about 7.5 hours at full-load when the sky is overcast or after sunset. The plant also utilizes a 12% fossil fuel back-up from a natural gas heater. Ground-breaking for Andasol-1 plant began in July 2006 and after 28 months of construction, it went online in November 2008.

Figure 2: View of the power block in Andasol-1

## Data Acquisition

This study used the Granada EPW climate file [5] as the best representation of Aldeire due to the two locations being only 40 km apart. The system specifications were primarily sourced from the NREL/ SolarPACES website [6]. The financial assumptions for this study were compiled mainly from IDAE and Deutsche Bank technical studies [7,8]. ACS-Cobra Energy has not released performance data for the plant; therefore, the data provided in this case study was obtained from referenced public sources.

## SAM Inputs

The SAM technology chosen for this system is CSP physical trough (as opposed to the empirical trough model) because the plant performance can be more accurately measured based on its physical characteristics. The market is Independent Power Producer because ACS-Cobra Energy sells the electricity at a price negotiated through a PPA that was established with the Spanish feed-in tariff. Table 1 shows all the changes from the default values based on the system description.

**Table 1: SAM performance inputs for Andasol-1 that differ from default values**

| Page | Variable | Default Value | Andasol-1 |
|---|---|---|---|
| **Climate** | Location | AZ Tucson (TMY2) | Granada (EPW) |
| **Solar Field** | Field aperture (Option 2) | 861590 m² | 510120 m² |
| | Irradiation at design | 950 W/m² | 700 W/m² |
| | Field HTF fluid | Therminol VP-1 | User-defined (below) |
| | Design loop outlet temp | 391ºC | 393ºC |
| | Number of SCA per loop | 8 | 4 |
| **Collector (SCAs)** | Configuration name | Solargenix SGX-1 | EuroTrough ET150 |
| **Receivers (HCEs)** | Configuration name (Type 2) | No library match | Solel UVAC 3 |
| **Power Cycle** | Capacity - Design gross output | 111 MW | 55 MW |
| | Rated cycle conversion efficiency | 0.3774 | 0.381 |
| | Aux heater outlet set temp | 391ºC | 393ºC |
| | Fossil dispatch mode | Minimum backup | Supplemental operation |
| **Thermal Storage** | Full load hours of TES | 6 hr | 7.5 hr |
| | Tank height | 20 m | 14 m |
| | Dispatch schedule | Summer Peak | Summer Peak |
| | TOD factor | Different values | All of them change to 1 |
| | Fossil fill fraction (Period 1) | 0 | 0.15 |
| | Fossil fill fraction (Period 2) | 0 | 0.20 |
| | Fossil fill fraction (Period 3) | 0 | 0.45 |
| **Performance Adjustment** | Year-to-year decline in output | 0 | 0.5 |

Since SAM does not have a heat transfer fluid model for Dowtherm A, we had to create a custom fluid. Using the "edit" button, we populated the table for each property at 10 different temperatures by using the DOW product technical data [9]. We changed the payment allocation factors to 1 because the Spanish feed-in tariff price is equal in all the periods. The Royal decree 661/2007 set an allowance for solar thermal plants to contain up to 12-15% natural gas back up. This increases the reliability of the plants, since natural gas can be used both to maintain the temperature of the heat storage during periods of interruption in solar thermal electricity generation and to continue generation during cloudy conditions or after sunset. We adjusted the fossil fill fraction values in order to reach a 12% fossil fuel back up without specific criteria. Further research should be done in order to clarify how Andasol-1 uses the 12% fossil fuel back up allowed.

As mentioned above, the financial inputs were compiled from two different studies, carried out for IDAE and Deutsche Bank. Screen shots of the Trough System Cost and Financing pages (with all of the adjusted inputs) are located in the Appendix. Table 2 shows the changes from the default values based on the system description.

Table 2: SAM financial inputs for Andasol-1 that differ from the default values

| Page | Variable | Default Value | Andasol-1 |
|---|---|---|---|
| **Trough System Costs** | Site Improvements | 30.00 $/m^2$ | 28.00 $/m^2$ |
| | HTF System | 80.00 $/m^2$ | 78.00 $/m^2$ |
| | Storage | 80.00 $/kWht | 78.00 $/kWht |
| | Fossil Backup | 0.00 $/kWe | 60.00 $/kWe |
| | Power Plant | 830.00 $/kWe | 850.00 $/kWe |
| | Balance of plant | 110.00 $/kWe | 105.00 $/kWe |
| | Fixed Cost by Capacity | 65.00 $/kW-yr | 66.00 $/kW-yr |
| | Variable Cost by Generation | 4.00$/MWh | 3.00$/MWh |
| | Fossil Fuel Cost | 0.00 $/MMBTU | 6.00 $/MMBTU |
| **Financing** | Minimum Required IRR | 15% | 12% |
| | PPA Escalation Rate | 1% | 0% |
| | Loan Rate | 8% | 7% |
| | Real Discount Rate | 8.20% | 8% |
| | Federal Income Tax | 35% | 30% |
| | State Income Tax | 7% | 0% |
| | Insurance Rate | 0.5% | 1% |
| | Up-front Fee | 1% | 3.5% |
| | Construction Period - Months | 24 | 28 |
| | Annual Interest Rate | 5% | 5.5% |
| | Allow SAM to pick debt fraction | ☐ | ☑ |
| **Depreciation** | Federal | 5-yr MACRS | Straight line (25 yr) |
| | State | 5-yr MACRS | No depreciation |

## Results and Discussion

Table 3 shows the key SAM metrics for the system along with reported values (when available) and the percent difference between the SAM estimates and the media reports.

Table 3: SAM metrics table

| Metric | SAM value | Reported Value | Difference (%) |
|---|---|---|---|
| **Annual Energy** | 174,511,024 kWh | 179,103,000 kWh | 2.6% |
| **PPA price** | 36.67 ¢/kWh | 37.05 ¢/kWh | 1.0% |
| **LCOE Nominal** | 36.67 ¢/kWh | | |
| **LCOE Real** | 29.72 ¢/kWh | | |
| **Internal Rate of Return** | 12.00% | | |
| **Minimum DSCR** | 1.40 | | |
| **Net Present Value** | $12,504,255 | | |
| **Debt Fraction** | 71.43% | | |
| **Capacity Factor** | 40.20% | 41.50% | 1.3% |
| **Gross to Net Conv. Factor** | 0.94 | | |
| **Total Land Area** | 476.80 acres | 481.85 acres | 1.0% |
| **Total Installed Cost (2006$)** | $418,440,431 | $411,690,000 | 1.6% |

The simulation gave an energy output of approximately 174.5 GWh/year. The reported annual output for Andasol-1 is estimated at 179.1 GWh/year, giving a 2.6% difference in the actual and simulated values. There was also a 1.0% difference between the simulated and reported values for the total land of the plant, and a 1.6% difference in the total installed cost values. Furthermore, the SAM value for PPA price differ 1.0% with the Spanish feed-in tariff price per kWh. To further analyze the financial side of the model, the SAM graphs are very useful. The three standard financial graphs are shown below:

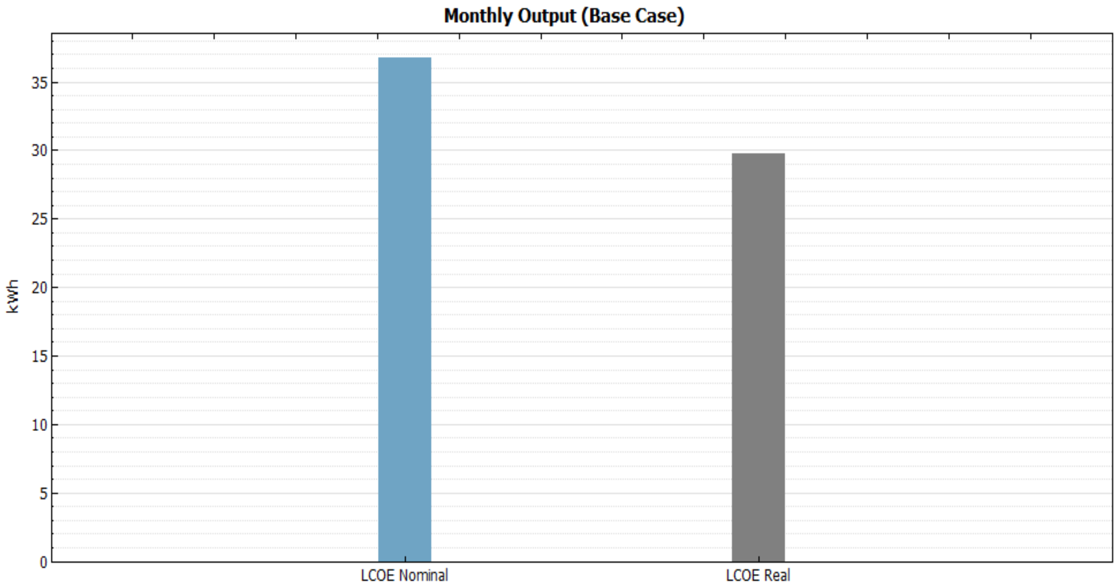



Figure 3: Simulated LCOE values for Andasol-1

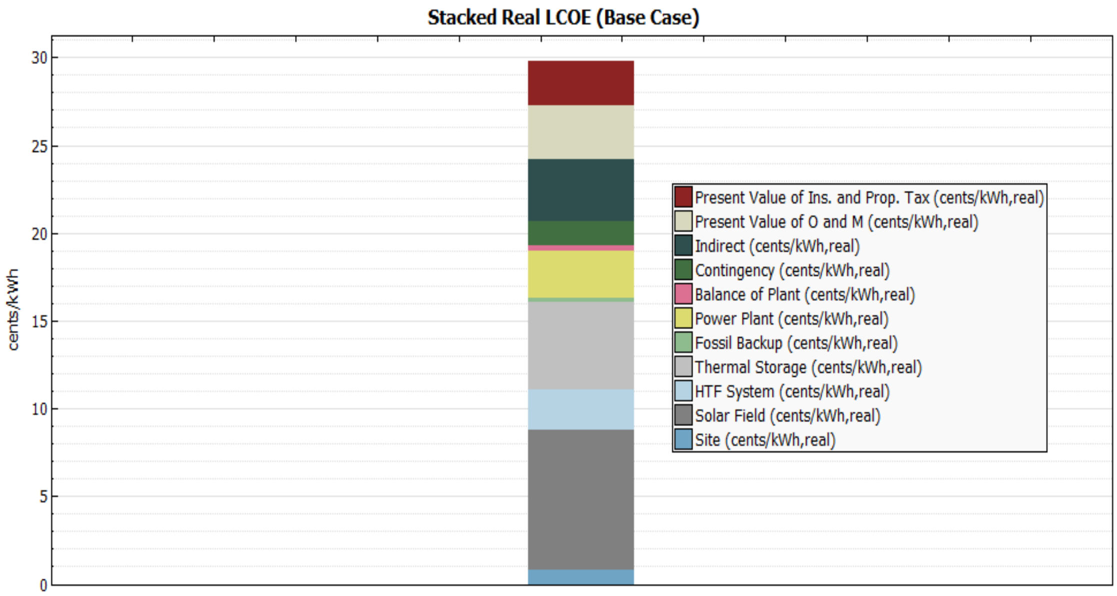



Figure 4: The stacked real LCOE shows the cost breakdown for different components of the system

From the stacked real LCOE (Figure 3), we can see how different components make up the LCOE for Andasol-1. For example, we can see the contribution of TES costs as well as the fossil fuel from the 12% fossil fuel back up costs. Figure 4 shows the after tax cash flow for the 25 year period analysis. We can see the negative payment for the installation of the project in year 0 as well as the diminishing profit until the 20-year loan term ends.

There are also many practical graphs for the performance side of the model. Figure 5 (below) shows the annual energy flow. From this, we can see the energy losses associated with certain processes throughout the system. For example, we can see the inefficiency of converting thermal energy to electricity during the power cycle (from over 500 GWh to less than 200 GWh). We can also obtain a more precise picture of the system's output using DView, SAM's hourly time series data viewer. To launch DView, click on Time Series in the Results menu. Figure 6 (below) shows the gross power output of the plant at different times of the day and different days of the year. This is useful in determining peak output hours throughout the year and could be used to make a comparison between peak output and peak demand hours or to compare time series outputs in different locations.

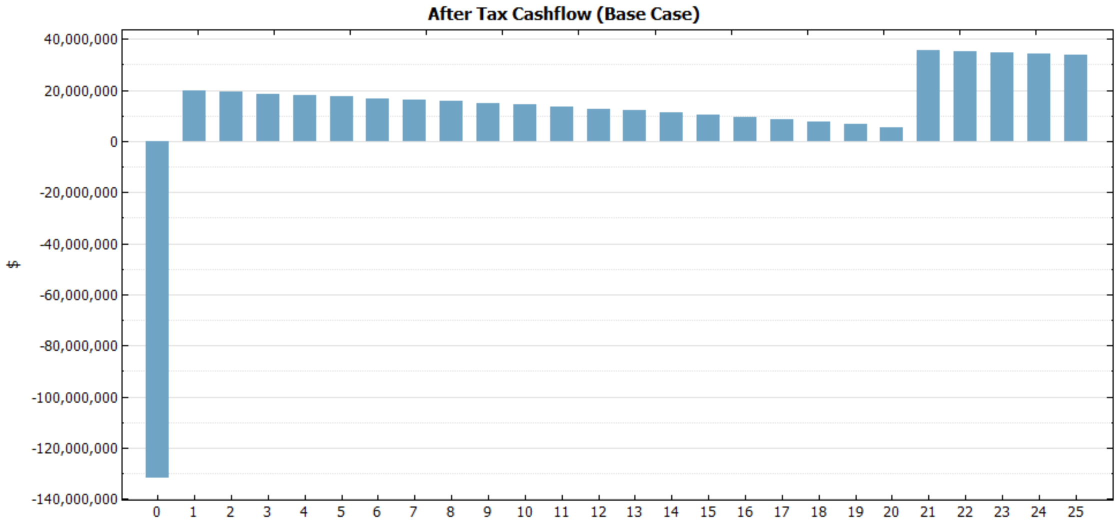



Figure 5: Shows the long-term financial profile for Andasol-1 over the 25 year period analysis. Positive values of cash flow represent an influx of money while negative values correspond to outgoing payments.

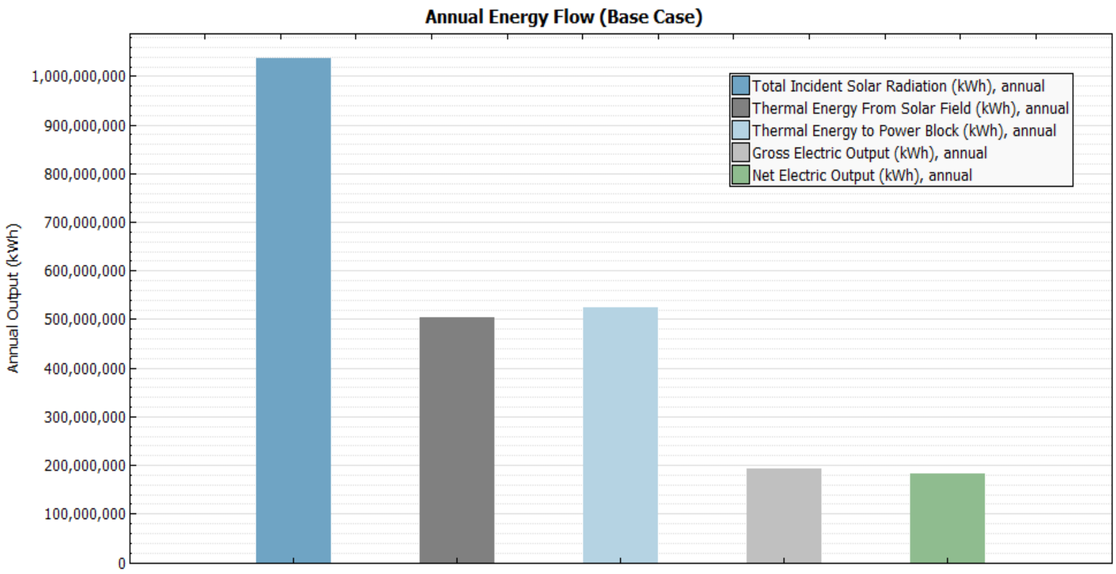



Figure 6: The annual energy flow shows the losses from different processes throughout the system

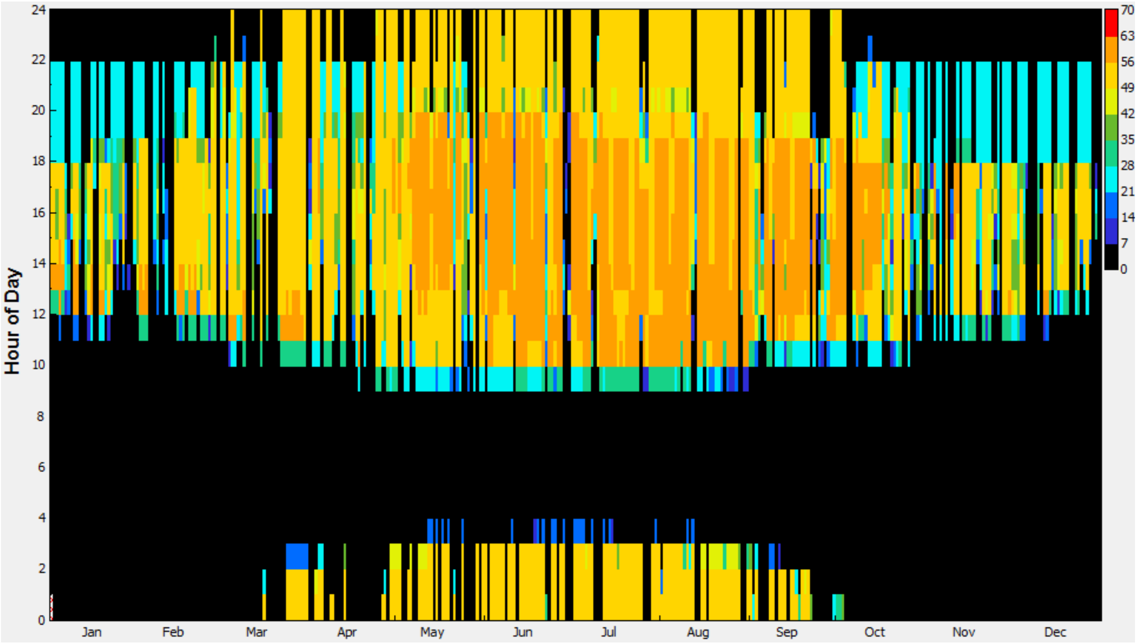



**Figure 7: The gross power output of the system shows the peak times of year. Each pixel represents a single hour of the year.**

## Conclusion

Utilizing SAM's capabilities, we modeled Andasol-1, one of the first CSP trough plants constructed in the world. We were able to model the plant with minimal changes to the default values, using the limited information that has been made publicly available. Even with lacking performance data, we were able to get within 3% of the reported annual output and found a PPA close to the Spanish feed-in tariff price per kWh. This case study is located in the SAM samples folder.

## References

[1] "Andasol Power Plants" *Solar Millennium*. <http://www.solarmillennium.de/Technologie/Referenzprojekte/Andasol/Die_Andasol_Kraftwerke_entstehen_%2Clang2%2C109%2C155.html>

[2] "Andasol 1 & 2" *Estela Solar*. <http://www.estelasolar.eu/index.php?id=32>

[3] "Andasol Solar Power Station" *Clean Energy*. <http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Andasol_Solar_Power_Station___Energy_Storage_Case_Study.html>

[4] Vincent, J. "The Future of Energy is Now." *Greenpeace Australia Pacific Blog*. 27 May 2009. <http://www.greenpeace.org.au/blog/?p=524>

[5] "Weather Data – Spain" *US Department of Energy*. <http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=ESP/cname=Spain>

[6] "Andasol-1" *SolarPACES. National Renewable Energy Laboratory.* <http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3>

[7] "Evaluación del potencial de energía solar termoeléctrica" *IDAE*. Madrid, 2011.

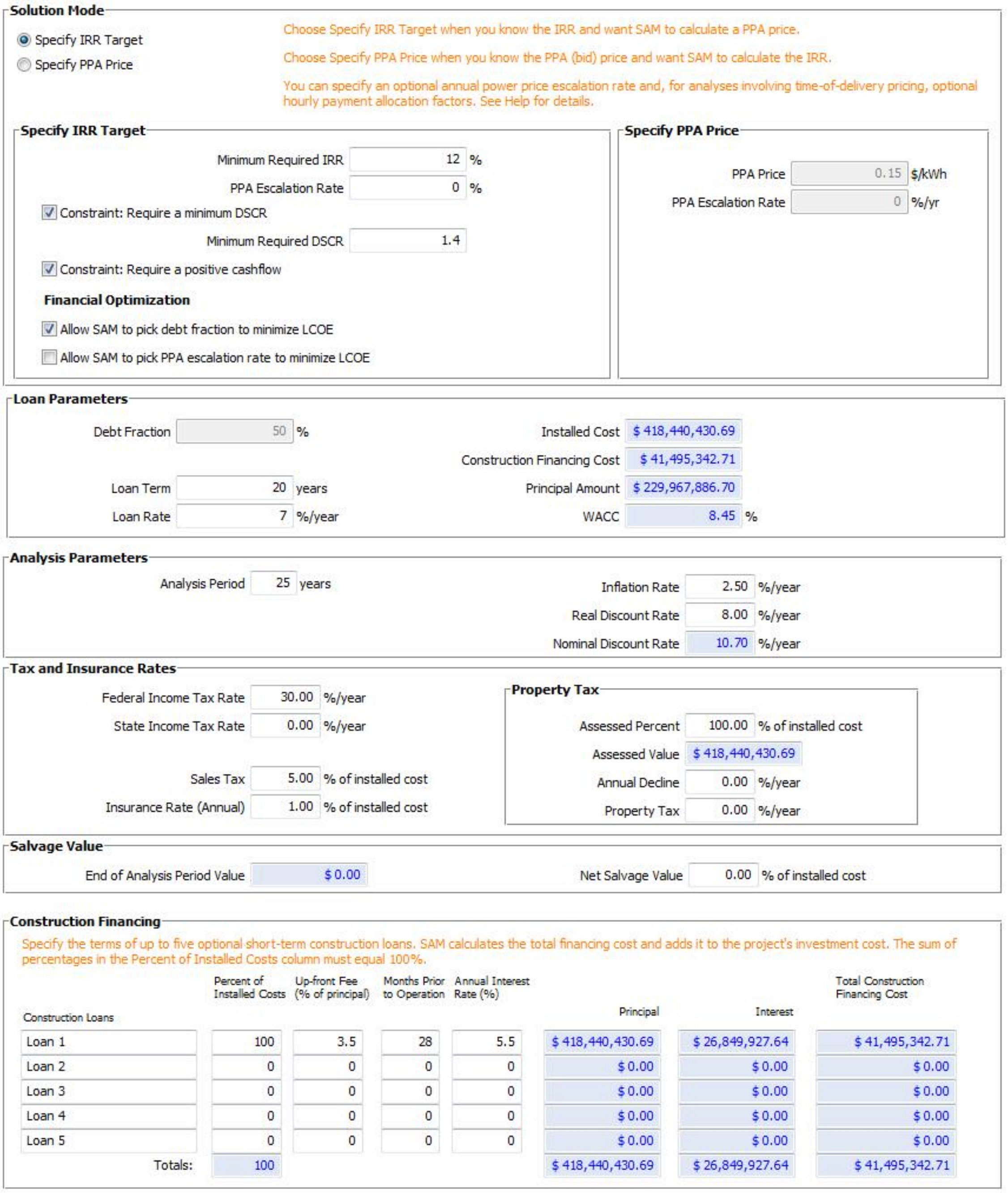
[8] "The CSP industry: An awakening giant" *Deutsche Bank*. Germany, March 2009.

[9] "Dowtherm A: Heat Transfer Fluid" Product Technical Data, *Dow Chemical Company*. March 1997.

[10] SAM templates available at: <https://www.nrel.gov/analysis/sam/templates.html>

## Appendix

The screenshots below show the Financing and Trough System Costs pages for the Andasol-1 system using SAM v2012.11.30.



**Solution Mode**

- (selected) Specify IRR Target
- Specify PPA Price

Choose Specify IRR Target when you know the IRR and want SAM to calculate a PPA price.

Choose Specify PPA Price when you know the PPA (bid) price and want SAM to calculate the IRR.

You can specify an optional annual power price escalation rate and, for analyses involving time-of-delivery pricing, optional hourly payment allocation factors. See Help for details.

**Specify IRR Target**

Minimum Required IRR: 12 %

PPA Escalation Rate: 0 %

[x] Constraint: Require a minimum DSCR

Minimum Required DSCR: 1.4

[x] Constraint: Require a positive cashflow

**Financial Optimization**

[x] Allow SAM to pick debt fraction to minimize LCOE

[ ] Allow SAM to pick PPA escalation rate to minimize LCOE

**Specify PPA Price**

PPA Price: 0.15 $/kWh

PPA Escalation Rate: 0 %/yr

**Loan Parameters**

Debt Fraction: 50 %

Loan Term: 20 years

Loan Rate: 7 %/year

Installed Cost: $ 418,440,430.69

Construction Financing Cost: $ 41,495,342.71

Principal Amount: $ 229,967,886.70

WACC: 8.45 %

**Analysis Parameters**

Analysis Period: 25 years

Inflation Rate: 2.50 %/year

Real Discount Rate: 8.00 %/year

Nominal Discount Rate: 10.70 %/year

**Tax and Insurance Rates**

Federal Income Tax Rate: 30.00 %/year

State Income Tax Rate: 0.00 %/year

Sales Tax: 5.00 % of installed cost

Insurance Rate (Annual): 1.00 % of installed cost

**Property Tax**

Assessed Percent: 100.00 % of installed cost

Assessed Value: $ 418,440,430.69

Annual Decline: 0.00 %/year

Property Tax: 0.00 %/year

**Salvage Value**

End of Analysis Period Value: $ 0.00

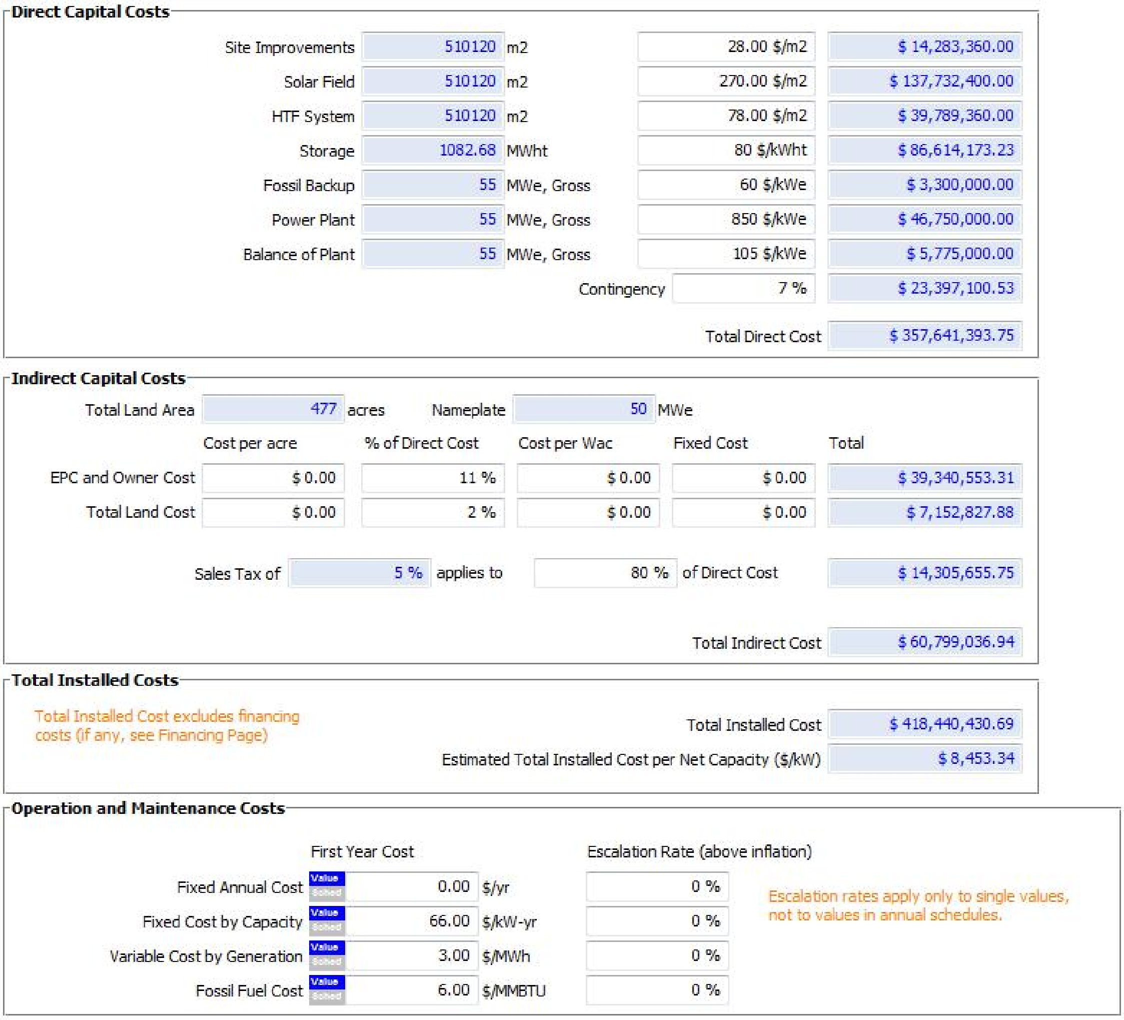
Net Salvage Value: 0.00 % of installed cost

**Construction Financing**

Specify the terms of up to five optional short-term construction loans. SAM calculates the total financing cost and adds it to the project's investment cost. The sum of percentages in the Percent of Installed Costs column must equal 100%.

| Construction Loans | Percent of Installed Costs | Up-front Fee (% of principal) | Months Prior to Operation | Annual Interest Rate (%) | Principal | Interest | Total Construction Financing Cost |
|---|---|---|---|---|---|---|---|
| Loan 1 | 100 | 3.5 | 28 | 5.5 | $ 418,440,430.69 | $ 26,849,927.64 | $ 41,495,342.71 |
| Loan 2 | 0 | 0 | 0 | 0 | $ 0.00 | $ 0.00 | $ 0.00 |
| Loan 3 | 0 | 0 | 0 | 0 | $ 0.00 | $ 0.00 | $ 0.00 |
| Loan 4 | 0 | 0 | 0 | 0 | $ 0.00 | $ 0.00 | $ 0.00 |
| Loan 5 | 0 | 0 | 0 | 0 | $ 0.00 | $ 0.00 | $ 0.00 |
| Totals: | 100 | | | | $ 418,440,430.69 | $ 26,849,927.64 | $ 41,495,342.71 |

Figure 8: SAM Financing page for Andasol-1



**Direct Capital Costs**

| | | | | |
|---|---|---|---|---|
| Site Improvements | 510120 | m2 | 28.00 $/m2 | $ 14,283,360.00 |
| Solar Field | 510120 | m2 | 270.00 $/m2 | $ 137,732,400.00 |
| HTF System | 510120 | m2 | 78.00 $/m2 | $ 39,789,360.00 |
| Storage | 1082.68 | MWht | 80 $/kWht | $ 86,614,173.23 |
| Fossil Backup | 55 | MWe, Gross | 60 $/kWe | $ 3,300,000.00 |
| Power Plant | 55 | MWe, Gross | 850 $/kWe | $ 46,750,000.00 |
| Balance of Plant | 55 | MWe, Gross | 105 $/kWe | $ 5,775,000.00 |
| | | Contingency | 7 % | $ 23,397,100.53 |
| | | | Total Direct Cost | $ 357,641,393.75 |

**Indirect Capital Costs**

Total Land Area 477 acres Nameplate 50 MWe

| | Cost per acre | % of Direct Cost | Cost per Wac | Fixed Cost | Total |
|---|---|---|---|---|---|
| EPC and Owner Cost | $ 0.00 | 11 % | $ 0.00 | $ 0.00 | $ 39,340,553.31 |
| Total Land Cost | $ 0.00 | 2 % | $ 0.00 | $ 0.00 | $ 7,152,827.88 |

Sales Tax of 5 % applies to 80 % of Direct Cost $ 14,305,655.75

Total Indirect Cost $ 60,799,036.94

**Total Installed Costs**

Total Installed Cost excludes financing costs (if any, see Financing Page)

Total Installed Cost $ 418,440,430.69

Estimated Total Installed Cost per Net Capacity ($/kW) $ 8,453.34

**Operation and Maintenance Costs**

| | First Year Cost | | Escalation Rate (above inflation) |
|---|---|---|---|
| Fixed Annual Cost | 0.00 | $/yr | 0 % |
| Fixed Cost by Capacity | 66.00 | $/kW-yr | 0 % |
| Variable Cost by Generation | 3.00 | $/MWh | 0 % |
| Fossil Fuel Cost | 6.00 | $/MMBTU | 0 % |

Escalation rates apply only to single values, not to values in annual schedules.

**Figure 9: SAM Trough System Costs page for Andasol-1**