NEW METHOD AND SOFTWARE FOR MULTI-VARIABLE TECHNO-ECONOMIC DESIGN OPTIMIZATION OF CSP PLANTS

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Abstract

This paper presents a new and integrated method and software for design optimization of solar thermal power plants. Thereby, optimization potential can be discovered which remains unrevealed when the sub-systems are optimized sequentially, like in today's state-of-the-art approaches. Using detailed component models, the approach includes the energetic and the economic simulation of a plant design as well as a multi-parameter optimizer.

Exemplarily, the integrated approach is applied to a 50 MW_{el} parabolic trough power plant using thermal oil as heat transfer fluid (HTF), a molten salt thermal storage and an air-cooled condenser at a site in the Californian Mojave desert. By changing eight plant design parameters of solar field (SF), storage and power block, the levelized cost of electricity (LCOE) could be reduced by 6.0%, starting from a power plant design similar to the Andasol-1 plant in Spain but transferred to the Californian site.

Keywords: simulation, optimization, plant design, storage, parabolic trough

1. Motivation (Introduction)

Today, designs of solar thermal power plants are developed by several sub-system calculations which make it difficult to optimize a plant as a whole system. This work presents a new and integrated method for design optimization of solar thermal power plants.

2. Model and Software Implementation (Methodology)

Using detailed component models, the approach includes the energetic and the economic simulation of a plant design as well as a multi-parameter optimization algorithm – an evolutionary algorithm – to optimize relevant design parameters of the plant.

The graph below shows the methodology that is being pursued.

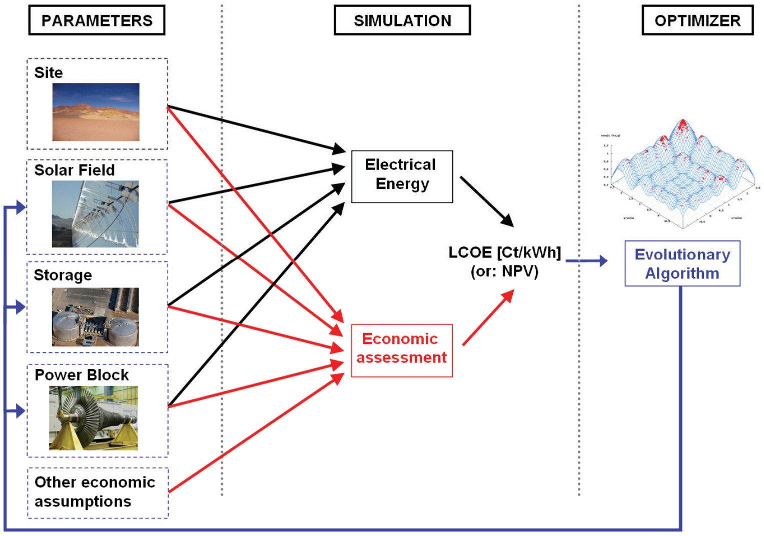


Figure 1: General structure of the techno-economic system simulation and optimization model

First of all, a set of technical and economic parameters has to be chosen to simulate a power plant configuration. The parameters refer to power plant site, power block, collector / solar field, storage (if used) and economic assumptions on installation and operation of the plant. Some of the parameters are fixed and independent of plant design, e.g. site and irradiation data. Variable parameters are optimized simultaneously by the evolutionary algorithm with respect to the objective function. The variables depend on the optimization requirements; an example for a variable parameter is the solar field (SF) size.

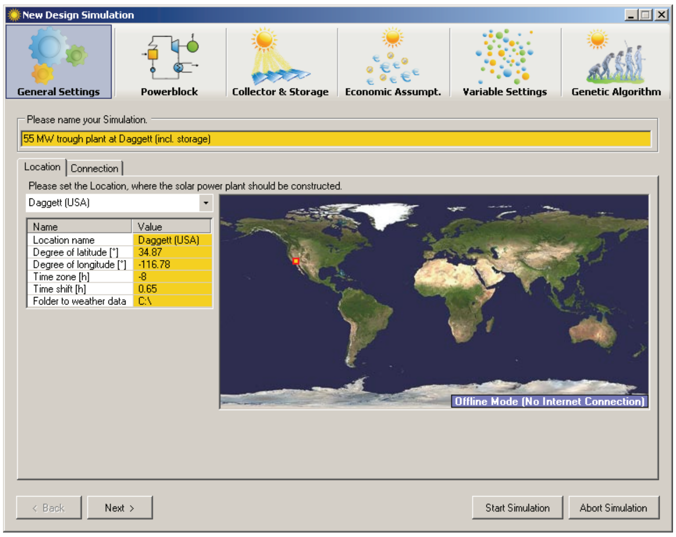
All these assumptions are used to calculate the energy yield for a representative time period (e.g. a year), based on hourly values. As opposed to conventional power plants, the permanently changing sun position and solar irradiation level require detailed energy yield calculations. Based on the economic assumptions, mean (e.g. annual) cost will be calculated.

Both technical and economic simulation results are combined in an objective function, e.g. the levelized cost of electricity (LCOE), which indicates the economic quality of the system layout. Other objective functions may be defined if suitable or necessary.

A multi-parameter optimization method is then used to optimize the relevant plant parameters with respect to the objective function. The optimizer has to be capable to solve steady parameters (e.g. live steam temperature or live steam pressure) but also the structure of the plant, e.g. different process designs with different number and arrangement of feed-water heaters and reheat section (0/1/2 reheat sections).

This model is implemented in software using the following tools. The power block is simulated using the software Thermoflex/PEACE by the company Thermoflow (thermodynamic and cost simulation) [1]. All other software modules describing the economic and energetic models of the power plant and its components are developed by Fraunhofer ISE [2]. The evolutionary algorithm *GAlib* by *M.I.T* [3] was used for the optimization. The detailed optimizer settings used for the results shown here, are described in [2].

The software OPTISIM, that integrates all these software modules in one integrated tool, including a Graphical User Interface (GUI), was developed in [4], see Figure 2. Beyond the scope of this paper, OPTISIM allows also for simultaneous multi-process optimization of the power block, such as number of feed-water heaters or number of reheat sections. Furthermore, OPTISIM includes an option to use neural networks for power block simulation in order to reduce the numerous time-consuming thermodynamic off-design calculations of the power block [4].



Please name your Simulation.

55 MW trough plant at Daggett (incl. storage)

Please set the Location, where the solar power plant should be constructed.

Daggett (USA)

Name	Value
Location name	Daggett (USA)
Degree of latitude [°]	34.87
Degree of longitude [°]	-116.78
Time zone [h]	-8
Time shift [h]	0.65
Folder to weather data	C:\

Figure 2: Graphical User Interface of the software OPTISIM for integrated simulation and optimization of CSP plant designs

3. Definition of Case Study – 50 MW parabolic trough power plant using thermal storage

In this paper, the optimization approach is applied exemplarily to a 50 $\mathrm{MW}_{\mathrm{el,net}}$ parabolic trough power plant using thermal oil as heat transfer fluid (HTF), a molten salt thermal storage and an air-cooled condenser at a site in the Californian Mojave desert. Eight design variables were simultaneously optimized with respect to the levelized cost of electricity (LCOE) as objective function. The optimized variables were:

1. solar field (SF) size in terms of cumulated mirror aperture [m^2]
2. distance between parallel collector rows [m]
3. storage size [tons of salt]
4. solar field outlet temperature [°C]
5. terminal temperature difference of oil-to-steam heat exchanger [K]
6. live steam pressure [bar]
7. reheat pressure [bar], affecting also the final feed-water temperature by setting equal temperature rise in each feed-water heater
8. Design ambient temperature [°C] for power block (at given design condenser pressure).

The models and assumptions which were used as well as their sources are in detail described in [2]. The following graph (process diagram) and the following two tables give a summary of the used assumptions.

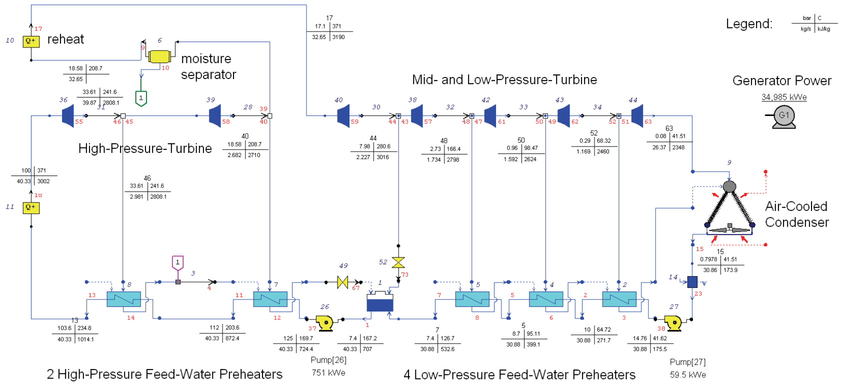


Figure 3: Process design of the reference power block as of [5], but subsequently scaled to 55 $\mathrm{MW}_{\mathrm{elgross}}$. Power block variables were: design ambient temperature (design condenser pressure 0.08 bar), live steam pressure, live steam temperature (via upper HTF temperature) and reheat pressure

Table 1: Main Technical Assumptions

General Plant Characteristics	**Value / Magnitude**
Site / DNI	Daggett, CA (USA) 2791 kWh/(m2a)
Nominal gross electrical output	55.0 MW
Nominal gross efficiency of the power block	depending on process parameters, 37.6 $\text{MW}_{\text{el}}/\text{MW}_{\text{th}}$ for reference design in Fig.3
Solar Field Properties	
Collector type	Skal-ET
Aperture width per collector	5.77 m
Optical efficiency relative to DNI on mirror aperture	75.0%
Average cleanliness / field availability	0.97% / 99%
HTF temperature at inlet	depending on live steam pressure, pinch point and HTF outlet temperature
Receiver thermal losses	new Schott-PTR70 (2008)
HTF pressure drop in solar field	depending on solar field size and mass flow, according to [6]
Specific thermal losses of field piping	depending on SF temperature (10 W/m^2 at 340°C)
Auxiliary Power Consumption	
Auxiliary power consumption of Solar Field	depending on HTF pressure drop and HTF mass flow (resp. HTF temperature rise)
Auxiliary power of storage	0.003 $\text{MW}_{\text{el}}/\text{MW}_{\text{th}}$
Auxiliary power consumption of Power Block	depending on power block design (optimized ACC part load operation)

Table 2: Main Economic Assumptions

Investment Cost	**Value / Magnitude**
Specific costs of the collector (incl. HTF and HTF heat exchanger)	260 €/$\text{m}^2_{\text{aperture}}$
Specific header piping cost	1000 €/m_{header}
Specific investment of storage system (incl. heat exchangers)	depending on size, for reference design of 28.5kt: 1009 €/t
Specific investment of power block	depending on design, for the reference design - 800 €/$\text{kW}_{\text{el,gross}}$
Specific land costs (land and site preparation)	7 €/m^2
Surcharge for engineering, EPC, project management and risk	20%
Annual insurance costs relative to total invest	1%
Useful life and amortization period	30 years
Interest rate	8%
Operation and maintenance	
Annual costs per employee	48000 €/a
Total no. of employees excl. solar field	30
Specific no. of employees for solar field	0.030·1/1000m^2
Specific water consumption	295 $\text{l/MWh}_{\text{el,net}}$
Annual replacement costs (as % of investment costs)	1%
Total plant availability	0.96

4. Results and Discussion

Starting from a power plant design similar to the Andasol-1 plant in Spain but transferred to the Californian site, the LCOE could be reduced by 6.0%, only by changing plant design parameters of solar field, storage and power block, see Table 3.

Table 3: Variable values for the starting configuration (incl. references) and resulting optimal configuration for the Southern Californian site Daggett [t m² = thousand m², t tons = thousand tons]

LCOE or variable	Optimization Spectrum	Reference design incl. reference	Optimal design
LCOE (result)		14.33 €ct/kWh	13.47 €ct/kWh
1 Cumulated collector aperture area	100 – 2000 t m^2	510 t m^2	559 t m^2
2 Distance between collector loops	8.66 – 40.39 m	17.3 m	21.9 m
3 Storage size	0 – 50 t tons	28.5 t tons	33.3 t tons
4 Upper solar field temperature (oil)	340 – 393°C	391°C	392.9°C
5 Temperature difference hot oil to hot steam	2 – 30 K	20 K	2.2 K
6 Live steam pressure	65 – 150 bar	100 bar	98.7 bar
7 Reheat pressure	5 – 30 bar	17.1 bar	10.6 bar
8 Design temperature (ACC press. 0.08 bar)	10 – 38°C	30°C	24.1°C

4.1 Reliability Assessment of Stochastic Optimization

Against the background that an evolutionary algorithm is a stochastic optimization process, it is shown by several optimization runs that the optimization algorithm works very reliably to solve the optimization task. The LCOE-levels that were achieved in three subsequent optimization runs differ by less than 0.02% (Figure 4).

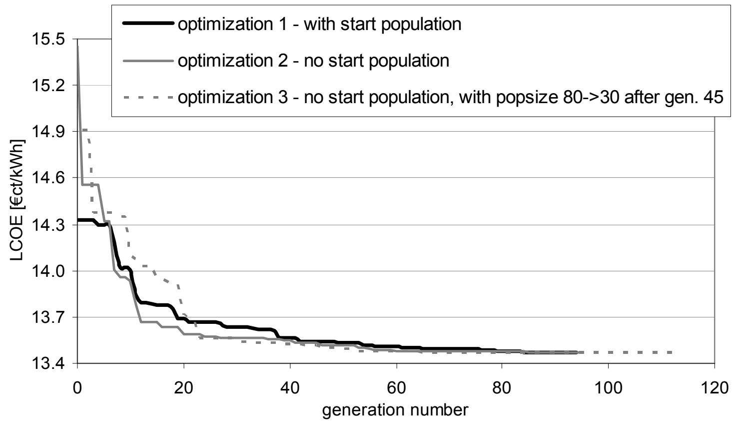


Figure 4: left: LCOE-decrease in the course of the optimization for three different optimization runs with different start parameters / side restrictions; every time the same (lowest) LCOE was reached.

Beyond repeating optimization runs, sensitivity calculations for all eight variables confirmed that the found optimum is (at least) a local optimum.

Beyond this, mutual influences of the sub-systems with respect to energetic and cost effects were assessed, with the help of the sensitivity analyses. In the past years, many publications have addressed the optimization of the solar block variables such as the size of solar field and storage. New in this approach is the integration of the power block into integral plant optimization. Therefore, the focus of result presentation is set on optimizing power-block-related design variables.

4.1 Optimizing the Power Block Design Ambient Temperature

For the design point of the power block, the condenser pressure is assumed 0.08 bar which corresponds to a condensing temperature of 41.5°C. Optimizing the design ambient temperature for the power block hence means optimizing the exergetic efficiency of the condenser: The larger the condenser, the higher is the net plant efficiency but also the cost of the condenser and consequently the cost of the total power plant.

Figure 5 shows the influence of the design ambient temperature on LCOE and on the two constituents of the fractional LCOE value: the net plant output $E_{el,net}$ and the levelized annual plant cost (LAC) – which includes levelized investment cost and running costs – , starting from the optimized design in Table 3.

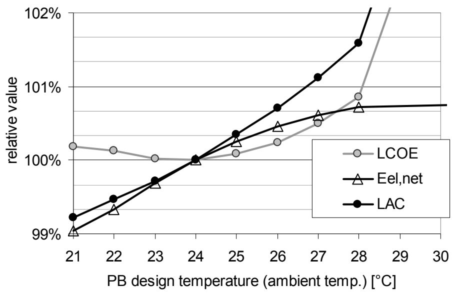


Figure 5:Power block design temperature (design condenser pressure 0.08 bar) – influence on net electricity generation $E_{el,net}$, total plant cost (LAC) and LCOE (LCOE is proportional to LAC/ $E_{el,net}$)

The LCOE becomes minimal where both net plant output ($E_{el,net}$) and levelized annual plant cost (LAC) have the same gradient, given that LAC is a concave function and $E_{el,net}$ a convex function near the LCOE optimum. The steep gradient of plant cost (LAC) and LCOE above the design temperature of 28°C results from the dramatically increasing condenser cost, accounting for more than 50% of the total power block components' cost at a design temperature of 30°C.

For the optimal design temperature which is 24.1°C – under the given (weather) conditions – the terminal temperature difference of the condenser is 17.4 K (= 41.5°C – 24.1°C).

Beyond reduced investment, a reduced condenser size results in reduced auxiliary power consumption for the power block (condenser fans).

In analogy to the condenser design optimization, the solar field size, the storage size and the distance between the collector rows are a trade-off of increased net electric output for larger values of each of the variables and corresponding higher cost on the other hand.

4.2 Optimal Upper Solar Field Temperature

Looking at the results of Table 3, it is obvious that an increase of temperature up to the assumed limit of 393°C is beneficial. The upper temperature limit was chosen according to material stability restrictions for the used thermal oil [7]. Disregarding material stability issues, an interesting question is up to what temperature this LCOE trend can be extrapolated until the heat loss in the collector compensates gains from further temperature increase. This can give first indications for the optimal operation temperatures when using other heat transfer fluids such as molten salt or direct steam generation (however, for more detailed indications, other factors like e.g. pumping parasitics should be adapted to the other HTF types as well).

Figure 6, left, shows the influence of the SF operating temperature on energy production and LCOE. Starting point was, again, the optimized design of Table 3.

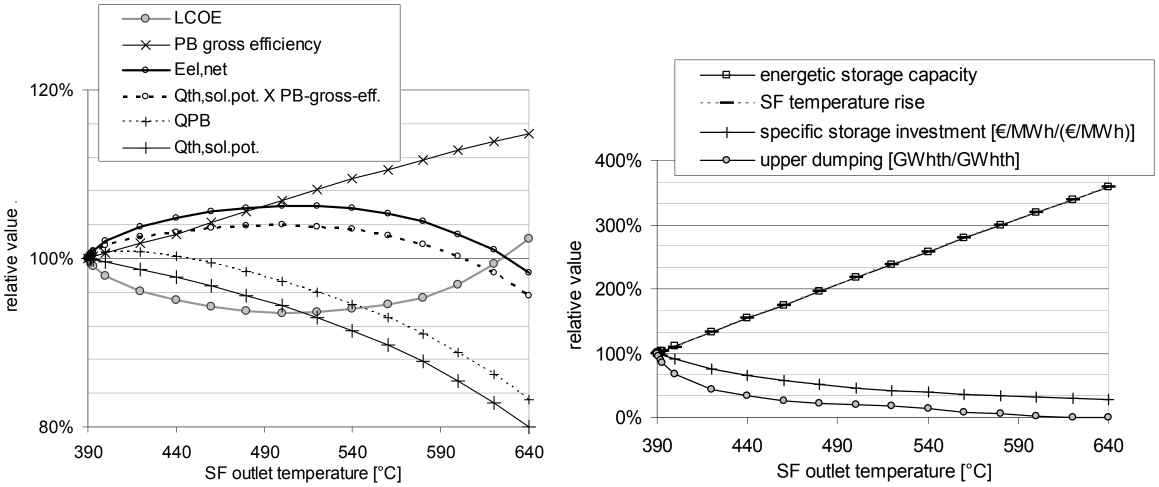


Figure 6: left: Influence of upper HTF temperature (at SF outlet) on annual efficiencies and LCOE; right: Relative change of storage-related parameters by increasing the upper solar field temperature (constant mass of storage medium). For definition of terms, see text.

For better visual comparability, 390°C instead of 393°C was chosen as the reference temperature in Figure 6, left. Both LCOE and net plant efficiency (in this context equivalent to $E_{el,net}$) show their optimum for 500°C upper fluid temperature. Whereas power block efficiency increases in the assessed temperature range up to 640°C, the efficiency of the collector (equivalent to $Q_{th,sol.pot.}$) decreases progressively because radiative thermal losses become significant for high temperatures. When looking at the two dotted functions, it is apparent that not only collector and power block influence the optimal operation temperature: The difference between the collector efficiency (equivalent to $Q_{th,sol.pot.}$) and energy used in the power block (Q_{PB}) is attributed to the storage. Storage to some extent compensates the collector efficiency decrease because its energetic capacity increases (physical storage size assumed constant). The leverage effect of storage in favor of higher temperatures can also be noted when comparing $E_{el,net}$ and the product of collector efficiency and power block efficiency (dotted line with "+" in Figure 6, left), the latter corresponding to the gross electricity production of a PTC plant without storage. For both, the optimum is 500°C, but the storage configuration benefits more from higher temperature. Increasing the upper solar field temperature from 390°C to 500°C will lead to an LCOE-improvement of 6.3% (with storage). Without storage, this benefit is only 4.0%.

The effect of increased solar field outlet temperature on storage is assessed in Figure 6, right.

Assuming the same fixed storage size in tons of storage medium, the energetic storage capacity increases linearly with the upper solar field temperature because a higher ΔT between hot and cold storage medium increases energetic storage capacity. Storage temperatures scale directly with solar field temperature. The increase in energetic storage capacity also implies reduced storage invest in €/MWh and reduced dumping of solar thermal energy due to full storage from initially 4.2% for 390°C down to 0% for hypothetic HTF temperatures above 600°C.

The calculated optimal temperature of 500°C will be lower:

- for sites with lower DNI because relative heat loss will be higher
- for higher receiver heat loss than assumed, e.g. with part of the receivers being degraded or with other (e.g. older) receiver technologies showing higher heat loss.
- for plants without storage.

To summarize, in a temperature range where costs can be assumed independent of temperature, the optimal operation temperature is an efficiency optimization problem between power block efficiency and solar field efficiency. Other factors that show an influence on optimal operation temperature are energetic storage capacity and solar field parasitics.

5. Conclusions and Outlook

The main result of this integrated design assessment is that most power-block-related design variables, such as upper process temperature, live steam pressure, reheat pressure and terminal temperature difference of oil-to-steam heat exchanger induce changes of the temperature rise in the solar field (The last-mentioned variables are not discussed here, but in [2].). High SF temperature rise reduces mass flow in the solar field and thereby reduces over-proportionally auxiliary power consumption for HTF pumping. Furthermore, high solar field temperature rise increases energetic storage capacity by higher temperature difference between hot and cold tank of the storage medium. In contrast, the effect of varying solar field inlet and outlet temperatures on heat loss is only minor within the temperature range of 340°C – 393°C (upper SF temperature). The effects which are induced by the SF inlet and outlet temperatures can reinforce or completely outweigh power block efficiency effects.

This integrated approach can discover optimization potential by simultaneously considering inter-dependencies of the sub-systems. Such optimization potential remains un-revealed when the sub-systems are optimized sequentially. Furthermore, time-consuming engineering efforts during the conceptual design phase of a plant can significantly be reduced by such an integrated approach. The presented optimization approach has been demonstrated using a specific set of tools, one specific plant model and one specific set of cost and performance assumptions. Today, many different tools are in use for the simulation of solar thermal power plants. The presented multi-variable optimization method in combination with a detailed techno-economic plant model – including power block simulation – can in principle be transferred to any kind of optimization task, to any plant model, and even to other simulation tools.

6. Acknowledgement

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