CHAPTER III

RESEARCH METHODOLOGY

The research methodology used in this thesis is divided into several stages. The first part consists of analysis and gathering of existing information regarding economical studies on solar thermal power plants. As these studies are made for large scale systems only, they can just be used as a guideline. Suitable factors need to be identified and defined for its particular purpose.

The second part of the study is developing an economical model for small scale solar thermal power plants with use of the defined factors and useful parameters. More general models used for the large scale systems are modified and impact zones for small scale stations are clearly defined. Necessary parameters need to be discussed and checked on its suitability for a model. The difference between large and small scale needs to be explained and assumptions need to be defined.

The third part is showing proofs of the economical model by analysing real projects under use of the developed economical model. The factors of the economical model are validated in comparism with real projects. This will allow to research the suitability of the model.

The result is a useful model to analyse planned project for small scale solar thermal power plants. A small number of criteria integrated into the model will allow to check the suitability of the technology for a planned site and give a rough estimate. The analysis can be done as a quick check for solar specialists and non-specialists like financers and investors. A defined factor catalogue will allow a sensitivity analysis, showing the possible economical range of the project. The model may not allow to prevent from detailed engineering and consultancy works, but it will be allow to give an assumption for a project and its suitability. The model will also show significance factors for different criteria of a solar thermal power plant project. These factors may differ, depending on the way we look at them. From a macro economical or even philosophic point of view the factors and the suitability are different then from purely techno-economic points of view. While an economical analysis is using global systematic factors, which are smooth and imprecise, the technical model is precise and does not allow irritations.

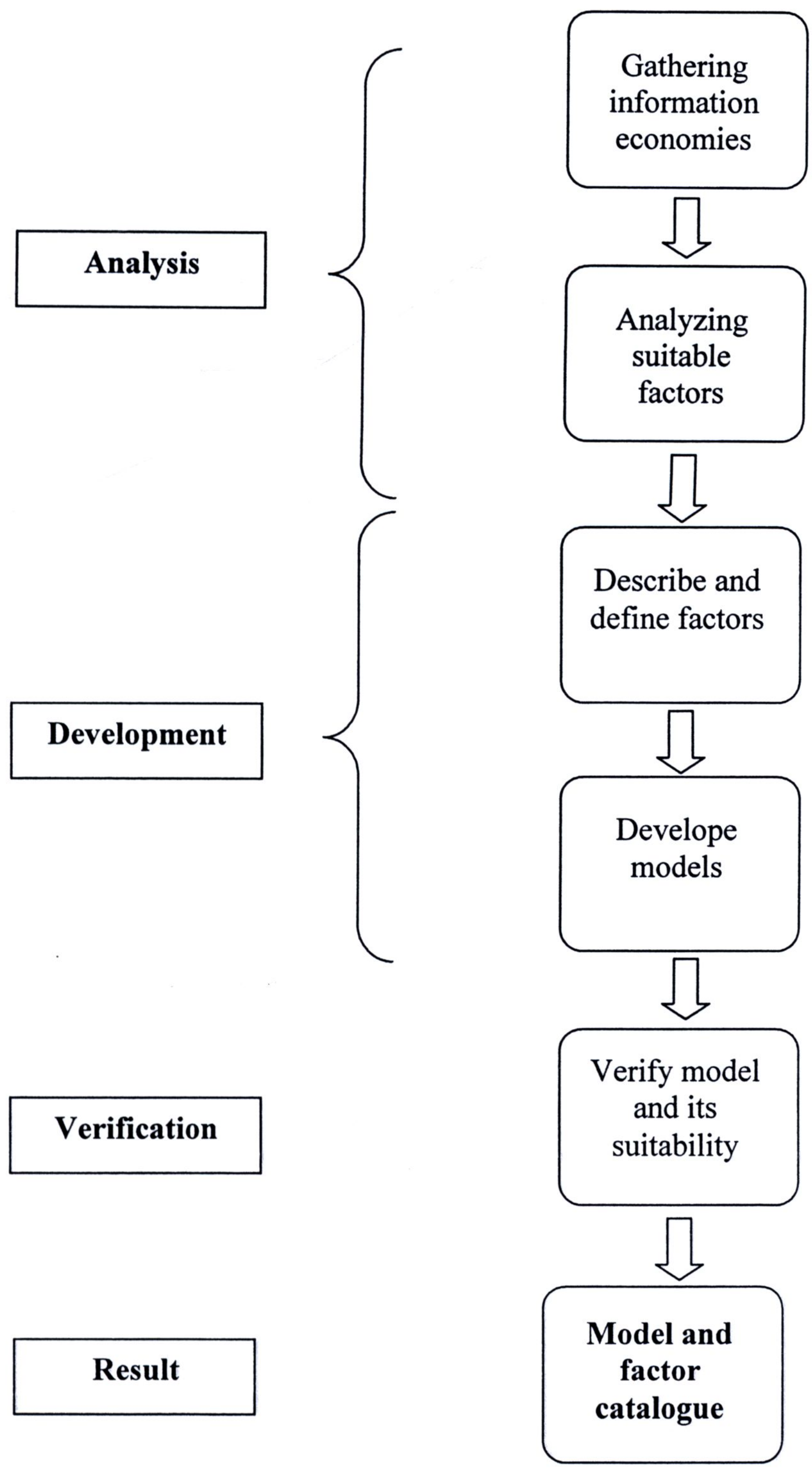


Figure 16 Flow chart Methodology to develop economical model

Both models are necessary to find out the suitability of a solar power plant at its specific site. The technical model will look at factors like: technical characteristics of the materials, turbine efficiency, electricity consumption, start up times, cooling issues, maintenance, etc. While the economical model looks at climate, investment, technical characters (as a result out of the previous model) and public impacts. Public impacts are factors like laws, feed-in tariffs, taxes/duties and models of financing. This work is focussing on the socio-economic model as an instrument to analyse a project before going into necessary detailed engineering.

All these criteria will be discussed and a factor will be developed, which then can be integrated into the models equasion. A discussion will allow to follow the percentages given to the criteria to permit to give a factor. As the models will follow a certain logic, this discussion needs to be carried out and will remain open for further discussion and new technical impacts. New technical developments as well as political changes may result in a change of the factors used in the models.

Equation Models

The economical model consists of the following criteria (CL, I, TC, PI) each multiplied with a factor (w, x, y z) and show the result as attractiveness for solar installations:

SOLAR A = CL (* w) + I (* x) + TC (*y) + PI (* z)

[Solar attractiveness = climate investment technical character public impacts]

Detailed information like radiation or concentrating factor or other technical specifications of a single technology have to be integrated into the factors. As the model is giving an answer to the general question of the suitability no detail engineering is required. The factors and criteria itself are resulting from previous analyses, made since the late eighties. They were heading for detailed cost analyses not for models, but they may help in validating the criteria and factors.

To be precise and to allow the existing experiences find their way into the models, a range must be defined for each factor. As we know that efficiencies, reliability and other outer impacts like climate and public issues, have different quantities and qualities, differencing must be possible. Also special advantages like the possibility to combine solar thermal with biomass or other steam producing facilities need to be expressed in a range, as well as the possibility to store thermal heat, which is more easy in CSP than in PV systems, which need battery systems only.

Existing Cost Analysing Models

Although most of the existing analyses were carried out to determine the lowest levelized cost of electricity (LCOE) based on increasing plant capacities, no study have been performed to analyse the potential to achieve a reasonable LCOE for smaller and medium capacity plants. This paper is aimed to describe the potential LCOE achievable considering the current technological and economical conditions for both medium and larger scale capacity plants likely.

Among several LCOE models, the models from the following Institutions/Governmental Agencies are most widely used and hence will be presented and discussed in this report

1. International Energy Agency (IEA)
2. National Renewable Energy Laboratories (NREL)
3. European Concentrated Solar Thermal Road-Mapping (ECOSTAR (IEA))

Throughout the report, stand alone Solar Thermal Power Plants (STPP) will only be given importance. The sensitivity of the model will be checked throughout the examples and proves, which are mainly driven by deductive conclusions as the small scale power plants or need operated on long term basis yet. This logical verification will be based on commonly acceptable assumptions.

All exisiting models are based on large scale CSP systems and focus on LCOE. This model is the first of its kind to show the general suitability of CSP and especially the positive aspects for small scale CSP – no comparable works have been done before.

IEA model for calculating LCOE

The methodology employed in the calculation of the levelized electricity costs is based on the procedures outlined in the International Energy Agency (IEA) guidelines [5]. The methodology has been developed explicitly to address the challenges posed in attempting to assess the economic feasibility of renewable energy technologies, which unlike conventional energy sources, do not have decades of experience.

Economic Assumptions

A 25-year assumed plant life is typically used in the power plant industry. Because of the relatively high discount rate, assuming a longer plant life has little impact on the LCOE. The SEGS plants in southern California have been operating for up to 15 years with little or no indication that they would not last 25 years according to a World Bank study from 1999.

Most studies of STPP have used a discount rate of 8% and this value was adopted for World Bank report. The World Bank however, typically uses a 10 to 12% discount rate in assessing projects in developing countries. Although this rate is high by developed world standards, it reflects the high opportunity cost for other investments in these countries.

$$LCOE_{plant} = \frac{(FCR \cdot I) + OM + L - C}{E}$$

Where:

FCR = fixed charge rate

I = Installed capital costs

OM = Annual operation and maintenance costs in year zero

L = Annual expenses for input energy

C = Annual CO2 reduction credit

E = Annual energy production (Wh)

$$FCR = \sum_{t=1}^{n} \frac{1}{(1+K_d)^t} + pl$$

Where:

n = Lifetime of the plant (years)

k_d= discount rate

pl = insurance rate

Among the several cases analysed with this model, the most appropriate model similar to the SEGS 30 MWe design except the back-up burner is presented below. This case includes no thermal energy storage and back-up or optional burners.

The LCOE was calculated as 14.85 \$cents/kWh$_e$. The World Bank concluded that at the current state of technology development, the cost of solar-generated electricity is between 10 and 15 cents per kWh (at a 10% discount rate). This is 1.5 to four times more expensive than power from conventional power plants.

Economic analysis:	5	30 MW	Trough	ISCCS
Net capacity	30 MW	Solar field	n/a	m^2
Solar capacity	30 MW	Fuel type	Gas	
Summary of base case parameters				
Project cost w/o tax ('000 USD) *	78,872	Expected lifetime	25	years
Grant for non-conventional fraction	-	Annual discount rate	10.0%	
Carbon credit ('000 USD)	-	Annual insurance rate	1.0%	
Fuel price (USD per GJ)	2.63	Fixed charge rate	12.02%	
Unit cost (USD/kW)	2,629	CO_2 credits	-	USD/tonne
Efficiencies				
Heat collection efficiency	44.2%	Annual solar efficiency		13.7%
Power cycle efficiency	38.0%	Plant capacity		26.0%
Parasitic efficiency	90.2%	Solar capacity		26.0%
Solar-to-electric net efficiency	15.1%	Plant efficiency (Back-up Mode)		53.5%
Levelised Electricity Cost calculations				
Net electricity by solar			68,328	MWhe/yr
Net electricity by fuel			-	MWhe/yr
Net electricity to grid			68,328	MWhe/yr
Solar share			100.0%	
Full load hours - total			2,278	h/yr
Full load hours - solar			2,278	h/yr
Annual fuel use			-	GJ/yr
Annual fuel cost			-	'000 USD
Annual O&M cost			668	'000 USD

Levelised Electricity Cost (entire plant)		**148.49**	**USD/MWh**
Capital cost fraction		138.71	USD/MWh
Fuel cost fraction		-	USD/MWh
O&M cost fraction		9.78	USD/MWh
Solar LEC calculations			
LEC for base case plant of equivalent power; type:	Combined Cycle	N/A	USD/MWh
Capital cost fraction		N/A	USD/MWh
Fuel cost fraction		N/A	USD/MWh
O&M cost fraction		N/A	USD/MWh
LEC (solar only component)		**148.49**	**USD/MWh**

Figure 17 Results for a 30 MWe solar only STPP with no hybrid or storage systems

NREL cost model

NREL has developed a spreadsheet-based parabolic trough performance and economics model [1, 2]. The model has been developed in Microsoft Excel® spreadsheet program. The spreadsheet is used for data input and output. The model uses the Visual Basic for Applications language built into Excel for programming the hourly performance simulation. One of the advantages to this approach is that users do not require special software to use the program.

A key feature of the NREL model is that capital cost, operation and maintenance (O&M) cost, and financial calculations have been added directly to the model, which allows the plant design configurations to be more easily optimized. The model performs a time-step performance simulation based on plant design and a user-supplied operating strategy. The parabolic trough solar technology is modelled using the methodology developed by Stine and Harrigan [6]. The model is capable of modelling a Rankine-cycle parabolic trough plant, with or without thermal storage, and with or without fossil-fuel backup.

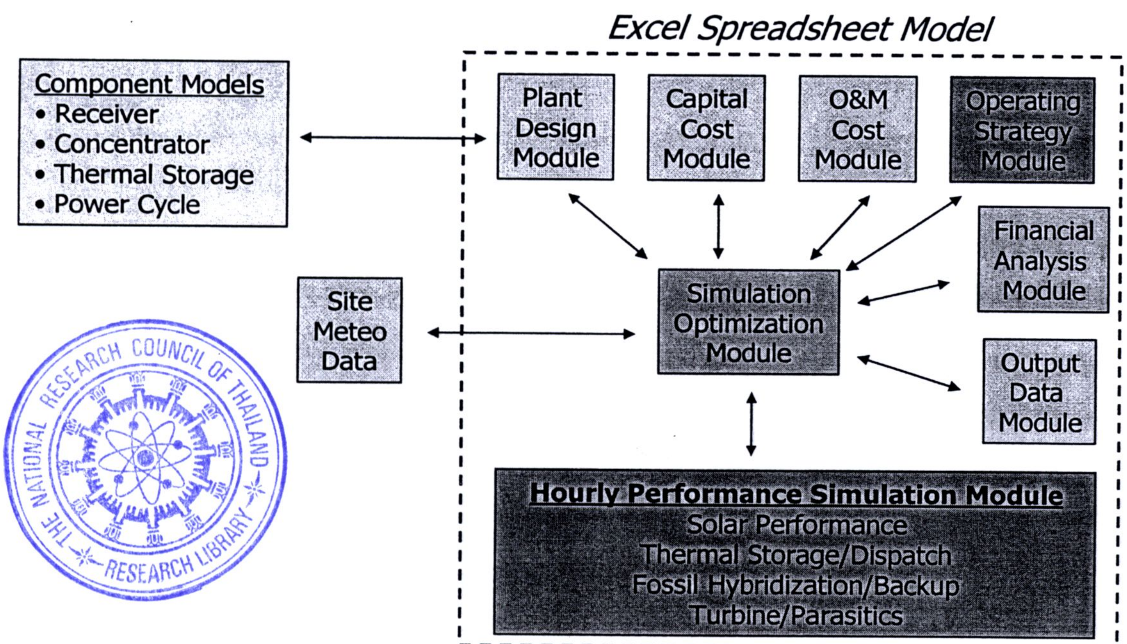


Figure 18 Integrated Performance Model of NREL

Source: Price, Hank, 2003

The performance module has been validated against the actual performance at the SEGS plants. For this study, the model predicted the annual gross solar-to-electric performance of SEGS VI during 1999 within 1% when using actual solar field availabilities, collector receiver conditions, mirror reflectivity and site solar radiation data. The capital cost module is in part based on detailed cost data from Flabeg Solar International [8]. The O&M cost module is based in part on data from KJC Operating Company. The project finance module is a 30-year cash flow model for evaluating independent power producer (IPP) power plant projects. The results presented in the below figure presents the LCOE for the SEGS VI plant taking into account with or without the natural gas backup burner. When analysed carefully, a difference in the energy conversion efficiency is observed that is due to the decreased part load operation hours during clouds weather. Although 0.1% increase does not represent a huge improvement, the fact that the Mojave desert has less disturbance due to clouds leads to the conclusion that hybrid systems are more meaningful in moderately sunny regions with higher cloud presence.

Site: Kramer Junction	**Solar Only**	**Hybrid (25%)**
Plant size, net electric (Mwe)	30	30
Collector aperture Area (km^2)	0.188	0.188
Thermal storage (hours)	0	0
Solar-to-electric efficiency (%)	10.6%	10.7%
Plant Capacity factor (%)	22.2%	30.4%
Capital cost ($/kWe)	3,008	3,204
O&M cost ($/kWh)	0.046	0.034
Fuel cost ($/kWh)	0.000	0.013
LCOE [2002$/kWh]	0.170	0.141

Figure 19 Reference 30 MWe SEGS Plant

The following figure shows the LCOE of a near term 50 MWe plant with improved solar field components (lower specific capital cost and better conversion efficiencies) and better O&M techniques.

Site: Kramer Junction	**Solar Only**	**Hybrid (25%)**
Plant size, net electric (MWe)	50	50
Collector aperture area (km^2)	0.312	0.312
Thermal storage (hours)	0	0
Solar-to-electric efficiency (%)	13.9%	14.1%
Plant capacity factor (%)	29.2%	39.6%
Capital cost ($/kWe)	2,745	2,939
O&M cost ($/kWh)	0.024	0.018
Fuel cost ($/kWh)	0.000	0.010
LCOE (2002$/kWh)	0.110	0.096

Figure 20 Near-Term 50 MWe trough Plant

Similar to the previous model, this model also describes the reduction in LCOE costs for the future STPP through

1. scale-up in individual plant MW capacity
2. integration with combined cycle plants
3. improved solar field components
4. increased deployment rates,
5. use of thermal energy storage, and
6. advancements in O&M methods

One of the primary opportunities for reducing cost is to increase the size of the power plant. In General, power plant equipment costs ($/kWe) decrease with the size of the plant. O&M costs also reduce with plant capacity because it typically takes a power plant O&M crew of about the same size to run a 30-MWe steam plant as it would to run a 200-MWe steam plant. Luz planning also included consideration of larger plant sizes in the 150 to 200 MWe range [11]. The upper limit is defined by a trade-off between economies of scale and the parasitic involved with the pumping of heat transfer fluid through the solar field. By replacing flexible hoses with ball-joint assemblies, sizes of 400 MWe or more are feasible because of the much lower pumping parasitic since the major solar system pressure losses are found in the solar collector loops, not in the main headers.

The following figure shows the impact on the cost of energy for different size power plants. It should also be noted that many of the advantages achieved in scaling up a plant can also be achieved by sitting multiple plants together in a power park.

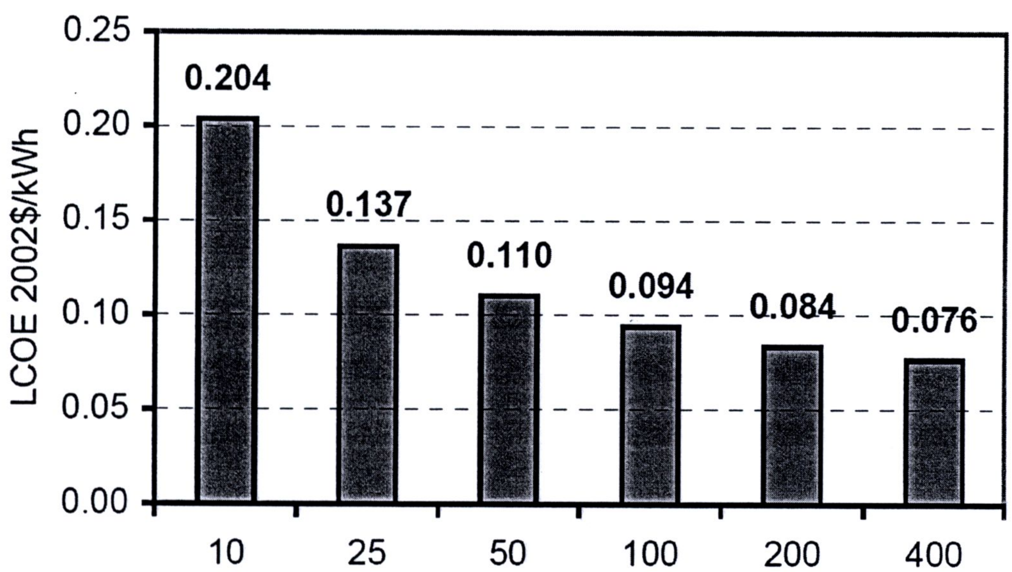


Figure 21 Impact of plant size on cost of electricity

Source: Price Henry Kearney David, 2003; Price Hank, 2003

The following figure shows the cost of energy from the 50-MWe plant with difference amounts of thermal storage [1]. Small amounts of thermal storage, up to 6 hours of full power output, result in an increase in the cost of energy, while storage capacities between 6 and 16 hours lower the cost of energy. It should be noted that small capacities might still be warranted by virtue of revenue considerations because they would allow the plant to dispatch solar power during the time of day with the highest electricity rates. Note that the lowest cost of energy occurs with approximately 12 hours of thermal energy storage (TES). Increasing TES beyond 12 hours results in increased dumping of energy during the summer when the plant would already be operating 24 hours a day.

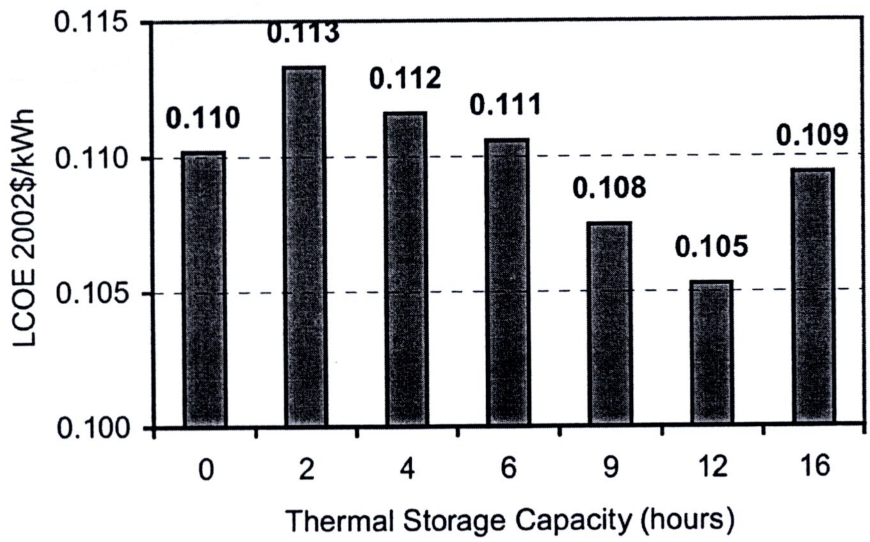


Figure 22 Effect of thermal storage on cost of energy

Source: Price Henry Kearney David, 2003; Price Hank, 2003

Apart from the above presented issues, the cost of energy can also be reduced through lower cost financing and through taxation or investment incentives. The United States and European parabolic trough industries have developed proprietary plans for lowering costs in future trough power plants. The evaluation performed in different studies provides a cost estimate that generally agrees with industry expectations for R&D advances in component and subsystem improvements.

Ecostart

The Sixth Framework Programme (FP6) project ECOSTAR has drawn up a roadmap for making solar electricity competitive, citing research results indicating that the cost of creating power in this way can be reduced from the current 15 to 20 cent/kWh to between 5 and 7 cent/kWh. The ECOSTAR project, coordinated by the German Aerospace Centre (DLR), and bringing together partners from France, Israel, Russia, Spain and Switzerland, assessed how costs could be brought down in order to make solar electricity a viable alternative to traditional energy technologies.

The methodology for the cost study is depicted in the following Figures. The essential figure of merit is the levelized cost of electricity (LCOE) which is calculated according to a simplified IEA Method [5] using current euro (see the grey box next page, where the common assumptions for the financial parameters are listed). The goal of this study is the comparison of different technical innovations, therefore any project specific data (e.g. tax influences, or financing conditions) are neglected. The approach is kept simple, but it appears to be appropriate to perform the relative comparison necessary to quantify the impact of different innovations.

For each reference system a detailed performance and cost model has been established in Microsoft Excel. The model uses common assumptions for a site in Sevilla - Spain , with a DNI of 2014 kWh/m^2a, an average temperature of 19,5 °C, Min = 4,1 °C, Max = 41,4 °C and a load curve, which is assumed with a free-load operation or in hybrid operation with 100% load between 9:00 a.m. and 11:00 p.m. every day and an average availability of 96% to account for forced and scheduled outages resulting in a capacity factor of 55%.

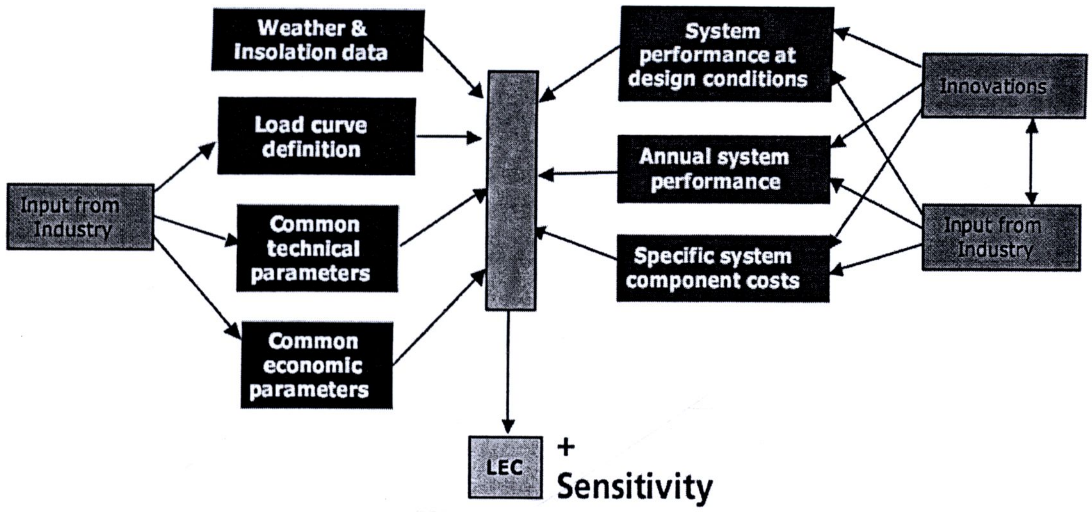


Figure 23 LEC and sensitivity analysis

Source: Pitz-Paal, Robert,Dersch, Jürgen, Milow, Barbara, 2005

Definition of "Levelized Electricity Costs" (LEC)

$$LEC = \frac{crf \cdot K_{invest} + K_{O\&M} + K_{fuel}}{E_{net}}$$

with

$crf = \dfrac{k_d(1+k_d)^n}{(1+k_d)^n - 1} + k_{insurance} = 9{,}88\%$ — k_d real debt interest rate = 8%

$k_{insurance}$ annual insurance rate = 1% — n depreciation period in years = 30 years

K_{invest} total investment of the plant — $K_{O\&M}$ annual operation and maintenance costs

K_{Fuel} annual fuel costs — E_{net} annual net electricity

Figure 24 Methodology for the cost studies

Source: Pitz-Paal, Robert,Dersch, Jürgen, Milow, Barbara, 2005

The abbreviation “LEC” used by ECOSTART is comparable to “LCOE”, but LCOE is more common and defined anyhow in each calculation by its author with an explanation of the assumptions.

It calculates the annual electricity production hour by hour, taking into account the instant solar radiation, load curve, part load performance of all components (depending on load fraction and ambient temperature),
operation of thermal energy storage, and parasitic energy requirements. The reference size of all systems is assumed to be 50 MW_e net.

The following figure represents the result for the two main technologies trough and tower.

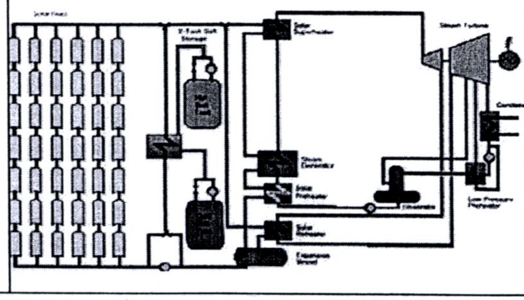
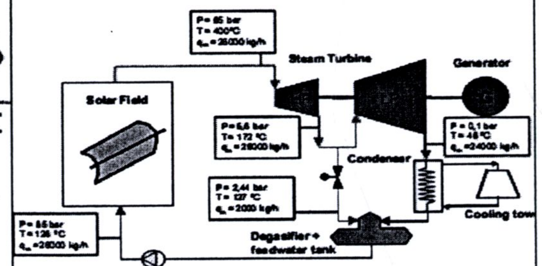
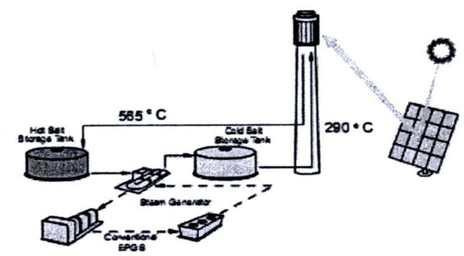
Technology	Parabolic trough / HTF	Parabolic trough DSG[4]	Molten salt Central receiver system
			
Technical design parameter:			
Collector	Parabolic trough	Parabolic trough	Heliostat field
Receiver	Linear receiver (tubes)	Linear receiver (tubes)	Molten salt receiver
Storage system	2-tank-molten-salt storage	No storage system available up to date	2-tank-molten-salt storage
Cycle	Rankine steam cycle	Rankine steam cycle	Rankine cycle
Planed / built power size			
	50 MW Andasol I & II, under preparation, Spain	4.7 MW INDITEP study	Solar Tres (17MW), planed, Spain
Maturity	Several commercial units up to 80 MW_e are in operation in southern USA	Single row experimental plant in Spain	Solar 2 (11 MW) experimental plant in California in the 1990ies
Temperature	393°C	411°C	565°C
Size of the reference system	50 MW_e	10 × 4.7 MW_e	3 × 17 MW_e
Solar capacity factor	29 %	22 %	33 %
LEC for a single ECOSTAR reference system, solar-only			
	0.172 €/kWh_e	0.187 €/kWh_e	0.183 €/kWh_e
LEC for power plant park consisting of several reference systems with total capacity of 50 MW, solar-only			
	0.172 €/kWh_e	0.162 €/kWh_e	0.155 €/kWh_e

Figure 25 Comparison between electricity costs for the major CSP technologies

As a further step, thermal oil HTF and DSG systems are considered as separate systems to evaluate the advantage of DSG. The higher LCOE refers to the single INDITEP DSG plant in comparison with the 50 MWe thermal oil plant. But when deployed as a power park, the LCOE for the DSG system is 6% less than the thermal oil plant. These results indicate the DSG based trough systems have a high cost reduction potential especially when operated up to 550 °C steam temperatures.

Economics of concentrating solar power

Apart from the above models, Sargent & Lundy study [7], German Aerospace Center (DLR) [12] and SolarPACES [] cost projections also helps the reader to have good insight into the current and future LCOE costs for CSP technologies therein especially for trough technologies.

S&L estimated a cost reduction of 14 % from larger power blocks (400 MW) and 17% by volume production effects when installing 600 MW per year. Assuming similar figures also for the other technologies, an overall cost reduction of 55 – 65% can be estimated in the next 15 years.

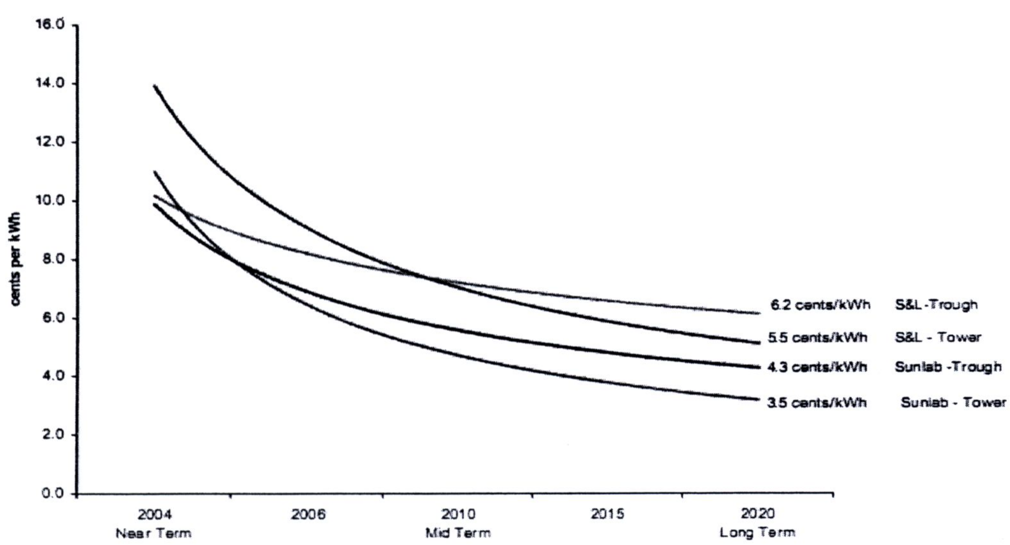


Figure 26 Sargent & Lundy LCOE reduction in mid and long term for tower and trough technologies

Source: NREL; Sargent and Lundy LLC Consulting Group, 2003

The DLR LCOE forecast are results of a separate study performed in Europe. Their LCOE in the smaller and medium capacities are based on the SEGS power plants and several trough and tower research pilot plants in Europe.

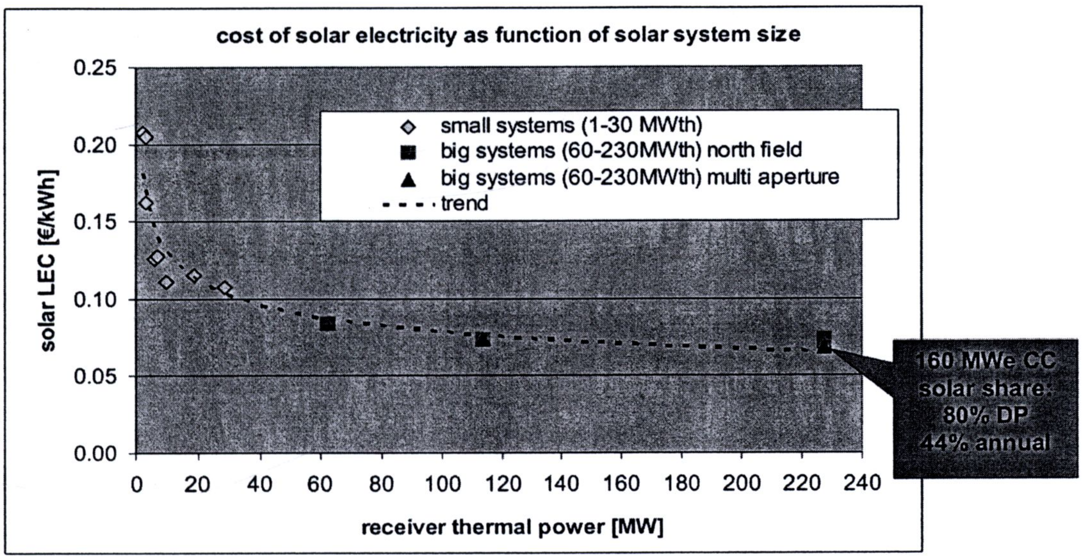


Figure 27 Cost of electricity for the existing and future trough power plants

Source: Pitz-Paal, Robert, 2008

The SolarPACES [14] LCOE trend is similar to S&L providing LCOE based on actual operating plants and then projecting for mid and long term based on the carbon taxing and technological advancement.

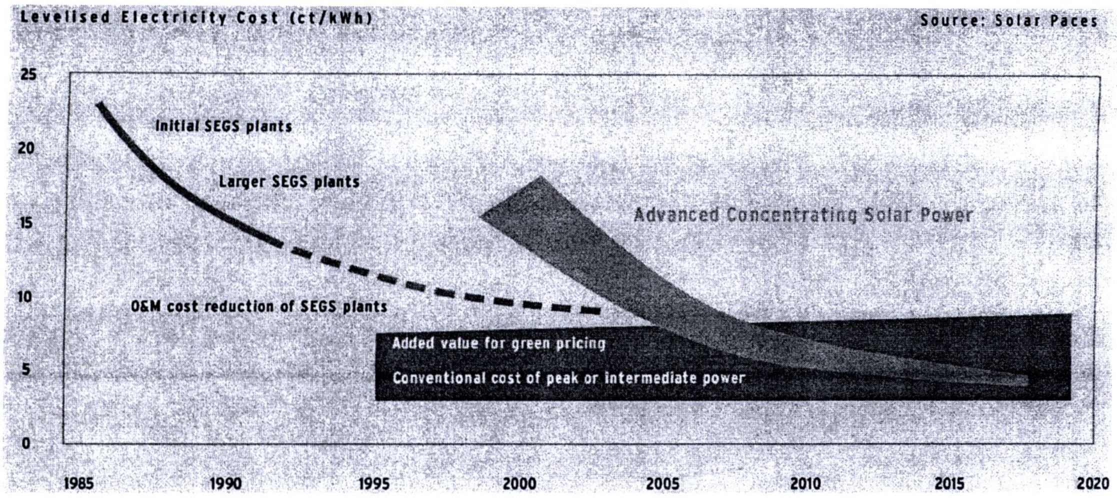


Figure 28 Cost perspectives of CSP until 2020

Source: Trieb, Franz and Dürrschmidt, Wolfhart, 2002

To summarize, the solar Levelized Cost of Electricity (LCOE) is expected to fall to less than half current values as a result of performance improvements and cost reductions. At these costs, the potential for STPPs to compete with Rankine cycle plants (coal, gas or oil fired) is promising. In the long-term, the LEC for Trough Rankine plants is expected to be within the cost range for conventional peaking plants. If a credit for reduced carbon emissions is included, all STPPs have a lower LEC than coal-fired Rankine plants. ISCCS plants are not expected to produce power that is less expensive than a gas-fired combined-cycle plant.

One other major study [13] performed relating to the parabolic trough STPP is the Operation and Maintenance cost reduction study at the SEGS. This study serves as a base for the electricity cost reduction and enhanced performance for all the current and future trough power plants.

Potential for reduction in Operation and Maintenance (O&M) Costs

During the initial years of operation at the 150 MWe SEGS solar power park (comprising five 30 MWe plants SEGS III to VII) - Kramer Junction, O&M requirements comprised 25% of total electricity costs. In order to reduce the O&M costs and eventually to reduce the "levelized cost of electricity" LCOE, an "O&M Improvement Program" (O&MIP) was proposed and executed. The project went on for six years with a funding of $6.3 million shared between the Sandia National Laboratories (SNL) and Kramer Junction California Operating Company (KJCOC). Program tasks focused on

1. Improving performance
2. Increasing reliability of individual components
3. Upgrading control systems
4. Reducing maintenance costs (through more effective planning and implementation)
5. Increasing the efficiency and life time of the solar field components
6. Improving the effectiveness of the power block/solar field interface and
7. Many other measures that either decrease costs, improve electrical output or both.

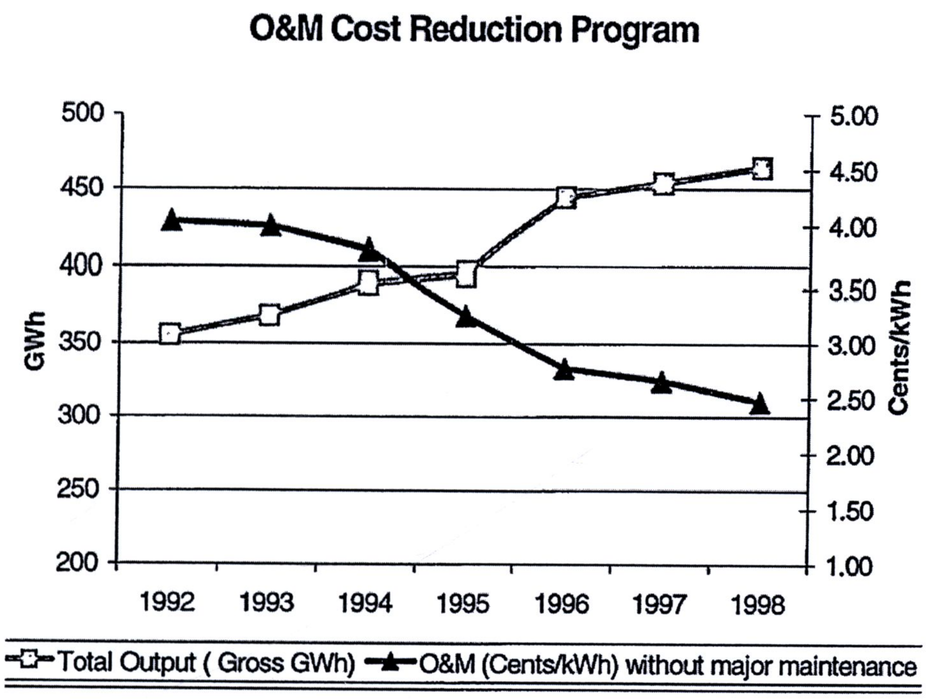


Figure 29 O&M costs and electrical output at Kramer Junction during the years 1992 to 1998

Source: Cohen, Gilbert; Kearney, David and Colb, Gregory, 1999

Due to these O&MIP, the SEGS operators were able to achieve nearly 40% reduction in O&M costs for the Kramer Junction power plant. This reduction is equivalent to a $ 4 million annual savings. This would mean that the amount spent for the O&MIP program will be paid back in a year and half.

The reliability of a system or a certain brand, as a part of O & M, needs to be included in a general way into the model as detailed performance is a matter of the detailed engineering, which is not part of this model.