Appendix B

Methodology

B. METHODOLOGY

B.1 SUMMARY

The study was carried out as follows. The methodology Sargent used to carry out the study is described in this section.

- Sargent & Lundy collected data and analyses of the current status of trough and tower technologies.
- Sargent & Lundy reviewed the SunLab Cost Models, industry data, and relevant studies regarding capital cost projections for near-term deployment, cost projections for technology improvements, and plant scale-up through 2020.
- Sargent & Lundy assessed the level of cost reductions and performance improvements, based on our experience, that are likely to be achieved.
- Sargent & Lundy developed a financial model to calculate LEC based on project financing assumptions, investment costs, and operations and maintenance costs.

B.2 COLLECTION OF DATA

Sargent & Lundy received relevant documents from NREL and Sandia Laboratory for our independent review. During the review process, additional documents were gathered from industry sources, the Internet, and our internal S&L library. The list of documents is included in Appendix A. Our objective was to review relevant documents, both pro and con, to make our assessment. For example, the Teagan report was critical of the methods used in previous reports to predict cost reductions, in particular learning curves (Teagan 2001).

B.3 REVIEW OF SUNLAB COST MODEL

Sargent & Lundy reviewed the SunLab cost model and determined that the SunLab cost model approach and methodology is reasonable. The SunLab cost model was developed based on industry cost data and engineering evaluation.

The following industry cost data were used for the cost models:

- Actual cost data from construction of the SEGS plants and costs of equipment being supplied for O&M were used (e.g., HCEs).
- Actual cost data from Solar Two were used as the “starting point” and adjusted for present prices. The steam generator cost estimate was based on four vendors’ designs and quotes for

100 MWe (SAND93-7083) and actual costs from Solar Two. The scaling factor was calculated and used to estimate other plant sizes.

An example of engineering evaluation is shown in Table B-1. The cost estimate for the tower height is based on an engineering formula and vendor cost information provided in the Central Receiver Utility Studies (1989).

Table B-1 — Cost Estimate for the Receiver Tower Based on the Central Receiver Utility Studies

Receiver Rating (MWt)	Tower Height (m)	Installed Cost (000's)	2001 Cost (000's)	Source
100	75.8	$1,160	$1,600	Central Receiver Utility Studies
195	94.7	$1,550	$2,200	Central Receiver Utility Studies
343	140.0	$3,010	$4,200	Central Receiver Utility Studies
390	149.3	$3,410	$4,800	Central Receiver Utility Studies
468	185.0	$5,290	$7,500	Central Receiver Utility Studies
780	190.0	$5,600	$7,900	Central Receiver Utility Studies
936	247.5	$10,020	$14,100	Central Receiver Utility Studies

Notes:

Tower height, m = $29.1 + 0.51129589 * (\text{Rating, MWt}) - 0.0088703442 * (\text{Rating, MWt})^{1.5} + 32{,}801.719 * (\text{Rating, MWt})^{-2}$

Tower cost = $600{,}000 + 17.72 * (\text{Tower height, m})^{2.392}$ Crane cost = $500,000

Sargent & Lundy evaluated the assumptions in the SunLab cost model: efficiency improvements, capital cost for the near-term deployment, and cost reductions through 2020. The review of cost reductions included technology improvements, increase in the size of the plant (scale-up), and production volume. Scale-up and production volume is discussed in more detail in this section. The cost model was compared to S&L's internal cost database, where appropriate (e.g., turbine, equipment, and commodities such as steel prices).

Differences between the SunLab and S&L cost estimates were a result of different assumptions. For example, S&L increased the duration between the deployment of the next generation plant from 1 year to 2 years to account for lessons learned and an adequate time for steady-state operation. The differences in assumptions are identified in the main body of the report.

B.4 TECHNICAL IMPROVEMENTS

Projected technical improvements that reduce costs by improving plant efficiency or by reducing initial capital costs were evaluated with respect to probability of the improvement and the estimated magnitude of cost reduction. The projected technical improvements investigated were those identified in the SunLab models, and the probability and magnitude of cost reductions are based on data from DOE, NREL, Sandia, and members of the CSP industry, including technology assessments and supporting studies for troughs and towers.

B.5 ECONOMY OF SCALE

Economy of scale was used, as appropriate; to estimate or evaluate cost estimates for components. Scaling factors were used to estimate the cost of a new size or capacity from the known cost for a different size or capacity. The Association for the Advancement of Cost Engineering (AACE) defines this method of estimating as plant component ratios (Humphreys and English 1993). The relationship is based on the following formula:

$$C_2 = C_1 (S_2/S_1)^{Sf}$$

Where:

C_2 = desired cost of equipment at size (or capacity) of S_2

C1 = desired cost of equipment at size (or capacity) of S_1

Sf = scaling factor

Example: If the cost of a 95-m^2 heliostat is $13,654 ($143.73 per m^2), then the cost of a 148-m^2 heliostat is estimated at $19,466 ($131.53 per m^2) based on a scaling factor of 0.80.

$$C_2 = \$13{,}654\ (148/95)^{0.8} = \$19{,}466$$

B.6 VOLUME PRODUCTION (VOLUME AND LEARNING CURVE)

Experience curves define how unit costs decrease with cumulative production. The specific characteristics of the experience curve are that the cost declines by a constant percentage with each doubling of the total number of units produced. The formula is as follows:

$$C_{CUM} = C_0 \times CUM^b$$

Where:

C_{CUM} = the cost per unit as a function of output

C_0 = the cost of the first unit produced

CUM = the cumulative production over time

b = the experience index

The cost reduction is ($1-2^b$) for each doubling of cumulative production, where the value (2^b) is called the progress ratio (PR). The progress ratio is used to express the progress of cost reductions for different technologies.

The formula is simplified for use as follows:

$$PR = (C_2/C_1)^{1/(\text{no. of doublings})}$$

Where:

Number of doublings = log 2 (Q2/Q1)

C_1 = cost of initial unit produced

Q_1 = production quantity for the initial unit cost

C_2 = desired cost of unit produced

Q_2 = cumulative production quantity for desired unit cost

PR = Progress Ratio

Example: The cost of a 148-m^2 heliostat is \$160 per m^2 based on production of 227,000 m^2. The cost estimate based on a production of 56,000,000 m^2 is \$109. The progress ratio is 0.95.

Number of doublings = $\log_2$ (56,000,000/227,000) = 7.9

PR = $(\$109/\$160)^{(1/7.9)}$ = 0.95

Many of the previous studies that assessed the cost reduction potential for tower and trough technologies based their findings on experience curves, including the World Bank (1999). As pointed out in the Tegan report (2001), "the review documents do not make a strong case that the cost of technologies (particularly the solar field) can be reduced to a point that they approach economic viability…." His primary example was the collector field: "the 'learning curve' arguments put forth lack sufficient backup to be credible given the fact that the materials of construction are already commodities and the fabrication techniques, for the most part standard." He also stated that he believed cost reductions are likely "via a combination of 'learning curve' and technology refinement." In response, S&L performed a thorough review of the cost reduction potential for heliostats. Heliostat cost reduction potential is more difficult to estimate since it is not based on actual costs with significant volume produced, whereas trough costs and the cost reductions are known based on actual SEGS construction data and recent costs for replacement during operations and maintenance. Our detailed evaluation of cost reduction potential for heliostats is provided in Appendix E.5.

We reviewed the engineering assumptions, industry data, and studies that constitute the basis of the SunLab Cost Model for the major cost drivers. The review was not based on just applying an experience curve, but an engineering review. We reviewed the assumptions and made adjustments as deemed appropriate based on our experience. We calculated the progress ratio and compared it to actual experience curves from other industries. The calculated progress ratio value was then used to determine estimated costs for a range of deployments.

For example, cost reductions for 148-m^2 heliostats due to a volume production of 100 million m^2 were calculated to be 0.961 by SunLab and 0.971 by S&L (see Table E-18). Each cost component was reviewed based on reviewing the initial cost estimate and final cost estimate and then calculating the progress ratio. One of the cost components is fabrication: initial fabrication costs were estimated based on the productivity (hr/unit) and labor rate ($/hr) for performing specific tasks (fabricating the mirror support structure, mirror modules, controls, and drives), and then final fabrication costs were estimated based on productivity improvements from volume production (see Section E.5.5). The calculated progress ratio was 0.96.

The range of progress ratios used for the comparison by S&L is between 0.85 and 0.96. Various studies on learning curves from actual data suggest that a progress ratio of 0.82 has been observed for photovoltaics (PV) and 0.82 for development of wind energy during early deployment (1980 to 1995). The higher end of the range is from the Enermodal study for the World Bank (1999), which identified a PV of 0.96 and the Wind Learning Rates compiled by Kobos (Table B-2) for development of wind plants. The Enermodal study projected a reasonable experience curve for trough and tower technologies to be between 0.85 to 0.92.

Table B-2 — Wind Learning Rates

Country or Region	Time Period	Est. Learning Rate (%)	Performance Metric (dependent variable)	Experience Metric (independent variable)	R2*	Reference or Data Source
OECD	1981–1995	17	investment cost ($/kW)	cumulative capacity (MW)	0.94	Kouvaritakis, Soria, and Isoard (2000)
USA	1981–1996	14	investment cost ($/kW)	cumulative capacity (MW)	0.95	Mackay and Probert (1998)
USA	1981–1987	16	investment price ($/kW)	cumulative “production” (MW)	n.a.	Christiansson (1995)
Denmark	1982–1997	4	investment price ($/kW)	cumulative capacity (MW)	n.a.	Wene (2000), Neij (1999) **

Country or Region	Time Period	Est. Learning Rate (%)	Performance Metric (dependent variable)	Experience Metric (independent variable)	R2*	Reference or Data Source
Denmark	1982–1997	8	investment price ($/kW)	cumulative capacity (MW)	n.a.	Neij (1999) ***
Germany	1990–1998	8	investment price ($/kW)	cumulative capacity (MW)	0.95	Durstewitz (1999)

Note: Adapted from Kobos (2002)

* As described in McDonald and Schrattenholzer (2001), comparing R^2 values between sources must be done with caution (e.g., different sources use differently sized data sets; therefore, the respective R^2 is relative to that data set).

** The Wene (2000) reference adapts results from Neij (1999).

*** The Neij (1999) results include all Danish-produced wind turbines.

B.7 OPERATION AND MAINTENANCE COSTS

The O&M cost projections provided in the SunLab cost model are based on actual data from Kramer Junction with projections for increased plant size and improvements in operation and maintenance. Kramer Junction provides a dependable basis for costs associated for near-term deployment.

Sargent & Lundy reviewed the SunLab cost model against interviews and actual data provided to us during our site visit and our knowledge and internal database information of O&M costs for electric power plants. We reviewed the SunLab assumptions and made adjustments as appropriate based on our experience and information provided by Kramer Junction.

B.8 FINANCIAL MODELING

B.1.1 Analysis Methodology

The financial model used for developing generating costs is a spreadsheet pro forma financial model of the type used in competitive industry to support power project planning and financing. S&L regularly reviews such models as part of our due diligence practice, working with lenders and investors in project financing. In some cases we also support project developers by writing and maintaining such models for them.

The main analysis engine is a standard income statement that includes calculations of energy production, revenues, operation and maintenance expenses, fuel expenses, depreciation, insurance, property taxes, interest, investment tax credit, and income tax. The investment tax credit for solar technologies is represented. Once after-tax income was determined in the income statement, depreciation was added back and payback of debt principal was subtracted to obtain cash available for dividends. The dividend stream and equity investment into the project was combined to compute the equity internal rate of return for the project. All evaluations were done on a lifetime $/MWh evaluated cost basis, covering 30 years of service.

All costs are expressed in constant 2002-dollar terms. Financing rates (return or equity and interest rates) were adjusted to remove the inflation premium rates.

Revenues were set to cover investment-related costs and fixed operation and maintenance costs, including property taxes. Revenues covering fixed operation and maintenance costs were treated as pass-through costs, with revenue assumed to exactly offset expenses. Investment costs were covered by a level $/kW/year capacity payment.

B.1.2 Cost of Capital

The financial analyses considered project financing, where the project is set up as a separate project company that is financed using borrowed funds and equity investments by the project company's owners. Costs of debt and costs of equity were developed from review of current market rates, resulting in the following assumptions shown in Table B-3:

Table B-3 — Costs of Debt and Equity

	Current Dollars	Constant Dollars
Return on equity	14.0%	11.5%
Permanent debt interest rate	8.5%	6.0%
Construction debt interest	7.0%	4.5%

The Project Company is subject to corporate income tax, assumed to be 35% at the federal level and 8% at the state level.

Although a high degree of financial leverage normally is used in project financing, favorable economics for solar plants correspond to lower degrees of leverage than with conventional power projects because of the 10% investment tax credit and favorable tax depreciation allowances for solar units (5-year MACRS). In these analyses, the financial leverage and revenue requirement to cover investment-related costs have been set to achieve the target return on equity and target debt service coverage ratio. The target debt service coverage ratio is 1.35 for all cases. Debt is paid off using a mortgage-style amortization over 20 years. Annual insurance expense was estimated to be 0.5% of initial cost, escalating. Annual property taxes were estimated to be 0.5% of initial investment, constant over the evaluation period. The evaluation period covers 30 years. Investment costs in the pro forma were adjusted for construction period financing costs by assuming that spending on average will be two years before the facility's initial commercial service. The cost of capital for this interest during construction adjustment was assumed to be 7% per year.

The summary of assumptions used for cost of capital is shown in Table B-4.

Table B-4 — Summary of Cost of Capital Assumptions

General		
Length of analysis period, yr	30	
General inflation, %/yr	2.5%	For non-fuel expenses
Base year for cost escalation	2002	When not otherwise specified in the model

Financial	Nominal $	Constant $
Equity rate of return	14.000%	11.50%
Debt rate of return	8.50%	6.00%
Debt repayment period	20	20
Percent equity in capital structure	Varies	Varies
Percent debt in capital structure	Varies	Varies
Entity is subject to income tax (yes/no)	Yes	Yes
Cost of construction, %/yr	7.00%	4.5%
Target DSCR	1.35	1.35

Amortization period for non-depreciable investment	20	
Percentage of investment not depreciable (exclusive of IDC)	2%	
Investment tax credit	10%	Applies only to solar investment, equal to this percentage of depreciable investment
State income tax rate	8.00%	Similar to 8.84% in California or 6.97% in Arizona
Federal income tax rate	35.00%	
Composite income tax rate	40.20%	Income tax rate (composite federal and state)
Insurance	0.50%	Of project cost; escalated at inflation rate
Property taxes	0.50%	Of project cost; remains constant in nominal terms throughout project life
Investment cost escalation rate	1.50%	

B.1.3 Levelized Cost of Energy

Levelized cost of energy was calculated based on the assumptions for cost of capital and the investment cost (capital cost) and operation and maintenance costs. S&L assessed the level of cost reductions and performance improvements, based on our experience, that are likely to be achieved in determining the investment and operations and maintenance costs.