Parabolic-Trough Technology Roadmap:

A Pathway for Sustained Commercial Development and Deployment of Parabolic-Trough Technology

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BOULDER, COLORADO, JANUARY 20-22, 1998

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EXECUTIVE SUMMARY

Technology roadmapping is a needs-driven technology planning process that helps identify, select, and develop technology alternatives to satisfy a set of market needs. The U.S. Department of Energy's Office of Power Technologies' Concentrating Solar Power (CSP) Program recently sponsored a technology roadmapping workshop for parabolic-trough technology. The workshop was attended by an impressive cross section of industry and research experts. The goals of the workshop were to evaluate the market potential for trough power projects, develop a better understanding of the current state of the technology, and to develop a conceptual plan for advancing the state of parabolic-trough technology. This report documents and extends the roadmap that was conceptually developed during the workshop. Key findings of the workshop were:

- A number of parabolic-trough power project opportunities may soon be realized. These projects are driven by the expanding global power market, increasing interest in greenhouse gas reduction, and a growing interest in “green” power. India, Egypt, Morocco, and Mexico have active trough project development programs in place and are in varying stages of the approval process to receive grants from the Global Environment Facility. Independent power producers are in the early stages of design and development for potential parabolic-trough power projects in Greece (Crete), Spain, and the United States (Arizona). Given successful deployment in one or more of these initial markets, additional project opportunities are expected in these and other regions.

- Parabolic-trough technology is the only CSP technology that has demonstrated sufficiently low risk to gain the attention of the financial community and independent power developers for near-term projects. The nine solar electric generating station (SEGS) plants, 354 MW_e of net solar electric generating capacity, continue to operate well in California's Mojave Desert and have accumulated nearly 100 plant-years of commercial operating experience.

- Significant technology advances have occurred since the last SEGS plants were developed. Proven and expected technology improvements indicate that cost reductions of over 50% and performance increases of up to 50% may be feasible. An appropriately focused research, development, and demonstration effort for trough technologies could achieve a levelized energy cost of 4¢–5¢/kilowatt-hour.

- A reasonable, modest cost pathway exists for moving parabolic-trough technology forward. The plan articulated in this roadmap suggests gradual steps in technology advances and deployments that allow parabolic troughs to mature to the point that they can compete directly with conventional power technologies in many sunbelt regions around the globe.

- U.S. industry currently has several competitive strengths for developing this market, but is unlikely to be successful in the near term without forming international collaborations. Without these collaborations the U.S. competitive position could erode significantly given the significantly greater funding (from both government and private industry) of European trough research efforts.

INTRODUCTION

TECHNOLOGY ROADMAPPING

The U.S. Department of Energy (DOE) has adopted the planning method known as *technology roadmapping* for much of its program development. Technology roadmapping is a needs-driven technology planning process that helps identify, select, and develop technology alternatives to satisfy a set of product needs. The roadmapping approach used here is one formulated by Sandia National Laboratories' Strategic Business Development Group. Using this approach, the development of a technology roadmap includes the following:

- Identify the "product" that will be the focus of the roadmap.
- Identify the critical market requirements and performance and cost targets.
- Specify the major technology areas.
- Specify the technology drivers and their targets.
- Identify technology alternatives and their time lines.
- Recommend the technology alternatives that should be pursued.
- Create the technology roadmap report.

PARABOLIC-TROUGH TECHNOLOGY ROADMAPPING

In January 1998, DOE's Concentrating Solar Power (CSP) Program sponsored an industry roadmapping session for parabolic-trough technologies. Representatives from a diverse mix of industry, laboratory, government, and nongovernment organizations (see Figure 1) attended the session. The working group reviewed the status of today's trough technologies, evaluated existing markets, identified potential future market opportunities, and developed a roadmap toward its vision of the industry's potential—including critical advancements needed over the long term to significantly reduce costs while further increasing performance and reliability.

This report documents this roadmapping effort and extends it to include a market assessment and a plan for the sustained development of parabolic-trough technologies.

Industry
- KJC Operating Company
- Bechtel
- SOLEL
- Pilkington Solar International
- Industrial Solar Technology
- Kearney and Associates
- Former LUZ experts

Laboratories
- DLR/MD-PSA
- SunLab/Sandia
- SunLab/NREL

Other
- World Bank
- California Energy Commission

Figure 1. Parabolic-Trough Roadmap Workshop participants (January 20-22, 1998, Boulder, Colorado)

WHY FOCUS ON TROUGHS?

In recent years, the U.S. Department of Energy's CSP Program has not directly supported the development of parabolic-trough technology. Trough technology was recognized to be commercially available, but believed by DOE to have only limited potential for future cost reduction. Technologies such as power towers and dish/engine systems were thought to offer greater opportunity for improved performance and lower cost. Several events, however, have recently caused DOE to reevaluate its position on parabolic-trough technologies.

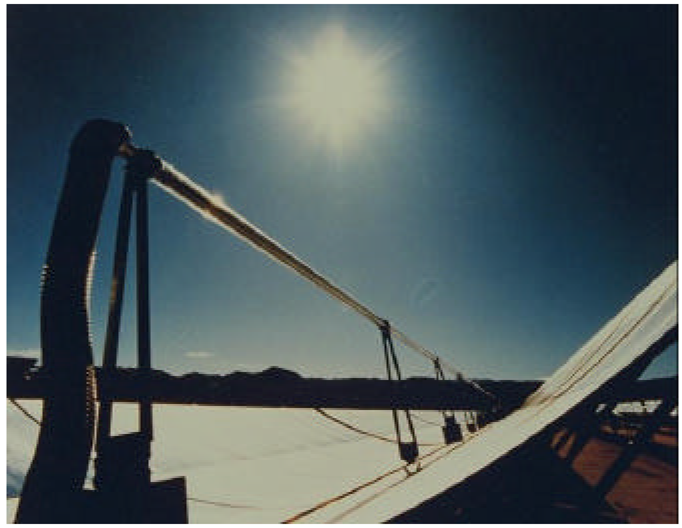


Figure 2. LUZ System Two Collector (LS-2)

- Dramatic changes in the world-wide power industry are causing changes in how new technologies are developed and deployed into the marketplace. As a result, tower and dish technologies that were being developed for utility customers who would share some of the initial deployment risk must now find new pathways into the competitive marketplace. This will likely delay deployment of these technologies.
- Financial markets view troughs, characterized by LUZ parabolic-trough collector technology (see Figure 2), as a low-to-moderate-risk, commercially available technology that is ready for deployment today. As a result, troughs are likely to be the only CSP technology available for near-term deployment in the competitive power market.
- Green power markets are currently developing. Parabolic troughs represent a potentially attractive technology option in these markets.
- The KJC Operating Company's Operation and Maintenance (O&M) Cost Reduction Program and international project feasibility studies have identified significant cost reduction opportunities for current and future parabolic plants.
- Through a structured development approach, it appears possible to foster a U.S. parabolic-trough industry that can significantly reduce the cost of energy from parabolic-trough technology and greatly expand deployment of the technology in both domestic and international markets.

WHAT FOLLOWS…

This document comprises the following sections: market assessment, trough technology baseline, roadmap development vision, technology roadmap, and roadmap initiatives.

- **Market Assessment**

  This section begins with an analysis that identifies potential future power market environments followed by a more detailed assessment of the current state of the power market. Probable near-term, mid-term, and long-term markets for trough technologies are then identified. Finally, the critical market requirements are identified for the next 20 years.

- **Technology Baseline**

  This section provides an overview of the current state of parabolic-trough technology followed by a review of the key opportunities to reduce the cost of future projects. Finally, the cost of power from a next-generation parabolic-trough plant is discussed.

- **Roadmap Development Vision**

  The section describes the key elements of the roadmap and the major challenges for the technology. It then describes the vision for how parabolic-trough technologies will be developed in the future.

- **Technology Roadmap**

  This section describes the major technology areas: crosscutting technology, component development, system development, and market development. In each of these areas, the key technology drivers are identified and various technology alternatives are addressed. Where possible, detailed metrics for the technology drivers have been included and time lines for various technology alternatives have been included. These time lines map back to the overall roadmap vision.

- **Roadmap Initiatives**

  This final section describes a number of initiatives that the DOE CSP program and SunLab might follow to implement the key elements of the parabolic-trough roadmap.

MARKET ASSESSMENT

POWER MARKET SCENARIOS

In attempting to understand future market opportunities it is useful to develop different scenarios about the nature of emerging markets. The trough workshop participants identified three market scenarios that seem to be relevant for future trough development.

- **Scenario 1: Low-Cost Competitive Power Market**

  Energy prices remain low for approximately the next 20 years. Power markets are dominated by the trend toward privatization and least-cost power options. Independent power producers (IPPs) are the primary suppliers of new power generation. Concentrating solar power technologies will be used in niche applications characterized by high fuel prices; in environmentally friendly markets that will pay a premium for green power; or in applications in which solar technologies can leverage off conventional technologies to drive solar costs down (such as the Integrated Solar Combined-Cycle System [ISCCS]). In this environment, CSP technologies need to focus on driving down costs. Wind power will likely be the primary competition for CSP applications.

- **Scenario 2: Global Climate Change**

  Global climate change causes more nations to invest significant resources to reduce greenhouse gas emissions. Carbon dioxide (CO_2) reduction becomes the major driver for the development of CSP technologies. Economic incentives are put into place to create a market opportunity. In this case, the primary focus will be on rapid deployment of CO_2 reduction technologies and development of large, high-capacity-factor grid-connected plants. Repowering of existing plants presents an important opportunity to minimize costs. Development of thermal or electric storage is a high priority.

- **Scenario 3: Fossil Fuel Price Escalation**

  Fossil fuel prices escalate due to declining production or through political developments or other events that result in reduced production of one or more fossil fuels. In this scenario, other fuel and energy technologies are developed to replace the demand for fossil fuels. During this period, significant price fluctuations are seen until demand for alternative fuel and energy technologies can replace a significant portion of the demand for conventional fuels. Increasing energy prices and energy price uncertainty will drive the demand for solar technologies in this scenario.

The activities developed later in the roadmap address one or more of these scenarios. Although Scenario 1 is generally thought to be the more realistic picture of the near-term future, Scenarios 2 and 3 are potentially of such significance that it is appropriate to include activities that also address these as an insurance policy for the future.

MARKET SUMMARY

- **Competitive Price of Power**

  The competitive price of baseload power in markets with well-developed infrastructure and access to low-cost fossil fuel (coal and natural gas) is 2.5¢–4¢/kilowatt-hour (kWh).

- **Intermittent Power**

  Power that is intermittent and that cannot be dispatched at will—such as wind power—is only valued at the fuel and incremental O&M cost of the avoided generation. This energy would typically be valued at 2¢–3¢/kWh. Dispatchable power, possible with CSP technologies using either storage or hybridization, does not suffer from this limitation.

- **Intermediate Load Power**

  In many cases, new capacity is needed to meet peak loads and is not needed for 24-hour-per-day operation. The competitive price of intermediate and peak load generation can be significantly higher than that for baseload generation. The competitive price for intermediate load generation (20%–40% annual capacity factors) is approximately 4¢–6¢/kWh for conventional power technologies. It is critical that an intermediate load technology be dispatchable to meet the peak load. For most developing regions, nighttime peaking will be important; for these markets, storage or hybrid design configurations will be necessary. Dispatchable technologies will have an advantage here.

- **Niche Markets**

  In general, niche market opportunities exist where the levelized cost of power is 6¢–8¢/kWh. These niche opportunities exist due to high fuel prices (e.g., island systems) or as a result of a higher value being placed on green power generation.

- **Current International Opportunities**

  The international market is driven by internal host country energy programs and encouraged by the positive attitudes of the Global Environment Facility (GEF) and the World Bank toward the implementation and development of CSP systems. These opportunities exist in developing countries, and their progress is strongly influenced (and frequently delayed) by bureaucratic snags, shifting internal politics, broader energy issues (such as requirements for restructuring imposed by World Bank policies), and other factors. In recent years, discussions have been active with energy planners, utilities, and government agencies in India, Mexico, Egypt, Jordan, Morocco, Greece (Crete), Brazil, Iran, China, and Spain (see Table 1). Interest and early steps are gaining momentum in other parts of Africa as well. Although it is impossible to predict how any of these initiatives will develop over the next few years, opportunities clearly exist. Most countries have focused on parabolic-trough technology as having already reached the commercial stage, with the recognition that power towers or dish-engine systems may become a more cost-effective option at some point in the future.

- **Current U.S. Domestic Market Opportunities**

  Concentrating solar power technologies are primarily suited to locations with a high direct normal solar resource, such as the Southwest. The current wave of deregulation and utility restructuring is driving the market toward least-cost power, making it difficult for CSP technologies to compete. However, a number of states are including green power requirements in their restructuring legislation. Arizona, Nevada, and California have included solar portfolio standards or a system benefits charge to help foster the deployment of solar power. These types of policies are likely necessary to allow continued development of the U.S. power market.

Table 1. Parabolic-Trough Project Status (as of December 1998)

Country/State	Plant Configuration	Status
India	135 MW_e ISCCS	GEF approved, waiting for RFP**
Egypt	Open	GEF PDF*** B Grant approved
Morocco	Open	GEF government request
Mexico	ISCCS	GEF government request
Greece	50 MW_e SEGS*	IPP development, EU****Thermie Grant
Jordan	ISCCS or SEGS	On hold pending conventional IPP
Spain	50 MW_e SEGS	Waiting outcome of solar tariff
Arizona	15–30 MW_e ISCCS	Waiting outcome of solar portfolio standard

*solar electric generating systems
**request for proposals
***project development funding
****European Union

ROADMAP PRODUCT

Based on the preceding market assessment, the long-term roadmap product will be dispatchable intermediate load solar power. Given this conclusion, the following markets are envisioned:

- **Near-Term Markets**

  Markets for solar-trough power plants will be focused in high-growth, developing countries where solar power is viewed as having a strong strategic significance and where GEF funding support can be made available, and in regions where special solar power or renewables incentives exist. Near-term markets, although driven by a demand for solar power, will rely on GEF grants and other financial incentives to achieve cost parity with conventional power generation. Trough technology is likely to be integrated into larger combined-cycle plants to help improve the solar project economics.

- **Mid-Term Markets**

  Solar power opportunities will emerge where green markets materialize and mature. Mid-term markets will require the technology to achieve 6¢–8¢/kWh without special financial incentives other than a green electricity premium of 1¢–2¢/kWh. This technology will need to be dispatchable, preferably through thermal storage.

- **Long-Term Markets**

  Solar-trough power will need to become broadly competitive with conventional alternatives and will enjoy expanding markets globally throughout sunbelt regions. Long-term market opportunities will open up when the technology can compete at 4¢–5¢/kWh.

CRITICAL MARKET REQUIREMENTS

The critical market requirements are the metrics that define the requirements of the product. Three critical market requirements have been defined: levelized cost of energy, risk, and dispatchability. The following sections define one or more metrics for each of the critical market requirements.

- **Levelized Energy Cost (LEC)**

  The cost of electricity is the primary system requirement for any electric power generation technology. The levelized cost of energy is the most common approach used for comparing the cost of power from competing technologies. There are two approaches for calculating the LEC. The first, a simplified approach, calculates an annualized cost using a fixed charge rate and divides it by the annual electric generation. The second approach uses a full financial cash-flow model to perform a similar calculation. The latter approach is the one used in this roadmap because it more accurately reflects the parameters that will drive decisions on selecting one project over another. In general, the cost of power must be competitive with alternative power generation options after taking into account any special incentives available to the technology. This could include green-pricing production incentives, grants (such as those from GEF), or special tax incentives.

- **Risk**

  The level of risk for the project must account for all potential sources of risk: technology, scheduling, finances, politics, and exchange rate. The level of risk generally will define whether or not a project can be financed and at what rates of return.

- **Dispatchability**

  One of the primary benefits of CSP technologies is that they can be dispatched either through the use of thermal storage or through hybridization with conventional fuels. Dispatchability means that power can be generated when it is needed to meet peak-system power loads. The primary metrics for dispatchability are the time when the peak load occurs, the length of the peak-load period, and the capacity factor the system must maintain during the peak period. For example, the current SEGS plants in California have a peak period between 1200 and 1800 hours on summer weekdays, and the plants must maintain an 80% capacity factor during this period.

The following table sets tentative quantitative goals for critical market requirements out to 2020.

Table 2. Critical Market Requirements for Intermediate-Load Dispatchable Power

	1990	**2000**	**2005**	**2010**	**2015**	**2020**
Levelized Energy Cost (¢/kWh)	15–18	10—12	7–8	5–6	4–5	4
Risk						
Equity IRR*	18%	18%	15%	15%	15%	15%
Debt Interest Rate	9.5%	9.5%	8%	8%	8%	8%
Performance Warranty (years)	10	3	3	1	1	1
*internal rate of return						
Dispatchability						
Peak-Capacity Factor	95%	95%	95%	90%	90%	90%
Peak-Period Duration (hours)	6	3	3	6	6	6
Peak Season	summer	annual	annual	annual	annual	annual
Time of Day	afternoon	evening	evening	evening	evening	evening
Preferred Technology	fossil hybrid	fossil hybrid	fossil hybrid	thermal storage	thermal storage	thermal storage
Annual Capacity Factor	34%	30%	30%	40%	50%	50%

TECHNOLOGY BASELINE

Although all nine of the original SEGS plants continue to operate today, no new plants have been built since 1990. During the construction of these plants, significant cost reductions were achieved, driving the cost of electricity down from 24¢/kWh to 8¢/kWh (1988 dollars). Tax incentives and attractive power purchase contracts that were available at the time were largely responsible for the economic viability of these projects. With the expiration of many of these tax incentives and the continued drop in conventional energy prices, these plants would not be competitive in today's power market. Updating these costs to show the cost in 1998 dollars and the current tax environment raises the cost of power to about 12¢/kWh for an 80-MW SEGS plant.

CURRENT STATUS OF TROUGH TECHNOLOGY

The SEGS trough plants have performed well. Taking the cumulative 150-MW capacity of SEGS plants at Kramer Junction, California, as the best example, the electrical output of the plants has had an overall upward trend during the last 10 years, with some variations due to the influences of weather, significant alterations in the O&M structure and procedures, maturity of operation and experience, and spare parts availability. In recent years, the output has risen markedly. As a result, performance in 1996–1997 set many new records for output and efficiency.

The Kramer Junction plants are very reliable in terms of solar field availability and on-peak production. The annual solar field availability—defined as the capability to operate—started at an adequate level in the 96%–97% range but then slowly climbed to about 99.5% as maintenance practices sharpened and spare parts problems were solved. (The power blocks also have shown very high availabilities.) With good solar field performance, well-maintained power systems, and the intelligent use of natural gas, the on-peak capacity factors have climbed to almost 110% of rated capacity.

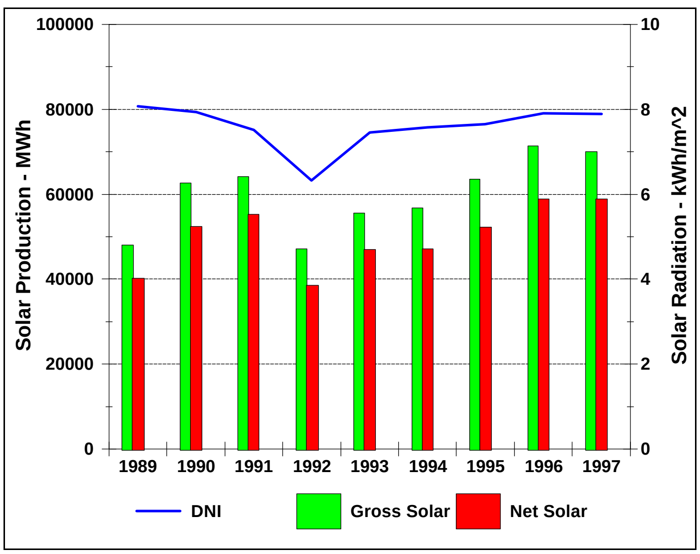


Figure 3. SEGS VI historical performance

Figure 3 shows the historical SEGS VI solar electrical output. On a net basis, the SEGS VI annual solar-to-electric efficiency was 10.8% in 1997, higher than that of the other plants but a valid representative number. Reasonable projections for advanced troughs put that efficiency at the 15%–16% level. As would be expected, the peak solar-to-electric efficiencies are much higher than annual values. (Other technologies, such as photovoltaics, often give only peak values.) In July 1997 the peak instantaneous solar-to-electric efficiency reached about 21% and the daily efficiency was near 20% from 0900 to 1800 hours. The thermal efficiency of the solar field peaked at 60%. Once again, these achievements are for plants that have been in operation for 10 years.

Cost projections for parabolic-trough plants are based on the SEGS experience and the current competitive marketplace. Recent feasibility studies project SEGS-type plant costs at about $2,000/kW and ISCCS plants at about $850/kW. Of particular note are solar field costs, which are currently projected at about $215/m^2 installed. The cost breakdown for solar field components or subsystems is shown in Figure 4. Note that the structure, reflective surface, and receiver together constitute about 85% of the total costs, clearly identifying targets for cost reduction.

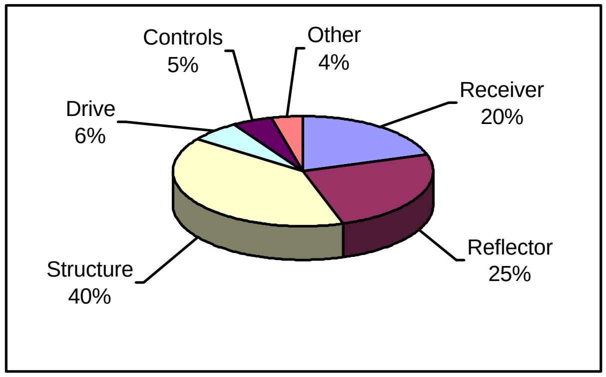


Figure 4. Collector cost breakdown

OPPORTUNITIES FOR COST REDUCTION

In recent years, trough technology has sometimes been viewed as dated, with limited potential for continued reduction in the levelized cost of electricity; however, workshop participants identified a number of opportunities that will likely lead to substantial cost reduction and performance improvement over the current trough technology.

- **Power Plant Size**

  Increasing plant size is one of the easiest ways to reduce the cost of solar electricity from parabolic-trough power plants. Studies have shown that doubling the size reduces the capital cost by approximately 12%–14%. This cost reduction typically comes from several factors. Economies of scale due to increased manufacturing volume reduce unit costs for both the power block and solar field. Also, O&M costs for larger plants will typically be less on a per-kilowatt basis because significantly fewer operators and somewhat fewer maintenance crews per megawatt are needed for larger plants. Power plant maintenance costs will be reduced with larger plants, but solar field maintenance costs, while lower, will scale more linearly with solar field size.

- **ISCCS**

  The Integrated Solar Combined-Cycle System is a proposed configuration that would utilize the steam bottoming cycle in a combined cycle plant to convert the solar thermal energy into electricity. In the ISCCS configuration, the steam turbine would be increased in size by as much as 100% over the conventional combined cycle. The ISCCS design offers a number of potential advantages over a stand-alone Rankine-cycle plant. The incremental capital and O&M costs of the ISCCS are significantly lower than the cost of a conventional Rankine plant. Also, the solar electric operating efficiency should be higher due to reduced start-up losses. However, some design optimization remains to be completed to minimize the potential impact to gas-mode operation. Initial studies show that the ISCCS configuration could reduce the cost of solar power by as much as 22% over the blended cost of power from a conventional SEGS plant (25% fossil) of similar size.

- **Advanced Trough Collector**

  As illustrated above, the structure constitutes about 40% of the solar field cost, whereas the reflectors and receivers each cost from 20%–25% of the total. In the SEGS design, steel provides the major strength, with thick glass mirror panels giving the parabolic shape to the reflecting surface. Lower-cost designs can be explored for the steel structure, with a possible alternative of a lighter aluminum or composite structure integrated with a front surface reflector on film, thin glass, or structural member. Evolutionary improvements in the receivers are also possible.

- **Direct Steam Generation (DSG)**

  In the DSG concept, steam is generated directly in the parabolic-trough collectors. This saves cost by eliminating the need for the heat transfer fluid (HTF) system and reduces the efficiency loss involved with using a heat exchanger to generate steam. DSG should also improve the solar field operating efficiency due to lower average operating temperatures and improved heat transfer in the collector receiver. The trough collectors would require some modification due to the higher operating pressure and lower fluid flow rates. Control of a DSG solar field likely will be more complicated than the HTF systems and may require a more complex design layout and a tilted collector. DSG also makes it more difficult to provide any thermal storage. A pilot demonstration of DSG technology is in progress at the Plataforma Solar de Almería (PSA) in Spain.

- **Solar Power Park Development**

  One opportunity for significantly reducing the cost of CSP plants is to develop multiple plants at the same location in a solar power park environment. The power park offers a number of potential opportunities for reducing cost. If multiple projects are planned together, project development and engineering costs per project will likely be reduced. If the O&M is performed by a single company, significant reductions in overhead and improved O&M efficiency and skill coverage are possible. If the plants are built consecutively and the same construction crews are used for all plants, construction costs should be reduced through labor learning curve efficiencies. Multiple projects will mean multiyear manufacturing runs on solar collector components, resulting in reduced cost per collector. Competitive bidding of major power plant equipment, materials, and services will likely result in greater cost reduction for multiple projects. Building five plants in a phased project approach at the same site could in fact reduce costs by 25% to 30% for a single project.

- **Project Financial Structure**

  Parabolic-trough plants are capital-intensive projects. The cost of capital and the type of project financing can have a significant impact on the final cost of power. In the past, the SEGS projects were all financed as IPP projects. Significant cost reductions are possible if projects are owned by investor-owned utilities (IOUs), municipal utilities, or by the new generation companies (GenCos) that are being created as part of utility restructuring. Cost reductions approximately 10%–40% are possible through alternative ownership and financing structures.

- **Tax Equity**

  Studies have shown that capital-intensive power projects, such as parabolic-trough plants, pay a higher percentage of taxes than expense-intensive projects, such as fossil fuel technologies.

One study for the California Energy Commission comparing taxes paid by concentrating solar power technologies with taxes paid by fossil technologies showed that approximate tax equity was achieved with a 20% federal investment tax credit and property tax exemption for CSP technologies. Tax equity in this case results in an 18% reduction in levelized energy cost. Although these results apply to the specific case tested, it shows the approximate level of tax equalizers necessary to gain parity between solar and conventional technologies.

- **Low-Cost Debt**

  Finally, a number of institutions have indicated that low-cost debt may be available for renewable power projects. Given the capital intensity of solar technologies, this offers one of the largest opportunities for cost reduction. For example, the availability of 2% debt in place of 9.5% debt could reduce the levelized cost of energy by more than 30%.

Figure 5 summarizes the opportunities for cost reduction in parabolic-trough power technology. These cost reduction opportunities are generally multiplicative, but not all would be taken together. Although cost reduction is often thought to result primarily from the introduction of advanced technologies, it is clear that the most significant opportunities for cost reduction are through non-technology development areas. The largest opportunities result from the type of project financing and the existence of a power park to consolidate construction and O&M costs.

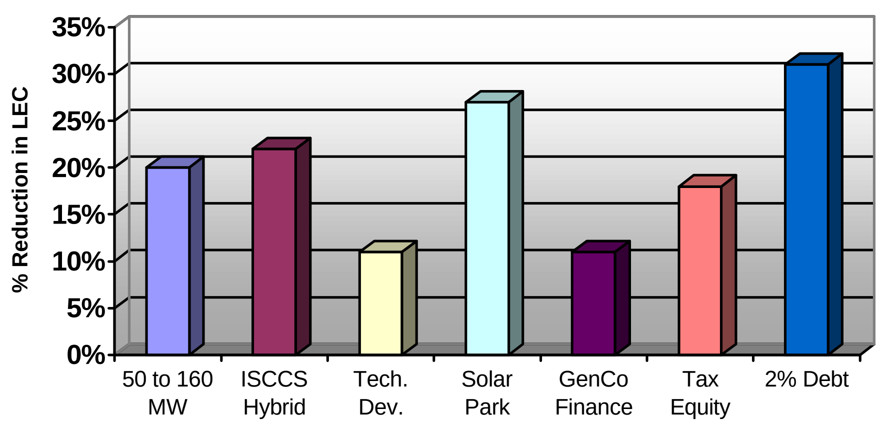


Figure 5. Cost reduction opportunities

THE COST OF TROUGH TECHNOLOGY TODAY

What would a trough power plant cost today? LUZ reported costs starting at 24¢/kWh for SEGS I down to 8¢/kWh for SEGS IX. These values were calculated in 1988 dollars and with the tax and financial structure of the projects at the time. Figure 6 shows what the cost of power from the 30-MW SEGS VI would be today after correcting for inflation, incorporating changes in the tax code, and adjusting for the actual performance of the plant. In the case of SEGS VI, if the same plant were built again today, the levelized cost of energy from the plant increases from 11.5¢/kWh in 1988 dollars (based on predicted performance) to 18.3¢/kWh in 1998 dollars (based on actual performance).

Assuming a 50-MW SEGS project were built today, significant reductions in cost could be expected. The KJC Operating Company O&M Cost Reduction Program has demonstrated a number of improvements, including (1) the replacement of flex hoses with ball joint assemblies, which significantly reduces pumping parasitic electric consumption; and (2) an improved receiver tube, which significantly reduces solar field heat losses. Additional expected cost reductions are based on other O&M gains that cannot be fully demonstrated at an existing plant, on economies of scale resulting from increased plant size, and on the general cost reduction trend over the last 10 years for large power plant equipment. The second bar in Figure 6 represents the LEC for a 50-MW SEGS plant built today.

The third bar in Figure 6 represents the cost of solar power from a 50-MW solar increment ISCCS plant. The ISCCS bar represents the incremental cost for solar electricity only. The fossil electricity cost would be substantially lower. The cost for the SEGS plants is a blended cost of 75% solar and 25% fossil, so the reduction in the cost of solar electricity is even larger than what is shown in the figure. The final bar reflects the cost of solar power from a 50-MW increment ISCCS plan built in a developing country that would have access to a GEF grant and special low-cost financing. Given these assumptions, solar power is close to the competitive range for power in many regions.

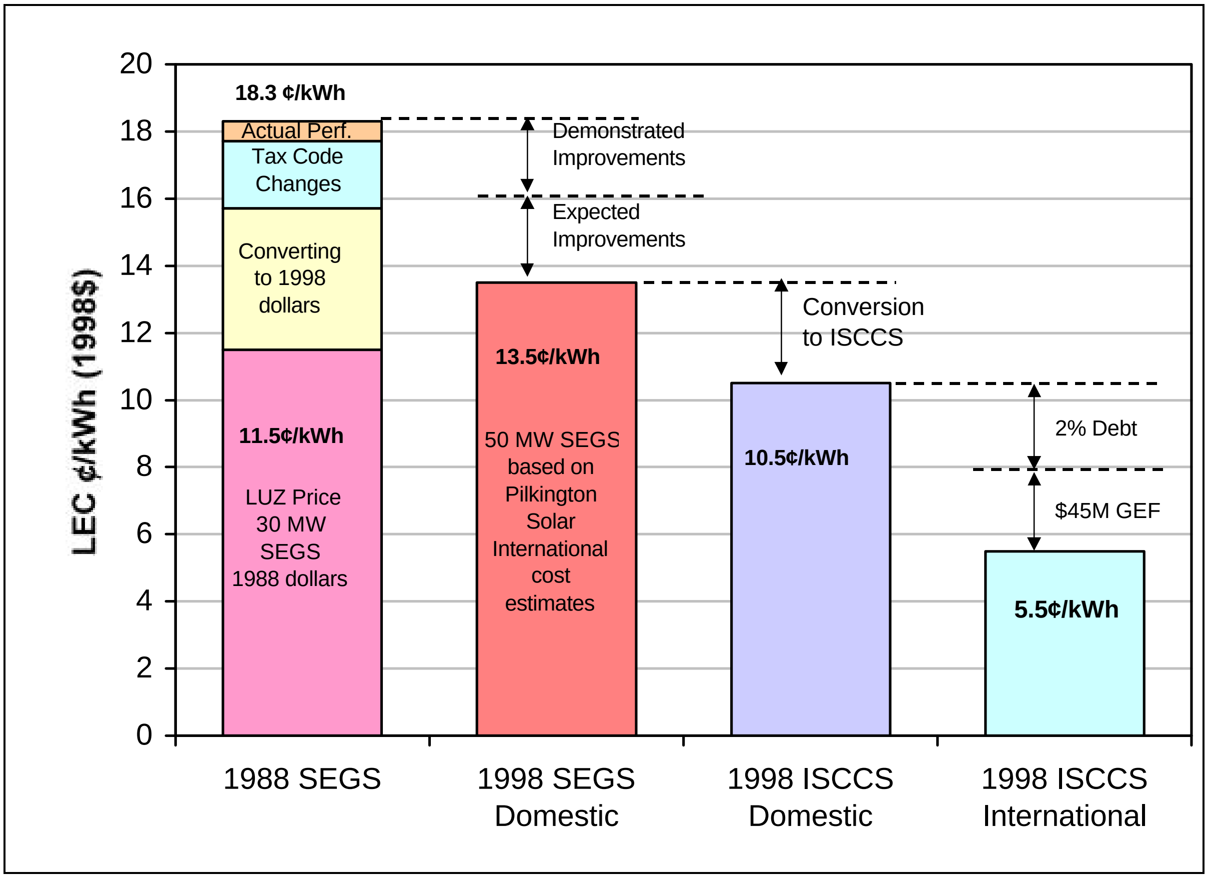


Figure 6. Cost of trough technology today

TECHNOLOGY VISION

Based on the market and technology information provided above, the participants at the trough roadmap workshop created a vision for sustained development and deployment of parabolic-trough technology. The sections below highlight the key elements of this vision and the key technology challenges that must be addressed. The final section provides the development vision assumed by the trough roadmap.

KEY ELEMENTS OF THE TROUGH ROADMAP

- **Technology and Market Development**

  The roadmap must include both technology and market development components. Even with significant technological improvements, trough technology would achieve only a fraction of its potential without a concerted market development effort. Likewise, a market development effort without a significant technology development focus would be ineffective.

- **Near-Term and Long-Term Opportunities**

  Based on the market scenarios outlined, opportunities exist for trough technologies both in the near and long term. For troughs to be successful, the trough roadmap must have both near-term and long-term components.

- **Collaborations**

  In order for trough technology to be successful, all stakeholder groups (industry, government, laboratories, financial institutions, regulators, and policy makers) must work together to develop a cohesive development program. U.S. collaboration with European and Israeli technology providers and research facilities that have been working to market and improve the technology will also enhance U.S. industry's chances for success.

KEY TECHNOLOGY CHALLENGES

A number of technology challenges must be addressed if trough technology is to be successful in the future power market.

- **Cost Reduction and Performance Improvement**

  The cost of trough technology must be reduced for it to be competitive in future power markets. Based on initial estimates, cost reductions of 50% appear to be possible, but this will require a focused technology development effort in combination with real project deployment opportunities. Performance improvements of up to 50% are within reach with advancements in the technology.

- **Reintroduction of Troughs**

  Even if the next trough project were to begin today, by the time it is completed, nearly 10 years will have passed since LUZ completed its last trough project. Some of the knowledge base developed by LUZ will have been lost in that time. Even with the lessons learned since then, it will be difficult for the next developer to immediately improve on the LUZ experience. This lag effect will be even more pronounced if the next project is developed at a location outside the United States.

- **Industry Development**

  Since the time that LUZ went out of business, the IPP industry has matured significantly. Although a single developer/technology provider such as LUZ is not required, a trough consortium will need to work together efficiently with a common set of development objectives. In addition, the consortium must determine how the technology will be warranted, and how risk will be shared.

- **Information Transfer**

  Although troughs are often treated as a dated technology with little room for improvement, the KJC O&M Cost Reduction Program identified a number of opportunities for cost reduction and performance improvements. The opportunity remains for significant changes in key design elements (e.g., structure, reflectors, and HCEs). In addition, parabolic troughs have demonstrated excellent performance to date as characterized by the existing LUZ trough plants. The challenge will be to bring the message about the capabilities and opportunities for parabolic trough technology to governments and to the power and financial industries.

- **Risk Reduction**

  Risk is a general term used to describe the uncertainties that could have a negative impact on a project. Risk can result from uncertainties in cost, schedule, technology, resource availability, power sales, financial parameters, political stability, or location. When a project is being considered, investors (debt and equity) will analyze it to evaluate the financial merit versus the risk. If the risk is high, the financial return must be sufficiently high to justify the potential risk, thus increasing the cost of capital. Unfortunately, projects using new technologies and projects in developing countries are usually considered high risk. It is important to minimize project risk whenever possible.

TROUGH DEVELOPMENT VISION

During the workshop a vision for the future development of parabolic-trough technologies was defined. The vision builds on the successes of current trough experience and identifies a low-risk approach to advance the state of the technology. This vision expresses a synergy of technology development steps and market expansion following defined scenarios. The technology development is foreseen to proceed in a multi-step process with several clear technology advances that correspond to very distinct cost reduction steps. Table 3 outlines the basic developments within these steps, and also shows the simultaneous market and policy deployment steps required for success.

Table 3. Technology Development and Deployment Activities

Step	Technology Development	Deployment
1	State-of-the-Art Collector ISCCS Design Optimization	GEF Market Aggregation Low-Cost Financing and Grants
2	Optimized Steel Collector Improved HCE Lifetime Thermal Storage Process Design Optimization Standardized Designs Specialized O&M Tools and Equipment	Green Market Development Solar Tax Equity Standard Financing Packages Systems Analysis Tools High-Resolution Satellite Insolation Data
3	Advanced Trough Collector Advanced Reflector Advanced O&M	Solar Power Parks Solar Investment Funds
4	Tilted Collector Direct Steam Generation	

Figure 7 illustrates the steps and timing of this vision, showing the interrelationship of the technology and market development activities along with the expected electricity costs achieved during the process. Each of the technology steps is followed by additional cost reductions resulting from plant deployment. Based on this vision, a sustained market is envisioned for trough technology during the next 20 years.

Initially, the cost of trough solar power is expected to be 10¢–12¢/kWh, depending on plant configuration. Initial projects will be built using state-of-the-art technologies that take advantage of lessons learned since the last trough projects were built. These markets are expected to be subsidized by GEF cost buy-down grants or other special green/renewable financing options. The next level of technology development is expected to reduce the cost of trough power to 6¢–8¢/kWh, which should allow trough technology to compete in the emerging green markets. To achieve this cost target, a next-generation collector and other cost reductions will be needed. Additional technology development and cost reductions will be necessary to achieve later cost reductions that drop costs below 6¢/kWh. Though market penetration is traditionally very difficult to predict, rough estimates suggest that achievement of up to 1 gigawatt (GW) installed capacity by 2005 and 5 GW by 2010 is possible.

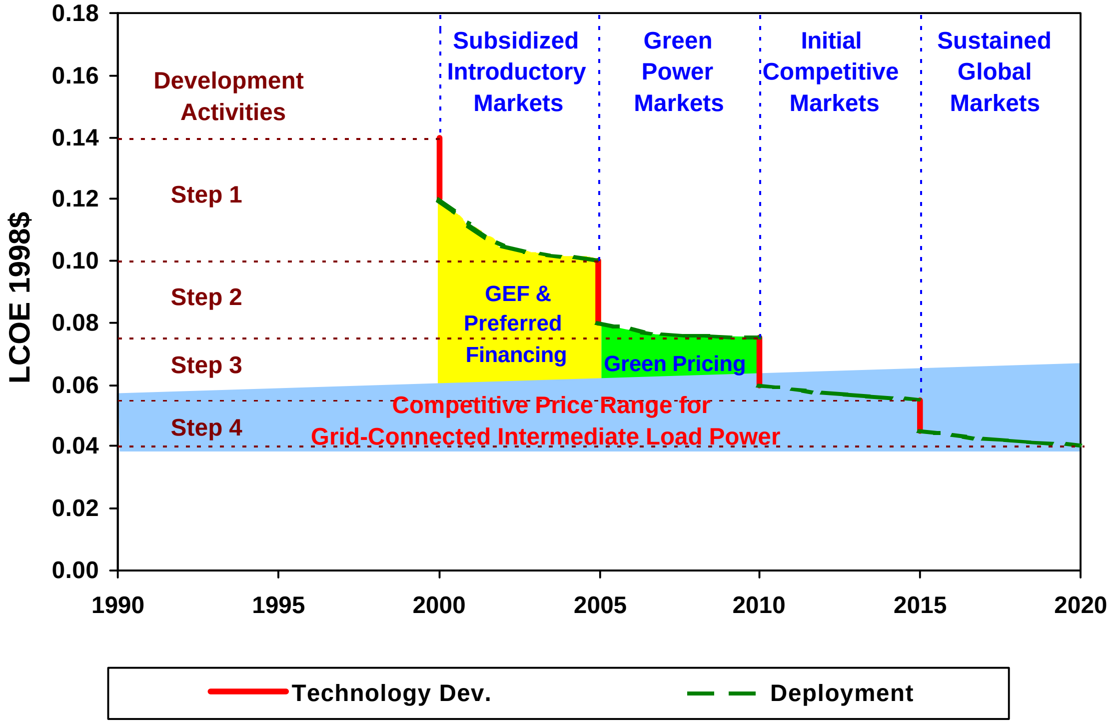


Figure 7. Trough technology development steps and cost vs. market opportunities

TECHNOLOGY ROADMAP

The roadmapping approach used here defines "major technology areas" that can help achieve the critical market requirements for the product. The product in this case is intermediate-load dispatchable solar power. The major technology areas for the trough roadmap are crosscutting technology, component development, system development, and market development.

CROSSCUTTING TECHNOLOGY ISSUES

Crosscutting technology issues cut across all areas of the technology roadmap.

SYSTEM METRICS AND BASELINE DATA

A consistent set of metrics needs to be developed for evaluating all activities in the roadmap. These metrics should define the key technology drivers and their targets and eventually tie back into the critical system requirements. These usually will be cost, performance, or reliability metrics.

ANALYSIS TOOLS

Analytical tools and models must be developed to allow system metrics to be assessed and valued. These tools include performance and financial models.

QUALITY AND RELIABILITY

Procedures and training should be put in place to ensure that standards are maintained through design, manufacture, construction, start-up, operation, and maintenance. These include design control, documentation control, and component and system reliability tracking.

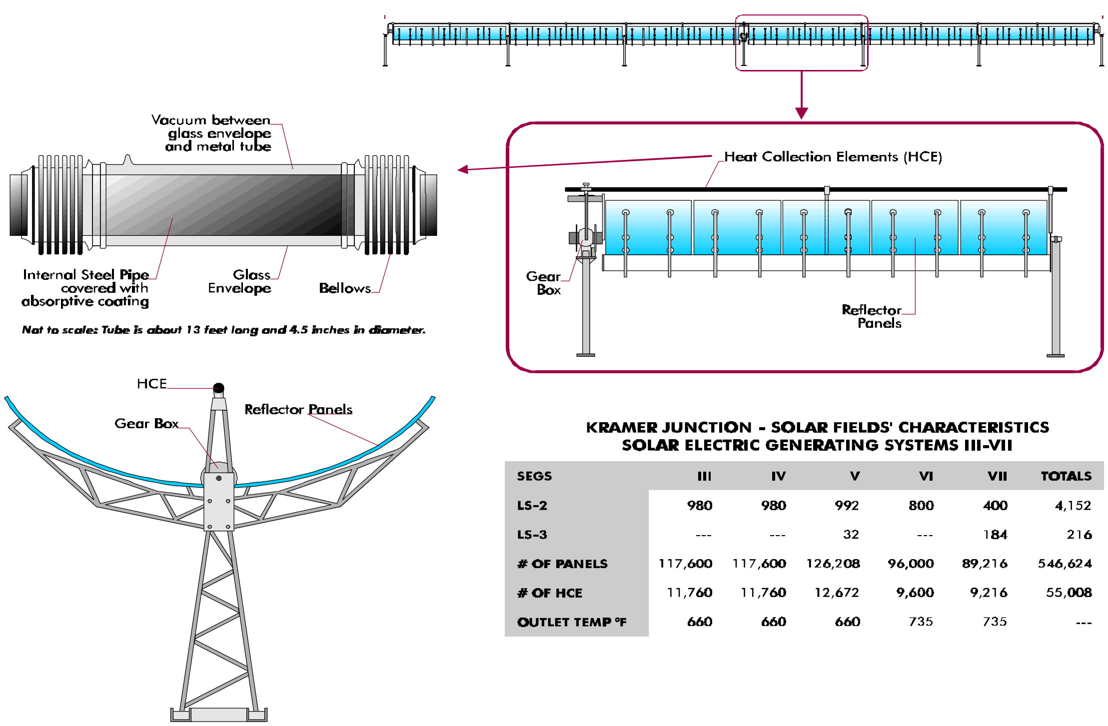
COMPONENT DEVELOPMENT

This section focuses on technology development of components or subsystems of the collector and solar field. Collector components include all the components and subsystems that are part of the modular trough concentrator assemblies. The basic subsystems are the structure, receiver, reflector, tracking system, interconnecting piping, and the control system. Solar field systems requiring further development include direct steam generation in the field itself, and thermal storage. The key technology metrics for each of the subsystems are shown in Table 4. Time lines for various subsystem technology alternatives are shown in Figure 10 (see page 23).

TROUGH STRUCTURE

This subsystem includes all of the structure, including the foundations, pylons, trusses and torque tubes, mirror and receiver support arms, and fasteners. The structure establishes and maintains optical alignment of the parabolic shape, withstands the wind, and supports the other subsystems. This category also includes all labor required to install and align the structure during construction, and subsequent O&M of the structure during the life of the project.

The baseline structure of the SEGS LS-3 structure is shown in Figure 8. It consists of steel trusses mounted on periodic pylons set in concrete foundations, and is designed to withstand winds of 70 mph (31.3 m/s) in a collector stow position. The precise parabolic reflector shape is provided by shaped glass mirror panels that are accurately supported and positioned by the structure. The structure weighs approximately 32 kg/m^2. The LS-3 design was optimized for large (80-MW) projects, with interconnected collector assemblies in long rows of about 300 m. Cost issues include the required degree of conservatism in the design (dictated by wind forces), the ability to maintain alignment over time, and the basic design philosophy. Other approaches to trough structure exist



KRAMER JUNCTION - SOLAR FIELDS' CHARACTERISTICS
SOLAR ELECTRIC GENERATING SYSTEMS III-VII

SEGS	III	IV	V	VI	VII	TOTALS
LS-2	980	980	992	800	400	4,152
LS-3	---	---	32	---	184	216
# OF PANELS	117,600	117,600	126,208	96,000	89,216	546,624
# OF HCE	11,760	11,760	12,672	9,600	9,216	55,008
OUTLET TEMP °F	660	660	660	735	735	---

Figure 8. Schematic of a third-generation LUZ parabolic-trough collector (LS-3)

(e.g., torque tubes and lighter metals, with a cable system providing strength), and new innovative designs may be possible. The structure currently represents about 40% of the total collector cost—easily the highest single subsystem cost and a prime target for cost reduction. Collector technology development, however, must advance in a logical manner. The first step is to define the current state-of-the-art collector that will be used in the next plants constructed. The second step is to develop an optimized trough collector design that will focus on further cost reduction in the next-generation trough plants. Advanced designs must be developed to continue driving down the cost and increasing collector efficiency.

- **State-of-the-Art Collector**

  The current LUZ trough collector has proven durable in field experience; however, in turn, this experience has pointed to needed improvements and suggested opportunities for evolutionary change. The LS-3 was designed to satisfy the perceived need for very large collector assemblies (545 m^2, 99 m long) to reduce costs in large collector fields. Although this effort was successful, hindsight suggests that the previous LS-2 design (see Figure 9), based on a torque tube approach rather than trusses, may allow for better optical alignment over time because field realignment is easier. Other characteristics of the two designs should also be reexamined to develop an optimum mix.

- **Optimized Steel Structure**

  New materials and innovative designs must be integrated into a lower-weight, lower-cost solution. The design process for the structure, in particular, can benefit from a full design for manufacture and assembly (DFMA) methodology, which emphasizes standardized parts, minimal components, and efficient manufacturing and assembly operations. Reduced weight will be the primary outcome, coincident with reduced cost. Work being undertaken by European companies beginning in 1998 on the "EuroTrough" collector may offer opportunities for a collaborative solution.

Figure 9. Row of LS-2 collectors at Kramer Junction

- **Advanced Design Concepts**

  New, innovative directions can lead to radical changes and steps resulting in reductions in cost. A strong steel structure supporting thick glass mirror panels is not the only solution to a trough structure-reflector combination. An approach taken by Industrial Solar Technology and others, including LUZ, is to utilize a lighter sandwich (sheet-metal panels reinforced by a nonmetallic internal layer, such as honeycomb) in a parabolic shape integrated with a front surface or film reflector. Other lightweight members, such as cables, can provide torsional strength against wind loads. Important issues such as reflector lifetime, ultimate strength, long-term alignment, and O&M requirements must be critically evaluated; however, the potential for significant cost reduction is attractive.

Parabolic-trough collectors have traditionally been installed horizontally, simplifying structural design but suffering from the cosine effects fundamental to a one-axis tracking system. A partial solution is to tilt the trough axis toward the south, allowing a higher useful flux on the collector but introducing design and maintenance complexity. Risk and cost-benefit analyses should be performed for this modification.

RECEIVER TUBE

The receiver tube has a major influence on the efficiency and reliability of the solar field. The newest receiver currently in use at the SEGS plants—termed a Heat Collection Element (HCE) and supplied by SOLEL—was initially developed by LUZ. During the last few years, the HCE has undergone additional development. Currently, the selective surface and the overall design characteristics are excellent. However, reliability and maintainability continue to be unsatisfactory. Relying on an evacuated annulus to minimize convection losses, this receiver suffers from excessive failures in the integrity of the outer glass envelope and the long-term level of vacuum. Additionally, the cost of the tube is significant in terms of overall solar field costs. Hence, increased lifetime, better maintainability, and lower cost must all be achieved.

Several design features that maintain the vacuum also require further development. First is a glass-to-metal seal between the glass enclosure tube and the expansion bellows. Little is known about its long-term integrity, and accurate field monitoring of vacuum degradation is needed. Second is the means to maintain the vacuum. In the SEGS HCE, the vacuum is maintained over time by the use of absorbing getters or a special hydrogen removal device, which uses reverse osmosis. The latter, although effective, has led to premature failures of the HCEs due to excessive thermal stresses. Because the vacuum adds significantly to receiver efficiency, this area requires close attention.

MIRROR FACETS

The current glass mirrors have an excellent reflective surface design; however, reduced mirror breakage would lead to reduced spare parts and maintenance costs. Although only on the order of 1% per year, this is significant in absolute terms because of the large number of mirror panels. The as-new reflectivity of the mirrors—about 94%—can be reestablished after soiling by high-pressure washing with demineralized water, and corrosion of the silver layer has not proven to be a problem in the desert environment. However, the method of attachment of the mirrors to the structure is not as reliable as required, especially in high winds, leading to excessive failures at the attachment interface. New advancements in the attachment method, or strengthened mirror panels, are required.

Front-surface mirrors or film reflectors could reduce the cost of the reflective surface in the solar field. This is an important goal, as the current design constitutes about 25% of the solar field cost. Although the reflector and structure form an integral unit to provide a highly reflective, accurately shaped parabolic trough, the issue is not simply one of a better reflective surface. A front-surface mirror on less-expensive glass (e.g., ordinary “green” glass) is one concept; silvered nonmetallic film on a structure consisting of both metallic and nonmetallic components is another. Fundamental cost-trade-off studies and advancement of the necessary components are required to explore cost-reduction approaches.

THERMAL STORAGE

Thermal storage can be valuable in a number of operating conditions, such as markets requiring production shifts (e.g., where demand peaks occur in the evening) or locations where partly cloudy conditions are common and short-term buffering would be beneficial (e.g., Hawaii). Trough system feasibility studies have identified the need for thermal storage systems in locations such as northern Morocco, Crete, and Hawaii. The system usually postulated is a concrete-oil-iron sensible-heat storage system, though LUZ proposed the use of phase-change salts in a cascade design. However, neither system is ready for deployment: serious engineering development and prototype implementation are required for the first, whereas more basic development is required for the latter. A molten salt similar to the one used in the Solar Two power tower system, but for lower temperatures, also deserves evaluation. Success in this area will significantly extend the marketability of trough technology.

Table 4. Component Development Metrics

		1990	2000	2005	2010	2015	2020
Collector							
Cost	$\$/m^2$	$300	$215	$160	$130	$120	$110
Annual Optical Efficiency		40%	44%	45%	47%	49%	50%
Mean Time Between Failures	hours	TBD*					
Mean Time to Repair	hours	TBD					
HCE							
Cost	$/unit	500-1,000	500	400	300	275	250
Failure Rate	%/yr	2%-5%	1.0%	0.5%	0.2%	0.2%	0.2%
Absorptance		0.94	0.96	0.96	0.96	0.96	0.96
Emittance		0.15	0.1	0.05	0.05	0.05	0.05
Operating Temperature	ºC	391	400	425	450	500	500
Mirror							
Cost	$\$/m^2$	120	90	75	60	55	50
Failure Rate	%/yr	0.1%-1.0%	0.10%	0.05%	0.02%	0.01%	0.01%
Reflectivity		0.94	0.94	0.94	0.95	0.95	0.95
Lifetime	years	20	25	25	30	30	30
Thermal Storage Cost	$\$/kWh_t$	-----	-----	25	15	10	10
Round-Trip Efficiency		-----	-----	0.80	0.90	0.95	0.95

*****to be done

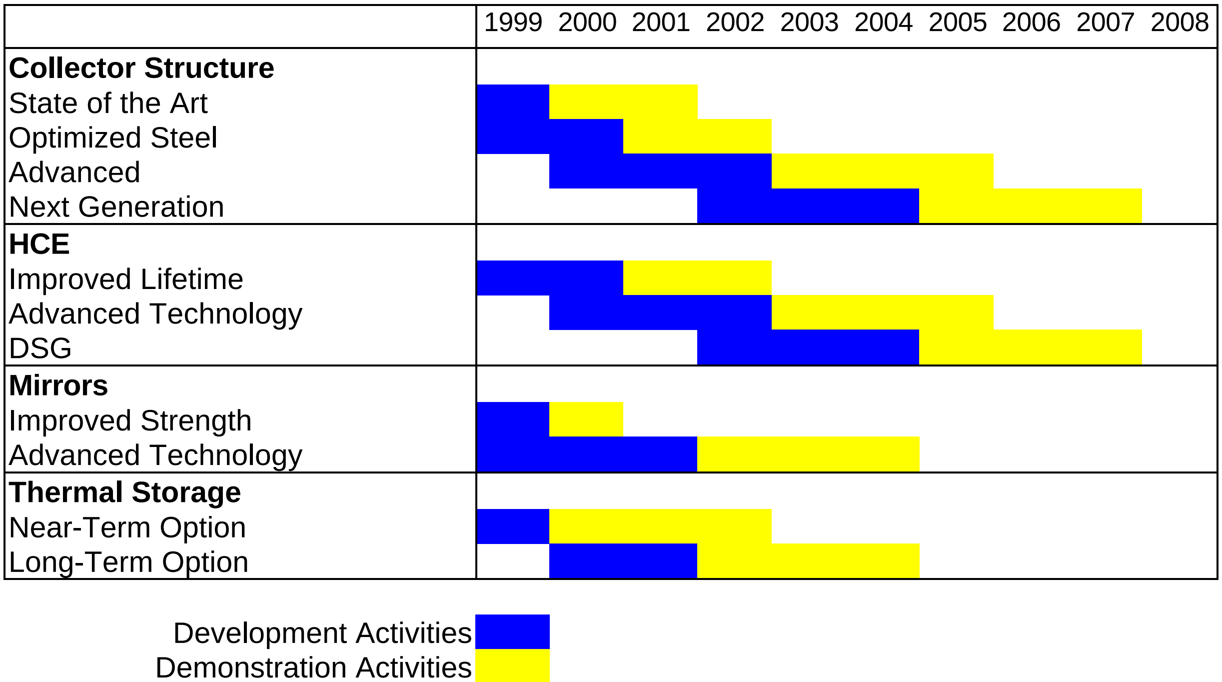


Figure 10. Component development activity time line

SYSTEM DEVELOPMENT

System development refers to all aspects of integrating solar and non-solar components and systems into a complete, fully integrated concentrating solar power plant product. Key areas of focus identified by the trough roadmap working group are solar power cycle optimization, design optimization, the development of standardized products, and improved integration of operation and maintenance activities. The key metrics for each of the system development areas focus are shown in Table 5. Time lines for various system development alternatives are shown in Figure 13.

SOLAR POWER CYCLE OPTIMIZATION

Power cycle optimization represents a significant opportunity for cost reduction and possibly performance improvement in future plants. Early SEGS plants basically used off-the-shelf power plant technology. At later SEGS plants, LUZ attempted to optimize the power cycle design through custom component selection. As a result, steam cycle efficiency was improved, parasitic electric consumption was reduced, and plant start-up improved. This resulted in the use of reheat steam turbine cycles and variable-speed pumps, for example. Additional improvements in plant efficiency and operation are thought to be possible through continued efforts in design integration.

- **ISCCS Design Integration**

  The ISCCS design represents one of the most important opportunities for near-term trough development. A small trough solar boiler added to a large combined-cycle system potentially offers significant advantages and represents a unique market niche. However, no detailed analysis has been performed to verify these assertions. A detailed design integration study is needed to look at turbine selection and performance issues, waste heat recovery unit design and operation, operating scenarios, and realistic emissions reduction potential.

Figure 11. SEGS VI power block

- **HTF System Design Optimization**

  Hydraulic and heat loss analyses are needed to optimize the layout of the solar field. Replacing flex hoses with ball joint assemblies may allow more collectors to be located in a single collector loop. The field layout optimization should also reconsider the use of rows of collectors instead of loops of collectors to eliminate the crossover pipe.

- **Rankine-Cycle Design Optimization**

  In recent years, significant reductions in cost have been demonstrated in conventional Rankine-cycle power plants. Rankine-cycle trough plants need to take advantage of these cost reductions. In addition, further optimization of the integration between the solar plant and the steam plant are possible. Key focus areas are start-up time and parasitic electric consumption.

➢ **Direct Steam Generation**

For a number of years it has been proposed that parabolic-trough systems will benefit in both performance and cost from generation of steam directly in the solar field, eliminating the expensive heat transfer fluid, the thermodynamic disadvantages of an intermediate heat transport system between the solar field and power block, and the HTF-to-steam heat exchangers. Although there are both pros and cons to this approach, it has generally been viewed positively by LUZ and the current trough development community. An important prototype development is currently under way at the Plataforma Solar de Almería, albeit limited in scope to one to two rows of collectors. Because some flow-instability studies have suggested that instabilities between a higher number of parallel rows may be the most important concern, further prototype systems may be required after testing at the PSA.

PLANT DESIGN OPTIMIZATION

Suppliers of power plant technologies have identified a number of approaches for reducing the cost of conventional power plants. These include a focus on simplifying the design, using standard off-the-shelf components, minimizing field construction requirements, and developing standard designs. Yet the current SEGS plants are a mixture of complex and custom system designs. Very little standardization exists between the solar field, HTF system, and steam cycle designs. Valves, piping, and instrumentation are often different. Although LUZ made significant efforts to reduce complexity at the later plants (eliminating flow balance valves at SEGS IX and simplifying the steam plant design through elimination of the gas boiler), significant opportunities exist for design improvement.

➢ **Plant DFMA Methodology**

DFMA is a design review process used to simplify designs and to reduce the cost of a design. DFMA focuses on minimizing part count, eliminating custom or specialized components, and minimizing manufacturing steps. In the case of parabolic trough plants, this process could benefit many steps of the design, manufacture, and construction of a plant. In add-ition, the DFMA process should examine design issues that will affect the operation and maintenance of the plant. A formal DFMA study would seek opportunities to minimize the use of any unique or specialized components to minimize the number of sizes and vendors and attempt to standardize commodity items such as piping, valves, valve actuators, and instrumentation. In

Figure 12. Power block piping

addition, efforts should be made to minimize site construction requirements, use prefabricated or skid-mounted components and systems where possible, minimize the use of instrumentation and valves, and minimize piping runs.

- **Computerized Design**

  Significant advancements have been made in the last 10 years in developing computerized design tools. These tools not only allow for much quicker design and manufacture of components, but also for engineering analysis to be performed on the design. For example, wind-load testing can be performed on a concentrator design to make sure each component is designed (and not overdesigned) to handle the appropriate loads.

STANDARDIZED SOLAR BOILER PRODUCTS

In today's competitive marketplace, one of the approaches being used to reduce the cost of power generation technologies is to develop standard designs. Bechtel, for example, has its "Power Line" standard power plant designs that it uses to bid new projects. The concept is to develop a detailed design package that is 90% complete and only needs minor additions to account for the unique aspects of the site, infrastructure, and other local requirements. LUZ had developed a standard 80-MW_e design for the SEGS X–XII projects located at Harper Lake, California. However, each project under consideration today seems to be heading toward a customized design for each location. The industry must move toward standard products and designs that can be used for any location.

The following solar boiler products have been identified as the most probable designs for general application:

- Small Rankine plant for stand-alone applications (30–50 MW_e)
- Large Rankine plant for solar power park applications (150–200 MW_e)
- Small ISCCS for large fossil combined-cycle plants (30–50 MW_e solar equivalent—the same solar plant as the small Rankine system).

Standard design packages should be developed for each of the standard solar boiler products identified above. In addition, we need to start educating decision makers to stop focusing on small stand-alone Rankine plants and to start considering large solar power parks.

OPERATION AND MAINTENANCE

Operation and maintenance is an important element of the levelized electricity cost for concentrating solar power plants because of the large number of parts in the solar field. Important lessons have been learned and advancements made through the cooperative KJC Operating Company/Sandia program on O&M cost reduction, pointing to steps that need to be refined and implemented in future systems. Guidelines need to be developed to allow designers to include O&M considerations in the design phases, including such features as redundancy, ease of access, rapid replacement, and facilitation of nighttime maintenance.

- **Specialized O&M Equipment**

  Development of specialized industrial-grade O&M equipment can significantly reduce O&M costs at solar power plant facilities. Specialized O&M equipment includes mirror washing machines, tools for rapid reflectivity measurements, collector alignment jigs and tools, and HTF evacuation trailers.

- **Plant Information Management**

  Optimum management of a solar plant requires rapid access to plant information. Given the complex and distributed nature of a solar power plant, extensive information gathering, analysis, and reporting systems are required. This information includes plant operating data, engineering designs and specifications, maintenance data, spare parts inventory, procurement status, and all financial information. These are normally part of the conventional power plant management system, but must be modified to adequately handle a distributed solar field as well. In particular, tracking and handling of solar field maintenance requirements and planning can be critically important.

- **O&M Procedures and Training**

  Given the nonstandard nature of these projects, custom solar field and power plant O&M training manuals and procedures should be developed. The KJC/Sandia cooperative program mentioned above has made an excellent start in this area. Availability of these types of documents are critical for rapid start-up of new plants and the ability to obtain design-level performance from the plants.

Table 5. System Development Metrics

		1990	2000	2005	2010	2015	2020
Design Optimization							
Small Solar Boiler Cost	$\$/kW_e$	2500	1600	1100	830	730	630
Large Solar Boiler Cost	$\$/kW_e$		1350	950	720	600	500
Annual Solar Energy Conversion Efficiency	%	29	32	34	35	36	37
Start-up Time	hours	TBD					
Solar O&M							
O&M Cost	¢/kWh	1.00	0.90	0.75	0.60	0.55	0.50
Staffing Requirement	$\#/MW_e$	1.00	0.90	0.75	0.60	0.55	0.50
O&M Equipment							
Wash Rate	m^2/staff day	10,000	30,000	50,000	50,000	50,000	50,000
Average Cleanliness Factor		0.95	0.95	0.96	0.96	0.96	0.96
Loop Evacuate/Fill	hours	TBD					
Time to Align	staff hours	TBD					

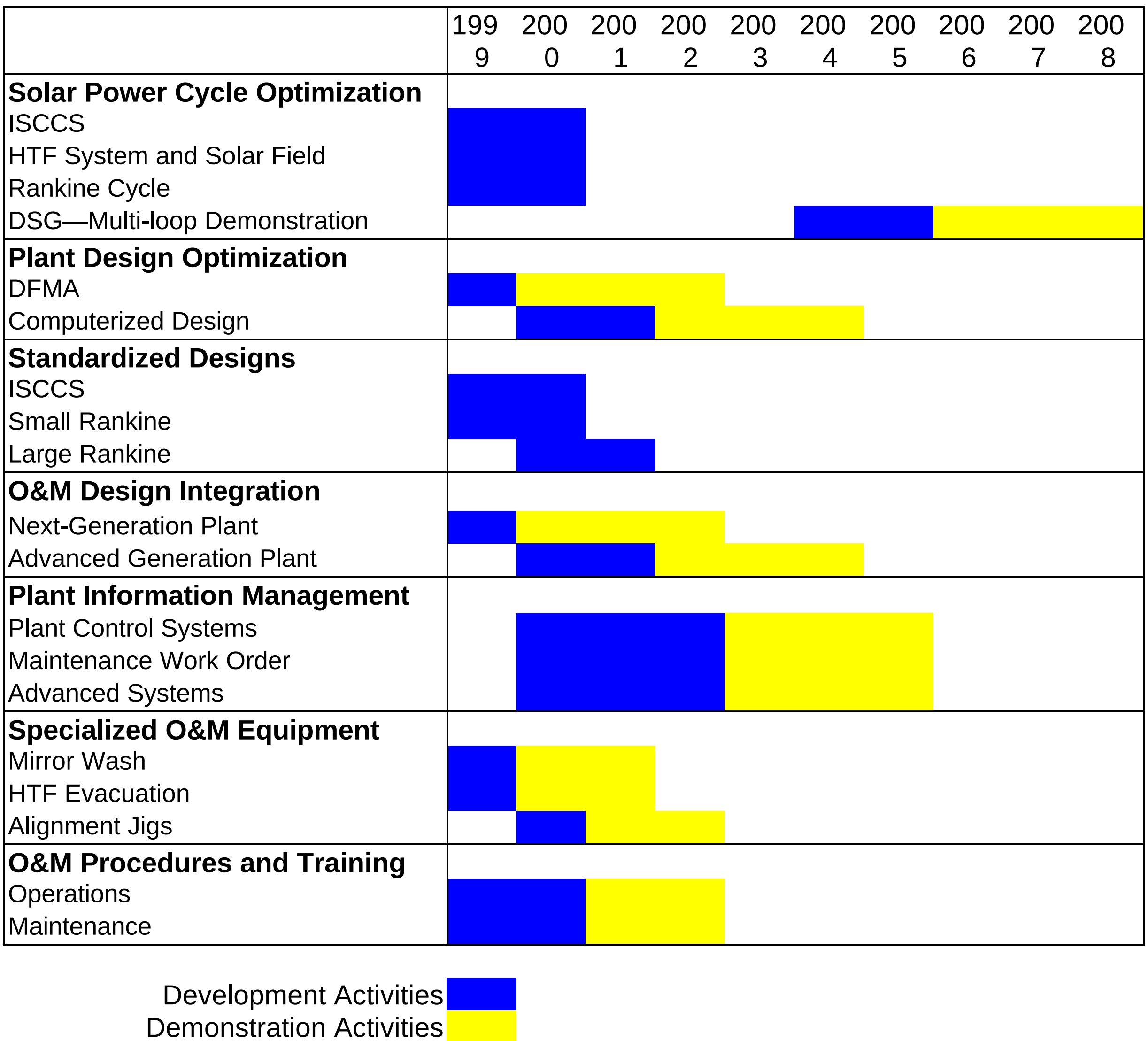


Figure 13. System development activity time line

MARKET DEVELOPMENT

Market development refers to all aspects of marketing and developing solar power projects. Key areas of focus identified by the workshop participants are the market creation, financing issues, risk reduction, taxation policy, resource assessment, and analysis tools.

MARKET CREATION

Although a number of countries are interested in parabolic-trough technology, no real projects are currently under way. Representatives from many countries express interest yet do not have the mandate from their government or power market environment to facilitate a real project opportunity. In this type of environment, many countries are looking for small custom pilot projects to evaluate. In addition, projects of this type must typically make their way through a complex maze of government bureaucracy full of potential pitfalls. This type of environment is not conducive to creating a healthy market or providing an environment that will help drive technology prices to competitive levels.

- **Market Aggregation**

  One approach under consideration is to aggregate GEF grant-type projects into a single-project, multiple-build scenario. In essence, this concept would develop three trough projects in different countries (though, perhaps, in the same region). The projects would be developed and financed as a single package and built in a phased approach. This approach would help reduce the cost of the projects and allow for lessons learned at one project to be used in the next.

- **Solar Power Parks**

  Although much effort is currently focused on developing the next project, it is important to look at the long-term market. If trough technologies are to eventually provide a significant contribution to the global power mix, they will need to be developed in large solar power park environments. Solar power parks offer a number of advantages through economies of scale and opportunities for continuous builds that can help drive prices down and overall efficiency up. The current focus should be on identifying the best regions and beginning to develop the policies that would enable the power parks to be developed.

FINANCING ISSUES

One of the key issues facing the development of large, grid-connected concentrating solar power technologies is the amount of capital resources required to finance projects. If the technology is successful, a multibillion-dollar capital market could emerge. As such, it is important to understand and address key issues relevant to trough technologies.

- **Low-Cost Capital**

  Access to low-cost capital is essential for capital-intensive technologies such as parabolic-trough power plants. Currently, projects require a risk premium on both equity and debt over the rates charged to conventional power technologies. Efforts must be made to reduce the risk premium and actively search for low-cost capital that is available to environmentally friendly technologies.

- **Grants**

  Several grants can be used to buy down the cost of environmentally friendly technologies. The Global Environment Facility,[1] as part of its effort to foster technologies that can help mitigate greenhouse gases, is one such opportunity. The European Union's Thermie project provides another grant opportunity.

- **Multi-Institutional Financial Facility**

  Complex mixtures of institutions usually participate in the financing of large power projects. The integration of these participants into a single financing package can have a detrimental impact on the amount of time required to achieve financial closure on a project, especially when the project is the first of a kind. The advanced development of a multi-institutional financial facility that would be used to finance a number of parabolic-trough projects could both speed the process and reduce the transactional cost of financing each project.

RISK REDUCTION

Risk is a general term used to describe the uncertainties that could have a negative financial impact on a project. Risk can result from uncertainties in cost, schedule, technology, resource availability, power sales, financial parameters, political stability, or location. When a project is being considered, investors (debt and equity) analyze the project to evaluate the financial merit versus the risk. If the risk is high, the financial return must be sufficiently high to justify the potential risk. Thus, increased risk results in increased cost of capital. Unfortunately, projects using new technologies and projects in developing countries are usually considered high risk. It is important to minimize project risk whenever possible.

- **Technology Risk**

  Technology risk is one of the key barriers to the development of new technologies. Financial institutions prefer to take no technology risk when possible and otherwise like to see any technology demonstrated for a number of years before investing in it. In place of demonstrated operating experience, financial institutions like to see a performance guarantee backed by a large corporation with deep pockets. LUZ, for example, was forced to issue letters of credit to cover potential warranty payments. Future projects will need to develop some approach to ensure investor confidence in trough technology. This will likely include some form of performance warranty with appropriate backing. One important contribution to reducing risk of future projects is the development of a fund to act as a guarantee for future projects. Other opportunities for reducing risk include building more conservatism into the design and performance projections, and using a team with experience from the original SEGS plants. Finally it is important to make sure that all new technologies are sufficiently demonstrated prior to introduction into a commercial project.

- **Development Risk**

[1] See World Bank/GEF Operational Program Number 7—Reducing the Long-Term Costs of Low Greenhouse Gas-Emitting Energy Technologies.

Parabolic-trough technologies carry many development risks. First, most market opportunities are believed to be in developing countries. These markets often have a large amount of risk because of political and or economic instability, currency exchange rates, the state of maturity of their private power industry, and the general issues of international business in a developing country. The general trend toward competitive markets is causing another key issue to surface—the lack of long-term power purchase agreements.

TAXATION POLICIES

In the global marketplace, taxation policies have a significant influence on major investment decisions. As a result, taxation policies can indirectly dictate which technologies will succeed. In the case of electric generation technologies in the United States, federal, state, and local tax codes tend to show a preference for expense-intensive technologies such as conventional fossil-fueled power plants over capital-intensive technologies such as parabolic-trough power plants. The special tax incentives that existed in the 1980s pushed the spectrum to the other extreme and encouraged the development of the SEGS plants.

There are two general reasons to focus on tax incentives. The first is to encourage the development of the technology because it provides special societal values that would not otherwise be addressed by the marketplace. These include the creation of new jobs, energy resource diversification, and potential environmental benefits. The second reason for special tax incentives is in cases in which the current tax code would unfairly penalize a technology compared to another technology that provides a similar service.

Many of the special taxation policies that stimulated trough development in the 1980s have been reduced or eliminated. Federal investment tax credits have been reduced to 10%, although federal law still allows accelerated depreciation of solar equipment. California state investment tax credits were eliminated, as was the solar property tax exclusion. As a result, new CSP technologies will pay a higher tax burden than conventional fossil technologies.

- **Investment and Production Tax Credits**

  Investment tax credits were a big part of the success of the SEGS projects. Early projects were largely driven by state and federal investment tax credits that were as high as 55% of the total project investment cost. Investment tax credits are intended to encourage the development of new technologies. However, in the case of wind power, investment tax credits resulted in a lot of tax-driven projects that either operated poorly or never operated at all. As a result, electricity production-based tax credits are being used for wind power technologies today. Given the current levels of investment and production tax credits, solar technologies would be better served by switching to the same production-based tax credits that wind technologies currently receive.

- **Solar Property Tax Exemption**

  At a solar power plant, the solar field can be viewed as a 30-year supply of fuel. Without special tax exemptions, a solar power plant would be forced to pay property tax on the solar field land and equipment. This would be equivalent to a conventional plant having to pay property tax on a 30-year supply of fuel. Because the solar field represents a major portion of the total capital cost of the plant, property tax on this equipment represents a significant cost penalty for solar technologies. In the past, California exempted large-scale CSP technologies from paying property tax on solar-related property. In the LUZ projects, this was assumed to include all land and equipment except those related to the backup fossil-fired systems. This means that the conventional part of the steam plant also received the property tax exemption because it was necessary for solar operation. This may give an unfair tax advantage to the solar plant and thereby penalizes the local government that operates on the income from property taxes. Future efforts may be better served by only asking for the property tax exemption on the "fuel" portion of the solar plant, and not including the conventional system. This approach simplifies the issue, especially when considering large hybrid systems that have small solar contributions.

- **Sales Tax Exemption**

  This exemption is similar to the property tax exemption. Because fossil fuels do not pay sales taxes, solar equipment should be exempted from sales tax. Paying sales tax on the solar property is comparable to a fossil plant having to pay sales tax on a 30-year fuel supply up front, while the plant is under construction. A property tax exemption on solar equipment would allow solar technologies to compete with fossil technologies.

RESOURCE ASSESSMENT

Access to high-quality direct normal insolation (DNI) data is essential for deploying parabolic-trough plants. Generally, there is either no measured solar resource data or only limited data available for most promising international locations. The desired format and accuracy of the DNI data depends on the stage of a project's development. For scoping studies, which look at the feasibility of a technology in a specific region, maps that show average daily DNI totals for each month and on an annual basis (+/-15% accuracy) are probably sufficient. For prefeasibility studies, hourly DNI data sets (+/-10% accuracy) are necessary. For feasibility and design studies, hourly or smaller time increment data (+/-5%) are needed, with some accounting for potential inter-annual variability.

- **High-Resolution DNI Maps and Data**

  NREL's Renewable Energy Resources group has generated a number of DNI and cloud cover maps for many promising locations (see Figure 14). These maps have proven to be very valuable to industry. This effort should be expanded to complete DNI maps for all promising regions and to utilize new higher-resolution satellite data to increase spatial and temporal resolution of the maps.

- **Meteorological Data Generator**

  Given the limited ground measurement data available and the time required for collecting a representative data set (7–10 years), it is desirable to have the ability to create an hourly DNI data set for any given location. The same data used to generate the DNI maps could be used to create hourly data sets.

- **Standard Meteorological Site Instrumentation**

  In most cases, it will be desirable to install some form of DNI, temperature, and wind measurement instrumentation at a site to verify the meteorological data prior to installation of a plant. Standardized designs, equipment, procedures, and Quality and Assurance processes should be developed and used.

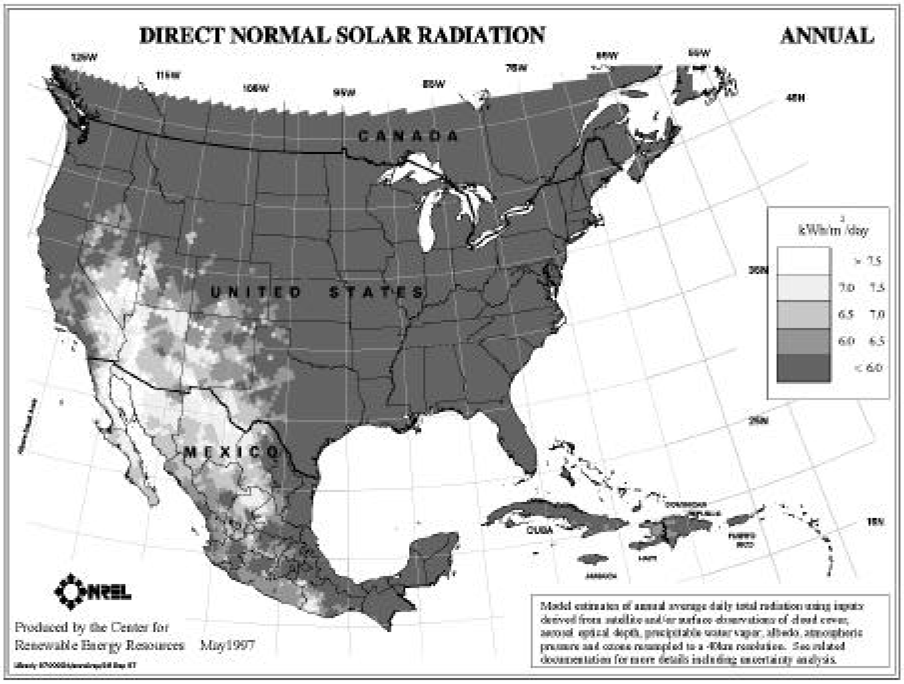


Figure 14. Annual direct normal solar radiation for the United States and Mexico

ANALYSIS TOOLS

Rapid and accurate analysis of project opportunities is very important. There are a number of tools for design and performance analysis of concentrating solar power technologies. Unfortunately, many of these tools are old and complex and in many cases are difficult to run on modern computer hardware and operating systems.

- **Simple Prefeasibility Tools**

  Industry would like to have a simple tool that can be used to perform a quick first-order feasibility analysis of CSP technologies for specific sites. The SolWin software currently being developed by DLR/SunLab is an example of this kind of tool.

- **GIS Analysis**

  In recent years, geographical information systems (GIS) have become an important data analysis tool for improving many business decisions. GIS can be used to account for many geographically variable factors such as meteorological data, site infrastructure, topography and land use, and other resource-based data. For solar plants, GIS can provide an opportunity to improve siting analysis studies. For example, GIS analysis could be used to identify the site that would produce the lowest-cost solar electricity.

ROADMAP INITIATIVES

WHAT NEXT?

Opportunities exist now for major advancements in the deployment of trough technology, based on bold steps on technology, system, and market development fronts. The technology has been commercially successful in early deployment; global environmental issues remain a strong concern, favoring renewable energy systems; and international demand for new power generation has changed the nature of power system implementation. Three initiatives have been initially identified to help implement this roadmap and move trough technology forward.

- **Near-Term Trough Development**

  The United States is uniquely positioned to play a key role in the future development of trough technologies as a result of the experience and expertise gained at the current SEGS plants. A U.S. trough R&D initiative could be used to expand U.S. industry involvement in worldwide trough deployments and to help advance the state of the technology. The specific objectives of the U.S. trough R&D initiative are:

  - *Bring industry together to form a trough consortium that will aggressively pursue projects.* Given the high up-front cost of power plant development, most companies are currently not willing to make the investment necessary on their own to push trough development forward. Although many look for the next "LUZ" to come forward to develop the next project, power plant development today may require an integrated supply and development consortium to share the risk of building new power plants. This initiative would encourage the development of a formalized parabolic-trough supply consortium that could supply trough power plants.

  - *Provide a mechanism for continued development of trough technology that supports the needs of industry.* Although the EuroTrough project is focusing on developing the next-generation tough collector, there is much research and development that needs to be done to advance the current state of the art in parabolic-trough technology to support the next trough plants built. Given the high-risk nature of future trough development, most companies are currently not willing to invest significant amounts of money to advance the state of the technology. The USA Trough initiative will provide seed money to encourage development activities necessary to support the next trough plants built. Many lessons have been learned from the existing SEGS plants, which can improve the next plants built. This initiative would focus on those lessons and make sure they are applied in the next trough plants built.

  - *Increase U.S. content of domestic and international trough projects.* Although current trough plant designs utilize mirrors from Germany (Pilkington) and receiver tubes from Israel (SOLEL), the majority of system cost (over 75%) comes from other sources. For the next plants built, the mirrors and receiver tubes would most likely come from those same sources. U.S. companies could provide much of the remaining system for domestic projects, and even a significant portion for international projects. However, for this to occur, U.S. industry must be an active participant in future developments, otherwise other international firms are likely to take their place. This initiative would also focus on increasing the U.S. scope and supply of trough power plants for both domestic and international projects.

- *Provide a mechanism for U.S. companies to collaborate with Europeans, Israelis, and others to promote development of international trough projects.* Currently, a number of international companies are working to advance the state of parabolic-trough collector technology. In many cases, this work has proceeded along divergent paths, which could lead to confusion and inefficient use of limited resources. The participants in the trough workshop felt that strengthened collaborations between all parties could allow for a more focused and unified plan with the greatest chance of success. As such, the USA Trough project should include collaborations with the EuroTrough group and the Israeli firm that continues to advance the state of the LUZ trough technology. Possibly more importantly, these collaborations should also include activities that focus on the development of international trough project opportunities.

➢ **Strategic Alliances and Market Awareness**

Although parabolic-trough technology represents the most successful and lowest-cost solar power technology available today and for the foreseeable future, it has limited stakeholder support from the renewable community, and is often portrayed as a dated technology with no place in the evolving power environment. Although the participants in the parabolic-trough workshop believe that many of these perceptions are incorrect, it is clear that these issues need to be addressed and efforts need to be made to better understand the potential and the benefits of parabolic-trough technology. Unfortunately, these are not simple issues to sort out.

One approach being considered is to convene a new workshop that would address many of the market-related issues and barriers that are hindering the deployment of parabolic troughs and other CSP technologies. Key stakeholders and experts would be brought together to help create a vision and a plan to carry trough development forward.

The specific objectives of the workshop would be to:

- Look for opportunities to encourage the development of solar power markets both domestically and abroad
- Look for opportunities to address financing and taxation issues
- Develop a new vision for trough power and provide a mechanism for disseminating information to key stakeholders.

Those at SunLab believe that parabolic-trough technology represents the lowest-cost near-term option for solar power. Support for trough technology today could help pave the way for other, less mature technologies such as power towers and dish/engine systems to be more readily accepted in the future.

➢ **SEGS Collaborations**

The existing SEGS facilities provide an important showcase for trough technology that is important for future trough development. In addition, access to O&M experience at these plants provides SunLab a unique opportunity to observe how real commercial systems and components perform after extended operation. A strategic opportunity exists for collaborations between SunLab and the existing SEGS facilities. This will allow the laboratories to gain a better understanding of system performance, reliability, and cost, and the existing facilities to benefit from the technical experience and capabilities of SunLab.

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13. ABSTRACT *(Maximum 200 words)* Technology roadmapping is a needs-driven technology planning process to help identify, select, and develop technology alternatives to satisfy a set of market needs. The DOE's Office of Power Technologies' Concentrating Solar Power (CSP) Program recently sponsored a technology roadmapping workshop for parabolic trough technology. The workshop was attended by an impressive cross section of industry and research experts. The goals of the workshop were to evaluate the market potential for trough power projects, develop a better understanding of the current state of the technology, and to develop a conceptual plan for advancing the state of parabolic trough technology. This report documents and extends the roadmap that was conceptually developed during the workshop.

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