Federal Technology Alert

A publication series designed to speed the adoption of energy-efficient and renewable technologies in the Federal sector

Prepared by the New Technology Demonstration Program

Parabolic-Trough Solar Water Heating

Renewable technology for reducing water-heating costs

Parabolic-trough solar water heating is a well-proven technology that directly substitutes renewable energy for conventional energy in water heating. Parabolic-trough collectors can also drive absorption cooling systems or other equipment that runs off a thermal load. There is considerable potential for using these technologies at Federal facilities in the Southwestern United States or other areas with high direct-beam solar radiation. Facilities such as jails, hospitals, and barracks that consistently use large volumes of hot water are particularly good candidates. Use of parabolic-trough systems helps Federal facilities comply with Executive Order 12902's directive to reduce energy use by 30% by 2005 and advance other efforts to get the Federal government to set a good example in energy use reduction, such as the 1997 Million Solar Roofs Initiative.

This *Federal Technology Alert* (FTA) from the Federal Energy Management Program (FEMP) is one of a series on new energy-efficiency and renewable energy technologies. It describes the technology of parabolic-trough solar water-heating and absorption-cooling systems, the situations in which parabolic-trough systems are likely to be cost effective, and considerations in selecting and designing a system. This FTA also explains energy savings performance contracting (ESPC), a method for financing Federal facility energy conservation and renewable energy projects. ESPC is available for parabolic-trough systems and offers many important advantages.

Parabolic-trough collectors use mirrored surfaces curved in a linearly extended parabolic shape to focus sunlight on a dark-surfaced absorber tube running the length of the trough. A mixture of water and antifreeze or other heat transfer fluid is pumped through the absorber tube to pick up the solar heat, and then through heat exchangers to heat potable water or a thermal storage tank. Because the trough mirrors will reflect only direct-beam sunlight, parabolic-trough systems use single-axis tracking systems to keep them facing the sun.

Application

Use of parabolic-trough systems is more limited by geography and system size than are other types of solar water heating, but where parabolic troughs are usable they often have very attractive economics. As concentrating systems, parabolic troughs use only direct radiation, so are less effective

Warren Gretz, NREL/PIX01019

where skies are cloudy and much more likely to be effective in areas such as the Southwestern United States that have good solar resources dominated by direct-beam sunlight. It is also more cost effective to build large systems that will be used on a continuous basis. Parabolic-trough solar water heating (and air-conditioning) is therefore most effective for large, 7-days-a-week, domestic hot-water users, such as Federal hospitals, prisons, or barracks. (For most situations, about 500 gallons per day of hot water use is a minimum for a viable parabolic-trough system.) Troughs also work well for district space or water heating systems serving multiple buildings from a central steam or hot-water plant. The cost of the collector system is a main economic factor, but as with any capital-intensive energy conservation or renewable energy installation, the critical factor is likely to be current cost of energy. Facilities that pay high utility rates for conventional water heating will always be the best prospects for cost-effective parabolic-trough solar water heating or air-conditioning.

Technology Selection

The FTA series targets energy efficiency and renewable energy technologies that appear to have significant untapped Federal-sector potential and for which some Federal installation experience exists. Many of the alerts are about new technologies identified through advertisements in the *Commerce Business Daily* and trade journals, and through direct correspondence soliciting technology ideas. This FTA describes a renewable energy technology with known energy, cost, and environmental benefits that has substantial untapped potential for the Federal sector. The U.S. Department of Energy has signed a "Super ESPC" indefinite delivery/indefinite quantity (IDIQ) contract with Industrial Solar Technology Corporation (IST), the only current manufacturer of parabolic-trough collectors. This contract encourages Federal facilities to use parabolic-trough technology by greatly facilitating financing and implementation through ESPC.

First, a preliminary analysis should be conducted on whether solar water heating generally or parabolic-trough systems particularly would be cost effective for any situation on the basis of energy load, conventional energy costs, and the location's solar radiation. Software that performs this task is available from FEMP's Federal Renewables Program at the National Renewable Energy Laboratory (NREL). (See Federal Program Contacts on page 20.)

IST can more specifically assess prospects for a trough system at a particular facility. The FEMP Help Desk can provide manuals and software for detailed economic evaluation and more information on ESPC financing. (See manufacturer's information and Federal Program Contacts.) ESPC, which IST can provide under the Super ESPC IDIQ contract, allows Federal facilities to repay contractors for solar water-heating systems through bills for energy savings instead of paying for initial construction. The Super ESPC with IST offers many significant advantages:

- No financial outlay by the facility to determine feasibility
- No need to seek competitive proposals
- Pre-identified savings
- No responsibility for operation and maintenance
- The current system stays in place as a backup for high reliability
- Guaranteed savings
- The facility pays only for energy savings it realizes
- The facility can benefit indirectly from tax incentives available only to private companies
- The facility can get credit for energy use reduction in compliance with Executive Order 12902 (mandatory 30% reduction by 2005) without reducing hot-water use
- Switching to a more economical conventional water heater or other related efficiency measures can be included in and financed by the ESPC project.

Case Studies

This FTA describes two examples of parabolic-trough solar water heating installations by IST on a payment-for-energy-savings basis.

The first case study is the parabolic-trough system at the Adams County Detention Facility in Brighton, Colorado, which has been operating since 1987. The 7200-square-foot (669-square-meter) collector system displaces about 2 billion British thermal units (Btus) per year of natural gas water heating, about 40% of that needed for the more than 800 inmates.

In the second case study, IST is just starting construction of 18,000 square feet (1672 square meters) of parabolic-trough collectors to provide domestic hot water for the Federal Correctional Institution in Phoenix, Arizona. Although this project was negotiated prior to granting of the IDIQ contract, it is being built on an ESPC basis. The facility, which houses about 1200 inmates, now depends on electric-resistance water heating. The new solar system was specifically designed to avoid peak demand charges from the utility by using a 21,000-gallon (79,494-liter) thermal storage tank controlled to deliver solar heat during facility peak periods. This will allow the system to meet a projected 82% of the facility's hot-water use. The solar system will displace 15 billion Btus per year of fossil fuel combustion, avoiding more than 80,000 kilograms of nitrogen oxides and nearly 100,000 kilograms of sulfur dioxide pollution over the project's life.

Implementation Barriers

There are no technological barriers to using parabolic-trough solar water heating. However, trough collectors are by nature limited geographically to areas with high direct-beam solar resources. They are also by nature more cost effective for facilities that use large amounts of hot water 7 days a week. But, because they directly replace conventional energy use, parabolic-trough collectors will provide energy savings and environmental benefits proportional to their use. From a financial perspective, however, relatively high conventional water-heating costs will be the biggest enabling factor. ESPC financing also provides advantages such as tax breaks for private investors that are important to project economics.

Improvements in reflective and absorbent coatings and development of triple-effect absorption cooling will incrementally improve economics, but there are no known technological developments that could dramatically lower the cost of parabolic-trough solar water-heating or absorption-cooling systems. Much higher sales volume would likely lower costs, but that would depend on the new technology being able to consistently compete with low-cost conventional energy. Parabolic-trough solar water heating is likely to remain most cost effective where natural gas is not available or is relatively expensive, and where consistent high-volume use provides economies of scale.

Federal Technology Alert

Parabolic-Trough Solar Water Heating

Renewable technology for reducing water-heating costs

Warren Gretz, NREL/PIX00327

Parabolic-trough solar water-heating system for Adams County Detention Facility, Brighton, Colorado.

Abstract

Parabolic-trough solar water heating is a well-proven renewable energy technology with considerable potential for application at Federal facilities. For the United States, parabolic-trough water-heating systems are most cost effective in the Southwest where direct solar radiation is high. Jails, hospitals, barracks, and other facilities that consistently use large volumes of hot water are particularly good candidates, as are facilities with central plants for district heating. As with any renewable energy or energy efficiency technology requiring significant initial capital investment, the primary condition that will make a parabolic-trough system economically viable is if it is replacing expensive conventional water heating. In combination with absorption cooling systems, parabolic-trough collectors can also be used for air-conditioning.

Industrial Solar Technology (IST) of Golden, Colorado, is the sole current manufacturer of parabolic-trough solar water heating systems. IST has an Indefinite Delivery/Indefinite Quantity (IDIQ) contract with the Federal Energy Management Program (FEMP) of the U.S. Department of Energy (DOE) to finance and install parabolic-trough solar water heating on an Energy Savings Performance Contract (ESPC) basis for any Federal facility that requests it and for which it proves viable. For an ESPC project, the facility does not pay for design, capital equipment, or installation. Instead, it pays only for guaranteed energy savings. Preparing and implementing delivery or task orders against the IDIQ is much simpler than the standard procurement process.

This *Federal Technology Alert* (FTA) of the New Technology Demonstration Program is one of a series of guides to renewable energy and new energy-efficient technologies. It is designed to give Federal facility managers the information they need to decide whether they should pursue parabolic-trough solar water heating or air-conditioning for their facility and to know how to go about doing so. Software available from FEMP's Federal Renewables Program at the National Renewable Energy Laboratory (NREL) enables preliminary

analysis of whether parabolic-trough collectors would be cost effective for any situation based on minimum data. (See Federal Program Contacts on page 20.)

This FTA describes the technology of parabolic-trough collectors, solar water-heating systems, and absorption cooling. It points out the types of situations where parabolic-trough solar water heating is most likely to be cost effective and describes the ESPC process available to Federal facilities for parabolic-trough projects. In addition, sidebars provide indicators that a system will be effective, tips for ensuring successful operation, and sources for determining system data. Case studies for a 10-year-old system at a county jail and for one just starting construction at a Federal prison include economic evaluation data.

Contents

This page left blank intentionally

About the Technology

The basic principle of solar water heating is intuitive and straightforward. A dark surface is positioned to absorb sunlight and convert it to heat. Water or another heat transfer fluid passes along that hot surface to pick up the heat—either for direct use or for transfer through a heat exchanger to the end use. Simple solar water heating has been around since ancient times. More than a million solar water heaters have been installed in the United States. Most of these were installed during the 1980s, when tax credits were available, and nearly all use "flat-plate" collectors, which essentially place the absorber surface inside an insulated box. (See Figures 1 and 2.)

Parabolic-trough solar water-heating systems carry solar water-heating technology a step further by concentrating the sunlight before it strikes the absorber. Mirrored surfaces curved in a parabolic shape linearly extended into a trough shape focus sunlight on an absorber tube running the length of the trough (Figure 3). A heat transfer fluid—usually a solution of water and antifreeze—is pumped around a loop through the absorber tube of the collector. There it picks up heat and then goes to a heat exchanger where it either directly heats potable water or heats a thermal storage tank. (See Figure 4.)

As concentrating systems, parabolic troughs use only direct radiation. Unlike flat-plate collectors, they cannot use diffused sunlight. Using tracking systems makes up for this inability to collect more of the direct light, but cloudy skies become a more critical factor. Parabolic-trough collectors are therefore much more likely to be effective in areas such as the Southwestern United States that have good solar resources dominated by direct-beam sunlight. (See Figures 5 and 6.)

To make efficient use of the tracking systems and of the much higher temperatures that can be generated by a concentrating system, it is more cost effective to build a larger system that will be used continuously. Parabolic troughs are generally impractical for small systems, but can be much less expensive than flat-plate collectors if the system is large enough. Parabolic-trough

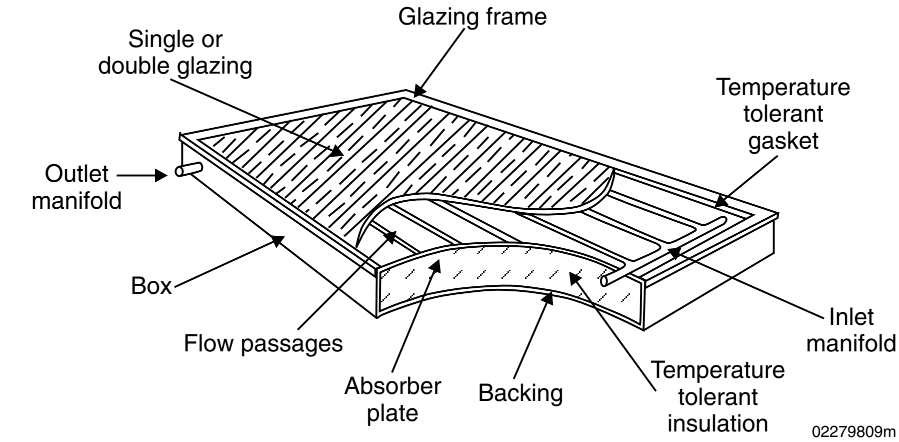


Figure 1. Flat-plate collector.

Figure 2. Flat-plate collector array providing domestic hot water for U.S. Environmental Protection Agency headquarters in leased space in the Waterside Mall in Washington, D.C.

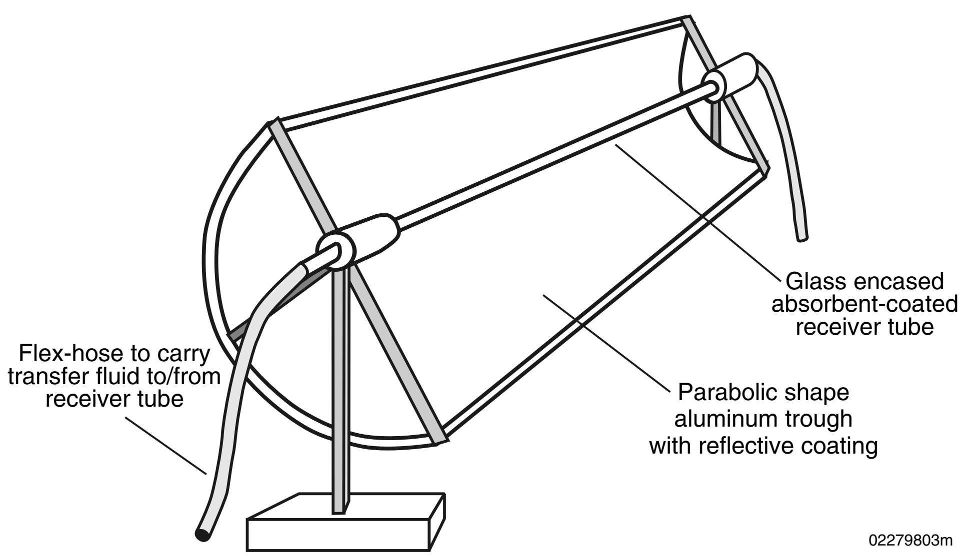


Figure 3. Parabolic-Trough Collector

Figure 4. Parabolic-trough array for domestic hot-water service for the Jefferson County Detention Facility, Golden, Colorado.

solar water heating is therefore an effective technology for serving large, 7-days-a-week, domestic hot-water users such as Federal hospitals, prisons, or barracks.

Application Domain

The Federal government provides energy to approximately 500,000 buildings and facilities with a total floor area of about 3 billion square feet (280 million square meters). In fiscal year (FY) 1995 the Federal government spent $3.6 billion for 365 trillion British thermal units (Btu) of energy for those buildings and facilities. Water heating accounts for a substantial portion of energy use at many Federal facilities. Nationwide, approximately 18% of energy use in residential buildings and 4% in commercial buildings is for water heating. Federal facilities with large laundries, kitchens, showers, or swimming pools will likely devote even more energy to water heating. Parabolic-trough solar water-heating systems can efficiently provide half or more of the hot-water needs of many Federal facilities—cutting back on utility charges and on pollution.

As for any solar water-heating system, parabolic troughs are most likely to be cost effective for facilities that otherwise must heat water with expensive conventional energy. As Table 1 on page 8 shows, parabolic-trough collector systems can provide hot water at a levelized cost of $6 to $12 per million Btu for most Southwestern areas. Parabolic-trough solar water-heating is therefore well worth investigating for economic viability if the available conventional water heating uses electricity or fossil fuel

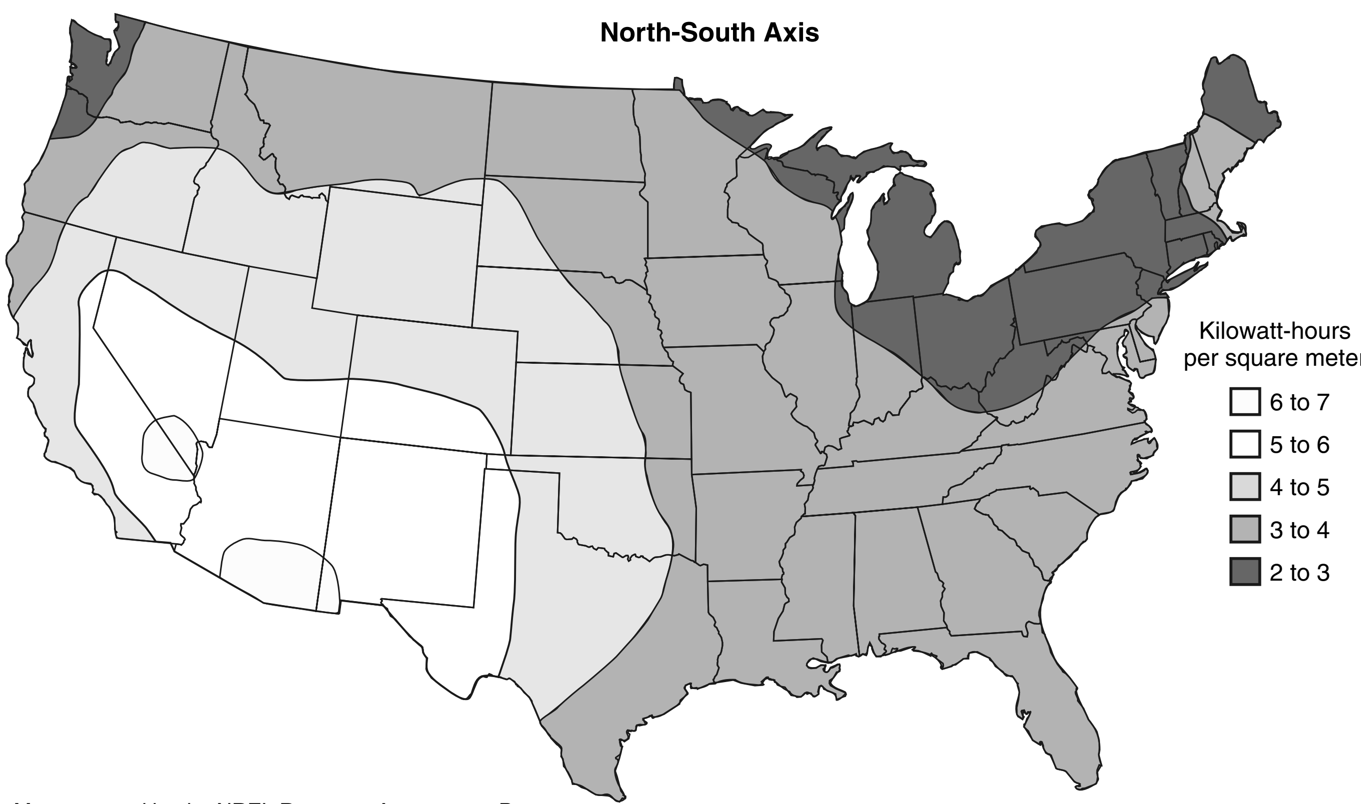


Figure 5. Average daily direct-beam solar radiation for horizontal, north-south, single-axis tracking parabolic trough collector systems. A north-south axis is better in summer and on a yearly average basis than an east-west axis.

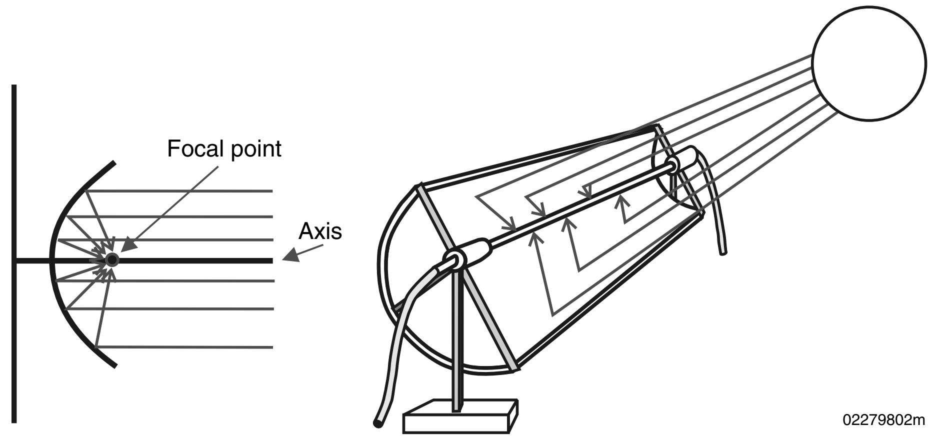
energy costing more than about $6 per million Btu. That is equivalent to about 2¢ per (kWh) of electricity, 55¢ per gallon of propane, 83¢ per gallon of fuel oil, or 60¢ per therm of natural gas. Depending on which conventional energy sources are available to them, many Federal facilities are likely to be paying more than $6 per million Btu for their water heating. As can be seen from Table 2 on page 6, national average effective energy costs to Federal facilities are greater than $6 per million Btu (MBtu) for electricity and propane and within possible regional variance for fuel oil and natural gas. (The Federal government's average cost for energy for buildings in 1995 was $9.95/MBtu.)

Parabolic-trough systems benefit greatly from economies of scale and are not as well suited to small projects as nonconcentrating collectors. Typically, 3600 square feet of collector (able to produce about 7500 gallons of hot water per day) would be the minimum size for a viable project. Solar water-heating economics are better when there is a relatively constant demand for hot water throughout the week and throughout the year, or higher demand in the summer. Facilities such as prisons, hospitals, and barracks that operate 7 days per week and have relatively constant populations throughout the year are therefore often excellent candidates.

Clear skies are important for any solar technology but are particularly so for parabolic troughs because they use only direct radiation. Facilities located within the three

The Power of the Parabola

The parabola is an intriguing geometric shape with important practical uses—including concentrating sunlight. The curve of a parabola is such that light travelling parallel to the axis of a parabolic mirror will reflect to a single focal point from any place along the curve. Because the sun is so far away, all light coming **directly** (excludes diffuse) from it is essentially parallel, so if the parabola is facing the sun, the sunlight is concentrated at the focal point. A parabolic trough extends the parabolic shape to three dimensions along a single direction, creating a focal line along which the absorber tube is run.



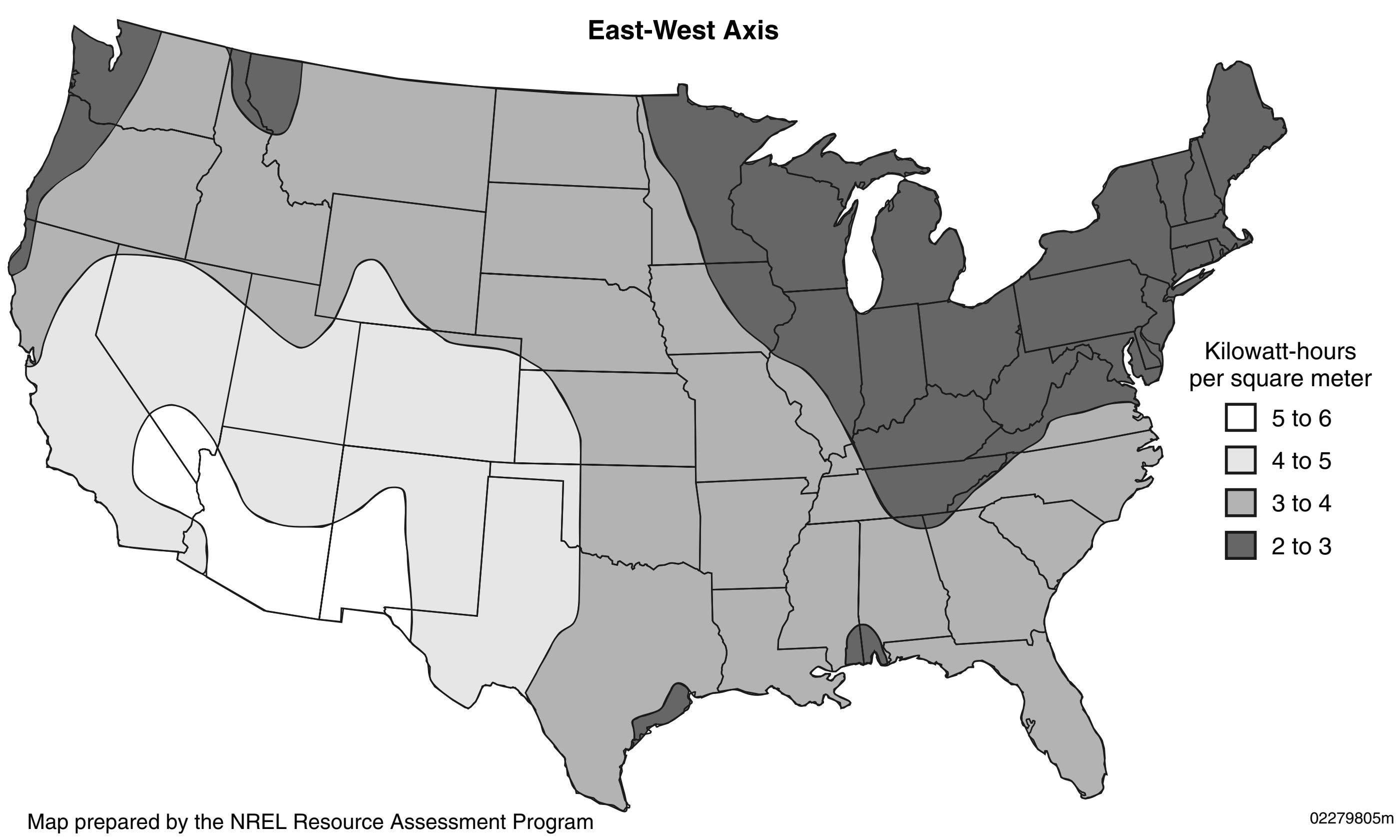


Figure 6. Average daily direct-beam solar radiation for horizontal, east-west single-axis tracking parabolic-trough collector systems. An east-west axis is better in winter and more even throughout the year than a north-south axis.

Table 1. Effective Levelized Cost of Energy ($/MBtu) for Solar Water Heating with Parabolic-Trough Collectors at Selected Locations

Installed cost per square foot of collector	Albuquerque, NM	Dallas, TX	Denver, CO	Phoenix, AZ	Sacramento, CA	San Diego, CA
$20	$6.16	$ 7.26	$6.26	$6.72	$ 7.39	$ 8.14
$24	$6.78	$ 8.15	$6.94	$7.30	$ 8.09	$ 8.92
$28	$7.39	$ 9.04	$7.61	$7.87	$ 8.78	$ 9.71
$32	$8.00	$ 9.93	$8.29	$8.45	$ 9.48	$10.50
$36	$8.61	$10.82	$8.96	$9.03	$10.18	$11.28
$40	$9.21	$11.71	$9.64	$9.61	$10.88	$12.07
Array size (sq. ft.)	6000	7800	7200	4800	6600	7200
% of load met	57%	53%	54%	54%	53%	55%

Calculations are based on F-chart analysis of energy savings for a 7,200-square-foot (669-square-meter) collector system designed to meet domestic hot-water need of 17,000 gallons (64 kiloliters) of hot water (140˚F/60˚C) per day (4652 MBtus) in the Denver, Colorado, area, adjusted in size to meet approximately the same percentage of the hot-water load. Locations were selected that have both reasonably good solar resources and a large number of Federal facilities nearby. Other assumptions include: Federal ownership and operation; backup by natural gas with costs inflated at 3.0% per year; 2% operation and maintenance costs inflated at 3.0% per year; continuous operation for a 25-year life with no salvage value; and present value of savings calculated on the basis of an annual nominal discount rate of 6.6% (equal to real discount rate of 3.4%). See "Costs" on page 16 for costs per square foot for some actual facilities. Note that costs include the cost of backup heating. Thus, the levelized costs for Phoenix (which has higher conventional energy costs) are higher than for Denver, even though the solar resource is better.

Table 2. Effective Energy Cost for Water Heating Based on 1995 National Average Federal Facility Utility Prices

	Energy Cost		Boiler Efficiency*	Effective Energy Cost*
Electricity	6.1¢/kWh	$17.87/MBtu	98/91%*	$18.23/19.64 per MBtu*
Propane	64¢/gal	$ 6.99/MBtu	75/59%	$ 9.33/11.85 per MBtu
Fuel oil	60¢/gal	$ 4.33/MBtu	80/59%	$ 5.41/7.34 per MBtu
Natural gas	35¢/therm	$ 3.54/MBtu	75/59%	$ 4.71/6.00 per MBtu

* (state-of-the art/typical) The first, state-of-the-art boiler efficiency figures (and corresponding effective energy costs) are based on what is available for large modern boilers and are higher than those available for individual home water heaters. The second, "typical" boiler efficiency figures are from the Gas Appliance Manufacturers Association October 1997 *Consumers' Directory of Certified Efficiency Ratings for Residential Heating and Water-heating Equipment*, pages 120, 142, and 144. Data are mid-range for a 50-gallon, first-hour rating, except for fuel oil boilers, which are for a 100-gallon rating. Efficiencies are for fuel conversion and do not include losses from the boiler or water heater, which also apply to heat supplied by solar collectors.

Sources: Energy costs are from Table 6-A, p. 47, Federal Energy Management Program *Annual Report to Congress on Federal Government Energy Management and Conservation Programs Fiscal Year 1995.*

highest level bands on Figure 5 or the two highest level bands on Figure 6 (4 kWh per square meter or more) are far more likely to be good candidates for parabolic-trough systems. (See Appendix A for specific data for nearly 70 locations with direct solar radiation.)

Handling wind loading is the predominant design challenge for parabolic-trough collector systems. High winds can exert torsional loads that are absorbed well by the ground, whereas roof-mounted troughs may require costly reinforcement to accommodate the stress. Also, trough systems require large installation areas that may not be available on a roof. Parabolic-trough systems therefore require large, unshaded installation areas near the place of use.

Energy Savings Performance Contracting

Industrial Solar Technology (IST) of Golden, Colorado, has installed parabolic-trough solar water-heating systems for several state or local facilities including prisons and an indoor-pool recreation center. IST is also building a major domestic water-heating system for a Federal prison. (See case studies on pages 15 and 17.)

The sole current manufacturer of parabolic-trough solar water-heating systems, IST has installed all of its systems so far on a payment-for-energy-savings basis. IST or a third-party investor typically builds, operates, maintains, and owns the system. The owner then bills the customer facility for the amount of energy delivered by the solar water-heating system at a rate slightly less than currently being charged by the facility's utility for supplying conventional energy.

The Federal Emergency Management Program (FEMP) of the U.S. Department of Energy (DOE) has now set up a program of Energy Savings Performance Contracts (ESPCs) that allows Federal facilities to install energy efficiency measures or renewable energy equipment under payment-for-energy-savings arrangements similar to those which IST has used. Many facilities have used ESPCs and found them highly advantageous.

ESPCs are Federal/private-sector partnerships in which an energy service company (ESCO) installs and operates a system, bearing all up-front design, installation, and hardware costs (including financing) and the government repays the ESCO out of budgeted utility dollars for a share of energy savings resulting directly from the project during the contract term. The agency never pays more than what its utility bill would have been without the ESPC project. Once the contract is completed, the government takes title to the equipment and retains all subsequent savings. The disadvantage of ESPCs is that the government does not immediately retain all savings generated, as it would if the project were funded by direct appropriations. The advantages of ESPCs, however, make them an attractive alternative for implementing energy savings,

First Things First

As a rule, conservation is the most cost-effective way to reduce water-heating bills. For example, a low-flow showerhead costing $9 saves nearly $17 for 275 kWh of electrical energy per year, for payback in less than 7 months. Other examples of hot-water-saving measures include faucet aerators; timed or optical-sensor faucets; water-saving clothes washers, dishwashers or other appliances; water heater insulation; lower-setting or timed water heaters; and swimming pool covers. If inexpensive conventional water heating is available, conservation measures alone may suffice and be the most cost-effective action. If, however, conventional water heating is expensive, solar water heating is also worth considering in addition to or in conjunction with conservation. Energy efficiency measures such as those mentioned above are all compatible with solar water heating, and often reduce the size of the systems needed. Reducing hot-water use saves on water and sewage as well as energy. For more information, ask the FEMP Help Desk about the Water Conservation Program. (See Federal Program Contacts.)

Next, check the conventional water-heating system. Is it the right size for the facility's needs? Is the system using the most cost-effective fuel in the area? Is it efficient? For larger systems, electric water heaters are now available with efficiency as high as 98%.* Large natural gas, propane, or fuel oil water heaters are available with 75% to 80% efficiency.* Switching boilers or water heaters alone may be the most effective action, but it can also be done as related work as part of a contract for parabolic-trough system installation.

Then do a quick assessment of whether solar water heating is likely to be effective for the facility and whether parabolic-troughs or nonconcentrating flat-plate or evacuated-tube collectors are more likely to be appropriate. (See Application Screening section and sidebar on page 14 for information on FRESA, computer software that can quickly give a preliminary assessment of whether solar water heating will be feasible.)

*These numbers are for fuel conversion and do not include heat losses from the tank or delivery system. These losses can be significant—particularly for smaller water heaters—so a better insulated tank or additional insulation may also be very effective.

Energy Savings Performance Contracting Simplifies the Process

Energy Savings Performance Contracting under Industrial Solar Technology's IDIQ contract makes it much simpler for Federal facilities to get a parabolic-trough solar water-heating system. The IDIQ allows Federal facilities to investigate with IST whether a parabolic-trough system would be effective for the facility, and if so, pursue a delivery order. ESPC agreements provide many attractive features:

- No financial outlay by the facility to determine feasibility
- No need to seek competitive proposals
- Pre-identified savings
- No responsibility for operation and maintenance
- The current system stays in place as a backup for high reliability
- Guaranteed savings
- The facility pays only for the energy savings it realizes
- The facility can benefit indirectly from tax incentives available only to private companies
- The facility can get credit for energy use reduction in compliance with Executive Order 12902 (mandatory 30% reduction by 2005) without reducing hot-water use
- Switching to a more economical conventional water heater or other related efficiency measures can be included in and financed by the ESPC project.

particularly when appropriated funds are not available. (See the sidebar at bottom.)

FEMP has now made it particularly easy for Federal facilities to have IST install a parabolic-trough solar water-heating system. FEMP has issued IST a Super ESPC—a technology-specific Indefinite Delivery/Indefinite Quantity (IDIQ) contract to install parabolic-trough solar collector systems for any Federal facility on an ESPC basis. If after reading this FTA, a parabolic-trough system seems feasible, contact IST. (See Manufacturers of Parabolic-Trough Collectors on page 20.) With a minimum of information, such as location, cost of conventional energy, and amount of hot-water use, IST staff can determine if economics are promising enough to warrant a visit and detailed assessment. (See the sidebar on page 14 and Appendix B.) The burden is then on IST staff to decide if they can design a viable project and obtain financing for it. If so, then write a delivery-order request for proposal (DORFP) to order a system. This is considerably easier than the standard procurement process, and DOE has a simplified-format DORFP that may be used for this. It is available from the DOE Golden Field Office. (See Federal Program Contacts.)

Rather than being tied to future utility prices or actual savings, delivery orders under the IDIQ assume both a fixed utility rate and projected, guaranteed savings to the facility. Monthly payments are made on that basis. IST's systems include meters to accurately measure the amount of energy provided, but are used just to verify that projected energy savings are being delivered.

ESPC contracts are highly suitable for renewable energy installations at Federal facilities and are a relatively easy procurement method. The facility doesn't need to make any initial capital outlay or budget request, bears no burden for proving favorable economics, faces minimal risk, and has no operation and maintenance responsibilities. (See sidebar at left.) At the end of the contract (maximum 25 years under the IDIQ), the government can own the system and no longer pays for the energy provided. The IDIQ also allows IST to include other features in the project that relate to the parabolic-trough collector installation—such as installing energy conservation measures or replacing the existing conventional water heater.

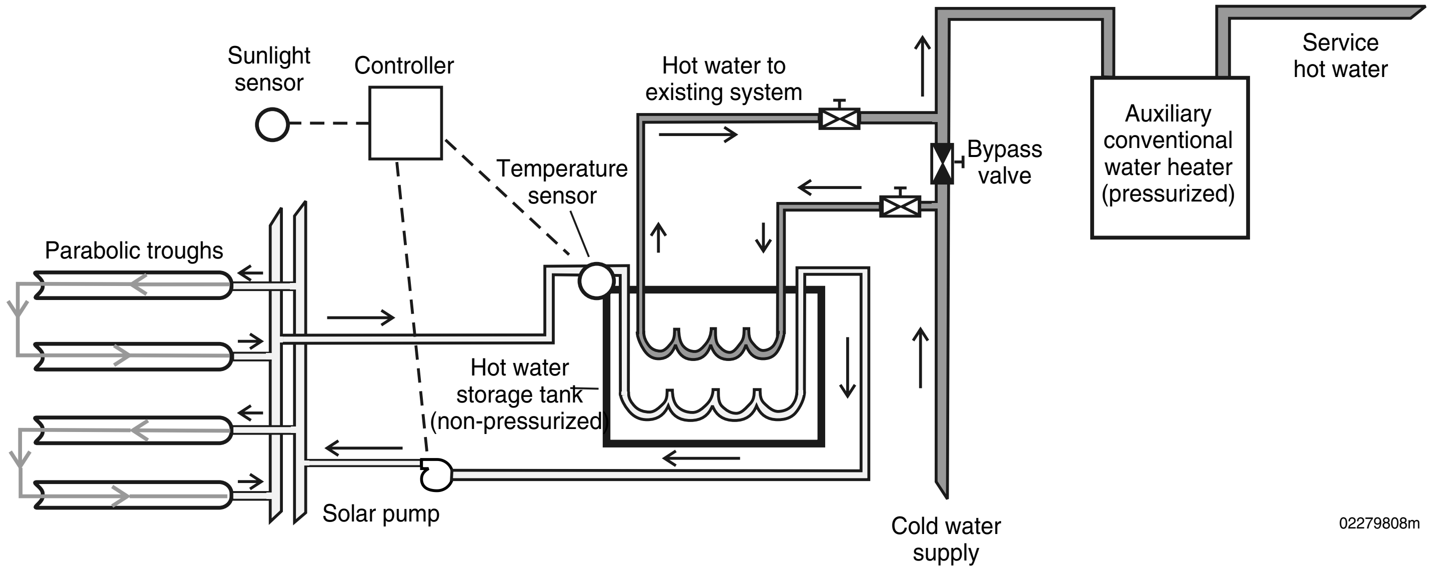


Figure 7. Typical parabolic-trough solar water heating system.

Alternatively, a facility may pay for initial system installation itself using traditional appropriations and financial analysis and project budgeting. (See Federal Life-Cycle Costing Procedures in Appendix D.) This brings the full energy cost savings achieved back to the facility rather than splitting it with an ESCO during the contract term, thus generating greater savings over the project life. For most Federal facilities, however, ESPC is also very attractive financially—especially for capital-intensive projects such as parabolic-trough systems. Private companies can often take advantage of tax credits for renewable energy or accelerated depreciation of the capital investment that the facility itself cannot. Thus, many projects for Federal facilities that do not meet the 10-year simple payback criterion that mandates construction, or the positive life-cycle cost analysis that allows construction, could be attractive investments for private companies. IST has, in fact, used third-party financing for all of its projects thus far. The investor pays IST to build and maintain the systems and then collects the energy-savings payments from the facility.

Energy-Saving Mechanism

Parabolic-trough collectors are typically used in active, indirect water-heating systems. Such systems use pumps to circulate an antifreeze solution between the collectors and the storage tank, where a heat exchanger transfers heat from the circulating fluid to water in the thermal storage tank. Potable water flows through a second heat exchanger in the storage tank, absorbing heat for the water that will actually be used. (See Figure 7). Parabolic-trough collectors generally require more supervision and maintenance than nonconcentrating solar collectors—the reflectors must be cleaned and checked for leaks two to four times per year. These systems particularly benefit from economies of scale, so are generally used for larger systems.

Parabolic-trough solar collectors use curved mirrors to focus sunlight on a receiver tube running through the focal line of the mirrors. The pressurized tube through which the antifreeze solution circulates is coated with a special heat-absorbent surface and encased in a glass tube. IST parabolic-trough collectors can heat their transfer fluid to as much as 520˚F (271˚C) or more, but for domestic water supply systems, they

Industrial Solar Technology/PIX05641

Figure 8. Parabolic-trough collector systems also work well for central plants serving district heating systems. This system at the California Correctional Institution at Tehachapi augments a central boiler that provides several buildings with hot water for space heating as well as for domestic use. District systems such as this one will generally not include storage—contributing only when they are actually operating. They will therefore meet a smaller portion of the load than the 50% to 60% typical for systems including storage.

typically operate at about 200˚F (93˚C) to deliver water at about 120˚F to 140˚F (49˚C to 60˚C). Efficiency is highest with a temperature difference of about 60˚F (33˚C) between input to the solar collector field and output from the field to the thermal storage tank.

In addition to the collectors, IST's parabolic-trough systems include an electric tracking system (to keep troughs facing the sun or turned downward when it's dark or too windy), a nonpressurized hot-water storage tank, a circulating pump to drive the hot transfer fluid from the troughs through a closed-coil heat exchanger in the storage tank to heat that tank (pressurized loop), a loop that draws cold intake potable water through a second heat exchanger in the storage tank on its way to the conventional water heater, and various sensors to trigger the proper operation. (See Figure 7.)

The system acts as a preheating system for the facility's conventional water-heating system. If the solar-heated water is too hot, a tempering valve mixes in cold water. If the water is not hot enough, the conventional system heats it to the proper temperature. As hot water is used from the conventional water heater, incoming cold water flows through a heat exchanger, drawing heat from the hot-water storage tank, and then to the conventional water-heating system.

In locations with no freeze danger, water can be used instead of antifreeze because it's cheaper and is a better heat transfer fluid. In the Southwestern United States, there is sufficient sunlight for parabolic-trough collector systems to operate about 30% to 35% of the time. The systems will generally be most cost effective if sized so that on the best summer days they are just able to meet the demand—that is, there is no excess capacity. Such a system will provide about 50% to 60% of annual water-heating needs. If conventional energy costs are particularly high, it may be economical to increase system size somewhat beyond this point.

Benefits

Solar water heating reduces the amount of water that must be heated by a facility's conventional water-heating system; it thereby directly substitutes renewable energy for electricity or fossil-fuel energy and cuts utility bills. Each unit of energy delivered to heat water with a solar heating system yields an even greater reduction in use of fossil fuels. For example, industrial-size water heating that uses natural gas, propane, or fuel oil is typically only about 60% efficient and 75% to 80% efficient at best. Electric water heating is typically about 90% efficient and can be 98% efficient. However, producing that electricity from fossil fuels is generally only 30% to 40% efficient. Furthermore, reducing fossil-fuel use for water heating not only saves fossil fuel stock, but eliminates the air pollution and climate-changing gas emissions associated with burning those fuels.

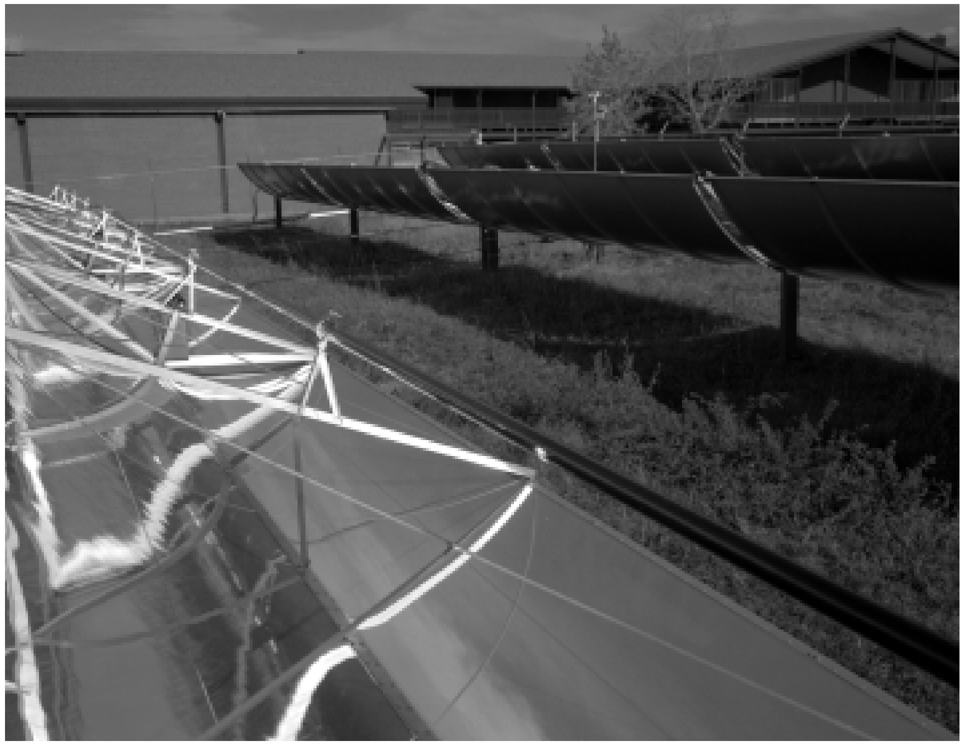

Warren Gretz, NREL/PIX05640

Figure 9. Parabolic-trough collectors at Paul Beck Recreation Center in Aurora, Colorado, heat water for a swimming pool and related facilities.

Variations

As described in this FTA, domestic water heating is the principal application for parabolic-trough collectors. They can, however, be used for other water-heating needs. At the Paul Beck Recreation Center in Aurora, Colorado, these collectors provide water for an indoor swimming pool, showers, and related facilities. (Smaller swimming pools—particularly outdoor ones—can generally be more effectively heated by inexpensive, low-temperature collectors that are nonconcentrating and uninsulated.)

Parabolic-trough solar collectors can also power air-conditioning. Air-conditioning systems are typically based on a compression cycle driven by an electric motor. But an alternative, mechanically simpler system is based on an absorption cycle driven by a heat source. One type of system that can be operated efficiently using solar energy is the water/lithium bromide absorption chiller. Water at very low pressure is used as the refrigerant and lithium bromide is used as the absorbent. Absorption chillers can be either direct-fired (usually by natural gas) or indirect-fired (by hot water or steam). They are produced commercially by heating, ventilation, and air-conditioning (HVAC) equipment manufacturers in the United States and abroad. Several major air-conditioning equipment manufacturers make indirect-fired absorption chillers that can run on solar-heated water or steam. (See manufacturer's information on page 20.)

Two varieties of indirect-fired absorption chillers are available—single-effect and double-effect. (See Appendix C.) Single-effect absorption cooling systems can use solar-heated fluid (usually water) at temperatures of 77˚C–99˚C (170˚F–210˚F) to drive absorption refrigeration cycles. Double-effect systems are more efficient but require temperatures of about 177˚C (350˚F), usually in the form of steam. Parabolic-trough collectors efficiently heat water to these required temperatures.

Double-effect absorption coolers usually have coefficients of performance (COPs) of about 0.9 to 1.2, compared to about 0.6 to

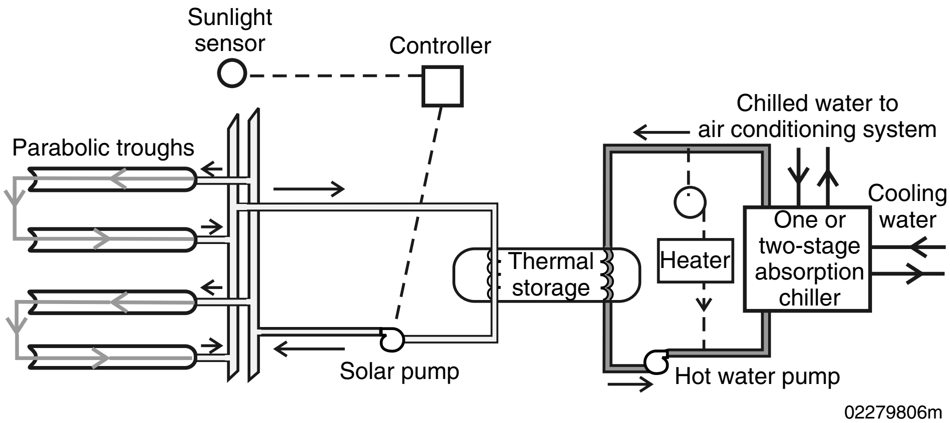


Figure 10. Schematic of trough cooling system.

0.8 for single-effect systems. COP is the ratio of the heat energy removed divided by the work required to remove it. That work is defined differently for absorption cooling than for compression cooling (based on heat input rather than electrical input). Therefore, these COPs cannot be directly compared to those for electrical compression cooling systems (generally 2.0 to 4.0).

Solar heat is well suited to heat water or generate steam for indirect-fired absorption cooling because of the close time match between solar heat generation and the need for cooling. Because air-conditioning frequently drives peak electrical demand, the time match of parabolic-trough energy collection to air-conditioning needs is significant. Electric utilities frequently charge commercial facilities two to three times as much for power during peak demand periods and may even subsidize customer projects that reduce peak demand.

Absorption cooling offers a critical additional benefit for hospitals and other facilities that cannot tolerate being without air-conditioning—only minimal electricity is necessary to keep a parabolic-trough system operating during a power outage. Facilities with parabolic-trough collector/absorption cooling systems need far smaller backup generators than those with electric compression cooling.

Nearly all solar absorption cooling systems include subsystems for space and water heating. This allows the expensive solar equipment to be used throughout the year, rather than just during the cooling season. Figure 10 shows how parabolic-collector and absorption cooling systems work together.

As with parabolic-trough water heating, the economic viability of parabolic-trough air-conditioning will largely be a function of the system cost and conventional utility costs. Absorption chillers will cost from 1.5 to 2.5 times as much as electric-compression air conditioners or chillers. But if the electricity cost is high enough relative to solar heat or fuel such as natural gas or propane, the extra equipment cost for absorption cooling may be a good investment. Similarly, if the conventional fuel cost is high enough, the cost of a parabolic-trough collector system to drive the absorption cooler may be a good investment. With a 9-month or longer cooling season and electricity costing about 10¢/kWh or more, a parabolic-trough/absorption chiller system is worth investigating. Because the parabolic-trough collector portion will usually account for more than half the cost of such a system, it is important for economic reasons that the system also be used for water heating and space heating.

Parabolic-trough systems can also be used to heat industrial or industrial-like process water or other fluids to high temperatures. (IST's systems can generate temperatures as high as 520˚F [271˚C]). Federal facility activities that might need such high-temperature water include cleaning engines or other equipment, industrial laundries, and certain hospital uses. For higher-temperature uses, oil is often used instead of antifreeze, both in the collector loop and in the thermal storage tank.

In addition, parabolic-trough collectors can be used to generate electricity. During the 1980s Luz International (no longer in business) built nine plants for solar thermal electrical generation. All are still operating. These systems, which encase the collector tube in a vacuum, use oil as a transfer fluid and reach temperatures of 730˚F (388˚C). Electrical generation facilities can also use parabolic dish systems that concentrate light in two directions instead of one, but nearly all existing solar thermal electrical generation is from parabolic-trough systems.

Installation

Because they use only direct-beam sunlight, parabolic-trough systems require tracking systems to keep them focused toward the sun and are best suited to areas with high direct solar radiation. (See Figures 5 and 6). Most systems are oriented either east-west or north-south with single-axis tracking during the day. East-west orientation is better in winter and more constant throughout the year, while north-south orientation is better in summer and provides greater annual output. The systems are programmed to turn the collectors upside down at night or during high winds to reduce stress on the structure and help keep the mirrors clean.

Because they transmit structural stress from wind loading and require large areas for installation, parabolic-trough collectors are usually ground mounted. IST is developing a smaller, lower-profile version of its collector system that will be more suitable for roof mounting, but its standard troughs are 20 feet by 7.5 feet (6.1 meters by 2.3 meters). IST typically installs sets of either 16 troughs (4 rows of 4 for 2400 square feet of collector) or 24 troughs (4 rows of 6 for 3600 square feet of collector). Each set can run on a single-drive-motor tracking system. These installations require about 6,000 and 9,000 square feet (557 and 836 square meters), respectively, of level or slightly south-facing, unshaded space with the latter being the smallest size generally viable project. The collector system should be fenced and within 1000 feet of the conventional water heater for the building where the water is being used (the closer the better). Parabolic-trough systems will usually be installed by the manufacturer. IST generally assembles the collectors onsite or nearby.

Federal-Sector Potential

Technology-Screening Process

The FTA series targets technologies that appear to have significant untapped Federal-sector potential and for which some Federal installation experience exists. Many of the

Figure 11. Gould Electronics of Chandler, Arizona, has had its parabolic-trough collector system since 1982. An example of use of oil for heat transfer for higher-temperature uses, the system provides process water for copper foil production.

FTAs are about new technologies identified through advertisements in the *Commerce Business Daily* and trade journals and through direct correspondence soliciting technology ideas. Those technologies are then evaluated in terms of potential energy, cost, and environmental benefits to the Federal sector.

Parabolic-trough solar water heating was included in the New Technology Demonstration Program because this renewable energy technology has obvious energy, cost, and environmental benefits and has substantial untapped potential in the Federal sector. IST is officially designated by DOE as an energy service company qualified for ESPC contracts. Additionally, the IDIQ contract with IST substantially simplifies procuring this technology. (The thermal performance of IST's parabolic-trough systems was independently measured by Sandia National Laboratories and reported in Sandia Report SAND94-1117).

Estimated Market Potential

In FY 1995 the Federal government spent $3.6 billion on energy costs for buildings—75% on electricity, 12% on natural gas, 6% on fuel oil, and 8% on other forms of energy. An estimated 12% of energy use for buildings is for water heating. Assuming a similar percentage for Federal facilities suggests that Federal water heating costs about $432 million per year.

The *FEMP Tracks* database of Federal facilities lists 16 prisons, 87 hospitals, and 147 housing complexes that are located within Southwestern or other states where there are probably adequate solar resources for parabolic troughs and that are large enough that they would likely benefit from a parabolic-trough system (Table 3).

Laboratory Perspective

Although only a few parabolic-trough solar water-heating systems have been installed so far, the technology is well developed and has been clearly demonstrated. The National Renewable Energy Laboratory and Sandia National Laboratories helped develop the technology, and as mentioned earlier, Sandia measured its performance. FEMP and the two laboratories have worked closely with IST to identify good opportunities to apply the technology at Federal facilities. The two laboratories also supported past efforts to use parabolic-trough heating for electrical generation and industrial process water and continue to work on solar thermal electrical generation.

Cost-shared, collaborative technology development testing and evaluation projects with NREL and Sandia have allowed IST to greatly improve the performance of parabolic-trough collector technology. Solgel antireflective coating for the glass enclosure surrounding the receiver tube is made by IST under license from Sandia National Laboratories. ECP-305+® silvered polymer reflector film was developed under a collaborative project between NREL and the 3M Company and was tested and evaluated by IST. Both of these improvements enhance energy capture. For example, the system installed in 1996 for the Jefferson County Detention Facility in Golden, Colorado, which features these enhancements, delivers about 38% more energy per surface area of collector than the one installed in 1990 at the California Correctional Institute at Tehachapi, which is not enhanced. Using these new technologies, however, only increases costs by about 10%. IST has also begun using a black-nickel-based selective-absorption coating for the receiver tube. Both costs and

Table 3. Federal Facilities of Size and Location to be Likely Candidates for Parabolic-Trough Systems

State	Prisons of more than 25,000 sq. ft.	Hospitals of more than 25,000 sq. ft.	Housing complexes of more than 100,000 sq. ft. or more than 10,000 sq. ft. and 5,000 sq. ft. per building
Arizona	2	14	16
California	5	24	67
Colorado	2	6	9
Hawaii	0	1	5
New Mexico	0	11	12
Nevada	1	3	4
Puerto Rico	0	1	0
Texas	6	23	26
Utah	0	1	5
Wyoming	0	3	3
Total	**16**	**87**	**147**

Source: FEMP Tracks database

environmental concerns with manufacture and disposal are less for this coating than for previously used black-chrome coatings.

Application

The two most important factors in determining economic feasibility for any solar water-heating system are the cost of building the system and the cost of operating conventional water-heating systems. Parabolic-trough collectors, in particular, require high direct normal solar radiation, high hot-water use levels, continuous hot-water use, and in the case of use for air-conditioning, a long cooling season. Therefore, parabolic-trough solar water-heating or air-conditioning systems could benefit many hospitals, prisons, barracks, and other Federal facilities in the southwestern United States.

Federal facilities have two options available for procuring a parabolic-trough solar water-heating system. The traditional option is directly purchasing the system. A simplified procurement and budgeting option is using ESPCs, as provided for in IST's IDIQ contract.

Application Screening

In either case, the first step toward determining if a solar water-heating system would be viable for a facility (or facilities) is to assess the hot-water needs. How much hot water at what temperature do the various facilities use (or are new facilities expected to use), on what kind of schedule? How much does it cost for the energy to heat that water? Could costs be reduced with a more efficient conventional water heater? What options are there for reducing hot-water use or lowering the temperature of water provided?

The next step is to obtain a preliminary estimate of whether solar water heating will be cost effective. The FEMP Federal Renewables Program at the National Renewable Energy Laboratory has developed a computer program entitled Federal Renewable Energy Screening Assistant (FRESA) that can make such a preliminary assessment. See the How Do You Figure sidebar for a list of the necessary information. IST can provide a similar rough assessment specific to using parabolic-trough collectors.

In order to directly purchase a parabolic-trough-collector solar water-heating or air-conditioning system, a positive FRESA assessment should be followed up with a formal feasibility study, including life-cycle cost analysis (Appendix D) in accordance with 10 CFR 436A and a request for proposals. A simpler economic criteria than life-cycle cost analysis is the payback period— the time it would take for energy cost savings to repay the investment cost. Executive Order 12902 directs that agencies shall build any energy-saving project with a simple payback of less than 10 years. This is generally a more rigorous criterium than life-cycle cost analysis, so there will be many projects with positive life-cycle cost analysis but with greater than 10-year simple payback. These may also be built, but Executive Order 12902 would not apply. Assuming a payback of less than 15 years and a system life of 30 years, one can expect 15 years or more of "free energy."

If, however, a project is built under ESPC, as IST's IDIQ contract allows, it is not necessary to do formal cost analysis or

How Do You Figure?

To obtain a preliminary analysis of whether solar water heating would be cost effective for a facility, use the Federal Renewable Energy Screening Assistant (FRESA) software package. It's available from the Federal Renewables Program at the National Renewable Energy Laboratory (NREL). (See Federal Program Contacts.) Federal Renewables Program staff can also do the analysis, if provided the following data:

- Hot-water use in gallons per day
- Fuel type and cost
- Zip code
- Incoming cold-water temperature
- Outgoing hot-water supply temperature
- Area of southern exposure roof or nearby grounds available for system
- Tilt and direction of roof area.

One can do a rough calculation before asking for FRESA or a more detailed F-Chart analysis. Divide 51.4 by the solar insolation for the area (single-axis tracking in kilowatt-hours per square meter per day as given in Appendix A). This should provide the number of years it would take for the system to pay for itself based on an installed cost of $22 per square foot.

The FRESA system does include solar resource data based on your zip code, but to obtain comprehensive solar resource data request the NREL *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* or the CDROM of the National Solar Radiation Data Base (Appendix A).

To estimate hot-water use, check the hot-water-use records; install a meter and track usage; or project demand based on average use for various facilities as found in the American Society of Heating, Refrigerating and Air-Conditioning Engineers' Handbook of Applications. Typical usage per day per occupant in gallons is 20–30 for housing, 30 for hospitals or prisons, 5 for dining facilities, and 3 for other uses.

To determine incoming water temperature, which may vary considerably with the season, call the water utility or check the supply with a thermometer. In some instances, the average annual air temperature also roughly indicates water supply temperature. These temperatures are important because solar water heating is more efficient when incoming water temperatures are lower (less heat loss to the environment); whereas, cold air temperatures reduce efficiency.

To calculate system output information more rigorously than the preliminary analysis provided by FRESA, use a computer program such as F-chart, or consult with Federal Renewables Program staff or a solar water-heating system supplier.

The optimum size for collectors and storage will depend on fuel cost, available solar resource, and the hot-water use pattern, but expect capacity on a good summer day to roughly match usage. The resulting system should meet about half of annual demand. Precise optimization of system size will require both a calculation of output and an evaluation of system economics.

To evaluate the economics of a contemplated system in detail, use the FEMP *Life-Cycle Costing Handbook* and associated BLCC software, available by calling the FEMP Help Desk. (See Federal Program Contacts.) One can also consult with the Federal Renewables Program or a private engineer.

request competitive bids. To pursue ESPC financing under the IDIQ, simply provide IST staff with the necessary information and they will determine whether it would be economically advantageous for them to build the system or—as they have for all their installations thus far—convince a third party to finance the project. To save on limited travel funds, IST personnel will usually do a preliminary assessment by telephone to determine whether economics are promising enough for them to further investigate the project and whether a DORFP should be done. They will look for the following positive factors.

- Expensive utility rates for conventional water heating—about \$6/MBtu or more (2¢/kWh of electricity, 60¢ per therm of natural gas, 55¢ per gallon of propane, or 83¢ per gallon of fuel oil; average energy costs for Federal facilities in FY 1995 were 6.1¢/kWh of electricity, 35¢ per therm of natural gas, 64¢ per gallon of propane, and 60¢ per gallon of fuel oil, according to a FEMP survey)
- High direct normal solar radiation—4 kWh per square meter or more, location in the three or two highest bands, respectively, in Figures 5 or 6 on pages 6 and 7.
- High levels of hot-water use—10,000 gallons per day or more; or a long cooling season of 9 months or longer
- Continuous facility use—preferably 7 days per week, 52 weeks per year
- Adequate unshaded space for the collector field
- For air-conditioning, inability to tolerate system shutdown during a power failure.

Certainly, it is not always necessary to meet each of these criteria. Furthermore, a very high indication in one area, such as energy costs, could overshadow counter-indications in another area. Lower sunshine levels or hot-water use might suggest alternative solar water-heating technologies.

Where to Apply

This technology is best applied at:

(1) Hospitals

(2) Other large health care facilities such as large clinics

(3) Military and civilian detention facilities

(4) Food preparation and service facilities

(5) Dormitories and barracks

(6) Laundries

(7) Central plants for district heating or water-heating systems

(8) Operation and maintenance (O&M) facilities, such as for transportation vehicles and equipment, requiring large volumes of hot water

(9) Production or assembly facilities requiring large amounts of hot water (e.g., munitions facilities)

(10) Gymnasiums and recreation facilities with heated, indoor swimming pools

(11) Bachelor officer quarters and guest residential facilities

(12) Any other facility requiring large amounts of hot water on a continuous basis or otherwise meeting most of the criteria listed in “Application Screening.”

What to Avoid

If purchasing a system or seeking an ESPC project, one should be aware of certain considerations. No one of these situations would preclude a project, but be sure to inform IST staff about:

- Areas particularly prone to very severe weather—high winds, tornados, hail storms or hurricanes—or to vandalism
- Areas with unusually high dust or dirt loads in the air
- Particularly mineral-rich water supply (can foul the heat exchanger and the rest of potable loop—less of a problem for troughs than for other solar water-heating systems)
- Facilities facing possible closure or reduction in hot-water or air-conditioning use
- Missed opportunities to make a parabolic-trough project more economically attractive by adopting water conservation measures, switching fuels, or installing more efficient conventional water heaters as part of the project. (The IDIQ does allow such measures to be incorporated into and financed as part of a trough project and IST will investigate their inclusion.)
- Situations where a conventional energy source is expected to become available that is significantly less expensive than that currently used
- Situations where the space dedicated to the collector field could later be needed for building expansion
- Oversizing the system so full capacity is not always used (if not an ESPC)
- Lack of commitment to system maintenance (if not an ESPC).

Equipment Integration

Integrating the parabolic-trough collector system into the existing hot-water system is simply a matter of adding a line routing the cold intake water through the heat exchanger in the thermal storage tank on its way to the existing conventional water heater. Prisons with security perimeters might need to penetrate a wall to do this. The collector field requires electrical connections for the pump and the tracking system. Valves are included for the intake and outflow of the fluid loop and one is added on the old line direct to the water heater, making it easy to bypass the parabolic-trough system if ever necessary.

Maintenance Impact

Parabolic-trough collector systems require somewhat more maintenance than most nonconcentrating solar water-heating or other renewable energy or energy efficiency installations. Because high-temperature and high-pressure fluid is involved, they should be monitored regularly. Also, the mirror surfaces should be washed every few months. Consequently, although facility staff could easily take on these duties, the system installers usually also maintain the system. Under an ESPC, this is standard practice.

The mirror surfaces will degrade slowly with time and may need replacement after about 15 years. The pumps and tracking equipment should last for the life of the project, but the pump seals will likely need to be replaced after about 10 years and the tracking equipment controls may need replacement as soon as 10 years or as late as 30 years.

Because the solar collector system reduces the amount of time that the conventional hot-water heater operates, the heater should last longer. There is no other real impact on existing equipment.

Equipment Warranties

If IST sells a system, they guarantee the general collector system for 5 years; individual components such as pumps carry whatever warranty the manufacturer provides. Note that under an ESPC, replacement responsibility rests totally with the installer and the facility pays only for energy delivered.

Codes and Standards

Other than local building and plumbing codes, there are no special standards that parabolic-trough solar water-heating systems need to comply with. In certain jurisdictions, codes could require double-walled heat exchangers or nontoxic antifreeze, but the system design IST usually uses is already double-walled. IST prefers to use an ethylene glycol/water solution as the heat transfer fluid, but can easily substitute nontoxic propylene glycol. If a facility does not already have one, it might need to add a material safety data sheet for ethylene glycol.

Costs

Parabolic-trough system installation costs will vary considerably with circumstances for particular projects. IST quotes costs on an individual basis. Costs per unit will, however, generally be higher for smaller projects and lower for larger projects. Costs for three completed projects ranged from $21 to $32 per square foot of collector and $101 to $135/MBtu of energy per year ($24 to $43 per square foot and $113 to $204/MBtu per year in 1997 dollars). New technology that IST is now using costs about 10% more but produces about one-third more energy. Two new projects cost $29 and $36 per square foot of collector and $101 and $132/MBtu per year. The larger of these projects, however, was oversized with unusually large storage to accommodate local utility peak pricing for electricity, so a large new project is quite likely to have lower costs than these.

Under an ESPC contract, the facility does not pay for the project cost, but instead pays for the resulting utility bill savings. A flowmeter on the intake and temperature gauges on intake and outflow are connected to a Btu meter that calculates energy delivered. If the facility has concerns about the energy delivery calculation, FEMP/NREL can set up an independent verification system for initial system operation.

The IDIQ contract directs establishment of an annual energy use baseline for the facility and projection of energy cost savings. Monthly billing is based on projected energy delivery and fixed energy costs agreed on in the delivery order. Otherwise, billing could be directly based on the Btu meter, at fixed or current energy prices. (Including improvements such as energy conservation measures or replacement of the conventional water heater, in addition to the parabolic-trough collector system, may require additional billing arrangements.)

Russ Hewett, NREL/PIX05649

Figure 12. Simple connections to intake and outflow temperature gauges and an intake flowmeter allow this Btu meter to quite accurately report how much energy has been delivered by a parabolic-trough collector system.

Utility and Government Incentives and Support

Utility company incentives for demand reduction and load management can be an important non-Federal source of financial assistance. Demand-side management (DSM) activities, such as promoting solar water-heating systems, can save a utility from investing in system expansions or help them comply with air quality programs. Some incentive programs are designed for residential customers, but others also apply to or are specifically designed for commercial facilities, including Federal buildings. Federal facilities may also negotiate specific incentives for larger projects beyond the scope of standard programs or in cases where standard programs do not exist.

The Hawaiian Electric Company, for example, has a commercial and industrial user rebate program that pays $125/kWh capacity reduction of evening peak usage plus 5¢/kWh for 1 year's production by solar projects displacing electric water heating. The Lakeland (Florida) Department of Electric and Water Utilities has started a program—which it expects to be adopted statewide—in which the department acts very much like an energy service company. The utility installs metered solar water heaters on a lease basis and charges the customer for the energy delivered. During the 5 years of operation of a Sacramento Municipal Utility District incentive program, more than 3000 solar water heaters were installed. On the one hand, anticipated utility industry restructuring may cut back on DSM programs such as these, but on the other, it may encourage utilities to spin off energy service companies specifically set up to design and install energy efficiency and renewable energy projects.

Although Federal facilities can accept utility rebates, they cannot take advantage of tax credits or incentives, so the following does not apply to Federal facilities that purchase a parabolic-trough system outright. Even with an ESPC project, the facility cannot use tax credits or incentives, but the installing company or third-party investor may be able to. Tax incentives can therefore be very important for parabolic-trough systems installed as ESPC projects. Because of such incentives, it is not unusual for ESPC projects to be financially attractive to the system installer or third-party investor even if it would be economically marginal for the Federal facility to purchase the system. (See case studies on pages 17 and 18.) System cost and the cost of competing conventional water heating will always be the dominant factors, but if those factors make the margins close, tax incentives may make projects financially feasible.

The Federal government currently provides a 10% business energy tax credit for purchase of solar and geothermal energy equipment (Section 1916 of the Energy Policy Act of 1992; 26 USC 48). Also, 26 USC 168 allows for accelerated depreciation of solar energy property investments — 5 years instead of 20 years. These two incentives can be quite significant to a third-party investor with a high tax bill. A hypothetical example on the Solar Energy Industries Association Internet Web site (http://www.seia.org/legdepre.htm) calculates the resulting combined savings as more than 40%.

Similarly, more than half the states and some local governments do provide incentives for solar thermal collector or solar cell system purchases. The State of Hawaii currently allows a 35% tax credit for solar projects for commercial buildings. Total tax credits for projects there can cut installation cost almost in half for a third-party investor in an ESPC project, and accelerated depreciation can add further savings. Other examples include an Arizona 6% loan program for renewable energy and energy efficiency equipment acquisition and a Texas corporate income tax deduction for solar energy equipment acquisition. A good source of information on state incentives is a DOE-North Carolina State University Internet web site: http://www-solar.mck.ncsu.edu/dsirexls.htm.

Additional Considerations

On the negative side, the facility loses use of the land occupied by the collector field. On the positive side, because the conventional water heater is used less, polluting and global warming air emissions are reduced (on site for gas or oil heaters; at the power plant for electric heaters).

Technology Performance

IST has installed parabolic-trough solar water-heating systems for three state or local prisons and one local indoor-pool recreation center. All were installed on a payment-for-energy-savings basis. The following is based on discussions with operators of a city pool in Colorado that has had a parabolic-trough collector system since 1985, a county jail in Colorado with a system since 1986, and a state prison in California with a system since 1990. A new system at another county jail in Colorado has only been operating a short time.

Field Experience

Facility managers indicated that the parabolic-trough collector systems were largely "transparent" to them and their staff. That is, they did not know all that much about the collectors, and said staff just knew that they were there and working. The existence of the system has no particular impact on their daily operations. Maintenance is minimal and performed by IST. Down-time is minimal. One system was down for 2 months after a backhoe broke the delivery line to the facility and the facility delayed repair. Another system was down for 3 weeks with a hose problem when IST personnel were tied up on another project. The third project had about 5% of the reflectors damaged by a freak wind storm, but IST had the system back up within a week. Very deep snow occasionally interferes with the tracking systems. Because the conventional water-heating system is still in place, system downtime causes no service disruption. Under an ESPC, facilities are also fully protected from any downtime because payments are based either on annual energy audits or directly on energy delivery meters.

Facility managers were generally quite impressed with how well the systems operated and with the service provided for the systems. The extent of the energy cost savings they were getting was not always that clear to them, but they thought projects were delivering about what was projected. Staff for the recreation center indicated that they are now considering expanding the center or building a new parking lot and that the collector field location could turn out to limit available options for those projects. There were no problems with vandalism of the collector fields, even when near heavy traffic by school-age children, nor were there problems with impacts on birds or animals.

Energy Savings

The three projects each produce about what was projected, about 200,000 Btu per year per square foot of collector. All three displace natural gas use. Assuming backup water-heater efficiency of 75%, this means they save about 267,000 Btu (200,000/.75) of natural gas per year per square foot of collector. (New projects incorporating improved technology are about one-third more efficient for production of about 267,000 Btu per square foot, displacing about 356,000 Btu of gas per square foot of collector. [See Laboratory Perspective on page 13]) For the California prison—a very large facility with a district heating system—the parabolic-trough system was built without storage and only large enough to displace 10% of total natural gas use for hot water and space heating. But for the other two projects, as they would for most facilities, the parabolic-trough system substitutes for about half of the conventional energy that would otherwise be used for water heating. One new project is sized to provide 80% of water-heating energy, but the larger system and storage size for that project is justified by a need to avoid high time-of-day peak pricing by the local electric utility.

Maintenance, Environmental, and Other Impacts

Managers noted very little impact on their operations or on their facilities. Maintenance of the parabolic-trough systems is all handled by IST under the Super ESPC and the systems have no impact on other systems except extending the life of conventional water-heating equipment by reducing its use.

Every unit of energy delivered by the solar collector directly eliminates conventional energy use—and the associated pollution and global warming impacts. Because of the inherent efficiency loss in heating water with conventional fuels, the environmental benefits of substituting parabolic-trough solar water heating for natural gas, propane, or fuel oil are actually about one and two-thirds times as great as the amount of energy provided (assuming a 60%-efficient heater) and about three times as great when substituting for electric water heating (assuming 30%- to 40%-efficient electric production at the power plant).

Case Study 1 — Adams County Detention Facility, Brighton, Colorado

The Adams County Detention Facility in Brighton, Colorado (about 30 miles [48 kilometers] northeast of Denver), was originally designed for about 500 inmates but is currently housing more than 800. The facility uses an average of about 18,000 gallons (68,000 liters) of hot water per day for kitchen, shower, laundry, and sanitation facilities. The facility's existing water-heating system included six natural-gas-fired boilers.

In 1986, IST installed a 6000-square-foot (555-square-meter) parabolic-trough collector system, together with a 5000-gallon (19,000-liter), nonpressurized, stainless-steel thermal storage tank, on a payment-for-energy-savings basis. IST expanded the system to 7200 square feet (669 square meters) of collector in 1988 in response to increased hot-water use resulting from increased inmate population. The parabolic-trough system preheats the water supply to five of the six boilers and thereby provides about 40% (1400 million of 3500 MBtus per year) of the energy required by the prison for water heating.

The parabolic troughs heat the transfer fluid (ethylene glycol mixture) to as much as 256˚F (124˚C). Whenever the amount of direct sunlight is above a set threshold, the circulating pump turns on, sending the heated antifreeze mixture through a copper-coil heat exchanger in the storage tank, heating that water to as much as 185˚F (85˚C).

The system has operated continuously since 1987 except for a 2-month period after the line from the collector field to the facility was broken by a backhoe during a construction project. Deep snows occasionally keep the tracking system from working and the system automatically shuts down during high winds. IST personnel clean the reflectors and check the system for leaks two or three times per year. The system's operation has little impact on facility personnel who know that it is there and how to turn it off if anything should ever go wrong. Otherwise they have nothing to do with it.

The Adams County Detention Facility system is owned and operated by third-party investors. The investors contracted with IST to design and construct the system. Initial cost of the system was $218,400 but a $40,000 state "buy-down" subsidy reduced the price to $178,400 and the investors benefitted $21,840 from a 10% tax credit. The owners are responsible (with guidance from IST) for major repairs or renovations and pay IST to operate and maintain the system. Adams County pays the owners for the heat provided by the system—based on readings from a Btu meter at the facility—at a discount from the current rate they pay for natural gas. The county spends about $200 per month less for the combination of the trough system plus utility bills than it would without the solar collector system.

The system has been operating for more than 10 years. Because the facility's backup conventional boilers are 70% efficient, the 1400 MBtus per year of solar energy provided by the parabolic-trough system saves 2000 MBtus of gas per year—enough energy for total energy consumption by more than 20 households. The total reduction in natural gas consumption thus far is about 20 billion Btus. Over the life of the project, approximately 50 billion fewer Btus of natural gas (equivalent to about 370,000 gallons of fuel oil) will be burned, with associated savings in pollution and greenhouse gas emission.

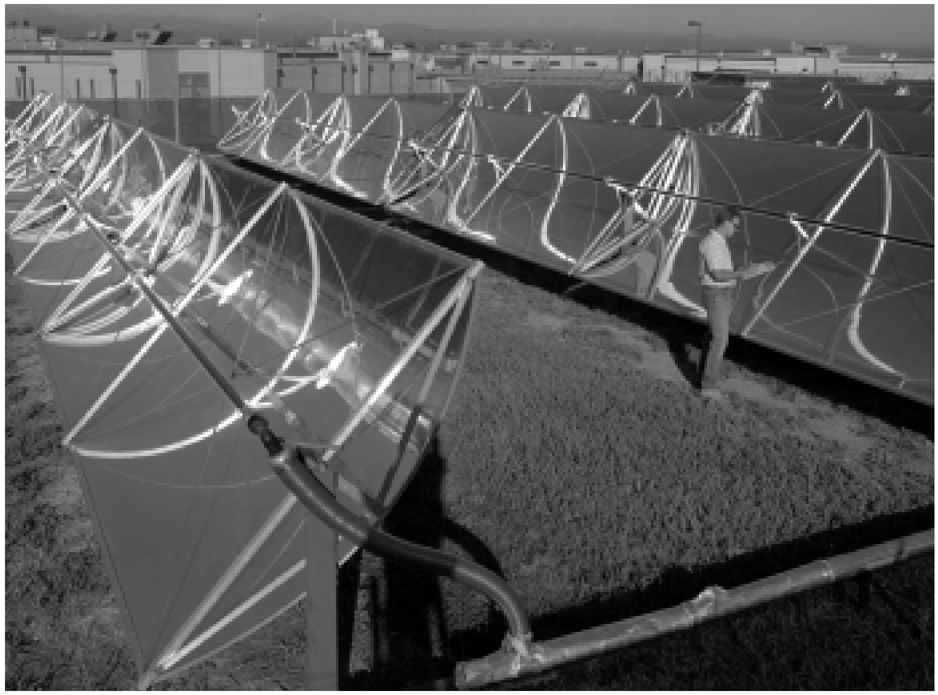


Figure 13. Parabolic-trough solar water-heating system for Adams County Detention Facility, Brighton, Colorado.

As can be seen from the added notes to the life-cycle cost calculations in Appendix E, the Adams County system would not have been economically viable at the full cost of $218,400. At the state-subsidized cost of $178,400, however, the parabolic-trough system yields discounted cost savings of about $29,000 over the life of the project. As can be seen from the cash flow calculation in Appendix F, however, the tax benefits of 10% investment credit plus accelerated depreciation that are available to the private investors who funded the project provide substantial additional savings. The investors are able to pass on about $200 per month savings to the facility and still get a 6% return on their investment, despite lower than anticipated natural gas costs. The county has already saved nearly $24,000; projected savings for the 25-year life of the project, based on actual natural gas costs for the first 10 years and 3% escalation for the future, are $58,000.

The 10-year operating history of the parabolic-trough solar water-heating system for the Adams County Detention Facility shows clearly that the technology works, and that with installation on a payment-for-energy-savings basis, operation posed no burden on the facility or on facility staff. The cost calculations for the project show that subsidies can provide the difference to make a project economically viable and that the tax benefits to a private funder can be very important. The project's economic history and less-favorable-than-anticipated return for the investors also shows that one cannot count too heavily on conventional energy prices rising (something not done under the IDIQ). From the facility's perspective, however, this reinforces the fact that payment for savings is a guaranteed-win situation, regardless of whether energy prices rise or fall.

Case Study 2 — Federal Correctional Institution, Phoenix, Arizona

Located about 10 miles (16 kilometers) north of Phoenix, Arizona, the Federal Correctional Institution (FCI-Phoenix) is a medium-security prison for males. It opened in 1985 and was designed for about 500 inmates but is currently housing about 1200. With five two-story housing units and a kitchen/laundry building, the facility uses an average of about 21,000 gallons (79,494 liters) of hot water per day for kitchen, shower, laundry, and sanitation needs. The facility now uses electricity for all of its hot-water heating (current cost 6.2¢/kWh) and other utility needs. It does not have access to natural gas and propane was considered a safety concern in the prison setting.

IST has an ESPC contract, which was negotiated prior to the new IDIQ, to build and install a parabolic-trough solar water-heating system for FCI-Phoenix. The designed system includes 18,000 square feet (1672 square meters) of parabolic-trough solar collectors to be located inside a fenced enclosure of about 1.2 acres (0.5 hectare). A 21,000-gallon (79,494-liter) thermal energy storage tank will be located adjacent to the solar field. This larger-than-typical storage will allow the system to meet a projected 82% of the facility's hot-water needs and also meet most of the morning peak demand at FCI-Phoenix—which will reduce charges from the utility. An incoming cold-water supply line is routed to a copper-coil heat exchanger in the thermal storage tank and then through insulated underground piping to seven buildings. The solar-heated water is tempered down to 140˚F (60˚C) when necessary and then serves as preheated incoming water for the existing electric water heaters in each building.

The system will include 120 parabolic-trough collectors built by IST. Each 150-square-foot (14-square-meter) collector (20 feet by 7.5 feet [6.1 meters by 2.3 meters]) will have an aluminized acrylic reflective surface mounted on a steel trough. The system is modular and the enclosure will have excess space, so the system can be easily expanded. The system will be controlled by one Honeywell Fluxline master start-up and field controller and four Honeywell local sun-tracking controllers. Four three-phase electric motors with jack/cable drive will actually turn the collectors. Water will be delivered to and from the collectors in insulated two-layer, flexible stainless-steel hoses. IST will fabricate the nonpressurized stainless-steel thermal energy storage tank.

The parabolic-trough collector system for FCI-Phoenix is designed to provide 4923 MBtu per year of energy for domestic water heating, displacing electric water heating. (The electricity saved is about the amount 150 people would use for all purposes.) Because electric power plants only convert about one-third of fossil-fuel energy to electricity, and electric water heaters are about 95% efficient, the fossil-fuel combustion saved will be about 15 billion Btu per year. As indicated in Appendix G, the 28 million kWh saved over the life of the project will eliminate more than 80,000 kilograms of nitrogen oxides and nearly 100,000 kilograms of sulfur dioxide pollution plus 27 million kilograms of carbon dioxide greenhouse gas emissions.

Life-cycle cost analysis for the FCI-Phoenix project is shown in Appendix G, and cash-flow analysis for the facility and for the investors is shown in Appendix H. The project has excellent economics, with life-cycle energy savings nearly twice the cost of the project and an 8-year simple payback. These figures reflect the favorable impacts of a good solar resource and a large facility, but also show how high conventional energy costs make a parabolic-trough system economically attractive. The utility in this case does not have a peak pricing system per se, but the case does show how time-of-day or highest-demand pricing systems can make renewable energy systems more attractive—particularly systems that meet more of the demand.

Construction of the parabolic-trough project for FCI-Phoenix will begin in early 1998, so lessons learned for the facility are limited so far. Even though ESPC was used on this project, finalizing the contract and commencing installation took longer than anticipated. This suggests the importance of lining up investors ahead of time and being aware of the regulations involved in dealing with Federal agencies and in setting up business in a new state.

The Technology in Perspective

Parabolic-trough solar water heating is a proven technology that can play a significant role in reducing conventional energy use at Federal facilities in the Southwest or other areas with high direct-beam solar radiation. Facilities such as prisons, hospitals, and military barracks with large, constant water use loads are particularly good candidates. As with any alternative energy technology, the primary economic factors will be the cost of the system and the cost of conventional energy. Facilities dependent on high-cost water heating are definitely more likely to find parabolic-trough solar water-heating systems economically attractive.

The technology for domestic water heating with parabolic-trough collectors was advanced considerably by higher-temperature systems built in the 1980s for steam electric generation. Although the company that built those systems is no longer in business, the systems are all still operating, demonstrating the technology's technical merits and durability of the technology. Only one company, IST, is currently manufacturing parabolic-trough collectors for solar water-heating systems, but that company has an excellent track record, having built several effective systems—all at government facilities and all operating quite well.

Just as importantly from a Federal-facility perspective, IST has an IDIQ contract with FEMP for installing parabolic-trough water-heating systems at any Federal facility where a system would be appropriate. The near future of parabolic-trough water heating will be as much a reflection of the attractiveness of ESPC financing as of the technology itself. The IDIQ greatly facilitates the procurement process. Once the system is in place, there is essentially no burden on the facility. The energy service company conducts all operation and maintenance and facility staff need not do anything extra. ESPC requires no funding from the facility and guarantees the facility savings. Virtually the only risk to the facility would be the inconvenience of removing the parabolic-trough system should it not work adequately. ESPC financing also enables the energy service company or third-party investor to exploit tax credits and accelerated depreciation—and pass on benefits to the facility—that would not be available to a facility purchasing a system.

The FEMP Federal Renewables Program at the National Renewable Energy Laboratory can quickly assess whether solar water heating is likely to be economically attractive for a Federal facility with a minimum of information. The potential for application at rural Federal facilities in the Southwest, which are more likely to have high energy costs and a high solar resource, is quite good.

Dramatic technological breakthroughs to make parabolic-trough solar water heating economically attractive in areas with less sun or for facilities that have low-cost conventional energy available are unlikely. Incremental improvements in mirror and absorber coatings, however, are quite likely, and will make parabolic troughs increasingly efficient for the situations where they already are attractive. Any major cost reductions would come from economies of scale associated with substantially increased sales volume. This in turn would depend on market acceptance, subsidies, or an increase in conventional energy prices.

The difficulty of competing with conventional energy water heating prices is the only major roadblock to extensive use of parabolic-trough solar water heating at Federal facilities that meet the criteria for good project candidates. From the standpoints of technological feasibility, compatibility with existing facilities, conventional energy use reduction, and pollution and climate-change-gas emission reduction, the outlook is quite good. The technology is more limited geographically to areas of high solar resource and to larger facilities than are other solar water-heating technologies, but the economics are better. With the IDIQ contract, Federal facilities that are good candidates for the technology really should investigate it. There is no cost and little effort required of the facility to find out if a parabolic-trough system is feasible. If one is feasible, the facility can reap at least modest cost savings along with substantial energy savings. Even where the economic payoff is small, parabolic-trough projects are of great value because of the added benefits of reducing pollution and climate-change emissions by reducing fossil-fuel combustion. Federal facilities also need to comply with Executive Order 12902 and can play a valuable role by setting good renewable energy use examples.

Manufacturers of Parabolic-Trough Collectors

Industrial Solar Technology Corporation
4420 McIntyre Street
Golden, CO 80403
(303) 279-8108 (Ken May or Randy Gee)
(303) 279-8107 (fax)
indsolar@msn.com

To our knowledge this is the only company currently making parabolic-trough solar collectors or installing parabolic-trough water-heating systems. Another company that has occasionally made troughs for its own ice-making systems is listed below with absorption cooling manufacturers. To see if new companies have entered the field, check the *Thomas Register* or call the FEMP Federal Renewables Program. (See Federal Program Contacts.) The Solar Energy Industries Association membership and the Interstate Renewable Energy Council's *Procurement Guide for Renewable Energy Systems* are also good sources of manufacturers.

Manufacturers of Indirect-Fired Absorption Cooling Systems

American Yazaki Corporation
10-ton single-effect
13740 Omega Road
Dallas, TX 75244
(972) 385-8725 (Trevor Judd)

Carrier Corporation
100–680-ton single-effect
100–1700-ton double-effect
P.O. Box 4808
Syracuse, NY 13221
(315) 432-7152 (Douglas Rector)

Dunham-Bush, Inc.
100–425-ton single-effect
100–1400-ton double-effect
101 Burgess Road
Harrisonburg, VA 22801
(540) 434-0711 (Daryl Showalter)

Energy Concepts Company
refrigeration/ice making/high-efficiency cooling
627 Rangely Avenue
Annapolis, MD 21401
(410) 266-6521 (Don Erikson)

McQuay International
100–1500-ton double-effect
P.O. Box 2510
Staunton, VA 24402
(540) 248-9557 (John Alcott)

The Trane Company
100–660-ton single-effect
380–1150-ton double-effect
3600 Pammel Creek Road
La Crosse, WI 54601-7599
(608) 797-3369 (Mike Thompson)

York International Corporation
120–1377-ton single-effect
120–1500-ton double-effect
P.O. Box 1592
York, PA 17405-1592
(717) 771-6386 (Dante Ferrente)

These manufacturers were identified from literature of and correspondence with the American Gas Cooling Center, 1515 Wilson Blvd., Arlington, VA 22209, (703) 841-8409; check with them or the *Thomas Register* to see if other companies are now making indirect-fired absorption cooling equipment that might be suitable for use in conjunction with parabolic-trough collector systems.

Federal Program Contacts

Federal Energy Management Program (FEMP)
Help Desk: (800) 566-2877
FEMP@tmn.com

FEMP Federal Renewables Program (at the National Renewable Energy Laboratory [NREL])
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 384-7509
nancy_carlisle@nrel.gov

U.S. Department of Energy (DOE), Golden Field Office, contracting officer for IDIQ contracts
Beth Peterman (303) 275-4719

Who is Using the Technology

Federal Sites

Federal Correctional Institution-Phoenix, Phoenix, Arizona, area
4923 million Btu/yr domestic hot water, construction initiated 1998
FCI-Phoenix
37900 North 45th Avenue
Phoenix, AZ 85207

U.S. Army Yuma Proving Ground, Yuma, Arizona
8,970 million Btu/yr absorption cooling, space heating, and domestic hot water, installed 1979, refurbished 1986
Jack Nixon (602) 328-2198
Mail Code STEYP-EH-P
Director of Engineering and Housing
U.S. Army Yuma Proving Ground
Yuma, AZ 85365-9104

Non-Federal Sites

Adams County Detention Facility, Brighton, Colorado
1400 million Btu/yr domestic hot water, installed 1986
Rob Neiman (303) 654-1850, x 3335
Maintenance Supervisor for Facility Management
150 N. 19th Avenue
Brighton, CO 80601

California Correctional Institution at Tehachapi, California
6000 million Btu/yr domestic hot water, installed 1990
Harry Franey (916) 327-1134
Energy Manager
California Department of Corrections
P.O. Box 94283
Sacramento, CA 94283

Paul Beck Recreation Center, Aurora, Colorado
569 million Btu/yr indoor swimming pool heating and domestic hot water, installed 1985
Richard Abrahams (303) 361-2995
Recreation Services
City of Aurora
14949 E. Alameda
Aurora, CO 80012

Jefferson County Detention Facility, Golden, Colorado
2100 million Btu/yr domestic hot water, installed 1996
Anne Panza (303) 271-5026
Jefferson County Detention Facility
200 Jefferson County Parkway
Golden, CO 80401

For Further Information

Government Agency Technology Transfer Literature

Dudley, V.E.; Evans, L.R.; Matthews, C.W. (1995). *Test Results Industrial Solar Technology Parabolic Trough Solar Collector*. SAND94-1117. Albuquerque, NM: Sandia National Laboratories; 137 p.

Federal Energy Management Program. (1996). *Program Overview: Energy Savings Performance Contracting*. Washington, D.C.: Federal Energy Management Program; 2 p.

Federal Energy Management Program. (1996). *Solar Water Heating Federal Technology Alert*. Washington, D.C.: Federal Energy Management Program; 44 p.

Federal Energy Management Program. (1997). *What’s New in Federal Energy Management: Measurement and Verification Guidelines for Energy Savings Performance Contracting*. Washington, D.C.: Federal Energy Management Program; 2 p.

FRESA. Software that evaluates the cost-effectiveness of solar water heating. Available from Andy Walker at the Federal Renewables Project at the National Renewable Energy Laboratory, Golden, Colorado (303) 384-7531.

Hewett, R.; Gee, R.C.; May, E.K. (1991). *Solar Process Heat Technology in Action: The Process Hot Water System at the California Correctional Institution at Tehachapi*. NREL/TP-253-4624. Golden, CO: National Renewable Energy Laboratory; 4 p.

Marion, W.; Wilcox, S. (1994). *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*. NREL/TP-463-5607. Golden, CO: National Renewable Energy Laboratory; 252 p.

United States Department of Energy (Golden Field Office)/Industrial Solar Technology Corporation. (September 30, 1996). "Indefinite Delivery/Indefinite Quantity Type Contract for Energy Savings Performance Contract Services to Install Line Focussing, Parabolic Trough Solar Collector and Related Systems in Federal Facilities, by Performance on Delivery Orders Issued Against the Contract." 91 p. Available from Beth Peterman at (303) 275-4719.

Other References

American Gas Cooling Center. (1995). *Natural Gas Cooling Equipment Guide*. Arlington, Va.: American Gas Cooling Center; 160 p. (703) 841-8409.

Gee, R.C. (1996). "Parabolic Trough Collectors for Industrial and Commercial Applications." *19th World Energy Engineering Conference Proceedings, Atlanta, Georgia, November 6-8, 1996*. pp. 267-271.

Gee, R.C.; May, E.K. (1993). "A Seven Year Operation and Performance History of a Parabolic Trough Collector System." *ASME International Solar Energy Conference Proceedings, Washington, D.C., April 4-9, 1993*. pp. 309-313.

Solar Energy Industries Association. (1995). *Catalog of Successfully Operating Solar Process Heat Systems*. Washington, D.C.: Solar Energy Industries Association; 44 p.

Appendixes

Appendix A: Available Solar Radiation for Selected National Solar Radiation Data Base Stations

(Greater than 4.0 kWh/m^2/day Direct-Beam Radiation for Horizontal Single-Axis Tracking Systems)

[Data excerpted with permission from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* (1994) National Renewable Energy Laboratory (NREL/TP-463-5607)]

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m^2/day), Uncertainty ±8%

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Flagstaff, Arizona	1-Axis, E-W Horiz Axis	Average	4.4	4.4	4.4	5.1	5.7	6.3	4.4	4.3	4.6	4.9	4.6	4.3	4.8
		Min/Max	2.5/6.0	2.9/6.0	2.7/6.4	3.8/6.1	4.2/6.8	4.7/7.7	2.8/6.0	2.3/5.6	3.4/6.4	2.5/6.3	2.6/6.1	2.3/5.7	2.9/5.3
	1-Axis, N-S Horiz Axis	Average	3.6	4.4	5.4	6.9	7.9	8.6	6.0	5.9	6.0	5.4	4.1	3.4	5.6
		Min/Max	2.1/5.0	2.8/5.9	3.3/7.8	5.1/8.4	5.8/9.4	6.3/10.3	3.7/8.1	3.3/7.7	4.4/8.4	2.7/6.9	2.2/5.4	1.8/4.5	4.6/6.2
Phoenix, Arizona	1-Axis, E-W Horiz Axis	Average	4.2	4.6	4.8	5.7	6.4	6.8	5.6	5.3	5.2	5.0	4.5	4.1	5.2
		Min/Max	3.0/5.4	3.0/5.9	3.4/6.3	4.8/7.1	5.2/7.1	6.0/7.5	4.5/6.7	4.4/6.3	4.1/6.3	3.5/6.0	2.6/5.8	2.5/5.8	4.5/5.6
	1-Axis, N-S Horiz Axis	Average	3.4	4.6	5.8	7.6	8.5	8.9	7.2	7.0	6.5	5.4	4.0	3.2	6.0
		Min/Max	2.4/4.5	2.8/5.9	4.0/7.7	6.5/9.8	7.0/9.7	7.9/10.0	5.7/8.8	5.6/8.4	5.1/8.1	3.6/6.6	2.2/5.1	1.8/4.5	5.2/6.5
Prescott, Arizona	1-Axis, E-W Horiz Axis	Average	4.4	4.5	4.5	5.4	6.1	6.8	5.0	4.7	5.0	5.2	4.8	4.4	5.1
		Min/Max	2.8/5.8	2.8/6.0	2.8/6.4	4.0/6.4	5.0/6.9	5.3/7.4	3.8/6.3	3.1/5.9	3.9/6.7	3.0/6.4	2.8/6.2	2.5/5.7	4.3/5.8
	1-Axis, N-S Horiz Axis	Average	3.7	4.5	5.6	7.3	8.3	9.1	6.7	6.4	6.5	5.7	4.2	3.4	6.0
		Min/Max	2.3/4.8	2.8/6.1	3.5/8.1	5.5/8.9	6.9/9.5	7.2/10.1	5.1/8.6	4.4/8.1	4.9/8.9	3.2/7.1	2.5/5.5	2.0/4.4	5.1/6.8
Tucson, Arizona	1-Axis, E-W Horiz Axis	Average	4.7	5.0	5.1	5.9	6.5	6.7	5.0	5.0	5.1	5.3	5.0	4.5	5.3
		Min/Max	3.1/6.0	3.8/6.3	3.6/6.5	4.8/6.9	5.4/7.1	5.3/7.7	4.2/6.0	3.8/5.9	4.3/6.3	4.0/6.4	3.0/6.0	3.1/5.9	4.7/5.7
	1-Axis, N-S Horiz Axis	Average	4.0	5.1	6.2	8.0	8.8	8.9	6.5	6.6	6.6	5.9	4.5	3.6	6.2
		Min/Max	2.6/5.2	3.8/6.6	4.4/8.1	6.5/9.5	7.4/9.6	6.9/10.4	5.4/7.8	5.0/7.9	5.4/8.2	4.4/7.2	2.6/5.5	2.5/4.8	5.4/6.8
Bakersfield, California	1-Axis, E-W Horiz Axis	Average	2.1	2.9	3.5	4.5	5.6	6.5	6.5	5.9	5.2	4.4	3.0	2.0	4.3
		Min/Max	0.6/3.8	1.4/4.2	1.8/5.1	2.5/5.5	4.6/6.6	5.7/7.1	5.6/7.3	4.5/6.6	3.7/6.1	3.3/5.2	1.6/4.0	0.9/3.9	3.5/4.8
	1-Axis, N-S Horiz Axis	Average	1.6	2.7	4.0	5.8	7.5	8.6	8.7	7.9	6.5	4.6	2.5	1.5	5.2
		Min/Max	0.5/3.0	1.3/3.9	2.1/5.9	3.2/7.2	6.0/8.8	7.5/9.5	7.3/9.9	5.8/8.9	4.6/7.7	3.4/5.5	1.3/3.3	0.7/2.9	4.1/5.6
Daggett, California	1-Axis, E-W Horiz Axis	Average	4.5	4.7	5.0	5.7	6.5	7.1	6.6	6.2	5.9	5.5	4.9	4.6	5.6
		Min/Max	2.9/5.8	3.0/6.2	3.9/6.5	4.4/6.8	5.6/7.0	6.1/7.8	4.6/7.6	4.6/7.2	4.2/6.8	4.1/6.3	3.4/5.9	3.5/5.6	4.8/6.0
	1-Axis, N-S Horiz Axis	Average	3.7	4.6	6.1	7.7	8.7	9.6	8.8	8.4	7.5	6.0	4.3	3.5	6.6
		Min/Max	2.4/4.7	2.8/6.2	4.7/8.1	5.8/9.1	7.6/9.5	8.2/10.4	6.0/10.4	6.0/9.9	5.1/9.0	4.3/6.9	2.9/5.2	2.6/4.3	5.6/7.1
Fresno, California	1-Axis, E-W Horiz Axis	Average	1.8	2.7	3.6	4.6	5.7	6.4	6.6	5.9	5.1	4.3	2.7	1.7	4.3
		Min/Max	0.5/3.4	1.7/4.4	2.0/5.2	2.7/5.9	4.4/6.8	4.6/7.4	5.7/7.3	4.2/6.7	4.0/5.9	2.9/5.0	1.2/4.0	0.5/3.8	3.2/4.8
	1-Axis, N-S Horiz Axis	Average	1.3	2.5	4.1	5.9	7.6	8.4	8.8	7.8	6.3	4.3	2.2	1.2	5.1
		Min/Max	0.4/2.6	1.5/4.1	2.1/6.0	3.6/7.9	5.8/9.0	5.8/10.0	7.2/9.9	5.2/9.0	4.8/7.4	2.8/5.2	0.9/3.3	0.4/2.7	3.7/5.8
Long Beach, California	1-Axis, E-W Horiz Axis	Average	3.2	3.3	3.5	4.1	4.0	4.2	5.2	4.8	4.0	3.7	3.5	3.2	3.9
		Min/Max	2.0/4.6	2.1/4.9	2.6/5.1	3.2/5.5	2.7/5.1	2.0/5.4	4.1/5.9	3.9/5.5	2.2/4.8	2.6/4.5	2.5/4.3	1.8/4.2	3.3/4.3
	1-Axis, N-S Horiz Axis	Average	2.6	3.2	4.1	5.3	5.2	5.4	6.6	6.2	4.8	3.8	2.9	2.4	4.4
		Min/Max	1.6/3.7	1.9/4.7	3.0/6.0	4.0/7.1	3.5/6.6	2.7/7.0	5.1\7.6	5.1/7.0	2.7/5.8	2.8/4.7	2.1/3.7	1.4/3.2	3.7/4.7

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Los Angeles,	1-Axis, E-W	Average	3.2	3.4	3.6	4.1	3.9	3.9	4.8	4.5	3.8	3.6	3.5	3.2	3.8
California	Horiz Axis	Min/Max	2.0/4.5	1.9/5.0	2.4/4.9	3.3/5.4	3.0/5.1	2.4/5.3	3.7/6.1	4.0/5.3	2.2/4.8	2.8/4.4	2.3/4.7	1.8/4.1	3.4/4.2
	1-Axis, N-S	Average	2.6	3.2	4.1	5.3	5.0	5.0	6.1	5.7	4.6	3.7	2.9	2.4	4.2
	Horiz Axis	Min/Max	1.6/3.6	1.8/4.8	2.8/5.8	4.2/7.0	3.7/6.6	3.2/6.9	4.6/8.0	4.9/6.8	2.7/5.8	2.9/4.5	1.9/4.0	1.3/3.1	3.8/4.7
Sacramento,	1-Axis, E-W	Average	1.8	2.6	3.4	4.3	5.5	6.2	6.6	5.8	5.2	4.1	2.5	1.7	4.1
California	Horiz Axis	Min/Max	0.7/3.0	1.2/4.6	1.8/5.3	2.1/5.4	4.0/6.5	4.9/7.3	5.6/7.1	4.7/6.6	3.8/5.8	3.2/4.8	1.1/4.1	0.6/3.6	3.4/4.6
	1-Axis, N-S	Average	1.3	2.4	3.8	5.6	7.3	8.3	8.8	7.7	6.3	4.1	2.0	1.2	4.9
	Horiz Axis	Min/Max	0.5/2.2	1.0/4.2	2.0/6.1	2.8/7.0	5.3/8.7	6.4/9.8	7.4/9.6	6.3/8.8	4.4/7.2	3.1/4.9	0.9/3.2	0.4/2.5	4.1/5.3
San Diego,	1-Axis, E-W	Average	3.8	3.8	3.9	4.3	3.9	4.0	4.9	4.8	4.2	4.1	4.0	3.8	4.1
California	Horiz Axis	Min/Max	2.4/4.9	2.5/5.1	2.9/5.3	3.4/5.5	2.5/5.2	1.8/5.7	2.9/5.8	3.8/5.6	1.9/5.2	3.0/5.2	2.7/5.2	2.5/4.8	3.6/4.5
	1-Axis, N-S	Average	3.1	3.8	4.6	5.6	4.9	5.0	6.2	6.1	5.1	4.4	3.6	3.0	4.6
	Horiz Axis	Min/Max	2.0/4.1	2.3/5.1	3.4/6.3	4.3/7.1	3.1/6.8	2.3/7.3	3.6/7.4	4.7/7.2	2.3/6.3	3.2/5.5	2.4/4.6	2.0/3.8	3.9/5.0
San Francisco,	1-Axis, E-W	Average	2.5	2.8	3.3	4.0	4.7	5.1	5.5	4.9	4.6	3.9	2.8	2.5	3.9
California	Horiz Axis	Min/Max	1.6/3.5	1.5/4.9	1.9/5.2	2.4/5.2	3.3/5.7	3.6/6.3	4.9/6.4	3.7/6.1	3.3/5.6	2.6/5.0	1.8/3.9	1.1/3.9	3.2/4.2
	1-Axis, N-S	Average	1.9	2.5	3.8	5.2	6.1	6.5	7.1	6.3	5.4	3.9	2.3	1.8	4.4
	Horiz Axis	Min/Max	1.2/2.6	1.3/4.6	2.1/6.0	3.1/6.7	4.2/7.5	4.6/8.3	6.2/8.3	4.7/8.0	4.0/6.8	2.5/5.0	1.5/3.2	0.8/2.8	3.7/4.7
Santa Maria,	1-Axis, E-W	Average	3.6	3.8	4.0	4.5	4.9	5.3	5.6	5.2	4.6	4.3	3.9	3.7	4.5
California	Horiz Axis	Min/Max	2.1/4.9	2.1/5.0	2.3/5.7	3.0/5.7	2.9/6.2	3.6/6.4	4.6/6.4	4.1/5.9	3.2/5.6	3.2/5.2	2.6/5.2	2.6/5.0	3.6/5.0
	1-Axis, N-S	Average	2.9	3.6	4.6	5.9	6.4	6.8	7.1	6.5	5.5	4.5	3.4	2.8	5.0
	Horiz Axis	Min/Max	1.6/3.9	2.0/4.8	2.7/6.7	4.0/7.5	3.8/8.2	4.5/8.3	5.7/8.3	5.0/7.5	3.7/7.0	3.3/5.5	2.2/4.5	2.0/3.8	4.1/5.5
Alamosa,	1-Axis, E-W	Average	4.8	5.0	4.7	5.0	5.4	6.2	5.5	5.0	5.1	5.2	4.8	4.6	5.1
Colorado	Horiz Axis	Min/Max	3.5/5.7	3.8/6.0	3.3/5.7	3.3/5.9	4.3/6.3	5.1/7.4	4.7/6.9	4.0/5.9	3.5/6.3	2.8/6.4	3.5/5.8	3.2/5.6	4.4/5.7
	1-Axis, N-S	Average	3.7	4.8	5.7	6.9	7.4	8.4	7.4	6.7	6.5	5.5	4.0	3.4	5.9
	Horiz Axis	Min/Max	2.6/4.6	3.6/5.9	3.8/6.9	4.6/8.3	5.8/8.8	6.9/9.9	6.2/9.4	5.4/8.1	4.2/8.0	3.0/7.0	2.8/4.9	2.3/4.2	5.0/6.6
Boulder,	1-Axis, E-W	Average	3.5	3.7	3.7	4.0	4.2	5.0	4.9	4.5	4.4	4.3	3.6	3.4	4.1
Colorado	Horiz Axis	Min/Max	2.3/4.6	2.8/4.5	2.1/4.8	2.9/5.0	2.9/5.7	3.5/6.4	3.8/6.1	3.4/5.4	2.8/5.5	2.5/5.2	2.7/4.7	2.0/4.3	3.4/4.5
	1-Axis, N-S	Average	2.6	3.4	4.2	5.3	5.6	6.6	6.5	6.0	5.4	4.3	2.8	2.3	4.6
	Horiz Axis	Min/Max	1.6/3.4	2.5/4.2	2.2/5.7	3.6/6.4	3.8/7.6	4.8/8.5	4.8/8.1	4.5/7.1	3.4/6.7	2.4/5.3	2.2/3.6	1.3/3.0	3.7/5.1
Colorado Spgs,	1-Axis, E-W	Average	3.9	4.0	3.9	4.2	4.2	5.1	4.8	4.5	4.4	4.5	3.9	3.8	4.3
Colorado	Horiz Axis	Min/Max	2.5/5.0	3.1/4.7	2.2/5.2	2.8/5.3	3.1/5.4	3.8/6.4	4.0/6.1	3.4/5.5	3.0/5.6	2.6/5.7	2.9/5.1	2.4/4.8	3.6/4.7
	1-Axis, N-S	Average	2.9	3.7	4.5	5.6	5.7	6.8	6.4	6.0	5.5	4.7	3.2	2.7	4.8
	Horiz Axis	Min/Max	1.8/3.8	2.8/4.5	2.4/6.0	3.7/7.1	4.2/7.4	5.1/8.5	5.2/8.1	4.4/7.4	3.6/7.1	2.6/5.9	2.3/4.2	1.6/3.5	4.1/5.3
Eagle,	1-Axis, E-W	Average	3.1	3.6	3.5	4.0	4.4	5.4	5.1	4.6	4.5	4.3	3.3	3.1	4.1
Colorado	Horiz Axis	Min/Max	2.0/5.2	2.6/4.6	2.3/4.5	3.1/4.9	3.2/5.5	4.5/7.1	4.3/6.1	3.3/5.7	2.8/5.4	2.5/5.6	1.7/4.8	1.4/4.3	3.6/4.5
	1-Axis, N-S	Average	2.3	3.2	4.1	5.3	6.0	7.3	6.9	6.2	5.6	4.4	2.6	2.1	4.7
	Horiz Axis	Min/Max	1.4/3.9	2.3/4.3	2.5/5.1	4.1/6.6	4.3/7.6	6.0/9.6	5.8/8.4	4.3/7.8	3.3/7.0	2.5/5.7	1.4/3.8	0.9/3.0	4.1/5.1
Grand Junction,	1-Axis, E-W	Average	3.3	3.7	3.7	4.3	5.0	5.9	5.5	5.1	4.9	4.5	3.6	3.4	4.4
Colorado	Horiz Axis	Min/Max	1.9/5.3	2.3/5.2	1.8/4.9	3.2/5.4	3.5/6.0	4.3/7.6	4.8/6.2	3.7/5.8	3.0/5.9	2.6/5.6	2.1/5.2	1.2/4.7	3.3/4.9
	1-Axis, N-S	Average	2.5	3.4	4.3	5.7	6.7	7.9	7.4	6.7	6.2	4.6	2.9	2.3	5.1
	Horiz Axis	Min/Max	1.5/4.0	2.0/4.9	1.9/5.7	4.0/7.2	4.5/8.2	5.6/10.2	6.3/8.2	4.7/7.9	3.7/7.3	2.5/5.8	1.6/4.2	0.8/3.3	3.7/5.6

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
			Direct Beam Solar Radiation for Concentrating Collectors ($kWh/m^2/day$), Uncertainty ±8%												
Pueblo, Colorado	1-Axis, E-W Horiz Axis	Average	4.0	4.2	4.2	4.6	4.8	5.7	5.5	5.1	4.8	4.8	4.1	3.9	4.6
		Min/Max	2.6/4.9	3.1/5.1	2.5/5.1	3.3/5.4	3.8/5.9	4.6/7.0	4.4/6.5	4.2/6.0	3.6/5.8	2.8/5.8	3.0/5.3	2.7/5.0	4.1/5.1
	1-Axis, N-S Horiz Axis	Average	3.1	3.9	4.9	6.1	6.4	7.5	7.2	6.6	5.9	4.9	3.3	2.8	5.2
		Min/Max	1.9/3.8	2.9/4.8	2.8/6.1	4.3/7.3	4.9/8.0	6.0/9.3	5.7/8.7	5.4/7.9	4.4/7.4	2.9/6.1	2.5/4.4	1.9/3.6	4.6/5.7
Key West, Florida	1-Axis, E-W Horiz Axis	Average	3.8	4.1	4.3	4.5	4.1	3.6	3.5	3.4	3.1	3.5	3.6	3.7	3.8
		Min/Max	2.3/4.9	2.7/5.1	2.9/5.3	3.6/5.5	2.8/4.7	2.5/4.5	2.9/4.0	2.8/3.9	2.4/3.7	2.4/4.5	2.5/4.5	2.6/4.7	3.3/4.1
	1-Axis, N-S Horiz Axis	Average	3.6	4.4	5.3	6.0	5.3	4.5	4.5	4.3	3.9	3.9	3.5	3.3	4.4
		Min/Max	2.1/4.6	2.8/5.6	3.5/6.7	4.7/7.5	3.6/6.2	3.1/5.7	3.6/5.1	3.6/5.0	3.0/4.7	2.8/5.1	2.4/4.4	2.3/4.3	3.8/4.8
Tampa, Florida	1-Axis, E-W Horiz Axis	Average	3.3	3.6	3.8	4.3	4.1	3.4	3.1	3.0	2.9	3.5	3.5	3.4	3.5
		Min/Max	1.9/4.6	2.4/4.8	2.6/4.8	3.5/5.3	3.1/5.0	2.2/4.6	2.3/3.9	2.0/4.0	2.0/3.7	2.0/4.4	2.3/4.6	2.2/4.5	2.8/4.1
	1-Axis, N-S Horiz Axis	Average	3.0	3.7	4.7	5.7	5.4	4.4	4.0	3.9	3.6	3.9	3.3	2.9	4.0
		Min/Max	1.6/4.1	2.4/5.1	3.2/5.9	4.7/7.1	4.1/6.7	2.8/5.9	3.0/5.0	2.7/5.3	2.5/4.8	2.3/4.9	2.2/4.3	1.8/3.9	3.2/4.7
Honolulu, Hawaii	1-Axis, E-W Horiz Axis	Average	3.5	3.8	3.7	3.6	4.1	4.4	4.6	4.4	4.1	3.8	3.5	3.5	3.9
		Min/Max	2.2/4.8	2.1/4.8	2.3/4.8	2.5/4.7	3.0/5.1	3.9/5.2	3.8/5.3	3.3/5.3	3.2/4.7	2.9/4.5	2.3/4.4	2.2/4.4	3.2/4.3
	1-Axis, N-S Horiz Axis	Average	3.5	4.3	4.7	4.9	5.5	5.7	6.0	6.0	5.5	4.5	3.6	3.3	4.8
		Min/Max	2.1/4.7	2.4/5.5	2.9/6.2	3.3/6.4	3.9/6.9	5.0/6.8	5.0/7.0	4.4/7.1	4.3/6.3	3.5/5.5	2.3/4.4	2.0/4.2	3.9/5.3
Kahului, Hawaii	1-Axis, E-W Horiz Axis	Average	4.0	4.1	4.0	4.0	4.6	5.1	5.1	4.9	4.7	4.3	4.0	4.1	4.4
		Min/Max	2.5/5.7	2.3/5.6	2.1/5.5	2.4/5.3	3.3/5.7	4.2/6.6	3.8/6.1	3.7/5.9	3.8/5.4	3.2/5.5	2.4/5.3	2.8/5.3	3.6/5.0
	1-Axis, N-S Horiz Axis	Average	4.0	4.7	5.2	5.4	6.2	6.7	6.7	6.7	6.3	5.2	4.2	3.9	5.4
		Min/Max	2.5/5.7	2.5/6.4	2.7/7.3	3.2/7.2	4.3/7.8	5.4/8.8	5.1/8.1	4.9/8.2	5.2/7.4	3.8/6.7	2.5/5.6	2.7/5.1	4.4/6.2
Lihue, Hawaii	1-Axis, E-W Horiz Axis	Average	3.3	3.4	3.1	3.0	3.7	3.9	3.8	3.9	3.9	3.5	3.0	3.2	3.5
		Min/Max	1.7/4.7	1.4/4.9	1.4/5.0	2.0/4.1	2.6/4.8	2.7/5.7	2.6/4.9	2.7/4.8	2.7/4.7	2.6/4.3	1.6/4.2	1.7/4.8	2.8/4.1
	1-Axis, N-S Horiz Axis	Average	3.2	3.8	3.9	4.0	4.8	5.0	4.9	5.1	5.1	4.1	3.0	3.0	4.2
		Min/Max	1.6/4.6	1.6/5.6	1.6/6.3	2.6/5.4	3.3/6.3	3.4/7.4	3.3/6.3	3.5/6.5	3.5/6.0	3.0/5.0	1.6/4.2	1.6/4.5	3.3/4.9
Boise, Idaho	1-Axis, E-W Horiz Axis	Average	1.7	2.4	3.0	3.8	4.7	5.5	6.4	5.6	5.0	4.0	2.2	1.7	3.8
		Min/Max	0.4/2.8	1.0/3.9	1.8/4.5	1.8/5.2	3.1/5.9	3.4/6.9	5.1/7.6	3.9/7.0	3.3/6.4	2.6/5.7	0.9/3.6	0.6/3.4	3.3/4.3
	1-Axis, N-S Horiz Axis	Average	1.1	2.1	3.4	4.9	6.3	7.3	8.7	7.5	6.1	3.9	1.6	1.1	4.5
		Min/Max	0.3/1.9	0.9/3.4	1.9/5.1	2.4/6.7	4.2/8.0	4.5/9.2	6.8/10.4	5.1/9.4	4.0/7.9	2.5/5.4	0.7/2.6	0.4/2.1	3.8/5.0
Pocatello, Idaho	1-Axis, E-W Horiz Axis	Average	1.7	2.4	2.9	3.5	4.3	5.3	6.0	5.2	4.7	3.9	2.1	1.7	3.6
		Min/Max	0.8/3.4	1.4/3.8	1.5/4.2	2.1/5.3	2.8/5.9	3.5/6.7	4.9/7.2	3.5/6.5	3.4/6.2	2.7/5.4	1.0/3.8	0.5/3.0	3.0/4.2
	1-Axis, N-S Horiz Axis	Average	1.2	2.1	3.3	4.5	5.7	7.0	8.0	7.0	5.7	3.9	1.6	1.1	4.3
		Min/Max	0.6/2.4	1.2/3.4	1.6/4.6	2.7/6.9	3.9/7.9	4.6/9.0	6.4/9.7	4.6/8.7	4.0/7.7	2.6/5.3	0.7/2.8	0.3/1.9	3.5/4.9
Dodge City, Kansas	1-Axis, E-W Horiz Axis	Average	3.7	3.8	3.8	4.2	4.3	5.1	5.2	4.5	4.1	4.1	3.5	3.4	4.1
		Min/Max	2.1/5.4	2.2/5.3	2.0/5.0	2.9/5.2	3.1/5.6	3.5/6.5	3.9/6.0	3.3/5.8	2.3/5.0	2.1/5.6	2.1/5.1	1.9/5.0	3.4/4.7
	1-Axis, N-S Horiz Axis	Average	2.8	3.6	4.4	5.5	5.8	6.6	6.8	6.0	5.0	4.2	2.9	2.5	4.7
		Min/Max	1.6/4.2	2.0/4.9	2.2/5.7	3.8/6.7	4.0/7.6	4.6/8.6	5.2/7.9	4.3/7.5	2.9/6.1	2.2/5.7	1.8/4.2	1.4/3.7	3.9/5.2
Goodland, Kansas	1-Axis, E-W Horiz Axis	Average	3.6	3.7	3.7	4.2	4.3	5.4	5.4	4.9	4.4	4.4	3.6	3.5	4.2
		Min/Max	2.5/4.8	2.7/4.6	2.3/4.8	3.1/5.3	3.3/5.7	3.8/7.0	4.3/6.7	3.9/6.2	2.5/5.5	2.0/5.7	2.4/4.8	2.8/4.4	3.7/4.7
	1-Axis, N-S Horiz Axis	Average	2.7	3.4	4.3	5.5	5.8	7.1	7.1	6.4	5.4	4.4	2.9	2.4	4.8
		Min/Max	1.9/3.6	2.5/4.3	2.5/5.6	4.1/7.1	4.5/7.6	4.9/9.2	5.7/9.0	5.1/8.2	3.1/6.8	2.1/5.9	1.9/3.8	1.9/3.2	4.2/5.3

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Wichita, Kansas	1-Axis, E-W Horiz Axis	Average	3.2	3.2	3.3	3.6	3.8	4.5	4.7	4.3	3.7	3.7	3.1	3.0	3.7
		Min/Max	1.6/5.1	1.8/4.5	1.7/4.5	2.5/5.1	2.9/5.1	3.3/5.7	3.8/6.2	3.0/5.5	1.9/5.3	2.0/5.0	2.0/4.7	1.9/4.8	3.1/4.3
	1-Axis, N-S Horiz Axis	Average	2.5	3.0	3.8	4.7	5.1	5.9	6.3	5.7	4.5	3.8	2.5	2.1	4.2
		Min/Max	1.2/4.0	1.7/4.2	2.0/5.2	3.2/6.7	4.0/6.9	4.3/7.6	5.0/8.2	3.9/7.4	2.4/6.5	2.0/5.2	1.6/3.8	1.4/3.5	3.6/4.9
Billings, Montana	1-Axis, E-W Horiz Axis	Average	2.3	2.7	3.1	3.4	3.9	4.8	5.6	5.1	4.1	3.5	2.5	2.2	3.6
		Min/Max	1.2/3.6	1.8/3.9	2.0/4.5	2.4/4.8	2.7/5.0	3.5/6.3	4.2/6.5	4.1/6.3	2.3/5.7	2.3/4.4	1.7/3.4	1.5/3.1	3.0/4.0
	1-Axis, N-S Horiz Axis	Average	1.4	2.2	3.3	4.3	5.2	6.4	7.4	6.7	4.9	3.3	1.8	1.3	4.0
		Min/Max	0.8/2.3	1.5/3.2	2.1/4.8	3.1/6.3	3.7/6.6	4.6/8.4	5.4/8.6	5.3/8.4	2.7/6.8	2.1/4.2	1.2/2.5	0.8/1.8	3.3/4.5
Miles City, Montana	1-Axis, E-W Horiz Axis	Average	2.3	2.7	3.1	3.4	3.9	4.9	5.5	5.0	4.0	3.4	2.4	2.1	3.6
		Min/Max	1.2/3.2	2.0/3.9	2.0/4.5	1.7/4.9	2.7/5.3	2.7/6.4	4.4/6.5	4.0/6.1	2.1/5.2	2.2/4.3	1.5/3.2	1.4/3.3	3.0/4.2
	1-Axis, N-S Horiz Axis	Average	1.4	2.2	3.3	4.4	5.2	6.5	7.4	6.5	4.8	3.1	1.7	1.2	4.0
		Min/Max	0.7/2.1	1.6/3.2	2.1/4.7	2.2/6.4	3.7/7.0	3.5/8.4	5.9/8.8	5.1/8.1	2.5/6.3	2.0/4.0	1.0/2.3	0.8/1.9	3.3/4.7
Grand Island, Nebraska	1-Axis, E-W Horiz Axis	Average	3.2	3.2	3.3	3.7	3.9	4.8	4.9	4.4	3.8	3.7	2.9	2.8	3.7
		Min/Max	1.5/4.5	1.9/4.1	1.7/5.1	2.0/4.8	2.3/5.1	3.3/5.8	3.7/6.0	2.9/5.4	2.1/5.3	2.3/4.9	1.8/4.1	2.1/3.7	2.9/4.2
	1-Axis, N-S Horiz Axis	Average	2.3	2.8	3.7	4.8	5.2	6.3	6.5	5.8	4.7	3.7	2.3	1.9	4.2
		Min/Max	1.0/3.3	1.5/3.8	1.8/5.7	2.6/6.4	3.1/6.8	4.4/7.7	4.9/8.0	3.8/7.2	2.6/6.5	2.3/4.9	1.3/3.1	1.4/2.5	3.4/4.7
North Platte, Nebraska	1-Axis, E-W Horiz Axis	Average	3.1	3.2	3.3	3.7	3.9	4.9	5.0	4.5	4.0	3.8	3.0	3.0	3.8
		Min/Max	1.7/4.6	2.1/4.1	1.9/4.7	2.5/4.7	2.6/5.3	3.5/5.9	4.0/5.8	3.3/5.8	2.3/5.4	2.0/4.9	1.7/4.0	2.0/4.1	3.1/4.2
	1-Axis, N-S Horiz Axis	Average	2.2	2.9	3.7	4.9	5.2	6.4	6.6	5.9	4.8	3.8	2.3	2.0	4.2
		Min/Max	1.1/3.3	1.8/3.7	2.0/5.4	3.2/6.3	3.5/7.1	4.5/7.8	5.1/7.7	4.3/7.6	2.8/6.7	1.9/4.9	1.3/3.0	1.3/2.8	3.4/4.6
Scottsbluff, Nebraska	1-Axis, E-W Horiz Axis	Average	3.0	3.3	3.3	3.6	3.9	5.0	5.4	4.9	4.3	3.9	3.0	3.0	3.9
		Min/Max	2.2/4.0	2.7/4.4	2.4/4.5	2.8/4.9	2.9/4.9	3.7/5.9	4.7/5.9	4.0/5.8	3.0/5.5	2.4/4.8	2.2/3.9	2.2/4.2	3.5/4.2
	1-Axis, N-S Horiz Axis	Average	2.1	3.0	3.7	4.7	5.2	6.6	7.0	6.4	5.2	3.8	2.3	1.9	4.3
		Min/Max	1.4/2.9	2.3/4.0	2.6/5.0	3.5/6.4	3.8/6.5	4.7/7.8	6.1/7.8	5.0/7.6	3.5/6.8	2.4/4.9	1.7/3.0	1.4/2.8	3.9/4.7
Albuquerque, New Mexico	1-Axis, E-W Horiz Axis	Average	4.5	4.6	4.6	5.3	5.9	6.3	5.5	5.2	4.9	5.1	4.6	4.4	5.1
		Min/Max	3.1/5.8	3.0/5.7	3.0/6.2	4.3/6.1	4.7/7.1	5.3/7.4	4.3/6.4	3.7/6.0	3.9/6.2	3.3/6.5	2.8/5.9	2.6/5.7	4.3/5.5
	1-Axis, N-S Horiz Axis	Average	3.7	4.6	5.6	7.2	8.0	8.4	7.2	6.7	6.2	5.4	4.0	3.4	5.9
		Min/Max	2.5/4.8	3.0/5.7	3.4/7.6	5.7/8.4	6.1/9.7	6.8/10.0	5.4/8.4	4.7/7.9	4.7/7.9	3.4/7.2	2.4/5.2	2.0/4.5	4.8/6.4
Tucumcari, New Mexico	1-Axis, E-W Horiz Axis	Average	4.1	4.3	4.4	4.9	5.1	5.6	5.3	4.8	4.5	4.7	4.2	4.1	4.7
		Min/Max	2.6/5.4	3.1/5.4	3.1/5.4	4.0/5.8	4.2/6.1	4.4/6.7	4.4/6.1	4.1/6.1	3.8/5.8	3.3/6.2	2.5/5.2	2.4/5.7	4.1/5.1
	1-Axis, N-S Horiz Axis	Average	3.3	4.2	5.2	6.6	6.8	7.4	6.9	6.3	5.7	5.1	3.7	3.1	5.4
		Min/Max	2.1/4.4	3.0/5.4	3.6/6.4	5.2/7.8	5.6/8.2	5.6/8.9	5.7/8.2	5.4/8.3	4.6/7.3	3.5/6.7	2.1/4.5	1.8/4.4	4.7/5.9
Elko, Nevada	1-Axis, E-W Horiz Axis	Average	2.8	3.1	3.2	3.6	4.4	5.4	6.0	5.4	5.1	4.4	3.0	2.8	4.1
		Min/Max	1.7/4.2	1.8/5.0	1.9/4.2	2.0/5.1	2.5/6.0	3.5/7.0	4.9/7.9	3.7/6.5	3.1/6.8	3.2/5.5	1.7/4.7	1.0/4.7	3.5/4.5
	1-Axis, N-S Horiz Axis	Average	2.1	2.8	3.7	4.8	5.9	7.2	8.1	7.3	6.3	4.5	2.3	1.9	4.8
		Min/Max	1.2/3.1	1.6/4.6	2.2/4.9	2.7/6.7	3.4/8.1	4.8/9.5	6.5/10.7	5.0/8.9	3.8/8.6	3.2/5.7	1.3/3.7	0.6/3.2	4.0/5.3
Ely, Nevada	1-Axis, E-W Horiz Axis	Average	3.6	3.8	3.7	4.2	4.6	5.7	5.7	5.1	5.2	4.7	3.7	3.5	4.5
		Min/Max	2.4/4.8	2.3/5.7	2.3/5.0	2.7/5.7	3.0/5.8	4.1/7.0	4.2/7.3	3.5/6.9	2.8/6.4	3.5/5.8	2.1/5.0	1.2/5.3	3.5/5.0
	1-Axis, N-S Horiz Axis	Average	2.7	3.5	4.4	5.5	6.3	7.7	7.8	7.0	6.5	4.8	3.0	2.5	5.1
		Min/Max	1.6/3.6	2.1/5.4	2.5/5.9	3.4/7.7	4.3/8.0	5.4/9.5	5.5/9.9	4.9/9.4	3.5/8.4	3.5/5.9	1.6/4.1	0.8/3.7	4.1/5.6

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Las Vegas,	1-Axis, E-W	Average	4.3	4.5	4.8	5.5	6.1	6.8	6.1	5.8	5.6	5.3	4.6	4.3	5.3
Nevada	Horiz Axis	Min/Max	2.7/5.7	3.0/5.8	3.8/6.3	4.1/6.4	5.2/7.1	5.7/7.6	4.4/7.1	4.4/6.9	4.0/6.6	3.5/6.1	3.1/5.7	2.7/5.3	4.5/5.8
	1-Axis, N-S	Average	3.4	4.4	5.7	7.4	8.2	9.1	8.2	7.8	7.1	5.6	3.9	3.2	6.2
	Horiz Axis	Min/Max	2.1/4.6	2.8/5.7	4.2/7.7	5.5/8.7	7.0/9.6	7.5/10.3	5.5/9.6	5.8/9.4	4.9/8.5	3.7/6.5	2.5/4.9	1.9/4.0	5.2/6.7
Reno,	1-Axis, E-W	Average	3.2	3.5	3.9	4.4	5.2	6.0	6.6	5.9	5.4	4.8	3.4	3.1	4.6
Nevada	Horiz Axis	Min/Max	1.8/5.1	2.0/5.6	2.1/5.8	2.7/6.1	3.5/6.3	4.6/7.2	5.3/7.7	4.2/6.9	3.5/6.9	3.7/5.6	2.0/5.0	1.5/4.8	3.6/5.2
	1-Axis, N-S	Average	2.3	3.2	4.5	5.8	7.0	8.0	8.8	7.9	6.8	4.9	2.7	2.2	5.4
	Horiz Axis	Min/Max	1.3/3.8	1.8/5.2	2.3/6.8	3.5/8.1	4.8/8.5	6.1/9.7	7.1/10.3	5.6/9.4	4.2/8.8	3.7/5.7	1.6/4.1	1.0/3.4	4.2/6.0
Tonopah,	1-Axis, E-W	Average	4.0	4.1	4.3	4.8	5.3	6.3	6.4	5.8	5.6	5.2	4.1	3.9	5.0
Nevada	Horiz Axis	Min/Max	2.5/5.6	2.5/5.9	2.7/5.7	3.0/6.0	4.0/6.4	5.1/7.6	5.0/7.9	4.3//6.9	3.2/6.8	3.9/5.9	3.0/5.7	2.4/5.5	4.0/5.5
	1-Axis, N-S	Average	3.1	3.9	5.1	6.4	7.2	8.4	8.6	7.8	7.1	5.4	3.4	2.9	5.8
	Horiz Axis	Min/Max	1.9/4.3	2.2/5.7	3.2/6.9	4.0/8.0	5.4/8.8	6.8/10.2	6.5/10.7	5.8/9.5	4.0/8.8	4.2/6.3	2.4/4.7	1.7/4.0	4.7/6.3
Winnemucca,	1-Axis, E-W	Average	2.8	3.0	3.3	3.8	4.6	5.6	6.3	5.6	5.2	4.4	2.9	2.7	4.2
Nevada	Horiz Axis	Min/Max	1.1/4.5	1.6/5.2	2.0/4.7	1.8/5.0	2.7/6.0	3.6/7.1	5.2/7.5	3.6/6.8	3.8/6.9	3.3/5.8	1.3/4.6	0.8/4.7	3.6/4.8
	1-Axis, N-S	Average	2.0	2.7	3.8	5.1	6.2	7.4	8.5	7.5	6.5	4.5	2.3	1.8	4.9
	Horiz Axis	Min/Max	0.8/3.3	1.4/4.8	2.3/5.4	2.3/6.6	3.7/8.2	4.9/9.5	6.9/10.2	4.9/9.4	4.6/8.8	3.2/5.9	1.0/3.5	0.5/3.2	4.2/5.5
Oklahoma City,	1-Axis, E-W	Average	3.4	3.4	3.5	3.9	3.9	4.5	4.9	4.4	3.7	3.8	3.3	3.2	3.8
Oklahoma	Horiz Axis	Min/Max	1.6/5.0	1.9/4.7	2.0/4.9	2.9/5.2	3.0/4.9	3.5/5.6	3.0/6.3	3.5/5.4	2.3/4.9	2.4/5.1	1.9/4.9	1.9/4.6	3.3/4.3
	1-Axis, N-S	Average	2.7	3.3	4.2	5.1	5.2	5.9	6.5	5.9	4.7	4.1	2.8	2.4	4.4
	Horiz Axis	Min/Max	1.3/4.0	1.8/4.6	2.2/5.7	3.7/6.9	3.9/6.5	4.6/7.4	4.1/8.4	4.7/7.3	2.9/6.2	2.4/5.4	1.7/4.2	1.5/3.5	3.8/4.9
Burns,	1-Axis, E-W	Average	1.9	2.4	2.9	3.5	4.4	5.1	6.2	5.5	4.8	3.8	2.0	1.8	3.7
Oregon	Horiz Axis	Min/Max	0.9/3.1	0.8/4.4	1.6/4.0	1.9/5.2	2.7/5.5	3.8/6.6	5.3/7.1	3.3/6.9	3.5/6.1	2.3/5.5	0.6/3.9	0.9/3.4	3.2/4.3
	1-Axis, N-S	Average	1.3	2.1	3.2	4.6	5.9	6.9	8.3	7.3	5.9	3.7	1.5	1.1	4.3
	Horiz Axis	Min/Max	0.6/2.1	0.6/3.8	1.7/4.4	2.6/6.6	3.7/7.4	5.1/8.9	7.2/9.6	4.4/9.4	4.3/7.6	2.3/5.3	0.5/2.9	0.5/2.2	3.7/5.0
Medford,	1-Axis, E-W	Average	1.3	2.1	2.7	3.5	4.5	5.4	6.5	5.6	4.8	3.4	1.3	1.0	3.5
Oregon	Horiz Axis	Min/Max	0.4/2.7	0.7/3.6	1.2/4.2	2.2/4.9	3.2/5.8	4.0/7.0	4.9/7.4	3.6/7.1	3.5/6.2	1.7/5.0	0.6/2.5	0.3/1.9	2.6/3.9
	1-Axis, N-S	Average	0.9	1.7	2.9	4.4	6.0	7.1	8.7	7.3	5.7	3.2	1.0	0.6	4.2
	Horiz Axis	Min/Max	0.3/1.9	0.5/3.1	1.2/4.6	2.6/6.3	4.1/7.8	5.1/9.3	6.4/10.0	4.6/9.6	4.1/7.7	1.6/4.8	0.4/1.8	0.2/1.2	3.1/4.5
Redmond,	1-Axis, E-W	Average	1.9	2.3	2.9	3.5	4.4	5.2	6.2	5.4	4.7	3.6	2.0	1.8	3.7
Oregon	Horiz Axis	Min/Max	1.3/3.3	1.1/3.8	1.9/4.5	2.1/4.8	2.7/5.4	3.7/6.4	4.6/7.7	3.8/6.8	3.1/6.1	2.1/5.2	1.2/3.3	0.8/3.2	3.0/4.2
	1-Axis, N-S	Average	1.3	1.9	3.2	4.5	5.9	6.9	8.3	7.2	5.6	3.5	1.5	1.1	4.3
	Horiz Axis	Min/Max	0.8/2.2	0.9/3.2	2.0/4.7	2.8/6.1	3.7/7.2	4.9/8.6	5.9/10.5	5.0/9.1	3.8/7.5	1.9/4.9	0.9/2.4	0.5/2.0	3.4/4.8
San Juan,	1-Axis, E-W	Average	3.5	3.5	3.7	3.7	3.2	3.6	3.6	3.5	3.2	3.1	3.2	3.2	3.4
Puerto Rico	Horiz Axis	Min/Max	2.8/4.3	2.9/4.2	2.9/4.3	2.6/4.5	1.6/4.3	2.6/4.8	2.9/4.3	2.5/4.4	2.4/4.0	2.2/4.1	2.0/4.5	2.2/4.8	2.9/4.0
	1-Axis, N-S	Average	3.5	4.0	4.8	4.9	4.1	4.5	4.6	4.6	4.2	3.7	3.3	3.0	4.1
	Horiz Axis	Min/Max	2.8/4.3	3.2/4.8	3.6/5.6	3.4/6.1	2.1/5.5	3.3/6.2	3.7/5.6	3.3/5.9	3.1/5.4	2.6/4.9	2.0/4.6	2.1/4.7	3.5/4.8
Rapid City,	1-Axis, E-W	Average	2.8	3.1	3.3	3.6	4.0	4.8	5.1	4.9	4.3	3.8	2.9	2.7	3.8
South Dakota	Horiz Axis	Min/Max	1.8/3.8	2.0/3.9	2.4/4.4	2.7/5.2	2.9/5.1	3.6/6.1	4.6/5.7	4.1/5.8	2.5/5.6	2.7/4.7	1.9/3.7	1.8/3.8	3.4/4.3
	1-Axis, N-S	Average	1.9	2.6	3.6	4.6	5.3	6.4	6.8	6.4	5.1	3.6	2.1	1.7	4.2
	Horiz Axis	Min/Max	1.2/2.6	1.7/3.4	2.5/4.8	3.4/6.7	3.8/6.9	4.8/8.3	6.0/7.7	5.4/7.7	3.0/6.8	2.5/4.4	1.4/2.7	1.1/2.4	3.7/4.8

Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Abilene, Texas	1-Axis, E-W Horiz Axis	Average	3.7	3.9	4.1	4.3	4.4	4.9	4.9	4.4	3.8	4.1	3.8	3.7	4.2
		Min/Max	2.0/5.2	2.7/5.3	2.7/5.9	3.0/5.4	3.1/5.3	3.8/6.3	3.5/6.6	3.2/5.7	2.8/5.0	2.6/5.2	2.5/5.0	2.2/5.2	3.7/4.6
	1-Axis, N-S Horiz Axis	Average	3.1	3.9	5.0	5.7	5.8	6.4	6.5	5.9	4.8	4.5	3.4	3.0	4.9
		Min/Max	1.7/4.4	2.8/5.4	3.2/7.2	4.1/7.3	4.2/7.1	5.1/8.3	4.6/8.8	4.2/7.8	3.5/6.5	2.9/5.7	2.3/4.5	1.8/4.2	4.3/5.4
Amarillo, Texas	1-Axis, E-W Horiz Axis	Average	4.0	4.1	4.2	4.6	4.6	5.2	5.0	4.6	4.2	4.6	5.0	3.9	4.4
		Min/Max	2.5/5.3	2.3/5.3	3.1/5.4	3.5/5.6	3.6/5.5	4.0/6.5	4.1/6.5	3.6/5.8	3.5/5.6	3.0/6.0	2.2/5.2	2.9/5.7	3.9/4.8
	1-Axis, N-S Horiz Axis	Average	3.3	4.0	5.0	6.1	6.2	6.8	6.7	6.1	5.2	4.9	3.5	3.0	5.1
		Min/Max	2.0/4.3	2.2/5.3	3.5/6.4	4.7/7.5	4.9/7.4	5.2/8.6	5.3/8.6	4.7/7.9	4.5/7.0	3.2/6.5	2.0/4.5	1.7/4.4	4.5/5.4
Austin, Texas	1-Axis, E-W Horiz Axis	Average	3.0	3.3	3.3	3.3	3.4	4.2	4.5	4.3	3.6	3.7	3.3	3.0	3.6
		Min/Max	1.6/4.4	1.9/4.7	2.0/4.6	2.2/5.1	1.4/4.4	3.0/5.3	3.0/5.8	3.2/5.5	2.4/5.0	2.1/4.7	1.4/4.9	1.9/4.9	3.2/4.0
	1-Axis, N-S Horiz Axis	Average	2.6	3.4	4.0	4.3	4.4	5.4	5.9	5.6	4.5	4.1	3.0	2.5	4.2
		Min/Max	1.4/3.9	2.0/4.9	2.4/5.6	2.9/6.7	1.9/5.7	3.9/6.9	3.9/7.7	4.1/7.2	2.9/6.4	2.2/5.3	1.4/4.5	1.5/4.1	3.7/4.7
El Paso, Texas	1-Axis, E-W Horiz Axis	Average	4.5	4.9	5.2	5.6	6.1	6.3	5.2	4.8	4.7	4.9	4.7	4.4	5.1
		Min/Max	3.0/5.9	3.4/6.3	3.3/6.6	4.3/6.4	5.2/7.3	4.9/7.6	4.2/6.1	3.9/5.9	3.7/5.6	3.7/6.2	2.7/5.8	2.8/5.5	4.6/5.6
	1-Axis, N-S Horiz Axis	Average	3.8	5.0	6.3	7.6	8.2	8.2	6.8	6.4	5.9	5.4	4.2	3.6	6.0
		Min/Max	2.7/5.1	3.5/6.5	4.0/8.2	5.8/8.8	7.0/9.9	6.4/10.0	5.4/8.1	5.1/7.8	4.7/7.1	4.0/6.9	2.4/5.3	2.2/4.5	5.4/6.5
Fort Worth, Texas	1-Axis, E-W Horiz Axis	Average	3.2	3.4	3.4	3.5	3.7	4.4	4.7	4.2	3.6	3.7	3.4	3.2	3.7
		Min/Max	1.5/4.5	2.3/4.8	2.1/4.7	2.4/5.2	2.0/4.9	3.5/5.4	3.5/6.2	2.9/5.4	2.4/4.8	2.3/4.9	1.8/4.4	1.9/4.5	3.3/4.1
	1-Axis, N-S Horiz Axis	Average	2.7	3.4	4.1	4.6	4.9	5.7	6.2	5.6	4.5	4.0	3.0	2.5	4.30
		Min/Max	1.2/3.8	2.3/4.7	2.5/5.7	3.2/6.8	2.7/6.5	4.5/7.2	4.7/8.3	3.8/7.4	3.0/6.1	2.5/5.3	1.7/4.0	1.5/3.5	3.8/4.7
Lubbock, Texas	1-Axis, E-W Horiz Axis	Average	4.0	4.1	4.2	4.6	4.7	5.1	5.0	4.5	3.9	4.4	4.1	3.9	4.4
		Min/Max	2.6/5.3	2.9/5.7	3.0/5.4	3.6/5.7	3.6/5.7	3.8/6.2	3.5/6.5	3.3/5.8	2.8/5.4	3.1/5.9	2.5/5.3	2.2/5.5	3.9/4.8
	1-Axis, N-S Horiz Axis	Average	3.3	4.1	5.1	6.1	6.2	6.7	6.6	6.1	5.0	4.8	3.6	3.1	5.1
		Min/Max	2.1/4.4	2.8/5.7	3.6/6.5	4.7/7.6	4.8/7.6	5.0/8.1	4.7/8.7	4.3/7.8	3.5/7.0	3.3/6.5	2.2/4.7	1.7/4.3	4.5/5.5
Midland, Texas	1-Axis, E-W Horiz Axis	Average	4.0	4.3	4.6	4.7	4.9	5.2	4.9	4.5	4.0	4.5	4.2	4.1	4.5
		Min/Max	2.7/5.6	3.0/5.6	3.0/5.9	3.6/6.0	3.9/5.7	4.2/6.8	3.2/6.4	3.3/5.6	2.9/5.2	3.1/5.8	2.8/5.6	2.6/5.7	4.2/4.9
	1-Axis, N-S Horiz Axis	Average	3.5	4.4	5.5	6.3	6.6	6.8	6.5	6.0	5.1	4.9	3.9	3.3	5.2
		Min/Max	2.3/4.8	3.0/5.7	3.5/7.2	4.7/8.1	5.2/7.7	5.3/8.9	4.2/8.6	4.5/7.6	3.6/6.8	3.3/6.5	2.5/5.1	2.1/4.6	4.9/5.7
San Angelo, Texas	1-Axis, E-W Horiz Axis	Average	3.7	3.9	4.2	4.3	4.3	4.8	4.8	4.5	3.8	4.1	3.9	3.7	4.2
		Min/Max	2.0/5.3	2.7/5.3	2.6/5.7	3.3/5.5	2.9/5.4	4.0/6.4	2.9/6.2	2.8/5.8	2.7/5.2	2.6/5.5	2.6/5.4	2.3/5.5	3.7/4.7
	1-Axis, N-S Horiz Axis	Average	3.2	4.0	5.1	5.6	5.7	6.3	6.4	6.0	4.8	4.5	3.6	3.0	4.9
		Min/Max	1.7/4.6	2.7/5.3	3.2/7.0	4.2/7.4	3.7/7.2	5.2/8.4	3.8/8.4	3.8/7.8	3.4/6.8	2.9/6.1	2.4/5.0	1.8/4.4	4.3/5.5
San Antonio, Texas	1-Axis, E-W Horiz Axis	Average	3.0	3.3	3.3	3.2	3.3	4.0	4.4	4.1	3.6	3.7	3.3	3.0	3.5
		Min/Max	2.0/4.2	2.2/4.8	1.9/5.0	1.5/4.5	1.6/4.1	2.5/5.1	2.6/5.8	2.9/5.2	2.2/5.1	2.0/5.0	1.5/5.1	2.1/4.7	3.1/3.9
	1-Axis, N-S Horiz Axis	Average	2.7	3.4	4.0	4.2	4.2	5.2	5.7	5.4	4.5	4.1	3.1	2.5	4.1
		Min/Max	1.7/3.8	2.3/5.0	2.3/6.1	1.9/6.0	2.1/5.3	3.1/6.7	3.3/7.6	3.8/6.8	2.8/6.4	2.2/5.7	1.5/4.8	1.7/4.0	3.6/4.6
Waco, Texas	1-Axis, E-W Horiz Axis	Average	3.1	3.3	3.4	3.4	3.6	4.4	4.8	4.4	3.7	3.8	3.3	3.2	3.7
		Min/Max	1.6/4.5	1.9/4.7	2.1/4.9	2.3/5.5	1.6/5.0	3.2/5.4	3.2/6.3	3.4/5.3	2.5/5.1	2.4/4.7	1.5/4.7	1.9/4.7	3.3/4.2
	1-Axis, N-S Horiz Axis	Average	2.6	3.3	4.1	4.4	4.8	5.7	6.3	5.9	4.7	4.1	3.0	2.6	4.3
		Min/Max	1.4/3.9	2.0/4.8	2.5/6.0	3.0/7.3	2.1/6.6	4.2/7.1	4.3/8.4	4.5/7.2	3.2/6.6	2.6/5.1	1.4/4.3	1.6/3.8	3.8/4.9

	Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
			Direct Beam Solar Radiation for Concentrating Collectors (kWh/m²/day), Uncertainty ±8%												
Wichita Falls, Texas	1-Axis, E-W Horiz Axis	Average	3.4	3.5	3.7	3.9	4.1	4.7	4.9	4.4	3.9	4.0	3.5	3.3	3.9
		Min/Max	1.6/4.7	2.4/5.0	2.5/4.9	2.8/4.9	3.2/5.1	4.0/5.9	3.7/6.6	3.2/5.4	2.7/5.1	2.5/5.2	2.2/4.7	2.0/4.9	3.4/4.3
	1-Axis, N-S Horiz Axis	Average	2.8	3.5	4.4	5.2	5.5	6.2	6.5	5.9	4.9	4.3	3.0	2.6	4.6
		Min/Max	1.3/3.9	2.4/5.1	3.0/5.8	3.6/6.6	4.2/6.7	5.3/7.8	4.8/8.8	4.2/7.4	3.4/6.6	2.7/5.6	1.8/4.2	1.5/3.8	4.0/5.1
Cedar City, Utah	1-Axis, E-W Horiz Axis	Average	3.7	3.8	3.8	4.5	5.1	6.2	5.5	5.1	5.1	4.8	3.9	3.7	4.6
		Min/Max	2.5/5.2	2.3/5.4	2.1/5.4	3.0/5.9	4.1/6.2	4.8/7.5	4.1/6.9	3.6/6.6	3.2/6.3	2.3/5.8	2.8/5.8	1.9/5.6	3.6/5.6
	1-Axis, N-S Horiz Axis	Average	2.9	3.6	4.6	6.0	7.0	8.3	7.5	6.9	6.6	5.1	3.3	2.7	5.4
		Min/Max	2.0/4.1	2.0/5.2	2.6/6.5	4.1/7.9	5.6/8.5	6.3/10.1	5.5/9.4	4.8/9.0	4.0/8.1	2.5/6.1	2.3/4.9	1.4/4.1	4.2/6.5
Salt Lake City, Utah	1-Axis, E-W Horiz Axis	Average	2.0	2.7	3.2	3.7	4.5	5.6	5.8	5.2	4.8	4.1	2.6	1.9	3.8
		Min/Max	0.6/4.9	0.9/4.0	1.6/4.3	2.5/4.8	3.1/5.9	3.8/6.8	4.7/6.8	4.3/6.4	3.4/6.1	2.9/5.3	1.4/3.9	0.3/3.6	3.1/4.4
	1-Axis, N-S Horiz Axis	Average	1.4	2.4	3.6	4.8	6.1	7.4	7.6	6.9	5.8	4.1	2.0	1.2	4.5
		Min/Max	0.5/2.8	0.9/3.5	1.7/4.9	3.3/6.2	4.1/8.0	5.0/9.2	6.3/9.1	5.5/8.6	4.1/7.5	2.7/5.4	1.1/3.0	0.2/2.4	3.6/5.1
Yakima, Washington	1-Axis, E-W Horiz Axis	Average	1.4	2.2	3.0	3.5	4.4	5.0	5.8	5.2	4.5	3.4	1.7	1.3	3.5
		Min/Max	0.6/2.5	0.4/3.4	1.9/4.0	2.3/4.6	2.9/5.4	3.6/6.5	4.6/6.9	3.9/6.6	2.9/5.8	1.9/4.3	0.9/2.5	0.6/2.5	3.1/3.8
	1-Axis, N-S Horiz Axis	Average	0.9	1.8	3.2	4.5	5.9	6.6	7.8	6.8	5.3	3.1	1.2	0.8	4.0
		Min/Max	0.3/1.6	0.4/2.8	2.1/4.2	2.8/5.7	4.0/7.3	4.7/8.7	6.1/9.3	5.2/8.8	3.3/6.9	1.7/4.1	0.6/1.8	0.4/1.5	3.5/4.4
Casper, Wyoming	1-Axis, E-W Horiz Axis	Average	3.1	3.4	3.5	3.6	4.1	5.2	5.5	5.1	4.5	3.9	3.1	2.9	4.0
		Min/Max	2.2/4.2	2.4/4.5	2.4/4.5	2.7/5.1	2.8/5.1	3.5/6.3	4.7/6.3	3.6/5.9	3.1/5.8	2.6/5.1	2.3/3.7	2.2/4.1	3.3/4.4
	1-Axis, N-S Horiz Axis	Average	2.1	3.0	3.9	4.7	5.5	6.9	7.3	6.8	5.5	3.8	2.3	1.9	4.5
		Min/Max	1.5/2.9	2.1/4.0	2.6/5.1	3.4/6.6	3.8/6.9	4.6/8.4	6.2/8.4	4.9/8.0	3.7/7.1	2.5/4.9	1.7/2.8	1.4/2.7	3.6/5.0
Cheyenne, Wyoming	1-Axis, E-W Horiz Axis	Average	3.3	3.6	3.6	3.8	3.9	4.8	4.9	4.5	4.3	4.1	3.3	3.2	3.9
		Min/Max	2.1/4.3	2.8/4.3	2.5/4.5	3.0/4.6	2.6/4.8	3.4/6.1	4.3/5.7	2.9/5.2	2.9/5.3	2.4/4.9	2.6/3.9	2.3/4.3	3.5/4.3
	1-Axis, N-S Horiz Axis	Average	2.3	3.2	4.1	5.0	5.2	6.4	6.5	6.0	5.2	4.1	2.6	2.1	4.4
		Min/Max	1.7/3.1	2.5/3.9	2.7/5.3	4.0/6.1	3.5/6.5	4.5/8.2	5.7/7.6	3.8/7.0	3.5/6.6	2.4/4.9	2.0/3.1	1.5/2.9	3.9/4.9
Lander, Wyoming	1-Axis, E-W Horiz Axis	Average	3.2	3.7	3.9	3.9	4.2	5.2	5.3	5.0	4.5	4.1	3.3	3.2	4.1
		Min/Max	2.3/4.4	2.6/4.8	2.4/4.8	2.7/5.3	2.7/5.4	3.5/6.5	3.7/6.1	3.8/5.5	2.9/5.8	2.9/5.3	2.4/4.0	1.8/4.0	3.5/4.6
	1-Axis, N-S Horiz Axis	Average	2.2	3.2	4.3	5.0	5.6	7.0	7.1	6.6	5.5	4.0	2.5	2.0	4.6
		Min/Max	1.5/3.1	2.1/4.2	2.5/5.4	3.5/6.9	3.5/7.3	4.7/8.7	4.6/8.2	4.9/7.5	3.5/7.2	2.8/5.2	1.8/3.0	1.1/2.6	3.8/5.1
Rock Springs, Wyoming	1-Axis, E-W Horiz Axis	Average	3.0	3.4	3.6	3.8	4.4	5.3	5.4	5.0	4.7	4.2	3.1	2.9	4.1
		Min/Max	2.1/4.2	2.2/4.3	2.1/4.4	2.7/4.9	3.0/5.6	4.0/6.6	4.5/6.3	3.6/6.0	2.9/6.1	2.8/5.3	2.2/4.3	1.5/3.9	3.2/4.5
	1-Axis, N-S Horiz Axis	Average	2.1	3.0	4.0	5.0	5.9	7.2	7.3	6.7	5.8	4.2	2.4	1.9	4.6
		Min/Max	1.5/3.0	2.1/3.9	2.2/5.1	3.4/6.4	4.0/7.6	5.3/8.9	6.0/8.6	4.7/8.2	3.5/7.7	2.8/5.5	1.7/3.3	0.9/2.6	3.6/5.2
Sheridan, Wyoming	1-Axis, E-W Horiz Axis	Average	2.3	2.7	3.1	3.4	3.7	4.7	5.3	4.8	4.1	3.4	2.5	2.3	3.5
		Min/Max	1.1/3.5	2.2/4.1	2.2/4.2	2.5/5.2	2.7/4.8	3.3/6.1	4.1/6.3	4.0/6.0	2.3/5.3	2.4/4.4	1.8/3.6	1.4/3.1	3.0/4.0
	1-Axis, N-S Horiz Axis	Average	1.5	2.3	3.3	4.4	5.0	6.3	7.1	6.4	4.9	3.3	1.8	1.4	4.0
		Min/Max	0.8/2.3	1.8/3.4	2.2/4.5	3.3/6.8	3.5/6.5	4.4/8.1	5.3/8.4	5.1/8.0	2.8/6.6	2.2/4.2	1.2/2.6	0.8/1.9	3.4/4.5

Map showing the location of the 239 stations in the National Solar Radiation Data Base, the data of which were used to calculate values for this appendix.

Appendix B: Data Necessary for Evaluating Parabolic-Trough Solar Water-Heating Systems

(Based, with a few additions and deletions, on checklists 1-2, 1-3, and 1-5 of ASHRAE's *Active Solar Heating Systems Design Manual*. Copyright 1988 by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Atlanta, Georgia. Reprinted by permission)

A. Building hot-water requirements

1. Daily Load ________________ gal/day (L/day) maximum,
   ________________ gal/day (L/day) minimum
   How determined? ____
2. Daily use pattern ____
3. Hot-water delivery temperature ______________%F (%C)
4. Load profile (list monthly hot-water load estimates, gallons [litres]):
   Jan _______ Feb _______ Mar ______ Apr _______ May _______ Jun ______
   Jul _______ Aug _______ Sep ___ ___ Oct _______ Nov _______ Dec ______
5. Total annual load ________________

B. Main heating system

1. Energy source: Gas _______ Electric ________ Oil ________ Steam _______
   Cost _________
2. Hot-water heater/storage capacity ________________ gallon
   Hot-water heater efficiency _______________
3. Hot-water circulation: Yes ________ No ________
4. Cold-water temperature ________%F (%C) maximum ________%F (%C) minimum

C. Building information

   Date of construction ________________
   Building name ____
   Location (including Zip code) ____
1. Primary building use: ____
2. Number of floors: ________________ Total floor area _______________ ft^2 (m^2)
3. Utilities available:
   Natural gas ______________ Propane gas ____________ Fuel oil ___________
   Electric: ________________ volt, ________________ phase, ___________ kW
4. Water quality: pH ________________ Dissolved solids ________________ ppm

D. Collector and storage locations

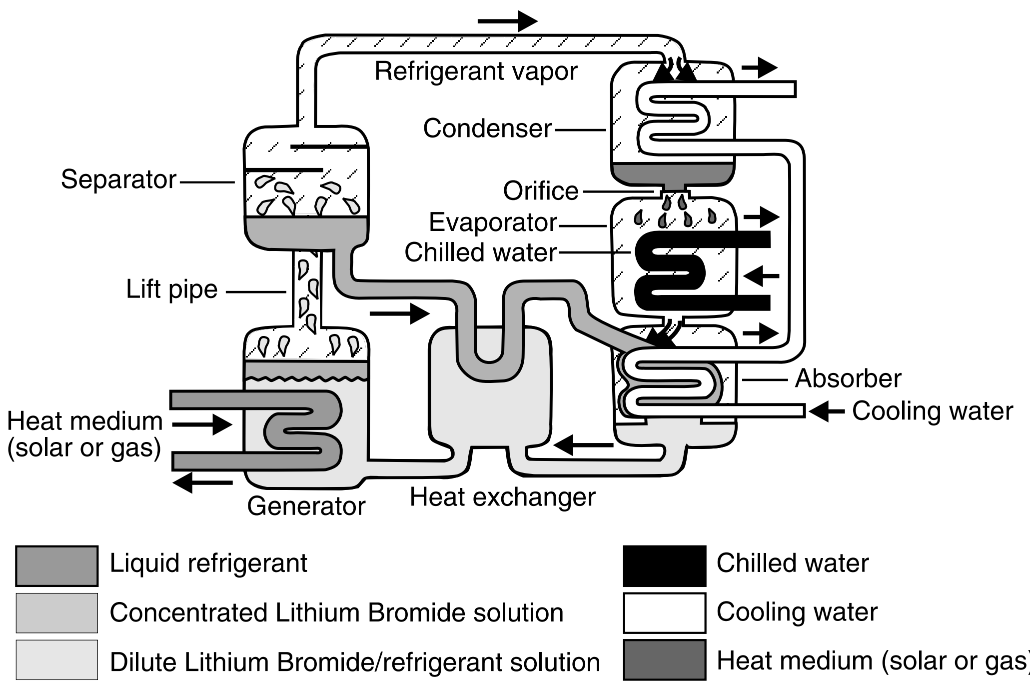
1. Area available for collectors _________ ft (m) (N/S) x _________ ft (m) (E/W)
   Potential shading problems ____
   Provide sketch showing shape and overall dimensions of potential collector locations and orientations with location and type of any obstructions of potential shading sources.
2. Potential storage location: Indoor ____________ Outdoor ____________
   If indoor, available area ____________ ft (m) x ____________ ft (m);
   Ceiling height ____________ ft (m)
   Access to storage location: ____________ door sizes ____________ other
3. Potential mechanical equipment location: Indoor ____________ Outdoor ____________
   If indoor, available area ____________ ft (m) x ____________ ft (m)
4. Approximate distance collector to heat exchanger or storage __________ ft (m) elev, ____________ ft (m) horizontal
5. Approximate distance heat exchanger to storage _________ ft (m) elevation _______ ft (m) horizontal

Appendix C: Absorption Cooling Technology

Single-Effect Absorption Chillers

Single-effect absorption-chiller systems consist of an evaporator, absorber, generator, separator, and condenser. They operate as follows:

- The evaporator generates chilled water at 4˚–10˚C (40˚–50˚F) that is pumped to one or more air-conditioning units in the air distribution system of the building. Chilled water is produced when refrigerant water at very low pressure extracts heat from the water to be chilled. As it absorbs heat, the refrigerant water vaporizes.
- The vaporized refrigerant water flows from the evaporator to the absorber. The absorber contains lithium bromide, which is capable of absorbing large quantities of refrigerant vapor on contact. The refrigerant vapor is absorbed by concentrated lithium bromide solution as it flows across the surface of the absorber coil.
- The diluted solution is preheated by a heat exchanger before being pumped to the generator. The generator boils the dilute refrigerant/lithium bromide solution so that the refrigerant and lithium bromide can be separated and recovered for reuse. Solar flat-plate, evacuated-tube or parabolic-trough collectors are used to heat water to 76.7˚–98.9˚C (170˚–210˚F), which is circulated through the generator to heat the refrigerant/lithium bromide solution. The solution boils under low pressure. The refrigerant vapor is raised to a high temperature and pressure so that it can reject the heat picked up in the evaporator. When sunlight is insufficient or unavailable to generate thermal energy for the generator, an auxiliary electric, natural gas, or steam subsystem is used.
- The boiled solution is then sent to the separator and into a condenser, where it collects on the surface of the cooling coil. Heat is removed by the cooling water and rejected through a cooling tower. Refrigerant liquid accumulates in the condenser and passes into the evaporator, starting the cycle anew.



Source: American Yazaki Corporation

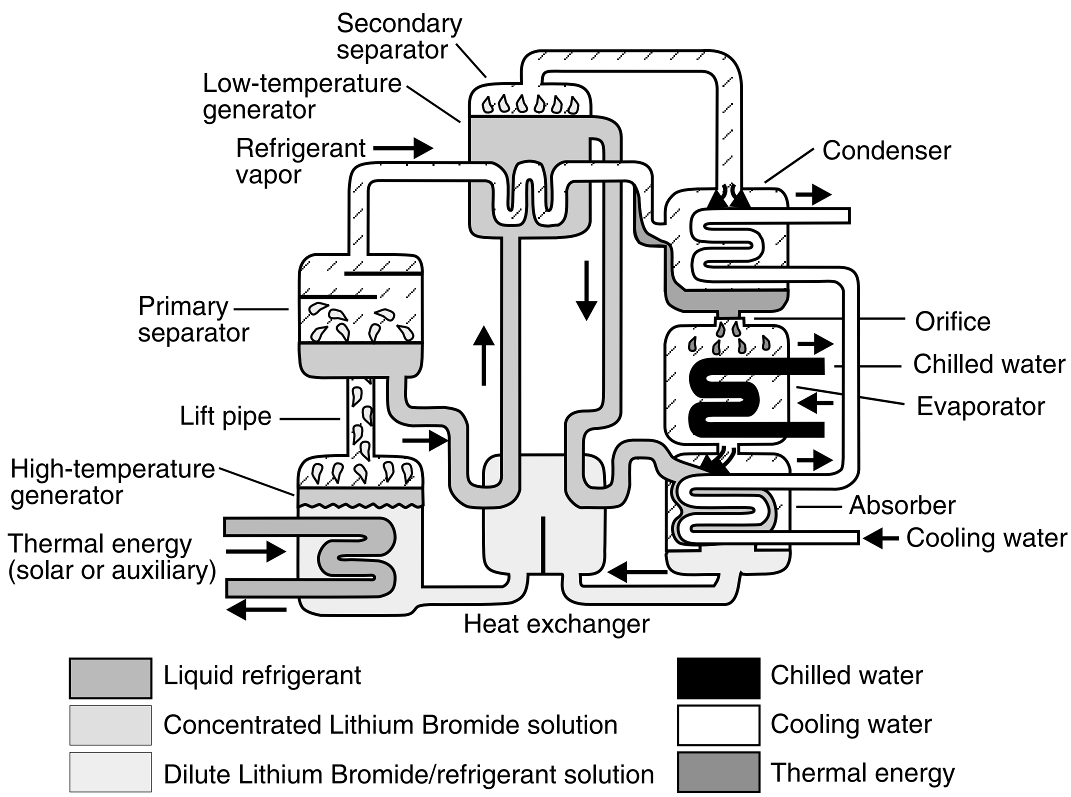
02279801m

Double-Effect Absorption Chillers

Double-effect absorption-chiller systems use a high-temperature (HT) generator and a low-temperature (LT) generator to improve the thermodynamic efficiency of the absorption cooling cycle.

- Operation of the evaporator and the absorber are the same as in the single-effect system.
- The diluted lithium bromide/refrigerant solution flows from the absorber into the HT generator. There, it is boiled using thermal energy from solar collectors or an auxiliary subsystem. This drives the refrigerant vapor and semiconcentrated lithium bromide into the primary separator. From the separator, the lithium bromide solution flows to the heat exchanger, where it is precooled before flowing into the LT generator.
- The hot refrigerant vapor flows from the primary separator to the LT generator, where it surrenders its heat to the semiconcentrated lithium bromide solution. This decreases the temperature at which it enters the condenser to less than that of a single-effect system. Also, additional refrigerant is separated from the lithium bromide in the secondary separator, which further concentrates it.
- The concentrated lithium bromide is precooled by the heat exchanger before flowing back into the absorber.

The refrigerant vapor flows to the condenser where its heat is removed by cooling water and rejected through a cooling tower. Refrigerant liquid accumulates in the condenser and then passes into the evaporator, starting the cycle over.



Source: American Yazaki Corporation

02279811m

Appendix D: Federal Life-Cycle Costing Procedures and the BLCC Software

Federal agencies are required to evaluate energy-related investments on the basis of minimum life-cycle costs (LCC) (10 CFR Part 436). A life-cycle cost evaluation computes the total long-run costs of a number of potential actions, and selects the action that minimizes the long-run costs. When considering retrofits, sticking with the existing equipment is one potential action, often called the baseline condition. The LCC of a potential investment is the present value of all of the costs associated with the investment over time.

The first step in calculating the LCC is to identify the costs. Installed Cost includes cost of materials purchased and the labor required to install them (for example, the price of an energy-efficient lighting fixture, plus cost of labor to install it). Energy cost includes annual expenditures on energy to operate equipment. (For example, a lighting fixture that draws 100 watts and operates 2,000 hours annually requires 200,000 watt-hours [200 kWh] annually. At an electricity price of $0.10/kWh, this fixture has an annual energy cost of $20.) Non-fuel Operation and Maintenance (O&M) includes annual expenditures on parts and activities required to operate equipment (for example, replacing burned-out lightbulbs). Replacement costs include expenditures to replace equipment upon failure (for example, replacing an oil furnace when it is no longer usable).

Because LCC includes the cost of money, periodic and non-periodic O&M and equipment replacement costs, energy escalation rates, and salvage value, it is usually expressed as a present value, which is evaluated by

$$LCC = PV(IC) + PV(EC) + PV(OM) + PV(REP)$$

where PV (x) denotes "present value of cost stream x",
IC is the installed cost,
EC is the annual energy cost,
OM is the annual non-energy cost, and
REP is the future replacement cost.

Net present value (NPV) is the difference between the LCCs of two investment alternatives, e.g., the LCC of an energy-saving or energy-cost reducing alternative and the LCC of the baseline equipment. If the alternative's LCC is less than baseline's LCC, the alternative is said to have NPV, i.e., it is cost effective. NPV is thus given by

$$NPV = PV(EC_0) - PV(EC_1) + PV(OM_0) - PV(OM_1) + PV(REP_0) - PV(REP_1) - PV(IC)$$

or

$$NPV = PV(ECS) + PV(OMS) + PV(REPS) - PV(IC)$$

where subscript 0 denotes the baseline condition,
subscript 1 denotes the energy cost-saving measure,
IC is the installation cost of the alternative (the IC of the baseline is assumed to be zero),
ECS is the annual energy cost saving,
OMS is the annual non-energy O&M saving, and
REPS is the future replacement saving.

Levelized energy cost (LEC) is the break-even energy price (blended) at which a conservation, efficiency, renewable, or fuel-switching measure becomes cost effective ($NPV \geqq 0$). Thus, a project's LEC is given by

$$PV(LEC*EUS) = PV(OMS) + PV(REPS) - PV(IC)$$

where EUS is the annual energy use savings (energy units/year). Savings-to-investment ratio (SIR) is the total (PV) saving of a measure divided by its installation cost:

$$SIR = (PV(ECS) + PV(OMS) + PV(REPS))/PV(IC)$$

Some of the tedious effort of LCC calculations can be avoided by using the BLCC software, developed by NIST. For copies of BLCC, call the FEMP Help Desk at (800) 363-3732.

Appendix E: Adams County Detention Facility Case Study: NIST BLCC Comparative Economic Analysis

****

*   N I S T B L C C: COMPARATIVE ECONOMIC ANALYSIS (ver. 4.4-97)   *

****

Project: Adams County Detention Facility in Brighton, Colorado
Basecase: Brighton-Gas Water Heating System—No Solar
Alternative: Brighton-Parabolic Trough Solar Water Heating System with Gas Backup

Principal Study Parameters

Analysis Type:	Federal Analysis—Energy Conservation Projects
Study Period:	25.00 Years (APR 1987 through MAR 2012)
Discount Rate:	3.4% Real (exclusive of general inflation)
Basecase LCC File:	ACDFNOSO.LCC
Alternative LCC File:	ACDFSOLR.LCC

Comparison of Present-Value Costs

	Basecase: Brighton-No Sol	Alternative: Brighton-with Solar	Savings from Alt.
Initial Investment item(s):			
Capital Requirements as of Service Date	$0	$178,400	-$178,400
Subtotal	$0	$178,400	-$178,400
Future Cost Items:			
Annual and Other Recurring Costs	$111,794	$45,986	$65,808
Energy-related Costs	$353,493	$212,096	$141,397
Subtotal	$465,287	$258,082	$207,205
Total Present Value of Life-Cycle Cost	$465,287	$436,482	$28,805
(without state buydown)	$465,287	$476,482	-$11,195
(with subsidy, but adjusted to reflect actual natural gas prices for 1987–1997)	$401,851	$394,114	$7,737

Net Savings from Alternative ‘Brighton-with Solar’ compared to Basecase ‘Brighton-No Solar’

Net Savings = P.V. of Noninvestment Savings	$207,205
- Increased Total Investment	$178,400
Net Savings:	$28,805

Note: the SIR and AIRR computations include differential initial costs, capital replacement costs, and residual value (if any) as investment costs, per NIST Handbook 135 (Federal and MILCON analyses only).

Savings-to-Investment Ratio (SIR) For Alternative ‘Brighton-with Solar’ compared to Base Case ‘Brighton-No Solar’

$$SIR = \frac{\text{P.V. of non-investment savings}}{\text{Increased total investment}} = 1.16$$

ADJUSTED INTERNAL RATE OF RETURN (AIRR) for Alternative ‘Brighton-with Solar’ compared to Base Case ‘Brighton-no Solar’ (Reinvestment Rate = 3.40%; Study Period = 25 years)

AIRR = 4.02%

Estimated Years to Payback:
Simple Payback occurs in year 17;
Discounted Payback occurs in year 22

ENERGY SAVINGS SUMMARY

Energy Type	Units	—— Average Annual Consumption ——- Basecase	Alternative	Savings	Life-Cycle Savings
Natural Gas	MBtu	5,000.0	3,000.0	2,000.0	50,000.0

EMISSIONS REDUCTION SUMMARY

Energy Type	—— Average Annual Emissions ——- Basecase	Alternative	Savings	Life-Cycle Savings
Natural Gas:				
CO_2 (Mg):	264.1	158.4	105.6	2,640.7
SO_2 (Kg):	1.0	0.6	0.4	10.5
NO_x (Kg):	205.8	123.4	82.3	2,057.5
Total:				
CO_2 (Mg):	264.1	158.4	105.6	2,640.7
SO_2 (Kg):	1.0	0.6	0.4	10.5
NO_x (Kg):	205.8	123.4	82.3	2,057.5

c:\lcc\brighton.cmp

Appendix F: Adams County Detention Facility Case Study: ESPC Economic Analysis

CASE 3: ESCO OWNERSHIP OF THE SOLAR SYSTEM

(Gas Cost Data for the Period 1987 - 1997 Are Actual Gas Cost Rates as Provided by Public Service Company of Colorado)

SYSTEM: Parabolic Trough Solar System with Natural Gas Backup	
SYSTEM INSTALLED COST (Gross):	$218,400
SYSTEM INSTALLED COST (net of 10% tax credits and buydown by Colorado):	$156,560
ANNUAL ENERGY REQUIREMENT(Million BTUs):	3500
Energy Requirement to Be Met by Gas(MMBTUs):	2100
BOILER EFFICIENCY:	70%
Annual Requirement for Gas(MMBTUs):	3000
Energy Requirement to Be Met by Solar	1400
Gas Savings Because of Solar (MMBTUs):	2000
Cost of Natural Gas in 1997 ($/MMBTU):	3.78
Gas Cost Inflation Rate	0.02
Starting O&M Cost:	$600
Starting Insurance Cost	$600
General Inflation Rate:	0.02
Discount Rate:	0.038

YEAR	GAS COST RATE	ANNUAL VALUE OF GAS SAVINGS ($)	REVENUE FOR USER ($ SAVINGS)	REVENUE FOR ESCO($)	GENERAL INFLATION FACTOR	O&M COST	INSUR-ANCE COST	CAPITAL COST	DEPRE-CIATION	GROSS INCOME	TAXES (31%)	NET INCOME	ANNUAL NET CASH FLOW	CUMUL-ATIVE NET CASH FLOW	ANNUAL TAX SAVINGS ($)
1986								156560							
1987	3.36	$6720	$2016	$4704	1.00	600	600	0	$7828	-4324	$0	$-4324	$7828	$7828	$1340
1988	3.06	$6120	$1836	$4284	1.03	615	615	0	$59493	-56439	$0	$-56439	$59493	$67321	$17496
1989	3.33	$6660	$1998	$4662	1.05	630	630	0	$35696	-32295	$0	$-32295	$35696	$103017	$10011
1990	2.83	$5660	$1698	$3962	1.08	646	646	0	$21417	-18747	$0	$-18747	$21417	$124434	$5812
1991	3.18	$6360	$1908	$4452	1.10	662	662	0	$17128	-14001	$0	$-14001	$17128	$141562	$4340
1992	2.99	$5980	$1794	$4186	1.13	679	679	0	$14998	-12170	$0	$-12170	$14998	$156560	$3773
1993	3.27	$6540	$1962	$4578	1.16	696	696	0	$0	3186	$988	$2199	$2199	$158759	$0
1994	3.56	$7120	$2136	$4984	1.19	713	713	0	$0	3558	$1103	$2455	$2455	$161213	$0
1995	3.48	$6960	$2088	$4872	1.22	731	731	0	$0	3410	$1057	$2353	$2353	$163566	$0
1996	2.95	$5900	$1770	$4130	1.25	749	749	0	$0	2631	$816	$1816	$1816	$165382	$0
1997	3.78	$7560	$2268	$5292	1.28	768	768	0	$0	3756	$1164	$2592	$2592	$167973	$0
1998	3.86	$7711	$2313	$5398	1.31	787	787	0	$0	3823	$1185	$2638	$2638	$170611	$0
1999	3.93	$7865	$2360	$5506	1.34	807	807	0	$0	3892	$1206	$2685	$2685	$173297	$0
2000	4.01	$8023	$2407	$5616	1.38	827	827	0	$0	3962	$1228	$2734	$2734	$176030	$0
2001	4.09	$8183	$2455	$5728	1.41	848	848	0	$0	4033	$1250	$2783	$2783	$178813	$0
2002	4.17	$8347	$2504	$5843	1.45	869	869	21840	$21840	-17735	$0	$-17735	$21840	$200653	$5498
2003	4.26	$8514	$2554	$5960	1.48	891	891	0	$0	4178	$1295	$2883	$2883	$203536	$0
2004	4.34	$8684	$2605	$6079	1.52	913	913	0	$0	4253	$1318	$2935	$2935	$206471	$0
2005	4.43	$8858	$2657	$6200	1.56	936	936	0	$0	4329	$1342	$2987	$2987	$209457	$0
2006	4.52	$9035	$2710	$6324	1.60	959	959	0	$0	4406	$1366	$3040	$3040	$212498	$0
2007	4.61	$9216	$2765	$6451	1.64	983	983	0	$0	4485	$1390	$3094	$3094	$215592	$0
2008	4.70	$9400	$2820	$6580	1.68	1008	1008	0	$0	4564	$1415	$3149	$3149	$218741	$0
2009	4.79	$9588	$2876	$6712	1.72	1033	1033	0	$0	4646	$1440	$3205	$3205	$221947	$0
2010	4.89	$9780	$2934	$6846	1.76	1059	1059	0	$0	4728	$1466	$3262	$3262	$225209	$0
2011	4.99	$9975	$2993	$6983	1.81	1085	1085	0	$0	4812	$1492	$3320	$3320	$228530	$0
TOTALS		$194758	$58427	$136331			$20495		$178400			IRR:	6%		

Appendix G: Federal Correctional Institution—Phoenix Case Study: NIST BLCC Comparative Economic Analysis

```
******************************************************************************
*     N I S T  B L C C:  COMPARATIVE  ECONOMIC  ANALYSIS (ver. 4.4-97 )     *
******************************************************************************
```

Project: FCI PHOENIX-SOLAR WATER HEATING
Basecase: Electric Resistance Water Heating System
Alternative: Parabolic Trough Solar Water Heating System with Electric Resistance Backup Subsystem

Principal Study Parameters

Analysis Type:	Federal Analysis—Energy Conservation Projects
Study Period:	20.00 Years (AUG 1997 through JUL 2017)
Discount Rate:	3.4% Real (exclusive of general inflation)
Basecase LCC File:	FCINOSOL.LCC
Alternative LCC File:	FCISOL.LCC

Comparison of Present-Value Costs

	Base Case: Electric Res. System	Alternative: Parabolic Trough System	Savings from Alt.
Initial Investment item(s):			
Capital Requirements as of Service Date	$0	$650,000	-$650,000
Subtotal	$0	$650,000	-$650,000
Future Cost Items:			
Annual and Other Recurring Costs	$143,419	$226,891	-$83,473
Energy-related Costs	$1,528,397	$290,465	$1,237,932
Residual Value at End of Study	$0	$0	$0
Subtotal	$1,671,816	#517,356	$1,154,460
Total Present Value of Life-Cycle Cost	$1,671,816	$1,167,356	$504,460

Net Savings from Alternative ‘Parabolic Trough System’ compared to Basecase ‘Electric Resistance System’

Net Savings = P.V. of Noninvestment Savings	$1,154,460
- Increased Total Investment	$650,000
Net Savings:	$504,460

Note: the SIR and AIRR computations include differential initial costs, capital replacement costs, and residual value (if any) as investment costs, per NIST Handbook 135 (Federal and MILCON analyses only).

Savings-to-Investment Ratio (SIR) For Alternative ‘Phoenix-with Solar’ compared to Base Case ‘Phoenix-No Solar’

$$\text{SIR} = \frac{\text{P.V. of non-investment savings}}{\text{Increased total investment}} = 1.78$$

Adjusted Internal Rate of Return (AIRR) for Alternative ‘Parabolic Trough System’ compared to Base Case ‘Electric Resistance System’ (Reinvestment Rate = 3.40%; Study Period = 20 years)

AIRR = 6.41%

Estimated Years to Payback:
Simple Payback occurs in year 8;
Discounted Payback occurs in year 10

ENERGY SAVINGS SUMMARY

Energy Type	Units	—— Average Annual Consumption —— Basecase	Alternative	Savings	Life-Cycle Savings
Electricity	kWh	1,768,000.0	336,000.0	1,432,000.0	28,640,000.0

EMISSIONS REDUCTION SUMMARY

Energy Type	—— Average Annual Emissions —— Basecase	Alternative	Savings	Life-Cycle Savings
Natural Gas:				
CO_2 (Mg):	1,713.8	325.7	1,388.1	27,762.4
SO_2 (Kg):	5,971.3	1,134.8	4,836.5	96,729.9
NO_x (Kg):	5,162.8	981.2	4,181.6	83,632.7
Total:				
CO_2 (Mg):	1,713.8	325.7	1,388.1	27,762.4
SO_2 (Kg):	5,971.3	1,134.8	4,836.5	96,729.9
NO_x (Kg):	5,162.8	981.2	4,181.6	83,632.7

c:\lcc\fciphoex.cmp

Appendix H: Federal Correctional Institution—Phoenix Case Study: ESPC Economic Analysis

SCENARIO: THE SOLAR SYSTEM IS OWNED AND OPERATED BY AN ESCO
SYSTEM: Parabolic Trough Solar Water Heating System with Electric Resistance Backup

SYSTEM INSTALLED COST (Gross):	$650,000
SYSTEM INSTALLED COST (net of 10% tax credits and buydown):	$585,000
ANNUAL ENERGY REQUIREMENT(kWh):	1768000
SOLAR COLLECTOR AREA(sq ft):	18000
ANNUAL ENERGY REQUIREMENT(kWh):	1432591
AMOUNT OF SYST COST FINANCED:	$585,000
FIRST YR ELECTRICITY COST($/kWh):	0.062
MORTGAGE:	18.5 years @ 9.5%
ELECTRICITY COST INFLATION RATE:	3%
ANNUAL MORTGAGE PAYMENT:	$67,741
GENERAL INFLATION RATE:	3%
DISCOUNT RATE (Real):	3.40%
Electricity Savings Going to ESCO (%):	90%
FIRST YR INSURANCE COST($):	$10,022

YEAR NO.	YEAR	ELEC COST INFLATION FACTOR	ANNUAL VALUE OF ELECTRICITY SAVINGS	ANNUAL SAVINGS GOING to GOVERNMENT	ANNUAL REVENUE for ESCO($)	GOVERNMENT PAYMENT and TAX CREDITS	TOTAL AVAILABLE CASH for ESCO	GENERAL INFLATION FACTOR	O&M EXPENSE	INSURANCE EXPENSE	CAPITAL REPAYMENT	INTEREST EXPENSE	LOAN BALANCE	DEPRE-CIATION	GROSS ANNUAL PROFIT	GROSS CASH FLOW	NET ANNUAL PROFIT	NET CASH FLOW
0	1997	1.00	$0	$0	$0	$108191		1.00	$0	$0	$0	$0	$585000			-$541809		-$541809
1	1998	1.03	$45743	$4574	$41168	$0	$41168	1.03	$2318	$5161	$33871	$27788	$578917	$29250	-$23348	$29250	$0	$29250
2	1999	1.06	$94230	$9423	$84807	$0	$84807	1.06	$4774	$10632	$67741	$54997	$566173	$222300	-$207897	$222300	$0	$222300
3	2000	1.09	$97057	$9706	$87351	$0	$87351	1.09	$4917	$10951	$67741	$53786	$552219	$134550	-$116854	$134550	$0	$134550
4	2001	1.13	$99968	$9997	$89972	$0	$89972	1.13	$5065	$11280	$67741	$52461	$536938	$81900	-$60734	$81900	$0	$81900
5	2002	1.16	$102967	$10297	$92671	$0	$92671	1.16	$5217	$11618	$67741	$51009	$520206	$64350	-$39523	$64350	$0	$64350
6	2003	1.19	$106056	$10606	$95451	$0	$95451	1.19	$5373	$11967	$67741	$49420	$501885	$52650	-$23959	$28691	$0	$52650
7	2004	1.23	$109238	$10924	$98314	$0	$98314	1.23	$5534	$12326	$67741	$47679	$481823	$0	$32775	$32775	$22615	$22615
8	2005	1.27	$112515	$11252	$101264	$0	$101264	1.27	$5700	$12696	$67741	$45773	$459855	$0	$37095	$37095	$25595	$25595
9	2006	1.30	$115891	$11589	$104302	$0	$104302	1.30	$5871	$13076	$67741	$43686	$435801	$0	$41668	$41668	$28751	$28751
10	2007	1.34	$119368	$11937	$107431	$0	$107431	1.34	$6048	$13469	$67741	$41401	$409461	$0	$46513	$46513	$32094	$32094
11	2008	1.38	$122949	$12295	$110654	$0	$110654	1.38	$6229	$13873	$67741	$38899	$380618	$0	$51653	$51653	$35641	$35641
12	2009	1.43	$126637	$12664	$113973	$0	$113973	1.43	$6416	$14289	$67741	$36159	$349036	$0	$57110	$57110	$39406	$39406
13	2010	1.47	$130436	$13044	$117392	$0	$117392	1.47	$6608	$14718	$67741	$33158	$314454	$0	$62908	$62908	$43407	$43407
14	2011	1.51	$134349	$13435	$120914	$0	$120914	1.51	$6807	$15159	$67741	$29873	$276586	$0	$69075	$69075	$47662	$47662
15	2012	1.56	$138380	$13838	$124542	$0	$124542	1.56	$7011	$15614	$67741	$26276	$235120	$0	$75641	$75641	$52192	$52192
16	2013	1.60	$142531	$14253	$128278	$0	$128278	1.60	$7221	$16082	$67741	$22336	$189716	$0	$82638	$82638	$57020	$57020
17	2014	1.65	$146807	$14681	$132126	$0	$132126	1.65	$7438	$16565	$67741	$18023	$139998	$0	$90101	$90101	$62169	$62169
18	2015	1.70	$151211	$15121	$136090	$0	$136090	1.70	$7661	$17062	$67741	$13300	$85557	$0	$98068	$98068	$67667	$67667
19	2016	1.75	$155748	$15575	$140173	$0	$140173	1.75	$7891	$17574	$67741	$8128	$25943	$0	$106580	$106580	$73541	$73541
20	2017	1.81	$160420	$16062	$144378	$0	$144378	1.81	$8128	$18101	$67741	$0	$0	$0	$118150	$118150	$81523	$81523
TOTALS				$241250			$2171251		$122227	$272212	$67741			$585000	$497659	$1531015	$669282	
									INTERNAL RATE OF RETURN FOR ESCO(%)						14%		12%	

About the Federal Technology Alerts

The Energy Policy Act of 1992, and subsequent Executive Orders, mandate that energy consumption in the Federal sector be reduced by 30% from 1985 levels by the year 2005. To achieve this goal, the U.S. Department of Energy's Federal Energy Management Program (FEMP) is sponsoring a series of programs to reduce energy consumption at Federal installations nationwide. One of these programs, the New Technology Demonstration Program (NTDP), is tasked to accelerate the introduction of energy-efficient and renewable technologies into the Federal sector and to improve the rate of technology transfer.

As part of this effort FEMP, is sponsoring a series of Federal Technology Alerts (FTAs) that provide summary information on candidate energy-saving technologies developed and manufactured in the United States. The technologies featured in the Technology Alerts have already entered the market and have some experience but are not in general use in the Federal sector. Based on their potential for energy, cost, and environmental benefits to the Federal sector, the technologies are considered to be leading candidates for immediate Federal application.

The goal of the Technology Alerts is to improve the rate of technology transfer of new energy-saving tech-nologies within the Federal sector and to provide the right people in the field with accurate, up-to-date information on the new technologies so that they can make educated judgments on whether the technologies are suitable for their Federal sites.

Because the Technology Alerts are cost-effective and timely to produce (compared with awaiting the results of field demonstrations), they meet the short-term need of disseminating information to a target audience in a timeframe that allows the rapid deployment of the technologies—and ultimately the saving of energy in the Federal sector.

The information in the Technology Alerts typically includes a description of the candidate technology; the results of its screening tests; a description of its performance, applications and field experience to date; a list of potential suppliers; and important contact infor-mation. Attached appendixes provide supplemental information and example worksheets on the technology.

FEMP sponsors publication of the Federal Technology Alerts to facilitate information-sharing between manufacturers and government staff. While the technology featured promises significant Federal-sector savings, the Technology Alerts do not constitute FEMP's endorsement of a particular product, as FEMP has not independently verified performance data provided by manufacturers. Nor do the Federal Technology Alerts attempt to chart market activity vis-a-vis the technology featured. Readers should note the publication date on the back cover, and consider the Alert as an accurate picture of the technology and its performance at the time of publication. Product innovations and the entrance of new manufacturers or suppliers should be anticipated since the date of publication. FEMP encourages interested Federal energy and facility managers to contact the manufacturers and other Federal sites directly, and to use the worksheets in the Technology Alerts to aid in their purchasing decisions.

Federal Energy Management Program

The Federal Government is the largest energy consumer in the nation. Annually, in its 500,000 buildings and 8,000 locations worldwide, it uses nearly two quadrillion Btu (quads) of energy, costing over $11 billion. This represents 2.5% of all primary energy consumption in the United States. The Federal Energy Management Program was established in 1974 to provide direction, guidance, and assistance to Federal agencies in planning and implementing energy management programs that will improve the energy efficiency and fuel flexibility of the Federal infrastructure.

Over the years several Federal laws and Executive Orders have shaped FEMP's mission. These include the Energy Policy and Conservation Act of 1975; the National Energy Conservation and Policy Act of 1978; the Federal Energy Management Improvement Act of 1988; and, most recently, Executive Order 12759 in 1991, the National Energy Policy Act of 1992 (EPACT), and Executive Order 12902 in 1994.

FEMP is currently involved in a wide range of energy-assessment activities, including conducting New Technology Demonstrations, to hasten the penetration of energy-efficient technologies into the Federal marketplace.

For More Information

FEMP Help Desk:
(800) 363-3732
International callers please use: (703) 287-8391
Web site: http://www.eren.doe.gov/femp/

General Contacts

Ted Collins
NTDP Program Manager
Federal Energy Management Program
U.S. Department of Energy
1000 Independence Avenue SW, EE-92
Washington, D.C. 20585
Phone: (202) 586-8017
e-mail: theodore.collins@ee.doe.gov

Steven A. Parker
Pacific Northwest National Laboratory
P.O. Box 999, Mail Stop K5-08
Richland, WA 99352
Phone: (509) 375-6366
e-mail: steven.parker@pnl.gov

Technical Contact

Russ Hewett, Mail Stop 2714
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401
Phone: (303) 384-7463
Fax: (303) 384-7540
e-mail: russell_hewett@nrel.gov

Produced for the U.S. Department of Energy (DOE) by the National Renewable Energy Laboratory, a DOE national laboratory

DOE/GO-102000-0973
(A revision of DOE/GO-10098-485)
Revised January 2000
(Originally printed April 1998)