ADVANTAGE OF ADOPTING PARABOLIC TROUGH SOLAR COLLECTOR TECHNOLOGY FOR COST EFFECTIVE ENERGY SUPPLY

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***Abstract*— Due to rapid industrialization, power demand has outstripped the growth in generation and transmission network day by day. This has forced many industries, especially continuously process industries, to choose solar thermal power generation to satisfy the needs of numerous countries in the Sun-belt regions of the world. In these regions, the absence of significant biomass, hydrological or geothermal reserves makes solar thermal power the most promising solution for meeting the most fundamental demands" energy". Amidst the different options available for harnessing the Sun's power, solar thermal technologies has been adopted for producing electricity. This paper deals with the advantage of adopting Parabolic Trough solar collector technology for cost effective energy supply.**

***IndexTerms*—Parabolic Trough solar collector, solar thermal power**

I. INTRODUCTION

This paper provides an assessment of the cost of power for parabolic trough solar power technology for large-scale grid-connected power applications, for both near-term and future parabolic trough solar power plants Each year, all the country is becoming more dependent on foreign sources of energy. Already more than 50% of the oil consumed is imported. Environmental pressures to improve air quality and reduce carbon dioxide (CO2) generation are driving a shift from coal to natural gas for new electric generation plants. Domestic sources of natural gas are not able to keep up with growing demand, causing supplies of this key energy source to become increasingly dependent on foreign imports as well. The use of natural gas as a source for hydrogen generation could further aggravate this situation in the future. Taking an example of United States Solar energy represents a huge domestic energy resource for the it, particularly in the Southwest where the deserts have some of the best solar resource levels in the world. For example, an area approximately 12% the size of Nevada (15% of federal lands in Nevada) [5] has the potential to supply all of the electric needs of the United States. In addition, solar power often complements other renewable power sources such as hydroelectric and wind power. The solar resource is typically higher during poor hydroelectric periods, and solar output peaks during the summer, whereas wind power typically peaks in the winter. Solar can complement fossil power sources as well. Eskom, the coal dominated power utility in South Africa with one of the lowest power costs in the world, has identified large-scale solar power technologies as a good intermediate load power source for its grid. Although some renewable power technologies provide an intermittent energy supply, large-scale thermal electric solar technologies can provide dispatch able power through the integration of thermal energy storage. Thermal energy storage allows solar thermal energy collected during the day to be used to generate solar electricity to meet the utility's peak loads, whether during the summer afternoons or the winter evenings. Although solar energy is abundant and free, it is a diffuse energy source, so the cost to harness (or harvest) it with solar collectors can be significant. As a result, electricity generated from solar energy is currently more expensive than power from conventional fossil-power plants. However, the Western Governors' Association has determined that even at moderate levels of deployment, large-scale solar power can potentially compete directly with conventional fossil generation. The cost of energy can be reduced through technology improvements, scale-up in individual plant MW capacity, increased deployment rates, competitive pressures, use of thermal storage, and advancements in O&M methods. The cost of energy can also be reduced through lower cost financing and through taxation or investment incentives. The United States and European parabolic trough industries have developed proprietary plans for lowering costs in future trough power plants. The evaluation given here provides a cost estimate that generally agrees with industry expectations for R&D advances in component and subsystem improvements

II. TECHNOLOGY OVERVIEW

Parabolic trough collector technology

Parabolic trough technology is currently the most proven solar thermal electric technology. This is primarily due to nine large commercial-scale solar power plants, the first of which has been operating in the California Mojave Desert since 1984. These plants, which continue to operate on a daily basis, range in size from 14 to 80 MW and represent a total of 354 MW of installed

electric generating capacity. Large fields of parabolic trough collectors supply the thermal energy used to produce steam for a Rankine steam turbine/generator cycle. Figure 2 shows a process flow diagram that is representative of the majority of parabolic trough solar power plants in operation today. The collector field consists of a large field of single-axis tracking parabolic trough solar collectors. The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned on a north-south horizontal axis. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers via condensate and feed water pumps to be transformed back into steam. Condenser cooling is provided by mechanical draft wet cooling towers. After passing through the HTF side of the solar heat exchangers, the cooled HTF is recalculated through the solar field.

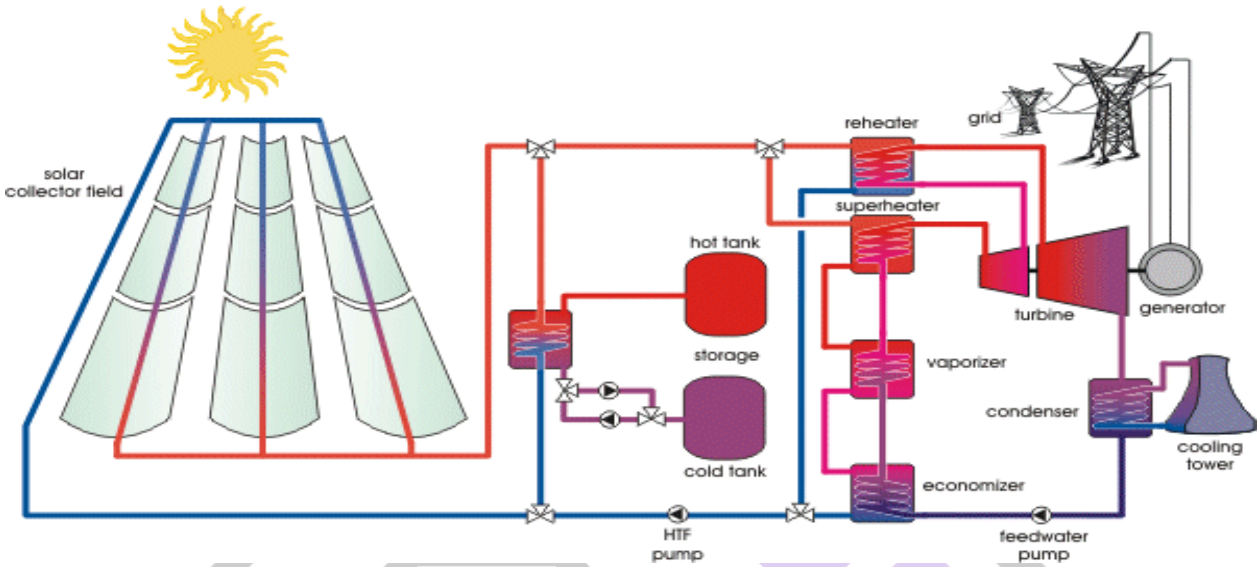

Fig 1. Solar parabolic trough system schematic

Historically, parabolic trough plants have been designed to use solar energy as the primary energy source to produce electricity. The plants can operate at full rated power using solar energy alone given sufficient solar input. During summer months, the plants typically operate for 10 to 12 hours a day at full-rated electric output. However, to date, all plants have been hybrid solar/fossil plants; this means they have a backup fossil-fired capability that can be used to supplement the solar output during periods of low solar radiation. In the system shown in Fig. 2, the optional natural-gas-fired HTF heater situated in parallel with the solar field, or the optional gas steam boiler located in parallel with the solar heat exchangers, provide this capability. The fossil backup can be used to produce rated electric output during overcast or nighttime periods. Figure 2 also shows that thermal storage is a potential option that can be added to provide dispatch ability. Parabolic troughs are one of the lowest-cost solar-electric power options available today and have significant potential for further cost reduction. Nine parabolic trough plants, totaling over 350 megawatts (MW) of electric generation, have been in daily operation in the California Mojave Desert for up to 18 years. These plants provide enough solar electricity to meet the residential needs of a city with 350,000 people. They have demonstrated excellent availabilities (near 100% availability during solar hours) and have reliably delivered power to help California meet its peak electric loads, especially during the California energy crisis of 2000–2001. Several new parabolic trough plants have been built or are currently under development. Growing interest in green power and CO2 reducing power technologies have helped to increase interest in this technology around the world. New parabolic trough plants are cur-rently under construction or in the early stages of operation in support of solar portfolio standards in Nevada and Arizona and a solar tariff premium in Spain. How parabolic trough power plants work Parabolic trough power plants use concentrated sunlight, in place of fossil fuels, to provide the thermal energy required to drive a conventional power plant. These plants use a large field of parabolic trough collectors that track the sun during the day and concentrate the solar radiation on a receiver tube located at the focus of the parabolic shaped mirrors. A heat transfer fluid passes through the receiver and is heated to temperatures required to generate steam and drive a conventional Rankine cycle steam power plant. A 30 MW parabolic trough power plant located at Kramer Junction, California. Parabolic trough power plants consist of large fields of parabolic trough collectors, a heat transfer fluid/steam generation system, a Rankine steam turbine/generator cycle, and optional thermal storage and/or fossil-fired backup systems .The collector field is made up of a large field of single-axis-tracking parabolic trough solar collectors. The solar field is modular in nature and comprises many parallel rows of solar collectors, normally aligned on a north-south horizontal axis. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's directbeam radiation on a linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF) is heated up as high as 393°C as it circulates through the receiver and returns to a series of heat exchangers (HX) in the power block, where the fluid is used to generate high-pressure superheated steam (100 bar, 371°C). The superheated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in

a standard condenser and returned to the heat exchangers via condensate and feed-water pumps to be transformed back into steam. Mechanical-draft wet cooling towers supply cooling to the condenser. After passing through the HTF side of the solar heat exchangers, the cooled HTF is recirculated through the solar field. The existing parabolic trough plants have been designed to use solar energy as the primary energy source to produce electricity. Given sufficient solar input, the plants can operate at full-rated power using solar energy alone. During summer months, the plants typically operate for 10–12 hr/day on solar energy at full-rated electric output. To enable these plants to achieve rated electric output during overcast or nighttime periods, the plants have been designed as hybrid solar/fossil plants; that is, a backup fossil-fired capability can be used to supplement the solar output during periods of low solar radiation. In addition, thermal storage can be integrated into the plant design to allow solar energy to be stored and dispatched when power is required.

Why parabolic Trough Collector is adapted?

In recent years, the U.S. Department of Energy's CSP Program has not directly supported the development of parabolic-trough technology. Trough technology was recognized to be commercially available, but believed by Department of Energy[3] to have only limited potential for future cost reduction. Technologies such as power towers and dish/engine systems were thought to offer greater opportunity for improved performance and lower cost. Several events, however, have recently caused DOE to re evaluate its position on parabolic trough technologies.

- Financial markets view troughs, characterized by LUZ parabolic-trough collector technology shown in Fig 1 as a low-to-moderate-risk, commercially available technology that is ready for deployment today. As a result, troughs are likely to be the only CSP technology available for near-term deployment in the competitive power market.
- Green power markets are currently developing. Parabolic troughs[2] represent a potentially attractive technology option in these markets.
- The KJC Operating Company's Operation and Maintenance (O&M) Cost Reduction Program and international project feasibility studies have identified significant cost reduction opportunities for current and future parabolic plants.

Through a structured development approach, it appears possible to foster a U.S. parabolic trough industry that can significantly reduce the cost of energy from parabolic-trough technology and greatly expand deployment of the technology in both domestic and international markets.

III. METHODOLOGY

This paper draws upon known data from technology improvements, R&D plans, and expected gains to project both reductions in investment costs and increases in performance. These data have been utilized in an NREL-developed model for evaluating the performance and economics of parabolic trough power plants, the primary metric being the levelized cost of electricity [3]. The model includes an hourly performance simulation module, a capital cost module, an O&M cost module, and a project-financing module. The performance module has been validated against the actual performance at the SEGS plants. For this study, the model predicted the annual gross solar-to-electric performance of SEGS VI during 1999 within 1% when using actual solar field availabilities, collector receiver conditions, mirror reflectivity and site solar radiation data. The capital cost module is in part based on detailed cost data from Flabeg Solar International [4]. The O&M cost module is based in part on data from KJC Operating Company. The project finance module is a 30-year cash flow model for evaluating independent power producer (IPP) power plant projects.

The evaluation reported here also draws from a recent study [5] that examines the cost expectations for near-term, mid-term, and long-term trough power plants, generally covering the time frames of 2004, 2010, and 2020.

Reference Plant

Potential parabolic trough plant cost reductions are discussed from a reference point of the operating SEGS plants in the California Mojave Desert. The efficiency of existing parabolic trough plants has been well characterized and provides a good basis for evaluating the potential performance improvements of future parabolic trough plants. We have used the 30-MWe SEGS VI plant as our reference plant for evaluating future cost and performance of trough plants. We selected SEGS VI as a reference because:

- It is the last of the SEGS plants that uses the LS-2 collector for the full solar field. The LS-2 collector has demonstrated the best overall O&M characteristics of the three collector designs used at the SEGS plants.
- It operates at the higher temperature also used at the later 80-MWe plants, with steam conditions of 100 bar and 371°C.
- The operator (KJC Operating Company) has provided detailed operation and maintenance data on the plant.

The NREL model has been used to model the cost and performance of the 30-MW SEGS VI plant. The SEGS VI plant is a hybrid plant and can produce electricity from both solar energy and natural gas. Federal law allows the SEGS plants to use 25% fossil fuel heat input into the steam on an annual basis. Table 1 shows the general design, cost, and performance characteristics of the 30-MWe trough plant. The solar field constitutes approximately 60% of the direct costs. While the technology is assumed to be the same as used in SEGS VI, the capital costs are based on current cost projections [4]. The calculated levelized cost of energy or LCOE [6] is based on current financial assumptions assumed to be available to a large-scale trough plant built in the United State and is stated in constant or real 2002 U.S. dollars. Unless otherwise noted, the analysis uses the 1999 insolation data from

Kramer Junction, California (2,940 kWh/m2-yr). The resulting cost of power for the 30-MWe SEGS VI trough plant, if built today, is 17.0¢/kWh for a solar-only plant and 14.1¢/kWh for the hybrid plant.

Table 1 Reference 30 MW SEGS Plant Site

Kramer Junction	**Solar only**	Hybrid (25%)
Plant size, net electric (Mw)	30	30
Collector aperture Area (km2)	0.188	0.188
Thermal storage (hours)	0	0
Solar-to-electric efficiency (%)	10.6%	10.7%
Plant Capacity factor (%)	22.2%	30.4%
Capital cost ($/kW)	3,008	3,204
O&M cost ($/kWh)	0.046	0.034
Fuel cost ($/kWh)	0.000	0.013
LCOE [2002$/kWh	0.170	0.141

Near term though Plants

A number of parabolic trough power plant projects are currently under consideration around the world. The technology used in these projects will build on the equipment and experience from the SEGS plants to see the cost effective supply. In addition, important advances have occurred since the last parabolic trough plant was built that will have an impact on the efficiency and cost of the next plants built. The KJC Operating Company (KJCOC) operation and maintenance (O&M) cost reduction program [1] resulted in a number of key advances that have significantly reduced O&M costs. Key among these are improvements in mirror washing-techniques, improved heat-transfer fluid pump seal O&M practices, improved O&M practices for reducing receiver tube failures, and improved control and information systems. Solel Solar Systems has recently developed a new parabolic trough receiver referred to as the universal vacuum (UVAC) receiver. The UVAC has improved thermal and optic properties. Field tests of the new receiver at SEGS VI shows a 20% increase in thermal performance compared to original receiver tubes. KJCOC has also implemented a new piping interconnection for the piping interface between collectors, referred to as ball-joint assemblies, for replacement of the original flexible hoses.

Integrated Solar Combined Cycle System (ISCCS)

The ISCCS is a new design concept that integrates a parabolic trough plant with a gas turbine combined-cycle plant [2, 3]. The ISCCS has generated much interest because it offers an innovative way to reduce cost and improve the overall solar-to-electric efficiency. A process flow diagram for an ISCCS is shown in Figure 2

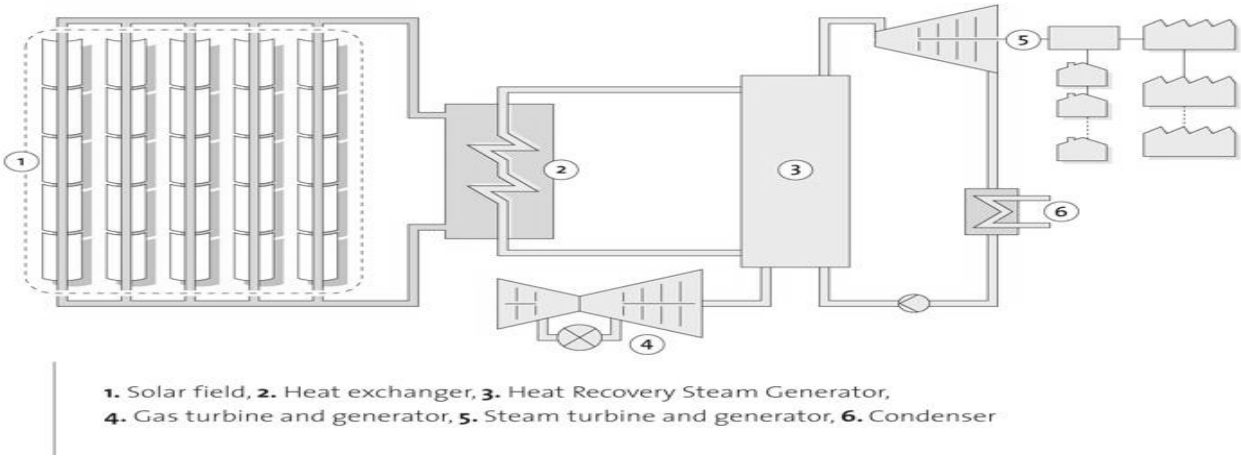

Fig 2 Integrated Solar Combined Cycle Syste

The ISCCS uses solar heat to supplement the waste heat from the gas turbine in order to augment power generation in the steam Rankine bottoming cycle. In this design, solar energy is generally used to generate additional steam and the gas turbine waste heat is used for preheat and steam superheating. Most designs have looked at increasing the steam turbine size by as much as 100%. The ISCCS design will likely be preferred over the solar Rankin plant in regions where combined cycle plants are already being built.From Table 2 the cost and performance of the 40-MW solar increment of an ISCCS plant compared to the baseline 50-MWe Rankine cycle plant is estimated. The fuel cost is the result of the steam turbine heat rate performance penalty when solar is not available compared to the reference combined cycle plant. The ISCCS configuration offers a significant opportunity to reduce the cost of solar power.

Table 2 ISCCS Cost Reduction Potential Site:

Kramer Junction	Solar Rankine	ISCCS Solar Increment
Plant size, net electric (Mwe)	50	40
Collector aperture Area (km2)	0.312	0.222
Thermal storage (hours)	0	0
Solar-to-electric efficiency (%)	13.9%	15.7%
Plant Capacity factor (%)	29.2%	29.2%
Capital cost ($/kWe	2,745	1,988
O&M cost ($/kWh)	0.024	0.008
Fuel cost ($/kWh)	0.000	0.003[3]
LCOE [2002$/kWh	0.110	0.073

Receiver Technology Development

The Solel UVAC receiver tube is a significant advance over the previous Luz cermet receiver design [10]. Table 3 shows the key thermal and optical properties of both receivers. In addition, improving reliability of the receiver has a significant impact on the cost of energy. New O&M procedures and are expected to improve receiver reliability at future plants. The new UVAC receiver should reduce the cost of electricity by about 17%. Of this, approximately 7% is due to the improved solar transmittance of the glass envelope, 2% is due to improved solar absorptance of the black absorber, 5% is due to reduced thermal emittance of the absorber, and 3% is due to improved receiver reliability. With continued development of receiver design and selective coatings, further improvements in receiver tube properties and reliability are believed to be possible. Targets of 96% absorptance and a 7% thermal emittance at 400°C appear to be feasible. Reducing receiver failures to 0.5% per year and improving properties can reduce the cost of energy by an additional 5%. Of this, approximately 2% is from the improved solar absorptance, 2% from the improved thermal emittance, and 1% from the improved receiver reliability.

Table 3 Trough Receiver Thermal/Optic Properties

Kramer Junction	Luz Cement	Solel UVAC	Future Goal
Envelope solar transmittance	0.915	0.96	0.96
Coating solar absorptance	0.915	0.941	0.96
Coating thermal emittance	0.14	0.091	0.07
@ temperature (°C)	350	400	400
Assumed annual failure rate	5%	2%	0.5%
LCOE 2002$/kWh	0.133	0.110	0.104

Concentrator Size

The size of the collector can have a significant effect on the cost. Luz increased the length and aperture of the LS-3 collector significantly from the LS-2 size. The EuroTrough consortium is looking to further increase the length of the collector [13]. We compare the cost of collectors that are the size of the LS-2, the size of the LS-3, and a collector that is 1.5 times as long as the LS-3 — similar to the EuroTrough design. This analysis assumed that the cost of the structure and mirrors are constant on a per–square-meter basis for all three sizes. This is not completely correct because the cost of the structure will be slightly higher for the larger sizes assuming similar structural stiffness [14]. However, the reduction in cost because of fewer interconnections, drives, electronics and controls, and receivers is a much more significant impact. For example, because the LS-3 uses the same receiver as the LS-2, but has a larger aperture, an LS-2 field of the same size would require 15% more receivers. Although not accounted for in this analysis, mirror costs on a per-square-meter basis are also likely to be lower for the LS-3 size mirrors in comparison to the LS-2 size. Table 4 shows a comparison of cost of the three sizes of collectors. Collector costs for this analysis are based on cost data from Pilkington [4].

Table 4 Effect of Concentrator Size on Cost of Energy

Kramer Junction	LS-2 50	LS-3 100	LS-3 150 1
Aperture (m)	5	5.75	5.75
Length (m)	50	100	150
Aperture area (m2)	235	545	818
Number of collectors relative to LS-2 collector	100%	43%	29%
Number of receivers relative to LS-2 collector	100%	87%	87%
Estimated cost ($/m2)	233	208	202
LCOE 2002$/kWh	0.110	0.103	0.102

Thermal Energy Storage

Some of the most significant advances in parabolic trough technology is the development of a thermal energy storage (TES) technologies that will work with the higher solar field operating temperatures required for the later more efficient SEGS plants.

A near-term TES option is a two-tank system that uses molten nitrate salt as the storage medium and has an oil-to-salt heat exchanger to transfer thermal energy from the solar field to the storage system [15]. When the storage system is discharged, the molten salt is circulated back through the heat exchanger to reheat the solar field heat-transfer fluid, which is then sent to the solar steam generator to make steam to operate the power plant. The thermal energy storage system described here is relatively expensive due to the need for a large oil-to-salt heat exchanger and the relatively small temperature difference between hot and cold storage tanks (80-90°C), which means a larger storage volume is required than if a larger temperature difference were possible. The temperature difference in the storage system is currently constrained by upper temperature limit of the heat-transfer fluid (400°C) on the hot side and the steam power cycle on the cold end. The cost of energy from the 50-MW plant with different amounts of thermal storage is shown in Fig 3 [16]. Small amounts of thermal storage, up to 6 hours of full power output, result in an increase in the cost of energy, while storage capacities between 6 and 16 hours lower the cost of energy. It should be noted that small capacities might still be warranted by virtue of revenue considerations because they would allow the plant to dispatch solar power during the time of day with the highest electricity rates. Note that the lowest cost of energy occurs with approximately 12 hours of TES. Increasing TES beyond 12 hours results in increased dumping of energy during the summer when the plant would already be operating 24 hours a day.

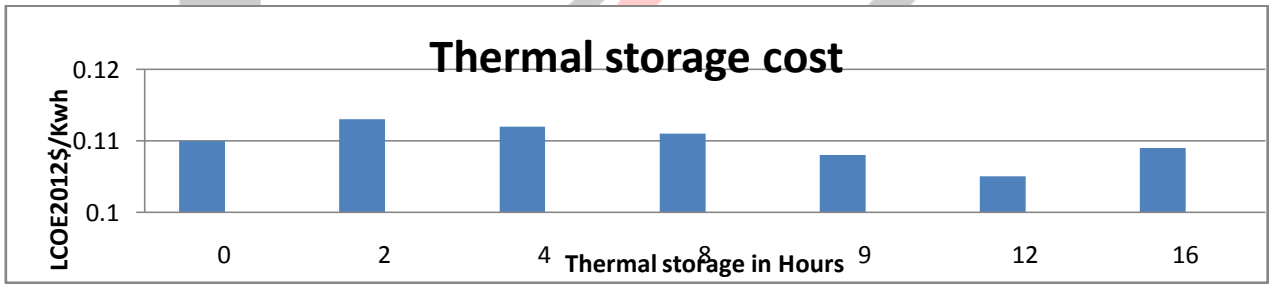

Fig. 3 Effect of Thermal Storage on Cost of Energy

A number of advanced storage concepts have been identified that have the potential to significantly reduce the cost of thermal energy storage for parabolic trough plants. The current near-term TES option has a unit cost of $30 to 40/kWh$_t$ depending on storage capacity. For comparison, the cost of storage for large molten-salt power towers, with a larger operating temperature difference, is expected to be less than $10/MWh$_t$ [5]. Three approaches are considered for reducing TES costs for troughs. The first is to move from a two-tank system to a single tank thermocline storage system. The second is to go from an indirect system that requires a heat exchanger to one that uses the same fluid in the solar field and storage system (similar to SEGS I or the Solar Two power tower). The third approach is to find a way to increase the hot and cold temperature differential in the storage system, thereby shrinking the storage volume required. Pacheco [17] evaluated the thermocline TES system concept. This approach eliminates one of the storage tanks and allows most of the liquid stored in the tank to be replaced with a lower cost filler material, in this case quartzite rock and sand. The disadvantage of the thermocline is that there is a thermocline zone that occupies part of the tank, which reduces the useful capacity of the tank and also causes an increase in solar field supply temperature at end of the

charge cycle as well as a decay in supply temperature to the power plant at the end of the storage discharge cycle. Appropriate design measures must be taken to maintain a tight thermocline zone in the storage system. The use of the thermocline can reduce the cost of storage by 30% to 50%, depending on the relative cost of liquid to the low cost filler material. In the two-tank TES configuration, the heat exchanger and related equipment add between 15 to 30% to the total system cost. In addition, the heat exchanger reduces the maximum temperature difference between the hot and cold fluids. Therefore, eliminating the need for a heat exchanger will reduce the TES cost. In a recent study [18, 19], the use of molten-salts directly in the solar field as the heat-transfer fluid and the storage medium has been proposed. This concept eliminates the need for a heat exchanger and allows the solar field operating temperature to be increased to 450°C or possibly higher. The major concern with molten-salts as a heat-transfer fluid in a trough plant is the high freeze point. A ternary nitrate salt mixture has been identified that has a freeze point of approximately 120°C. This temperature appears to make the use of molten-nitrate salt a possibility, although other issues such as loop freeze recovery, maintenance practices and ball-joint seals in molten salt remain technical issues.
Figure 3 below shows the potential impact of advanced thermal energy storage technologies on the cost of energy for a 50-MWe SEGS plant with 12 hours of thermal storage. The chart shows the cost of energy for a plant without thermal storage, a plant with the near-term storage options (a two-tank indirect system), an indirect thermocline system, a direct (molten salt) two-tank system operating at 450°C, and direct thermocline molten-salt system operating at 450°C and 500°C. The advanced thermal storage systems offer a 14% reduction in the cost of energy over the near-term thermal storage option.

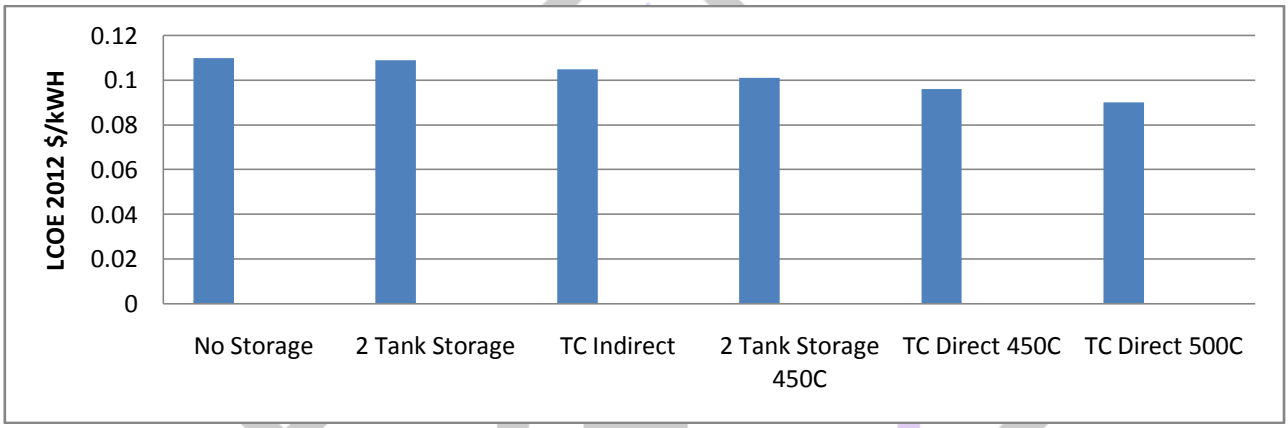

Fig. 4 Impact of Advanced Storage Technologies on the Cost of Energy

The advanced TES cases shown in Figure 3 assume that The advanced TES cases shown in Figure 4 assume that inorganic molten salts are used as the heat-transfer fluid in the solar field. It should be noted that a number of alternative advanced TES concepts are being developed in parallel that may be used for these future higher temperature cases. NREL is currently working to develop organic salt heat-transfer fluids that remain liquid at ambient temperatures [20]. These fluids, if they can be developed to be stable at high temperatures and at a reasonable cost, could substantially reduce the technical risk of moving to a direct TES and a higher operating temperature in parabolic trough plants.

Operation and Maintenance

The KJCOC O&M study [1] has shown that significant reductions in O&M cost have been possible at the existing SEGS plants through improved equipment and methods. It is likely that not all of the O&M cost reduction potential has been realized at the existing plants. Future plants will likely benefit from further improvements in O&M equipment and methods, reductions in solar field spare part costs due to improved technology, increases in apacity factors through implementation of thermal energy storage, and economies of scale with scale-up in plant size and power park developments. All of these cost reductions were not explicitly illustrated above, but are implicitly included in the cost of energy.

Financial Incentives

Capital is the money invested to build a project. This is the complete cost including equipment, construction, and project development. There are two major types of capital investments in a project: equity and debt. The equity investment is made by the parties that will own the plant. Equity investments in typical independent power producer (IPP) projects require a 12 to 18% internal rate of return (IRR) after taxes. The debt investment is similar to a mortgage on a house. P projects typically use non-recourse debt, which simply means that the loan is secured by the cash flow of energy sales from the project and the debt investors cannot go after the owners if the project cannot make the loan payments. A primary difference between solar and fossil plants is that the solar plant has a large solar field that is equivalent to a 30-year fuel supply at the fossil plant and that incurs a high front-end capital investment. Even if the capital cost of the solar field is the same as the fuel cost at the fossil plant, the cost of power from the solar plant will end up being more expensive primarily because of two factors. First any capital investment

must be paid back to investors at a high rate of return. Second, tax policy typically treats capital investment less favorably than expense type investments such as fuel. Access to low-cost capital can significantly reduce the cost of solar power. r baseline 50-MW trough plant assumes an IRR to equity of 14% and a debt interest rate of 8.5%. Figure 5 shows the impact on the cost of energy from our baseline 50 MWe plant for different debt interest rates and equity IRRs when the other is held constant. The availability of low cost sources of debt and equity capital can significantly reduce the cost of energy from capital-intensive solar plants. A more detailed discussion of project finance for trough plants is presented by Kistner and Price [21]

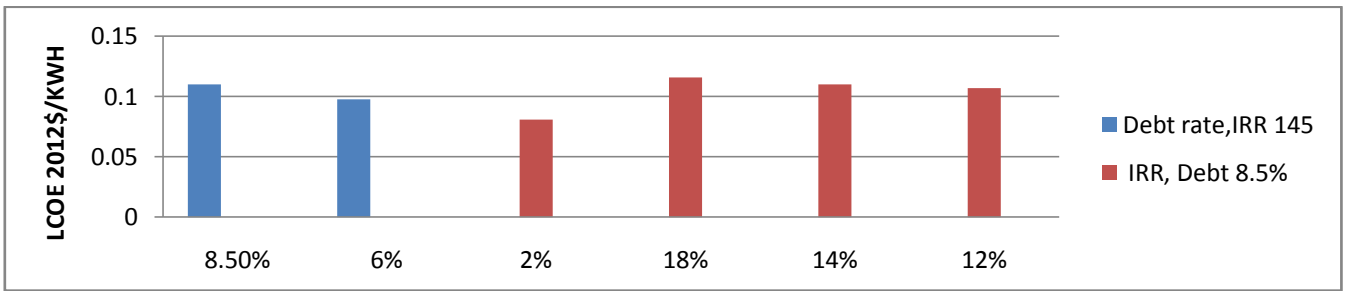

Fig. 5 Effect of the Cost of Capital on the Cost of Energy

Without special property tax exemptions, a solar power plant would be forced to pay property tax on the solar field land and equipment. Because the solar field represents a major portion of the total capital cost of the plant, property tax on this equipment represents a significant cost penalty for solar technologies. simiilarly, fossil plants also do not pay sales tax on their fuel. To help achieve tax neutrality with fossil technology, solar plants should be exempted from paying sales tax on solar equipment. In addition, because of the greater amount of capital investment for solar plants, the state and federal governments collect more taxes on the income received by debt and equity investors. Thus, the state and federal governments can offer special incentives to help encourage investment in capital-intensive renewable technologies and still remain whole through increased tax revenues. Historically, several types of incentives have been offered to renewable energy technologies. The SEGS plants benefited from federal and state investment tax credits (ITC) ranging from 10 to 50% of the capital investment. A 10% federal ITC is currently still in place. The SEGS plants also benefited from a property tax exemption on all solar equipment, which is currently still in existence in California. The ITCs proved to be very successful for encouraging the development of the SEGS plants. Currently production-based incentives are the preferred approach for encouraging the development of a healthy renewables industry. A 1.8¢/kWh production tax credit (PTC) is currently available to wind and biomass technologies and is largely responsible for the rapid growth in wind capacity in the United States. The 1.8¢/kWh PTC is also being considered forlarge-scale solar technologies, but is currently not sufficient toencourage near-term projects. In the recent DOE 1000-MWeCSP Report [22], tax incentives including a 1.8¢/kWh PTC and a 30% ITC were considered necessary in the short term to help CSP technologies be competitive. Figure 5 shows the impact on the cost of power with different tax incentives. Note that the current 10% ITC alreadyreduces the cost of power by almost 1¢/kWh from the case with no ITC. The 1.8¢/kWh PTC is only marginally better than the current 10% PTC. The last bar shows the impact of the 30%ITC, the 1.8¢/kWh PTC, and property tax exemption. Theseincentives reduce the cost of power to under 8¢/kWh for the near-term solar-only 50-MWe trough plant.

Power Market Scenario

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

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

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

- **Scenario 2: Global Climate Change**

Global climate change causes more nations to invest significant resources to reduce greenhouse gas emissions. Carbon dioxide (CO2) reduction becomes the major driver for the development of CSP technologies. Economic incentives are put into place to create a market opportunity. In this case, the primary focus will be on rapid deployment of CO2 reduction technologies and development of large, high-capacity-factor grid-connected plants. Repowering of existing plants presents an important opportunity to minimize costs. Development of thermal or electric storage is a high priority.

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

Fossil fuel prices escalate due to declining production or through political developments or other events that result in reduced production of one or more fossil fuels. In this scenario, other fuel and energy technologies are developed to replace the demand for fossil fuels. During this period, significant price fluctuations are seen until demand for alternative fuel and energy technologies can replace a significant portion of the demand for conventional fuels. Increasing energy prices and energy price uncertainty will drive the demand for solar technologies in this scenario. The activities developed later in the roadmap address one or more of these scenarios. Although Scenario 1 is generally thought to be the more realistic picture of the near-term future, Scenarios 2 and 3 are potentially of such significance that it is appropriate to include activities that also address these as an insurance policy for the future Depending on the power market scenario.

We consider four different financing scenarios depending on market scenario. The first assumes the current financial incentives for an IPP power project. The second assumes the 1.8¢/kWh PTC in place of the 10% ITC. The third assumes the 30% ITC, the 1.8¢/kWh PTC, and a property tax exemption. The final case is similar to the low-cost capital assumption, which assumes that the project is purchased by a municipal utility. Municipal utilities have access to low cost financing with interest rates as low as 6%. Figure 6 shows the results of the analysis for the current and future plants for each of the financing scenarios. Figure 6 shows the results of the analysis for the current and future plants for each of the financing scenarios. The analysis shows parabolic trough technology has significant potential for reducing the future cost of energy.

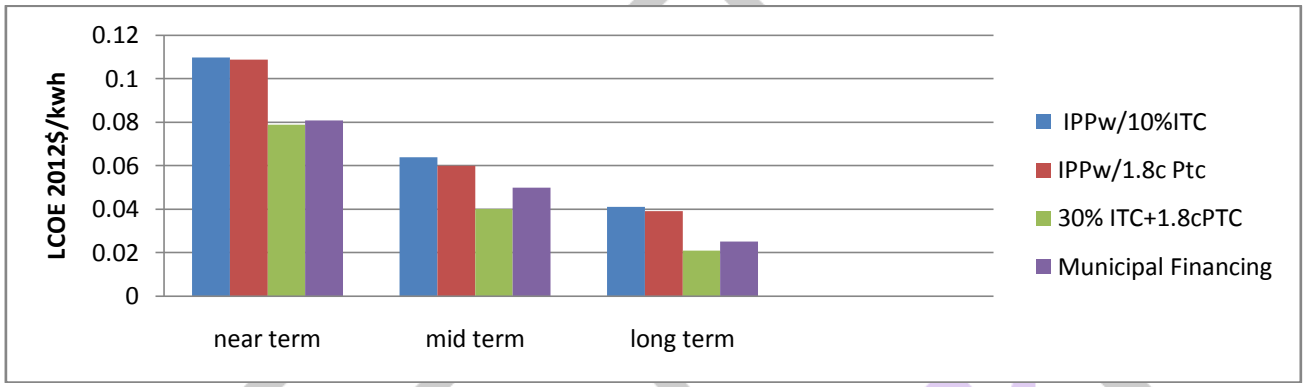

Fig. 6 The Cost of Energy for Near-Term and Future Parabolic Trough Power Plants with different Financing assumption

IV. PARABOLIC TROUGH POWER PLANTS - A PROVEN FUTURE TECHNOLOGY.

Parabolic trough power plants are the only technology for utilizing solar energy in large power plants that has been commercially proved over a number of years. Parabolic trough power plants have been in successful commercial operation in California since 1985. They have already generated over twelve billion kilowatt hours of solar electricity, which equates to providing some 12 million people with electricity for one year. As with conventionally fuelled power plants, including nuclear power plants, the electricity in parabolic trough power plants is generated using a steam turbine connected to a generator. However, the steam required is not produced by burning fossil fuels but through the use of solar energy. The solar irradiation is captured and concentrated by long rows of parabolic mirrors. The heat generated in this way is enough to produce the steam required. Solar Millennium has developed Europe's first parabolic trough power plants. Solar Millennium's pioneer project Andasol 1 has been connected to the grid since December 2008. Andasol 2 was completed in early summer 2009 and has since been connected to the grid. Andasol 3 was inaugurated in autumn 2011 and is also generating climate-friendly solar power. Fig 7 shows parabolic trough collector in Solar Millennium's pioneer project Andasol 1.

Fig 7 Solar Millennium's pioneer project Andasol 1

V. NEW TECHNOLOGICAL INVENTION OF PARABOLIC TROUGHT COLLECTOR

HelioTrough

A more efficient collector design for parabolic trough power plants was developed by the Skal-ET research project. An 800-meter-long test chain of the new collectors was integrated into a commercial solar power plant in the United States. Efficiency increased by ten percent compared to the previous generation of collectors. The Skal-ET research project was concluded in 2003. The new Skal-ET collector design has been implemented in the Andasol power plants in Spain. Based on studies a design with less weight and fewer deformations of the collector structure due to dead weight and wind loading has been selected for the Skal-ET parabolic trough collectors. This reduces torsion and bending of the structure during operation and results in increased optical performance and wind resistance. This design also leads to easy manufacturing and minimizes assembly and construction efforts on site. Transportation requirements have been optimized for economic packing and shipping.

Fig .8 Skal-ET collector

The HelioTrough collector development follows the successful Skal-ET collector. Starting in 2005 and co-funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Flagsol developed a collector with improved optical efficiency and significantly lower costs than standard collectors. Together with partners, such as Schlaich Bergermann und Partner, the Fraunhofer Institute for Material Flow and Logistics and the German Aerospace Center (DLR) the development is under way. A demonstration loop at the commercial solar power plant in the United States has been in operation since the end of 2009. It is expected to prove the highest collector efficiency, thereby setting new standards in cost efficiency with parabolic trough collectors. This project is co-funded by the U.S. Department of Energy.

Fig.9 Helio Trough

VI. SOLAR PARABOLIC TECHNOLOGIES IN INDIA

Amid the growing demand for sustainable energy, concentrating solar power (CSP) technologies are on the verge of large scale global deployment. These technologies harness concentrated sunlight to generate electricity. In the coming decade, the CSP market is estimated to be worth over a billion dollars. The Government of India too has identified solar power as an important renewable energy resource and its commitment to develop solar power is reflected in the 'National Action Plan for Climate Change' wherein it has announced the 'National Solar Mission' as one of the eight missions to combat the challenges of climate change. Hence, it is important to understand the market readiness of different CSP technologies, the investment opportunities which these technologies are likely to create and the overall market development scenario. TERI was entrusted to undertake a comparative analysis of the different CSP technologies. The study also covered sub-technologies/components which by themselves are an important market segment and also addresses the cost benefit and investment opportunities in solar power projects. The study analyzed the market players and overall policy and regulatory situation, the main drivers for the growth of the renewable energy markets in India. The main factors influencing the CSP market in India is the government's commitment, its

budgetary support, and more importantly, availability of funds (grant, debt, equity and low cost finance) from international agencies. Technology development and technology providers' outlook about Indian market including political and economic stability and bureaucratic hurdles, water, grid, and gas network development in areas of high potential, indigenization of technologies and lowering of costs of equipment and services are other crucial factors. The government took a major step in promoting solar power in India by announcing the Jawaharlal Nehru National Solar Mission (JNNSM) in November 2009. The objective is to establish India a global leader in solar power generation. The mission also aims to achieve grid parity by 2022 and parity with coal-based thermal power by 2030 and feed 20000 MW of solar power by 2022. While in the first phase (2010-13) it targets 1000 MW of grid-connected solar power, and promotes different decentralized applications including off-grid systems to serve populations without access to commercial energy; in the second (2013-17) and third (2017-22) phases, the power generation capacity will be aggressively ramped up to create conditions for up-scaled and competitive solar energy penetration. Targets include ramping up capacity of grid-connected solar power generation through the solar-specific renewable purchase obligations for utilities, backed with a preferential tariff. Another impetus to the development of CSP technologies came from TERI and the William J Clinton Foundation. They have taken up the initiative to assist the central and state governments in developing an integrated solar power plant facility, appropriately named 'Solar Park'. A Solar Park is essentially a specially developed area where solar power plant project developers can establish large-scale power plants and/or manufacturing facilities for solar power projects. Typically, a solar park will have the capacity to establish about 3-5 GW capacity power plants. This concept has been well received by the respective state governments and work on land identification and survey is on in Gujarat and Rajasthan, and with that initiative, the Gujarat state government has inaugurated one solar park in Patan district.The study estimated the market for CSP technologies under three scenarios - the solar mission scenario, the optimistic scenario, and the conservative scenario. The solar mission scenario is the result of the government's policy following the JNNSM. The optimistic scenario is based on the efforts of governments and other initiatives to promote the technologies. The conservative scenario assumes that the development of CSP technology will take place in a sluggish manner. The projected market development indicates that the CSP market can reach about 15.2 GW by 2022 under the optimistic scenario where as under conservative scenario only about 5.7GW market is likely to be developed by 2022. It observed that while the government is taking steps to encourage the development of CSP technologies; much will depend on the implementation of these policies and the impetus from the private sector.

VII. CONCLUSIONS

The concentrated solar power technology is a globally proven technology. India's vast solar resource potential can be tapped through these technologies for energy generation. There is a need for great focus on the promotion and implementation of these technologies. With the indigenization of the technology, the CSP power generation may soon achieve grid parity. It is concluded that Parabolic trough collector (PTC) will be the most dominating CSP technology by 2020, Maximum Integrated Solar Combined Cycle (ISCC) projects will be of PTC Technology. Thus it can be concluded that

- Deserts and semi-deserts provide almost unlimited options in terms of location. Less than three percent of the area of the Sahara is sufficient to meet the world's energy requirements with parabolic trough power plants.
- Parabolic trough power plants are especially flexible in terms of their implementation. Hybrid power plants can combine solar energy with other forms of power supplies, such as natural or biogas, for example. This means that parabolic trough power plants can also cover base loads, i.e. generating reliable electricity on demand 24 hours a day.
- Parabolic trough power plants are the most efficient and cost-effective technology for converting solar energy into electricity on a power plant scale.
- Parabolic trough power plants enable cost-effective, efficient storage of energy whereby it is the heat energy and not the electricity which is stored. Thermal storage enables the power plants to deliver environmentally-friendly electricity at night as well. Such storage is already in commercial use at the Andasol power plants.
- Parabolic trough power plants have demonstrated real net results for the conversion of solar radiation into electricity of around 24% in summer and over 15% as an annual average. That is significantly more than with the ordinary photovoltaic cells in commercial use.
- Unlike other solar thermal technologies, parabolic trough power plants have been proven over a number of years. In California, nine power plants have been generating environmentally-friendly electricity in commercial operation for over 20 years. These power plants have provided an impressive demonstration of the reliability and sustainability of the technical components.

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