EVALUATION OF SOLAR POWER GENERATION TECHNOLOGIES FOR SOUTHERN AFRICA

Professor Nikolai V. Khartchenko
Department of Mechanical Engineering
University of Southern Africa
Private Bag 0061, Gaborone

Abstract - The paper evaluates the solar energy power generation technologies suitable for Southern Africa. The main criteria of selecting appropriate and economically feasible technologies are high efficiency and affordable initial cost of the plants. For central large-scale electricity generation supplying power to grid the most viable choice is either a parabolic trough or central receiver plant with an optimal electric capacity in the range of 100 to 200 MW. For distributed power generation in remote areas of Southern Africa, solar photovoltaic and dish / Stirling engine power plants promise to be the best near-term choice. The paper emphasizes that integration of solar energy resource into advanced total energy supply systems will accelerate the commercialization of solar electric technologies. Hybrid solar/fossil fuel power generation concepts and design are also considered.

1. INTRODUCTION

The current world's primary energy consumption is approx. 100x10^9 kWh, including Africa 3x10^9 kWh. World’s proven fossil-fuel reserves roughly are: coal 30x10^21 J, oil 6x10^21 J and natural gas 5x10^21 J. At the present rate of consumption these reserves will be exhausted in 225, 45 and 65 years respectively. In Sub-Saharan Africa only 25% of urban and 2% of rural population have access to modern forms of energy such as electricity.

Currently used energy resources are predominantly non-renewable and bound to exhaust in the mid-term. The patterns of the energy production and its use are unsustainable and lead to severe deterioration of the environment. The sustainable energy sector is based on efficient use of existing energy stocks and energy conservation and is able to satisfy the optimized energy needs of current and future generations without significant environmental impact.

To develop a sustainable energy sector of economy in Southern Africa, the energy policy should be directed toward:

1) reduction in energy consumption and energy conservation in all sectors of economy,
2) integration of efficient renewable energy, primarily solar energy, technologies into total energy supply systems.

The electricity is currently generated predominantly in coal-fired steam power plants, large hydroelectric power plants and nuclear power plants. Sustainable power generation systems show high energy conversion efficiency, low environmental impact and viable economics. High efficiency energy systems produce more electricity per unit of fuel burned and thus produce less emissions of carbon dioxide (greenhouse gas) and pollutants (sulfur and nitrogen oxides, unburned hydrocarbons, and carbon monoxide). Advanced energy systems such as combined cycle power plants and clean energy technologies offer enhanced efficiencies, improved economics and reduced environmental impact.

Integration of renewable energy sources into energy supply systems will minimize problems associated with finite fossil-fuel resources and environment deterioration due to emissions from fossil-fuel based energy systems. Renewable energy systems will ultimately replace fossil-fuel based energy sector in the long-term.

Out of all renewable energy resources, Southern Africa possesses abundant solar energy resources but their current utilization is limited mainly to solar domestic water heating and to a very small degree to photovoltaic electricity generation. However solar energy should be used as an inexhaustible source of pollution free energy to efficiently and economically produce electricity without adverse environmental impact of current fossil fuel-based power stations.

The objectives of this paper include the evaluation of Southern Africa solar energy potential for power generation, analysis and evaluation of current solar thermal electric technologies in relation to Southern Africa needs in clean and affordable power, performance analysis of solar power generation systems, and economic comparison of various power generation technologies.
2. SOLAR ENERGY POTENTIAL OF SOUTHERN AFRICA

Southern Africa receives an abundant solar radiation flux and has a hot semi-arid climate. This makes solar radiation a very attractive energy resource which can be used for various applications particularly for power generation. In all parts of Southern Africa, clear sky sunny weather is experienced more than 300 days a year. The annual global solar radiation incident on a square meter of horizontal surface in Southern Africa is about 2300 kWh/m² per year, the average daily insolation is 5.7 kWh/m² per day, annual sunshine duration is about 3500 hours and average beam radiation fraction is 0.67.

Our calculations show that the total annual solar energy flux incident on the entire surface area of Botswana in Southern Africa is approximately 1.6x10^{15} kWh. An estimate of the Botswana’s potential for solar thermal and photovoltaic electicity generation was based on the assumption that only solar radiation incident on 0.01% of Botswana urface area will be used for electricity production with an efficiency of 12%. In this case, the annual solar power generation in Botswana would be approx. 1.85x10^{10} kWh per year and the total installed electric capacity of solar power plants would be 7 GW (the current coal-fired power plants have a capacity of approx. 150 MW). It is evident that Southern Africa can carry out electrification of the whole country and also become an exporter of solar electricity.

Two generic types of solar power generation technologies can be used in Southern Africa:

1) solar thermal electric (STE) technologies utilizing thermodynamic cycles to convert solar heat to work in heat engines, and
2) photovoltaic (PV) technology for direct conversion of solar radiation to electricity.

Central and distributed solar thermal power plant concepts discussed in the following chapter can be installed in Southern Africa for electricity production.

3. CURRENT STATUS OF SOLAR THERMAL ELECTRIC TECHNOLOGIES

The following solar thermal electric (STE) technologies are currently used in experimental and commercial installations in Europe (France, Italy, Germany/Spain) and USA:

1) the parabolic trough or solar farm technology,
2) the central receiver or solar tower technology, and
3) the parabolic dish / Stirling engine technology.

However, only parabolic trough technology is currently used for commercially power generation in Southern California.

In general, a solar thermal power generation system includes the following subsystems and components:

1) a solar collector field such as a heliostat array or a large number of parabolic trough modules,
2) a thermal energy storage system which is used to improve availability and capacity factor of the plant,
3) a conventional energy conversion system based on the Rankine, Joule or Stirling cycles, and
4) an electric generator.

To enable a continuous electricity supply to the consumers, the solar thermal electric plant must have either a very large thermal energy storage (TES) or a fossil-fuel back-up power generation system. Large TES are very expensive and therefore an economically viable solution is the utilization of a fossil fuel-fired power generation system which provides the electricity supply on the diurnal basis and covers the low solar radiation periods. In Rankine cycle-based solar thermal power that converts heat to work which is then being converted to electricity in an electric generator.

Among the experimental solar thermal power plants, those built at the Plataforma Solar de Almeria (PSA) in Almeria, Spain, have the world longest record of continuous development and successful operation in the framework of a joint German-Spanish research programme. There are two solar tower power plants - CESA 1 plant with an electric capacity of 1.2 MW and SSPS/CRS plant having an electric capacity of 0.5 MW – and the 0.5 MW- parabolic trough power plant SSPS/DCS. Three 9 kW-dish / Stirling engine plants are also being operated at PSA.

For large-scale solar thermal electricity production, both parabolic trough and central receiver (solar tower) power plants are suitable. Economically viable size of such plants is the range of 100 to 200 MW of electric capacity.

3.1 Commercially Operated Parabolic Trough Power Plants

Nine large parabolic trough power plants SEGS (solar electricity generation systems) with a total electric capacity of 354 MW have been commercially operated in the Mojave in Southern California for more than a decade. The locations are characterized by a very high level of solar radiation and favorable climatic conditions, whereby the annual solar radiation incident on the horizontal surface is 2400 kWh/m². In modules each comprising a parabolic trough mirror and a absorber pipe, the beam solar radiation concentrated by the mirror with
a concentration ratio of 40 to 100 is absorbed by the pipe surface and used to heat a synthetic oil (heat transfer fluid HTF) to a maximum temperature of about 400°C. The HTF is stored in a hot storage tank and its heat is used to raise superheated steam at 100 bar and 370°C. The system uses a single-reheat steam turbine cycle and generates power at a thermal efficiency of 38%. Thereby 25% of heat are supplied by a natural gas-fired back-up boiler. The plants operated by a local utility produce electricity at a price of about $0.14 per kWh.

The performance of parabolic trough collectors can be improved by using advanced materials so that mirror reflectivity and receiver absorptance must be increased to 0.96 and 0.97, and receiver emittance must be reduced to 0.15. However, the major performance and cost-effectiveness ratio improvement is expected from application of direct steam generation.

3.2 Experimentally Operated Central Receiver Power Plants

A central receiver power generation system comprises the following subsystems:

1) a miniprocessor-controlled heliostat (flat mirror) array which concentrates the beam solar radiation,
2) a solar tower with central receiver,
3) a steam generator, and
4) a conventional steam turbine system including electric generator, condenser and heat rejection plant.

In addition to steam, molten salt or air can be used as an alternative heat transfer and working fluid.

The solar tower power plant Solar Two has been operating since 1996 at Barstow, California. Its predecessor plant Solar One was experimentally operated for about 2 years at the same location in 1980s. The rated electric capacity of Solar Two is 10 MW (the same as of Solar One). Contrary to Solar Two which used water / steam as working fluid both in the receiver and in the turbine, Solar Two features the utilization of molten salt both as HTF in the receiver and as heat storage medium in hot and cold storage reservoirs. During daytime hours, a heliostat (flat mirrors) filed of the Solar Two plant controlled by a miniprocessor continuously track the sun in such a way as to achieve the normal incidence of beam solar radiation onto the mirrors. They reflect the beam solar radiation on the aperture of the central receiver, thereby the concentration ratio reaches 500-1000. The concentrated solar flux is absorbed there and used to heat molten salt which acts in Solar Two as heat transfer fluid which has a thermal conductivity of 0.43 W/m K. The hot molten salt is stored in the hot salt tank. The temperature in this tank is above 565°C but below the maximum allowable temperature of 595°C which cannot be exceeded in order to prevent the decomposition of the salt. Its energy is subsequently used to raise superheated steam in a steam generator. After that the salt flows into cold salt tank where the temperature is higher than the salt crystallization temperature of 220°C. Thus the solar energy stored during daytime operation is used to generate electricity particularly during periods of peak demand for power.

It must be emphasized that the key advantage of the Solar Two plant is the utilization of an efficient TES which enables the power generation after sunset and during low solar radiation periods.

Within the European and USA solar thermal electricity programs, new concepts and projects have been developed such as the European project PHOEBUS. The receivers used in the projects are: salt-in-tube (SIT), direct absorption receiver (DAR), and volumetric absorption receiver (VAR). Tower height is about 160 m and the plant thermal efficiency is 41%. For a 110 MW central receiver power plant a heliostat field with the total mirror area of 0.8 km² is required. Such a power plant will occupy approximately 1.5 km² of land surface.

3.3 Parabolic Dish / Stirling Engine Power Generating Systems

A parabolic dish / Stirling engine power generating system comprises:

1) a parabolic dish point-focus concentrator,
2) a radiation receiver, and
3) a hot gas heat engine (Stirling engine).

The concentrator typically uses a certain number of curved reflective panels (facets) made of silver/glass or laminated plastic films, mounted on a structure that tracks the sun by rotating the dish about two axes. The dish reflects the beam solar radiation onto a concave receiver mounted at the concentrator’s focal point. The concentrated solar energy flux is absorbed by the receiver and heat the working fluid such as hydrogen or helium in the Stirling engine cycle.

The dish / Stirling engine power generating systems achieve the highest overall performance of all solar thermal electric technologies. During the past 15 years, a number of dish / Stirling engine systems have been developed in Germany, United States and Japan. Systems ranging in size from a 7.5 to 52.5 kW (electric capacity) have been built and operated in the USA, Spain, Saudi-Arabia, and Japan. To reduce the comparatively high current capital costs of dish/Stirling systems, more advanced engines and solar components are required. Hybrid solar / fossil fuel systems are a very promising concept. It is predicted that the capital costs of hybrid
The electric power output of a solar power plant is given by

$$P_{el} = A_{ap} I_{beam} \eta_{coll} \eta_{storage} \eta_{trans} \eta_{th} \eta_{gen} \eta_{aux} \eta_{sol, el}$$

(1)

where $A_{ap}$ is the total concentrator aperture area, $I_{beam}$ is the beam radiation intensity at normal incidence, $\eta_{coll}$ is the solar collector efficiency, $\eta_{storage}$ is the thermal storage efficiency, $\eta_{trans}$ is the efficiency of the heat transfer and piping system, $\eta_{th}$ is the cycle thermal efficiency, $\eta_{gen}$ is the generator efficiency, and $\eta_{aux}$ is the efficiency taking into account the auxiliary (parasitic) energy consumption of the plant.

The daily solar energy gain of a concentrating solar collector is

$$Q_{sol} = A_{ap} I_{beam} \eta_{opt} - Q_{loss}$$

(3)

where $\eta_{opt}$ is the optical efficiency of the collector, and $Q_{loss}$ is the rate of heat loss of the collector (absorber/receiver) by convection and radiation.

The overall electric efficiency of the solar power plant is

$$\eta_{sol, el} = P_{el} / A_{ap} I_{beam}$$

(2)

Advanced parabolic dish/Stirling engine systems comprising parabolic dish concentrator, radiation receiver, and hot air engine can achieve overall efficiencies of 25 to 30%. Total capacity of all installed plants is 8 MW. They are technically suitable for power generation in remote regions with high insolation rate provided that the present cost of 8-25 $/W will be reduced to about $2/W.

In the 50-kW dish/Stirling system installed by German firms in Saudi Arabia, the concentrator is a 17 m single-facet stretched-membrane dish. The membrane is a thin 0.5-mm sheet of stainless steel stretched on a rim with a second membrane on the back. A vacuum between the two membranes plastically deforms the front membrane to its required shape. Thin-glass mirrors are bonded to the membrane. The concentrator is set into a frame allowing azimuth/elevation tracking. The dish has at its focus a Stirling engine using hydrogen as the working gas with maximum operating conditions of 15 MPa and 620°C.

3.4 Performance Analysis of Solar Thermal Electric Systems

The optical efficiency of a concentrating solar collector is

$$\eta_{opt} = \gamma \rho \tau_g \alpha_{abs} \xi_{other}$$

(4)

where $\gamma$ is the intercept factor, $\rho$ is the reflectance of the concentrator (mirror), $\tau_g$ is the transmittance of transparent cover (glass), $\alpha_{abs}$ is the absorptance of the absorber, $\xi_{other}$ is the efficiency accounting for other energy losses such as blocking, shadowing, dust collection etc.

The rate of heat loss of an open absorber in the parabolic trough, dish or central receiver systems is given by

$$Q_{loss} = \eta_{conv} A_{abs} (T_{abs} - T_a) - k \frac{\text{grad} T}{dA} A_{wall} + \eta_{abs} \sigma A_{abs} (T_{abs}^4 - T_{sky}^4)$$

(5)

where $A_{abs}$ is the absorber surface area, $h_{conv}$ is the heat transfer coefficient by convection from absorber surface to ambient air, $T_{abs}$ is the absolute absorber temperature, $T_a$ is the ambient air temperature, $T$ is the temperature gradient in the wall, $dA_{wall}$ is the differential of the wall area, $\eta_{abs}$ is the emittance of the absorber, $\sigma$ is the Stefan-Boltzmann constant, and $T_{sky}$ is the absolute sky temperature.

The efficiency of a concentrating solar collector is

$$\eta_{coll} = \eta_{opt} \eta_{coll} \eta_{storage} \eta_{trans} (T_{abs} - T_a) - k \frac{\text{grad} T}{dA} A_{wall} + \eta_{abs} \sigma A_{abs} (T_{abs}^4 - T_{sky}^4)$$

(6)

where $C$ is the geometric concentration ratio of the collector, i.e. the ratio of the concentrator aperture area $A_{ap}$ and absorber area $A_{abs}$.

Thus, the efficiency of a concentrating collector strongly depends on such stochastic variables as beam radiation intensity, ambient air and absorber temperatures and wind speed, as well as on the concentrator and receiver types, design and materials, and radiation properties of concentrator and absorber surfaces.

The daily solar energy gain of a concentrating solar collector is given by

4. HYBRID SOLAR / FOSSIL FUEL POWER SYSTEMS

The solar part of a hybrid solar / fossil fuel combined cycle power generation system includes an air preheater and a steam reheater. The fossil fuel part includes a highly efficient combined cycle plant comprising a gas turbine train with a heat recovery steam generator (HRSG) and steam turbine train. The main advantage of hybrid solar / fossil fuel combined cycle power
generation systems is the high efficiency of solar heat conversion. Because of integration of solar components into the combined cycle the solar heat is converted to electricity with the efficiency of the combined cycle which can attain values up to 58% (Khartchenko, 1998).

Based on solar radiation data for Southern Africa, the fuel savings were calculated. The fuel savings that can be achieved in a hybrid solar power plant depend on the size and efficiency of solar concentrator-absorber unit. Choosing the total concentrator aperture area of 170,000 to 460,000 m$^2$, the fuel savings in the range of 10 to 27% have been predicted (Khartchenko, 1999). Cost-effectiveness ratios of hybrid solar power plants are depending on the initial cost and efficiency of solar collector plant. With improved and more advanced solar components, the economics of hybrid power plants and their commercialization perspectives look rather optimistic.

5. ECONOMICS OF SOLAR THERMAL POWER GENERATION

The performance of parabolic trough power plants in current commercial operation in California has significantly improved over the last five years and their operation and maintenance costs were reduced by 30% in the same period. If new parabolic trough plants with improved components will be constructed now they would generate electricity at 0.10 to 0.12$/kWh.

The next generation of parabolic trough technology will implement such innovations as improved absorber tubes with lower cost and support structures and direct steam generation (8) by substituting water for synthetic oil as the heat-transfer fluid in absorber tubes. Dish / engine plants can be used in stand-alone or grid-connected installations. The near-term electricity cost can drop to 0.15$/kWh or less by technological improvements in mirrors and receivers and by solar / fossil fuel hybrid operation of the Stirling and Brayton engines.

Development of improved control strategies and reduction of auxiliary plant power consumption will further improve performance of solar power plants. However the most promising improvement is expected from development of advanced solar/fossil hybrid systems, particularly the from integration of solar collector fields into highly efficient combined-cycle power plants.

6. CONCLUSION

The paper presents an evaluation of Southern Africa solar energy potential for electric thermal power generation. Current solar thermal electric technologies were analyzed and evaluated in relation to Southern Africa needs in clean power. Performance analysis of solar power generation systems can be conducted using relationships presented in the paper. Environmentally sound, efficient and economically viable solar thermal electricity production can be accomplished using immense solar energy potential of Southern Africa if the solar components will become an integral part of hybrid solar / fossil fuel combined cycle power generation systems. Integration of solar energy into global energy supply system of the country will greatly promote the development of sustainable energy sector. Further technological improvements of three major solar power generation system types will reduce the capital cost and enhance the performance and thus improve the cost-effectiveness of solar thermal electric technologies. With an international financial support, these technologies can soon be integrated in power generation sector of Southern Africa economy.

REFERENCES
