SENRA Academic Publishers, Burnaby, British Columbia
Vol. 5, No. 2, pp. 1547-1551, June 2011
Online ISSN: 1920-3853; Print ISSN: 1715-9997

Canadian Journal of pure&applied sciences

A DOMESTIC SOLAR POWER TOWER USING STIRLING ENGINE TECHNOLOGY

*Irfan Younas, Muhammad Zahoor and Saad Ul Haq
HITEC University Taxila Cantt., Pakistan

ABSTRACT

The world is undergoing significant changes both technologically and socially. Societies have witnessed growth unparallel in history over the past century. This growth world-over has been at the expense of ever increasing demand on energy; this demand is not showing any sign of abating. However the world's energy resources are depleting at a very fast rate, particularly fossil fuels. Solar energy is a renewable energy source that can be used to generate energy using heat engines. In this work we outline an innovative approach to generate electricity using a combination of existing technologies such as the solar tower, Fresnel reflectors and Stirling engines. It is proposed to erect a domestic solar tower that has embedded Stirling engines for power production. The UAE has vast amount of solar irradiation which on yearly average is about 400 - 500 Watts/m^2. Used intelligently, with carefully deployed Linear Fresnel reflectors, this technology can deliver electricity to far flung off-grid locations as well as feed into domestic electricity grid.

Keywords: Concentrated solar power, solar tower, linear fresnel reflectors, stirling engine technology.

INTRODUCTION

The world's energy demand is ever increasing. This is partly due to a growing population and technological advancements, but our very way of life is heavily dependent on the continuous and steady availability of energy. The developing countries are catching up with the developed world in terms of living standard and this very desire would inherently require increased access to, and consumption of energy. It is no secret that wealth and economic growth in society is fundamentally intertwined with continuous and uninterrupted power supply. As availability of fossil fuels are in sharp decline and can no longer be solely relied upon to cater for our growing energy demand, the quest for reliable and renewable energy resources has never been so important.

The world energy consumption has exceeded 508 quadrillion Btu (10^{15} Btu) in 2010 and is expected to increase by a rate of 8-10 quadrillion Btu per year (IEA, 2009). One major reason for this increase is the phenomenal growth of the Indian and Chinese economies which are expected to be the biggest contributor to the annual rise in energy consumption. Therefore most countries have, and wisely so, begun investing in renewable energy technologies in order to gradually shift the emphasis from conventional power production to that using renewable energy resources.

Energy production using thermal solar power is one important source of power production. This is due to the fact that the sun is abundantly available particularly in the Middle East region, which is classified as dry tropical region of the earth. The Gulf Corporation Countries (GCC) and the UAE in particular have shown enormous interest in developing expertise, and realise solar powered energy technologies for the nation (Kerney, 2008).

*Corresponding author email: iyounas101@gmail.com

DISCUSSION

CSP Overview

Solar thermal electricity may be explained as the result of a process by which directly collected solar energy is converted to electricity through the use of some sort of heat to electricity conversion device (Mills, 2004). Essentially energy of a system is measured as the maximum useful work that can be extracted during a process which brings the system into equilibrium with a heat reservoir (Perrot, 1998). Although solar radiation has a high radiosity (rough estimate indicates that it is larger than 60 MW/m^2 at the surface of the sun) the significant dilution of solar flux due to Earth's geometric position and reflection of solar rays caused by Earth's atmosphere, leaves solar energy to be less suitable for terrestrial use. Broadly speaking, solar flux available is slightly higher than 1 kW/m^2; therefore an essential requisite for solar thermal power plants and high-temperature solar applications is to deploy optical concentration devices which enable the thermal conversion to be carried out at high intensity and with relatively little heat loss.

The CSP system design combines a relatively large, efficient optical surface, for example a field of highly reflective mirrors where the incoming solar radiation is concentrated and reflected onto a solar receiver with a small aperture area. This solar receiver should be a highly absorbent and transmittance material with low reflectance. Its heat exchanger should as much as possible emulate a black body having negligible convection and conduction losses. In the case of a solar thermal power plant, the task is to transfer concentrated solar flux onto a thermal fluid which then attains a temperature high enough to feed a heat engine or a steam turbine that can be used as a power generator. The solar thermal element can be a parabolic trough, a Fresnel reflector or a parabolic dish, all with a common purpose of concentrating the terrestrial solar radiation to a high degree such that electromechanical work can be extracted with high efficiency.

Parabolic trough

Parabolic trough is a curved, mirrored trough (receiver) which reflects the direct solar radiation onto a glass tube containing a fluid. The trough is parabolic along one axis and linear in the orthogonal axis (Mills, 2004).

The absorber tube positioned above the reflector along the axis of the trough contains the Heat Conducting Fluid (HCF) that is usually enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat losses. As the HCF passes through the tube it becomes increasingly hot. The heated fluid is directed towards a heat engine where approximately one third of the heat is converted to electrical power.

As the sun changes its position during the course of a day an electronic tracking system tilts the trough from east to west so that the direct radiation remains focused on the receiver. It should be noted that during seasonal changes, or where the troughs are globally positioned away from equator, the sun is rising at an angle, but that does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the parabolic trough design does not require tracking on a second axis.

Current operational parabolic trough power plants are installed in the USA and Spain, others are under construction elsewhere in the world. The USA boasts a 354 MW plant in the Mojave Desert in California. This plant comprises a collection of 9 separate power units. Another is placed in the Nevada desert generating 64 MW power. Many power installations using this technology are also visible at various locations in Spain where a range of parabolic power systems having capacity from 20-100 MW are operational (Martin *et al*., 2010; The free Library, 2010).

Solar power tower

The solar tower is utilising the solar energy projected by a group of sun-tracking mirrors known as Heliostats. These heliostats are collectively capable of concentrating solar heat at the top of the tower, where heat can reach in excess of 1000 degree Celsius. Hence the name solar tower (Spiros and Bernhard, 2010).

A receiver located at the top of the tower acts as an energy exchanger. Typical receivers are made from ceramic or other metal structures capable of withstanding high energy density and exhibiting little thermal stress.

The attained heat is thereafter transported via ambient air to a thermo hydraulic circuit that feeds into a dedicated heat recovery steam generator.

World first solar power tower in Seville, Spain generates 11 MW, also known as the PS10. Subsequently the PS20 commercial Solar power tower was constructed (also in Seville) which produces 20MW of electricity (Garcia-Sobrinos and Gonzalo, 2007).

Yet another Solar tower installation known as the Sierra Sun tower by eSolar in California produces 5MW (Biello, 2009). Other relative small solar towers in Germany and France generate about 1.5 MW (Mark Schmitz, 2009).

Solar Stirling Dish

The Stirling engine was invented by Robert Stirling in 1816 also known as an externally operated heat engine. It operates by cyclic compression and expansion of air or other gas at different temperature levels such that there is a net conversion of heat energy into mechanical work. Since the Stirling engine is simple in design and construction it can be operated easily (Walker, 1980). There are various types of Stirling engine also known as the alpha, beta and gamma types. These types differ only in design and their basic principle remains the same.

The Stirling engine has been attracting more interest lately as a good foundation to an electro-mechanical renewable energy system using a concentrating solar dish. Although many concentrating solar dish systems have been designed using Stirling technology, but this technology is yet to gain widespread acceptance; currently only one commercially operational system exists in the USA with a power output of 1.5 MW (Patty, 2004).

Linear Fresnel Technology

The linear Fresnel Technology system consists of long mirrors which are flat or have a slightly curved optical surface. These mirrors are positioned in long parallel lines such as to reflect the direct sunlight onto a long target or receiver. This receiver could be a long absorber tube with a re-concentrator made from linear Fresnel lens technology as depicted in figure 1.

The linear Fresnel technology is relative new and currently deployed in the USA, Spain and Australia. A demonstration plant is placed at Bakersfield in California (Morrison, 2008) producing 5 MW. Another plant has been built at New South Wales (Mills, 2004) generating about 2 MW, while a third plant in Murcia, Spain (Ishan and Pallav, 2010) produces 1.4 MW. This CSP technology is new but relative mature and if deployed correctly on barren land or in a desert could potentially produce 10's of Megawatts.

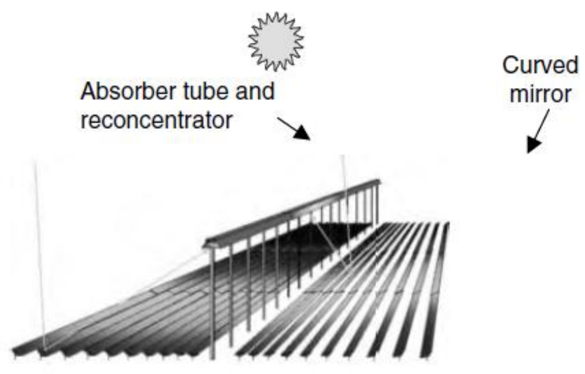

Fig. 1. Power generation using Linear Fresnel Lenses.

Solar flux and the UAE

It is an established fact that regions on or near the Earth's equator are subjected to more sunlight that other areas of the globe. Particularly the region between latitudes 40°N and 40°S, also referred to as the "solar belt" that witnesses abundant solar radiation.

The United Arab Emirates in general and Abu Dhabi in particular which lie in the solar belt region will be the subject of this study. Abu Dhabi has *latitude and longitude* denominations given as 24°28N and 54°22E respectively. An earlier study has shown that approximately 4500hours of sunlight per year can be expected for this region (Aksakal and Rehman, 1999). Solar radiation is usually divided into direct and diffuse radiation. We will however not make this distinction and simply use the total radiation that can be measured using a pyroheliometer.

(Islam *et al.*, 2009, 2010) have made extensive temperature and solar flux measurement for Abu Dhabi over the period of one year and their results are summarised in table 1. It can be seen from table 1 that the monthly average solar irradiance varies from approximately 300 W/m^2 to almost 500 W/m^2 during the course of a year. It is also noted that the yearly visibility index is around sixty percent which is adequate for a CSP power plant.

Therefore Solar Thermal Power is realisable power source that can be adapted and deployed throughout the United Arab Emirates and beyond. In the next section we present our take on how it could be deployed in the UAE.

Table 1. Solar Characteristics for Abu Dhabi (Islam *et al.*, 2009, 2010).

Month	Solar irradiance [Watts/m^2]	Temp. [°C]	Clearness index [0-1]
Jan	430.0	20	0.55
Feb	412.5	22	0.59
Mar	463.33	25.5	0.59
Apr	490.83	31.1	0.59
May	493.33	35	0.6
Jun	397.5	36.1	0.59
Jul	354.17	36.2	0.59
Aug	302.5	35.5	0.6
Sep	478.33	34.8	0.61
Oct	474.17	32	0.62
Nov	442.5	27.5	0.57
Dec	339.17	21.1	0.46
Average	423.19	29.7	0.58

The idea of the Solar Thermal Tower is not new and it has already been successfully deployed at various locations around the world. Spain has taken the lead with a plant producing around 20 MW of power. However there is an immense cost associated with this scale of power production which may not be viable for certain developing countries. Hence, we introduce the idea of a solar tower that has imbedded Stirling engines and powered by an array of Linear Fresnel Reflectors in the configuration shown in figure 2. This figure shows a schematic view of the total solar plant configuration. Linear Fresnel Reflectors (LFRs) are mounted on a rooftop and they are facing east. On the East side of the building a solar tower a positioned such that it is exposed to the high intensity concentrated solar radiation from the LFRs. This concentrated heat is then channelled through conduction to an array of Stirling Engines positioned at the lower parts of the Solar Tower. The acquired heat is used by the heat exchanger of each Stirling engine. A good choice for the conductive material would be pure copper encapsulated by glass shielded vacuum tubes.

For the Stirling engine the β-type engine was preferred because it has the displacer - and power piston arranged within the same cylinder and mounted on the same shaft (see Fig. 3). The displacer piston is used only to shuttle the working gas between the hot and cold ends of the cylinder. This configuration avoids the problem of hot moving seals, and both pistons are connected on a flywheel through connecting rods (Halit *et al*., 2009).

Mechanical power extracted from each engine is converted into electricity using a synchronous electric generator. This generator can subsequently feed into the domestic electricity grid or charge powerful batteries for electric storage and later usage. The β-type type Stirling Engine was chosen as it operates efficiently at constant Revolutions per Minute (RPM).

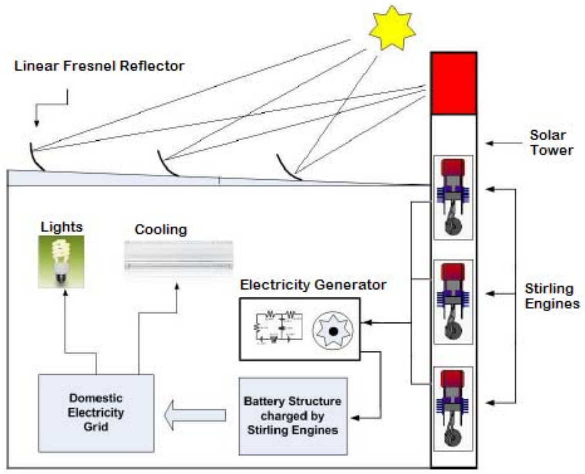

Fig. 2. Solar Tower with embedded Stirling Engines powered by Linear Fresnel Reflectors.

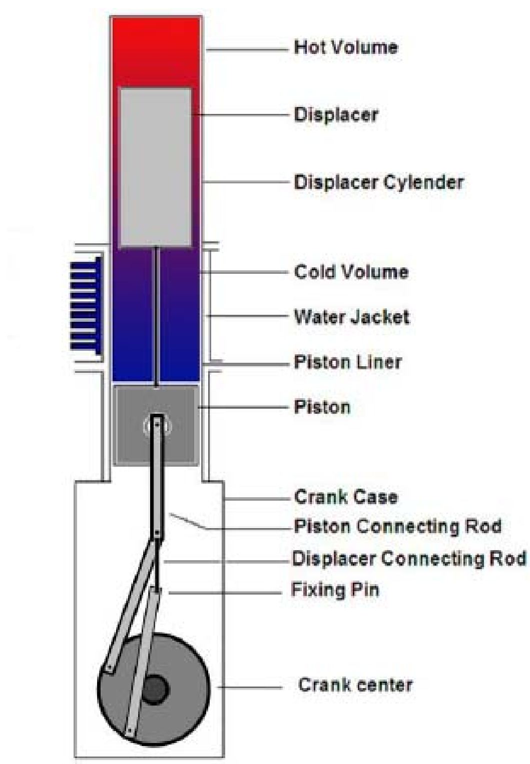

Fig. 3. A high level overview of a β-style Stirling engine.

For the chosen values for temperature difference between hot and cold side of the cylinder, area of swept volume, the working gas and operating pressure a power exceeding 100 Watts can be achieved (see Fig. 4). For the given configuration it can be seen that RPM of 450 would produce a power in excess of 125 Watts.

CONCLUSION

It is now generally accepted that CSP technologies are viable alternatives in generating power ranging from a few hundred watts to ten's of Megawatts. Spain has taken the lead, only followed by the USA and Australia.

A new approach to generate electricity using a combination of the solar tower, linear Fresnel reflectors and Stirling engine technologies has been presented in this research.

This approach is particularly useful for residential purposes where a huge amount of power is not required. It is envisaged that approximately 10 KW can be generated using the right configurations for Linear Fresnel Reflectors, Stirling engines, and battery backup.

This method for generating electricity is exceptionally valuable for the UAE where abundant amount of solar radiation is available, and technology deployment in far-flung areas will not be a problem. The solar power system can also be built as part of the design for a residential building where the Fresnel reflectors placed on roof top will generally not be visible.

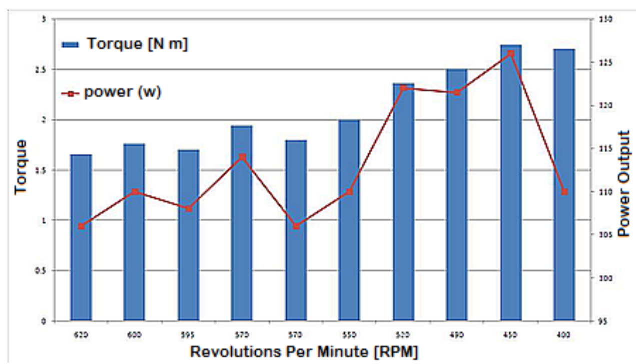

Fig. 4. Power and Torque output for given values of RPM of the Stirling engine.

REFERENCES

Aksakal, A. and Rehman, S. 1999. Global solar radiation in northeastern Saudi Arabia. Renewable Energy. 461-72.

Biello, D. 2009. First US "Power Tower" Lights up California. Scientific American Inc.

Garcia-Sobrinos. and Gonzalo. 2007. Tower of Power. Civil Engineering. 42-49.

Halit, K, Hüseyin, S Yücesu., Can, Ç. and Fatih, A. 2009. An experimental study on the development of a β-type Stirling engine for low and moderate temperature heat sources. Applied Energy. 86:68-73.

Iberdrola Renovables. 2009. Sustainability Report 2009 <http://www.iberdrolarenovables.es/wcren/corporativa/iberdrola?IDPAG=ENRENINFANUALINFSOSTE09>

International Energy Agency (IEA). 2009. World Energy Outlook. 75739 Paris Cedex 15, France.

Ishan, P. and Pallav, P. 2010. Techno-economic evaluation of concentrating solar power generation in India Energy Policy. 38(6):3015-3029.

Islam, MD., Kubo, I., Ohadi, M. and Alili, AA. 2009. Measurement of solar energy radiation in Abu Dhabi, UAE. Applied Energy. 86:511-515.

Islam, MD., Alili, AA. and Kubo, I. 2010. Measurement of solar energy (direct beam radiation) in Abu Dhabi, UAE. Renewable Energy. 35:515-519.

Kerney, AT. 2008. Tapping the sun: Solar energy in Middle East. ATKERNEY, Inc., Chicago, IL, USA.

Mills, D. 2004. Advances in solar thermal electricity technology. Solar Energy. 76(3):19-31.

Mark, S. 2009. Solar Institut Julich. Salt-Free Solar: CSP Tower Using Air. Renewable energy world.

Martin, R. and Hans, MS. 2010. Concentrating on Solar Electricity and Fuels, Science. 329(5993):773-774.

Mills, D. 2004. Advances in solar thermal electricity technology. Solar Energy Congress. 19-31.

Morrison, C. and Venture, B. 2008. Ausra's first solar thermal plant starts up. (New York Times, Oct 23, 2008).

Patty Garcia-Likens, P. and Coates, J. 2004. SRP and Tessera Solar Announce 1.5 MW Maricopa Solar Plant with Stirling Energy Systems SunCatcherTM Technology in Peoria. Stirling Energy Systems.

Perrot, P. 1998. A to Z of Thermodynamics. Oxford University Press. United Kingdom.

Spiros, A. and Bernhard, H. 2010. Solar tower power plant in Germany and future perspectives of the development of the technology in Greece and Cyprus. Renewable Energy 35:1352-1356.

The Free Library. 2010. Clean Energy Technologies: Wind Power, Solar Power, Biofuels, and Fuel Cells - Global Strategic Business Report.

www.thefreelibrary.com/Research and Markets: Clean Energy Technologies: Wind Power, Solar...-a0226581641>.

Walker, G. 1980. Stirling Engines. Oxford: Clarendon Press.

Received: Oct 12, 2010; Revised: Jan 3, 2011;
Accepted: Jan 7, 2011