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Editorial Open Access

Solar Aided Combined Cycle Power Plant

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Editorial

Integrated Solar Combined Cycle, ISCC, power plants can result in more efficient use of fossil fuels such as coal, natural gas and petroleum. The waste heat from the exhaust of the gas turbine can be used along with the solar energy to raise steam and drive a steam turbine. The world record for obtained power for less fuel was accomplished in April, 2011. Siemens setup a 580 MW power station with combined cycle operations of steam and gas turbines. The gas turbine blades were made out of crystalline nickel. The inlet gas turbine temperature was 1400–1500°C. The boiler weighs 7000 metric tons and the heat exchanger has an area of 510,000 m^2. Combined cycle power plant in China operates at efficiencies of about 59.7% recorded at a 430 MW power plant in operation. Thermo-economic analysis and 4E analysis – Energy, Exergy, Environment and Economic Analysis, second law costing methods can be used to confirm the feasibility of increases in thermal efficiency from 30% to ~60-75%. There is potential for power plant with higher combined cycle efficiencies in this country, United States from the current levels reported at ~40%.

By use of both the steam and gas turbines the Carnot cycle efficiency has been increased from 30% to 50%. After nearly two centuries since the discovery of the steam engine by James Watt, from the point of view of thermodynamics that defines the limits of machines, what are the issues involved in solar power plant. The power plant size for combined cycle power plant can be high, as high as nuclear power plants. The 2 GW power plant that is being constructed at Pembroke, Wales will be the largest and most efficient combined cycle power plant in the United Kingdom. A 1642 MW combined cycle power plant is expected to be commissioned in Iraq in 2016. Alstom will supply four gas turbines, four HRSGs, heat recovery steam generators, two steam turbines and six air-cooled turbo generators. 2.6 GW is the plant capacity that is expected to come on stream in 2016 or 2017 in Taipie, Taiwan. Mitsubishi Heavy Industries Ltd and CTCI Corp. in Engineering and Procurement have jointly received the order. The gas turbine inlet temperature is slated at 1600 0 C. The largest power plant there is the hydroelectric power plant with 22.5 GW capacity at Three Gorges, China. The suspended nuclear power plant in Kashiwasaki Kariwa in Japan has a capacity of 8.2 GW.

The federal government by its Sun Shot Initiative expects to make the abundant solar energy resources in this country, United States more affordable and accessible. Within 10 years the cost of photovoltaic, PV panels, is expected to be reduced by 75%. The solar PV panels can be used to raise saturated steam. Safety of birds and other living creatures near the concentrated regions of light is an important consideration during the design of the plant. Acreage use can come down from increases in light to electricity conversion.

The mass of the sun can be calculated from the period of the earth which is 365.25 days. The mass of the sun is ~2 x 10^{33} gm. The surface temperature of the sun is 5500°C. Using Boltzman's law if hydrogen molecules were made to travel at the speed of light the micro-scale temperature will be 7.22 x 10^{15} K. If that molecule was poly-fullerene then the temperature will be ~2.6 x 10^{18} K. Sun is a hot reservoir from which more heat engines can be made to work from. With improvements in energy storage materials energy from lightning can someday be transformed into useful work in earth surface.

The world's largest electric power generating system using CSP concentrated solar power technology has been commissioned by NRG solar along with Bright source energy in 2013. The capacity is 392 MW. CSP used a field of mirrors to concentrate sunlight onto thermal receivers mounted on top of towers. Lower cost of production and zero emissions are expected from use of solar power plants. The technology is low risk. The efficiency of conversion of sunlight to useful energy using photovoltaic cell technology hovers around 15%. Photovoltaic efficiency of PV cells is 8% for solar cells made from amorphous silicon. Their efficiency has increased now to 14%. This can be further increased to 20% by use of thin films that contain small amounts of crystals of silicon. Single crystal silicon can be used to make the "most efficient" solar cells with 30% efficiency. These PV cells are more expensive.

By 2021, six Public sector undertakings: BHEL, Bharat Heavy Electricals Ltd., PGCIL, Power Grid Corp. of India Ltd., SECI, Solar Energy Corporation of India, SSL, Sambhar Salt Ltd., REIL, Rajasthan Electronics & Instruments Ltd., and SJVNL, Satluj Jal Vidyut Nigam in India are planning to set-up solar power plant with 4 GW capacity in Rajasthan, India. The solar photo-voltaic power plant will use PV modules based on crystalline silicon technology. CO_2, Carbon dioxide emissions can be reduced by 4 million tons per year. The land area proposed to be used is 19,000 acres at Sambhar, Rajasthan. It can be the largest power plant in the world in its kind.

In 1955 Bell Labs, created a 6% PV cell for everyday use. Hoffman electronics increased the light to electricity conversion efficiency to 10% in 1959 in commercial applications. The first thin film cell to exceed 10% mark in conversion efficiency was made at University of Delaware, Institute of Energy Conversion in 1980. In 1985, Stanford University, Stanford, CA created a solar cell that is 25% efficiency using 200 X concentration. The 30% mark was shown using Stirling cycle at NREL in 1994 using a gallium indium phosphide/gallium arsenide solar cell.

A team of researchers from North Carolina State University has fabricated a "super-absorbing" design that can be used in order to maximize the light absorption efficiency of the thin film solar cells while minimizing the manufacturing costs. According to EE times – Asia dated March 3rd 2014. Their design can decrease the thickness of the semiconductor materials in thin film solar cells by an order of magnitude without compromising the capability of solar light absorption. 100 nm amorphous silicon layer is a requirement in state-of-the art solar cell design. 90% of incident solar beam can be absorbed using 10 nm thick layer of amorphous silicon.

The core of the super-absorbing layer in solar cell comprises of a rectangular onion like configuration that is made up of a semiconductor layer. This layer is coated by 3 layers of AR, anti-reflection coating that transmits light at a greater efficiency. The researchers first estimated the intrinsic light trapping efficiency of the semiconductor material. Then they devised a structure where the light absorption efficiency is equal to that of the intrinsic efficiency of the semiconductor material.

A team of scientists from CIT, California Institute of Technology, Pasadena, CA, developed flexible solar cells that enhance the absorption of sunlight and hence the photovoltaic efficiency using fraction of expensive semi-conductor material. They built their solar cells using silicon wires embedded within a transparent, flexible polymer film. Black paint can absorb light well, but may not generate electricity.

These solar cells convert most photons absorbed into electrical energy. These wires have what is called a near perfect internal quantum efficiency. A high-quality solar cell is built for high absorption of light and good conversion of photons to electric current. These wires are painted with anti-reflective coating prior to being embedded into the transparent polymer. Each wire is about 1 mm in diameter and 30-100 mm in length. 2% of the material is silicon and 98% polymer. This brings down the cost of the solar cell. These solar cells are also flexible. Photovoltaic cells respond only to a narrow part of the sun's spectrum. In order to circumvent the lower efficiency on account of absorption of narrow part of the spectrum some developers prepare layered materials. The efficiency goes up, but the material becomes expensive as well.

Cloudy days may lower the efficiency. Ohio State University developed a doped polymer, oligothiopene. The resulting substance was responsive to wavelengths from 300 nm to 1000 nm. The spectrum of Ultraviolet (UV) to near infrared is spanned in this range. Traditional silicon cells, au contraire, function in the 600 nm to 900 nm range. This narrower range is between orange and red. The doped polymer both fluoresces and phosphoresces. Fluorescence emanates from electrons that get excited by incident rays of sunlight travel from a higher energy state and drop back to a lower energy state. Some light is emitted. The wavelength of the emitted light is in infrared range and not visible. This emitted light is seldom reused. Reuse of emitted light may improve the photovoltaic efficiency. These polymers are cheaper to produce compared with silicon. Hence they can be considered even if their photovoltaic efficiencies are lower. The relaxation time of these electrons during fluorescence of the doped polymer comes up from a few picoseconds in other solar materials to a few microseconds.

A full spectrum solar cell that absorbs the full spectrum of sunlight from the near infrared and far ultraviolet to electric current can be prepared from an alloy of indium, gallium and nitrogen. This was made possible by a serendipitous observation by researchers at Lawrence Berkeley National Laboratory interacting with the crystal-growing research team at Cornell University and Japan's Ritsumeikan University. This observation was that the band gap of the semiconductor indium nitride is not 2 eV as previously thought, but instead is a much lower 0.7 eV. Solar cells made from this alloy would be the most efficient and can be lower in cost as well.

The efficiency of photovoltaic cells is limited because of a number of factors. Some light energy that gets absorbed is rejected as waste heat. There exists a band gap in semi-conductor materials that the solar cells are made out of. Incoming photons of the right energy knock electrons loose and leave holes and migrate in the n-p junction to form an electric current. Photons with less energy than the band gap slip right through. Red light photons are not absorbed by high-band-gap semiconductors. Photons such as blue light photons that possess higher energy than the band gap is absorbed. Excess energy is dissipated as heat. There is a maximum efficiency limit for a solar cell made from a single material for converting light into electric power. This is about 30%. In practical applications it is about 25%. Stacks or layers of different materials are attempted in order to increase the efficiency.

CIGS, CuInxGa1-xSe2 based photovoltaic thin films can deliver sunlight to electricity conversion performance greater than that of CdTe or silicon based thin films. Nano solar has developed a process with high-throughput, high-yield printing of nanoparticles onto low-cost substrates and formation of solar cells. CIGS based PV thin films can deliver sunlight to electricity conversion efficiencies of 19.5%. NREL has certified the solar cell efficiency of 14% achieved by Nano solar with lower cost materials using nanotechnology. CIGS based thin films result in higher efficiencies. They are coated with a homogeneously mixed ink of nanoparticles using wet coating techniques. CIGS roll-printing technology developed by Nano solar uses a combination of high-speed, high-yield, non-vacuum, wet coating of nanoparticles onto low cost per unit area of metal foil substrates with RTP (Rapid Thermal Processing) techniques. Nano solar's rapid thermal processing of nanoparticle-based coatings resulted in solar-cell efficiencies confirmed by NREL (National Renewable Energy Laboratory) to be 14.5% which amounts to a world record for any printable solar cell.

New discoveries such as the CNT (carbon nanotubes) are expected to increase the photovoltaic efficiency of solar cells to over 40%. For now, in areas, where the population density is sparse, and sunlight is abundantly available for most of the year the solar power plants may be profitable. This can be seen by a positive PW (present worth) value. They end up using large area. The solar panels are not protected from birds and other forms of dust that degrade their operations. Lenses and mirrors can be used to concentrate the sunlight and energy storage devices can store the energy in useful chemical forms such as batteries for use at night and during rainy days. Someday technology in solar energy generation will be as technically efficient as that of the combined steam and gas cycle power plant.

Solar energy may be tapped in six different ways:

1. Solar thermal power
2. Photovoltaic Panel
3. Solar Heaters
4. Concentrated Solar Power
5. Balance of Systems Costs
6. Systems Integration

In method (i) steam is generated in large boilers to turn turbines and generate electricity comparable in capacity to coal-fired boiler-based power plants. Photovoltaic panels can be used to convert directly the solar irradiance (w/m^2) into electricity. This technology is used to meet peak load needs and distributed power needs. Small power plants of up to 50 MW can be built using panels. The capacity of the recently commissioned De Soto Solar Power Generation Center in Florida is 24

MW and is less than 50 MW. Solar irradiance (w/m^2) is used to heat water or air and can be used for residential heating purposes.

Solar power plant technology can be used to produce base-load, large-scale power at low technical risk. These can replace coal-fired boiler based power plants. Heat energy storage devices have been invented that can provide for uninterrupted services such as during the night hours, rainy days, etc. Lunar power can also be tapped into. Heat storage elements used are concrete, molten salts and pressurized water. The capital solar plant costs and the plant utilization factor continue to affect the bottom line. Spain has five such plants under development and two that have been already commissioned. Investments have been made in several countries across the globe to advance the design of solar mirrors and lenses. These are used to gather the sunlight and focus on a fuel source to generate of electricity. Full scale commercial operations of such power plants with capacities in the range of 20-200 MW are expected by 2011. The cost per kWh is continuing to be the main concern. Optimization strategies are being developed. Cost effective storage devices are also expected.

Present Worth (PW) of solar power plants

A rapidly declining cost curve is seen in the photovoltaic cell technology. The price of solar modules is expected to fall from around $2/W today to $1 in the near future. The price per watt installed is likely to fall from $6.0-$8.0 to $3.0 per watt. Dominant in the costs are power electronics and installation. With current incentives in the United States and European Union the cost of electricity generation using solar technology is in the range of the IGCC (Integrated Gasification Combined Cycle) power generation plants. In the state of California the cost of electricity from solar power plants is about 14-15 cents per kWh. This is against the 8-10 cents per kWh cost of electricity from IGCC power plants. By 2013 with some incentives from the federal government the cost of electricity from solar power plant is expected to fall to 10-12 cents per kWh. The per kWh cost is sensitive to the capital cost and the cost of materials of construction of the plant. Sequestration related carbon credits at $30 t-1 of CO_2 can affect a per kWh reduction of 3 cents. Government carbon tax, cost of capital are sensitivity parameters on the bottom line of solar power plants.

Worldwide, the solar thermal power capacity can grow at least 30% per year from 2010 to 2020 or 2030. 200 GW of new power plant capacity can be added each year. About 1-2 GW per year could be added in 2012. Solar technology is relatively simpler. The NREL, National Renewable Energy Laboratory, has identified potential for 6 TW (terra watts) of solar thermal power in the Southwestern US. Few things are now known about the light to electricity conversion. The Carnot limit of efficiency of any man made machine is given by:

$$\eta_{carnot} = \left(1 - \frac{T_C}{T_H}\right)$$

By the Planck's theorem,

$$E = h\nu = \frac{hc}{\lambda}$$

The IV, current-voltage characteristics of a photodiode cannot be described using the Ohm's law of electricity. GaAs multi-junction devices are the most efficient solar cells reaching a record high of 40.7%. 20-30 different semi-conductors are layered in series. AR, antireflection coatings can be used to minimize reflection from the top surface. The IV characteristics can be given by:

$$I = I_0(e^{\left(\frac{qV}{k_B T}\right)} - 1) - qAG_0\left(L_p + L_n\right)$$

33% of solar insolation is lost as waste heat. The temperature of operation of the photovoltaic module can be determined from energy balance as follows:

$$\tau\alpha I_T = \eta_c I_T + U_L\left(T_c - T_a\right)$$

The physical significance of each term above Equation is as follows:

The fraction of radiation incident on surface of solar cells is given by ($\tau\alpha I_T$), where τ is the transmittance of any cover:

The efficiency of conversion of incident radiation into current is given by ($\eta_c I_T$):

Radiation and convection losses from top and bottom is given by (U_L ($T_C - T_a$)

Ta is the ambient temperature.

The temperature of the solar cell, T_c can be obtained by rearranging the terms and;

$$T_c = T_a + \left(\frac{I_T\alpha\tau}{U_L}\right)\left(1 - \frac{\eta_c}{\alpha\tau}\right)$$

It can be seen that as there exists an optimal working temperature of the solar cell. As the amount of concentrated solar flux is increased the absorption efficiency first increases and then decreases. As the working temperature increases the heat losses increase by radiation and convection. The optimal temperature of operation for maximum efficiency can be arrived at. The heat losses vary as T^4 and the efficiency increases linearly with the working temperature. At $\partial\eta/\partial T = 0$ the working temperature can be solved for. The UL the overall transfer coefficient will vary with temperature.

Solar aided combined cycle power plant may first come about in large numbers before solar along power plants will become ubiquitous. Nuclear power plant can be aided by solar or other cycles starting from the exhaust of the steam turbine. Supercritical steam can be generated from nuclear boilers and from the steam recovered from the steam turbines can be used to drive a bottom second cycle. This second cycle can be aided by solar or coal. This way large power plant size, higher efficiency of energy transformation and lesser land acreage can be used. The solar module can be operated at optimal temperature from the tradeoffs from radiation losses and temperature dependent heat absorption.