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CURRENT CONCENTRATING SOLAR RADIATION TECHNOLOGIES FOR ENVIRONMENTAL GENERATION OF STEAM, POWER, AND HYDROGEN

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ABSTRACT

This paper assesses current solar radiation concentrating systems for the purpose of industrial scale steam, power, and hydrogen generation with no or reduced amount greenhouse gas emissions. Solar power concentrating energy systems for the purpose of steam and power generation are presented along with brief information on advantages and disadvantages of these systems. Then the industrial scale applications of these systems are given to highlight the already commercial use of these systems as an alternative to coal or natural gas power plants. Solar power plants that are under construction are also summarized to point out the world wide ongoing investments in this field. Although there are no large scale hydrogen generation plants yet, the paper points out that the existing steam and power generation systems via concentrated solar energy can make use of already established infrastructure for hydrogen generation by replacing the receiver with a proper unit, such as a solar reactor. Then the paper provides an example solar concentrating system of a laboratory scale specifically constructed to generate hydrogen in a solar reactor. Based on this example, integration of that system into an existing solar concentrating power plant system is discussed. The paper concludes with examples of some of the industrial scale solar driven applications established in various countries as illustrative examples to underline the expectation for seeing similar commercial solar driven systems for the purpose of hydrogen generation as well.

INTRODUCTION

Inevitable need for steam and power by manufacturing, transportation, residential, and commercial sectors is the major reason for our high dependency on energy sources. The abundance of fossil fuels and their technically achievable utilization have created the fossil fuel based energy economy throughout the world. As it is very well known, fossil fuel based energy economy was not challenged until the 1970s oil crises. Since then, alternative energy sources and their applications have been an interest of many developed countries for the hope of finding a sustainable alternative to fossil fuels. Solar energy has been a focus of interest since the 1970s, where the initial research and development efforts were initiated. Although the idea of researching solar energy as an alternative to fossil fuels did not attract the governments later on as much as it did in the early 1970s, now there is high interest in solar energy research. The current situation is so much in favor of testing solar energy as an alternative energy source that there are government subsidized commercial steam and power plants utilizing solar energy, which looks promising. This is actually one of the major signs of world widely given serious consideration on this subject. If we look at the solar radiation distribution in Figure 1, it is seen that, although the solar radiation intensity is not equally allocated by the nature, still the majority of the world has solar energy as a consumable and accountable energy source [1].

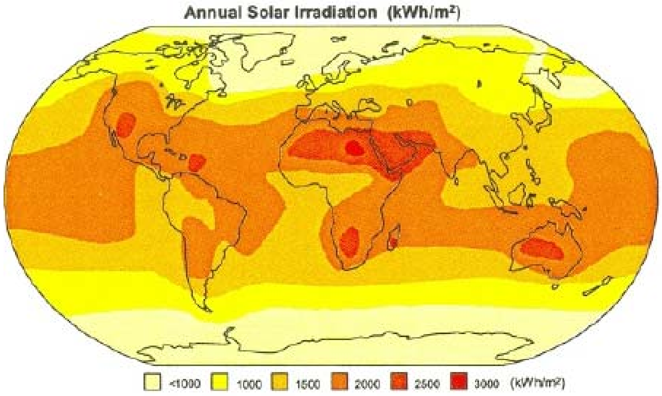

Figure 1 Solar radiation map of the world

Therefore, although the incoming solar radiation is not distributed equally, the majority of the world receives more than 1500kWh/m^2 a year which can be concentrated up to the ratios of 10,000 suns (kW/m^2) with the current solar concentrating systems for steam and power generation. Therefore it appears that the idea of giving solar energy research a one more chance appears to be a reasonable effort as it is practical to make use of this free energy source. The following sections briefly talk about the current solar power concentrating technologies.

SOLAR RADIATION CONCENTRATING SYSTEMS

Concentration of solar energy for high temperature has been extensively studied since 1960s [2-6]. Achievement of high temperature process heat with higher efficiency using solar radiation concentrating systems depends on two major components: (1) configuration of solar collector optics, and (2) design of solar receiver. As for the solar collectors, there are mainly three optical configurations that can concentrate intermitted solar radiation for the required high temperature process heat: trough, tower, and dish. On the other hand, receivers depend on the optical configuration of choice. For example, a receiver could be a boiler or a reactor for the case of tower systems, whereas it could be a pipe as in the case of trough systems. The following sections provide introductive information on these mentioned systems.

TROUGH

Solar trough is a parabolic reflector shaped like a trough. The mirror reflectors of a solar trough concentrate the incoming solar radiation towards a receiver, which is basically a pipe housing heat absorber thermal fluid. The tubular receiver is placed in the trough focal line as it is seen in Figure 2. The thermal fluid flowing through the pipes is heated by the concentrated solar power approximately to 400ºC and then pumped through heat exchangers to generate steam and to drive conventional Rankine cycle steam power plant.

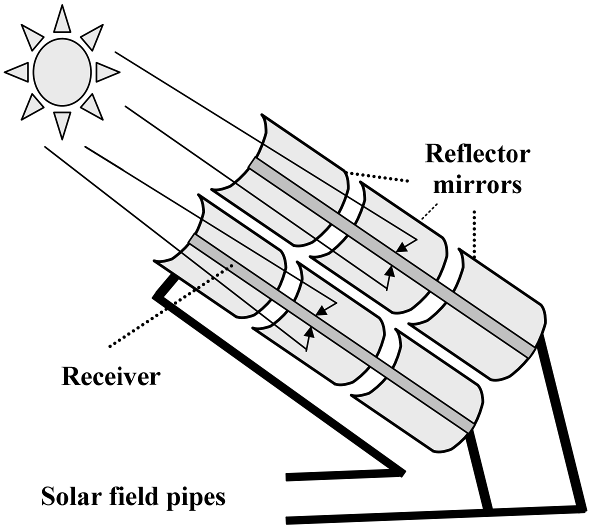

Figure 2 Parabolic through collectors placed on a solar field

The receiver tube is coated with highly absorptive material to increase solar radiation absorption by the thermal fluid inside, and the coated surface of the tubular receiver is surrounded by a glass tube to reduce the heat loss while letting the solar radiation pass through. Reflector materials could be silver or aluminum in order to maximize the reflectance of the parabolic shaped through. The size of these systems and typical problems with the described system components are thoroughly discussed in Kalogirou (2004) [7]. Solar trough systems are commercially available in both one-axis and two-axis sun tracking mechanisms.

TOWER

Solar tower or central receiver is basically a tower to hold a receiver or a reflector on top of it. It is surrounded by large Fresnel reflectors, called heliostats. The heliostats are placed on the solar field so that they all track the sun and reflect the solar radiation towards the receiver, or a reflector located on the top of the solar tower. The receiver absorbs the solar radiation and uses the solar sourced high temperature as process heat. Steam or the product gases are used in a Rankine or Brayton cycle for power generation.

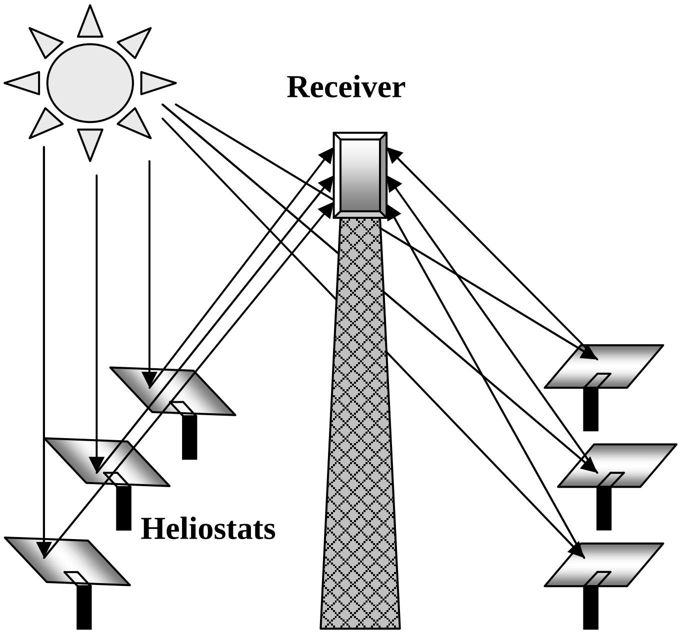

Figure 3 Solar tower

For the purpose of electricity generation, tower is either used to house the receiver, or to reflect the incoming radiation towards a receiver on the ground. The overall efficiency of a solar tower system depends on the individual efficiencies of system components. Therefore, heliostats, receiver, and power generator are the targets for development both in order to achieve higher efficiencies and to attain economically more reasonable system.

Parameters that have impact on the overall efficiency due to heliostats can be summarized as: (1) flatness and optical quality of heliostat mirrors, (2) sun tracking accuracy, (3) placement of heliostats against each other, and towards the tower, (4) interruption due to shading and blocking by another heliostat, (5) maintenance of the heliostats to preserve the mirror surfaces from contamination, and fracture.

As for the parameters that have impact on the overall efficiency due to the receiver can be summarized as follows: (1) heat losses from the receiver body through conduction, (2) inhomogeneous or less homogenous heat transfer and flow conditions inside the receiver body, (3) in the case of a quartz-windowed cavity type receiver, loss of solar power input due to multiple scatterings is also a parameter effecting the receiver efficiency, (4) misalignment of the receiver.

Power generation unit would be a Rankine cycle or a Brayton cycle, as well as it could be a Rankine-Brayton combined cycle. In order to obtain detailed information on the steam and gas turbine efficiencies, the reader can refer to Ozalp and Hyman (2006) to find a thorough research results on these prime movers from thermodynamic modeling studies using actual operating data [8].

Efficiency of the solar field composed of heliostats has an impact on the efficiencies of the receiver and the power generation. Segal and Epstein (2003) state that the receiver efficiency increases if the heliostat field density increases [9]. On the other hand, if the temperature inside the receiver increases, the efficiency of the receiver decreases [9]. A thorough assessment on the theoretical limitations and optimization of heliostat field parameters are described by Schramek and Mills (2003) [10], whereas a novel numerical approach for the optimization of heliostat fields and calculation of solar field efficiency by using MATLAB can be found in [11].

Heliostat field takes up the most expensive fraction of the investments in solar power plants. For example, in order to have 12MW$_e$ capacity, a solar field of 595 heliostats at 36m^2 each would be needed [9].

DISH

Solar parabolic dish is reflector used to concentrate incoming solar radiation towards a receiver placed at the focal point as it is shown in Figure 4. Optical axis of the collector is always exposed towards the sun.

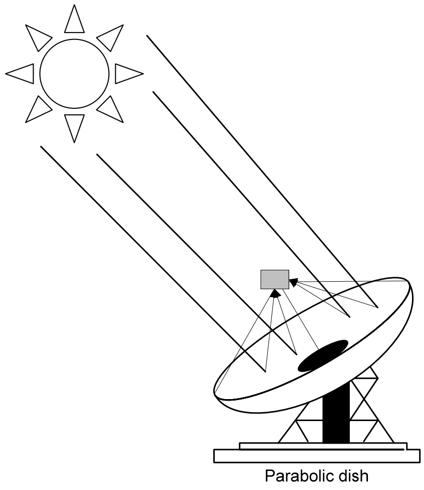

Figure 4 Parabolic shaped solar dish with a receiver

The receiver rotates with the parabolic dish which affects fluid dynamics and heat transfer characteristics of the thermal fluid inside the receiver [12]. Solar flux concentration ratio via parabolic dish collectors is the highest ratio among all solar parabolic collectors with 10,000 suns concentration ratio.

As for the receiver geometry, Kumar and Reddy (2008) gives convective heat losses simulations for three types of receivers: (1) cavity, (2) semi-cavity, and (3) modified cavity [13]. They report that their simulation results suggest that a receiver in the geometry of a modified cavity would secure less heat losses via convection.

The main difference between the parabolic shaped dish receiver and the solar tower receiver is that parabolic dish receiver moves along with the sun tracing dish, whereas the solar tower receiver stays stationary. Another difference is that the volumetric size of a solar tower receiver could be much bigger than that of a parabolic dish receiver. Solar tower receivers are easily used in commercial steam and power generation due this advantage. In order to generate same amount of steam and power via parabolic dish, many receivers are needed and therefore same number of parabolic dishes to hold them. On the other hand, very high conversion efficiency from solar to electricity is the major advantage of parabolic dishes over solar tower and solar trough systems.

COMPOUND PARABOLIC CONCENTRATORS

Compound parabolic concentrator (CPC) is a nonimaging concentrator concept that can approach thermodynamic limit of solar radiation concentration. Another advantageous feature of this type of collector is that they have a very large acceptance angle and occasional sun tracking is sufficient. The geometry of a CPC is made out of two parabolic shaped piece that are positioned such way that the focal point of the first piece is located at the bottom end point of the second parabolic shaped piece, whereas the focus of the second piece is located at the bottom end point of the first piece. The first compound parabolic concentrators were made to be used in high energy physics experiments for the purpose of detecting Cherenkov radiation. CPCs were not used for concentrating solar energy until 1974 by Winston [14]. CPCs can be used as trough collector.

HYDROGEN PRODUCTION VIA SOLAR REFORMING, SOLAR CRACKING AND SOLAR GASIFICATION

Solar reforming and solar gasification of hydrocarbons for hydrogen generation are basically the same processes as conventional steam reforming and gasification of fossil fuels, which occur via the following reaction:

$$\mathbf{C}_x\mathbf{H}_y + x\mathbf{H_2O} \rightarrow x\mathbf{CO} + \left(\frac{y}{2} + x\right)\mathbf{H_2} \qquad \mathbf{(1)}$$

For steam reforming of methane, this reaction is given as:

$$CH_4 + H_2O \rightarrow CO + 3\ H_2,\ \ \Delta H^{0}_{298} = 206.25\ kJ/mol$$

In order to produce more hydrogen, the syngas (CO and H_2) is shifted via water-shift reaction, where water reacts with CO in the syngas generating carbon monoxide and hydrogen as in the following reaction:

$$\mathbf{CO + H_2O \rightarrow CO_2 + H_2,} \quad \Delta H^{0}_{298} = -41.03 \ kJ/mol \qquad \textbf{(2)}$$

Then the carbon monoxide can be sequestrated, for example, via membrane.

Solar reforming and solar gasification processes can be demonstrated as in Figure 5.

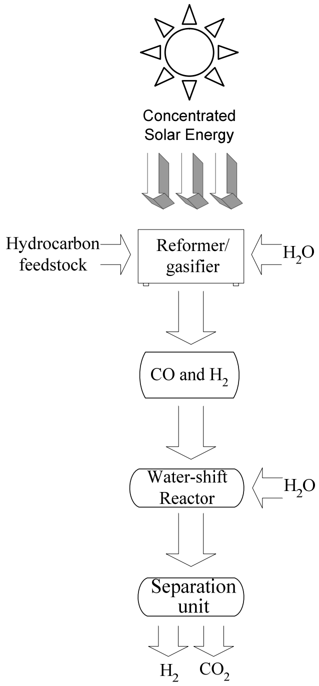

Figure 5 Solar reforming and solar gasification of fossil fuels

As it is seen in Figure 5, the first process step is the fossil fuels and water entry into the reformer/gasifier as reactants, which result in syngas as product. As a second process step, the water-shift reactor takes place to shift carbon monoxide to obtain more hydrogen. Finally on the third step, hydrogen production process is completed after separation. The main difference between solar cracking and solar reforming / gasification processes is the water entry as a reactant. For example, methane can be solar thermally cracked into hydrogen and black carbon via the following reaction without having water as a reactant.

$$\mathbf{CH_4 \rightarrow C\ (solid) + 2\ H_2,} \quad \Delta H^{0}_{298} = 75 \ kJ/mol \qquad \textbf{(3)}$$

As for the extraction of high grade black carbon from the hydrogen rich product gas, it is relatively easier to capture and store solid carbon in comparison to carbon dioxide. In terms of economical point of view, since this process results with two valuable marketable products, hydrogen generation cost via this process is shared by black carbon production. As for the environmental aspect, the solar cracking process does not produce carbon dioxide or any other environmentally hazardous gases.

The process step diagram of solar cracking is depicted in Figure 6. In comparison to solar reforming and solar gasification processes, solar cracking of fossil fuels result in hydrogen production in one step, which is more practical and therefore offers additional advantage over other solar thermochemical hydrogen production processes.

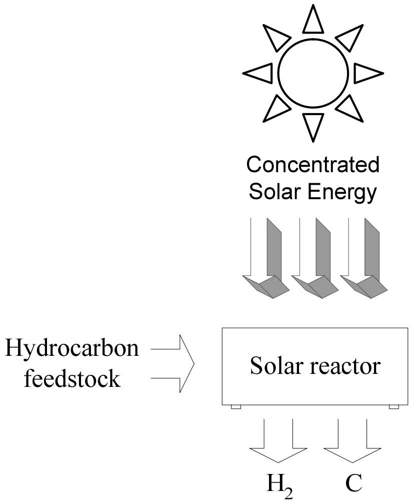

Figure 6 Solar cracking of fossil fuels

Zedtwitz et al. (2005) gives the second law efficiency comparison of the solar cracking of natural gas process vs. the solar reforming of natural gas process [15]. Produced hydrogen is used in a 65% fuel cell and the second law efficiency of the system –the solar reactor and the fuel cell– is calculated from the following ratio:

$$\eta_{exergy} = \frac{W_{out} \ \ by\ Fuel\ Cell}{Q_{solar} + HHV_{feedstock}} \qquad \textbf{(4)}$$

The thermal energy input to the system is taken as the summation of the higher heating value of the feedstock and the solar energy entry to the solar reactor. Zedtwitz et al. (2005) estimate the second efficiency of solar cracking of natural gas process to be 32%. On the other hand, they state that, in conventional thermal cracking of natural gas by fueling a combined cycle results in 36% more electric work output. Therefore, although solar craking of natural gas offers hydrogen production in one step along with a valuable byproduct with no greenhouse gas emissions, the work output of this process is substantially lower than what a traditional Rankine-Brayton cycle, with lots of green house emissions, can provide.

The reactor concept plays a key role in better absorption of incident solar radiation, more efficient heat transfer to the reaction site, and higher chemical conversion of natural gas [16, 17]. Therefore, in order to increase the first and the second law efficiency of the solar cracking process, the reactor design should be developed accordingly.

HYDROGEN GENERATION VIA PARABOLIC SOLAR DISH AND HELIOSTAT

Parabolic dish receiver would be a solar thermochemical reactor, which can be used to generate hydrogen. For example, one of the parabolic dishes of Prof. Steinfeld's group at ETH-Zurich is made out of 82 curved mirrors with a total normal projected area of 87 m^2 [18]. That parabolic dish has the capacity of 70kW at peak conditions with a receiver at the focal point that can hold up to 450 kg. This example is one of the demonstrations of hydrogen generation on a laboratory scale. The second parabolic shaped dish of Prof. Steinfeld's group at ETH-Zurich is placed in a solar furnace facing towards a 120m^2 sun tracking heliostat [19]. The 8.5 m diameter parabolic dish is faced towards a solar thermochemical reactor at its focal point. The optical setup for smaller scale parabolic dish and heliostat containing solar concentrating system is given in Figure 7, which is Figure 5 in Steinfeld et al. (1998) [20]. The 8.5m^2 diameter dish receives the concentrated solar radiation from the heliostat and then further concentrates it towards the receiver. A control mechanism holding the reactor and moving it in four directions until the reactor is placed at the focal point of the parabolic dish. This configuration avoids the surplus motion affecting the fluid dynamics and heat transfer characteristics due to sun tracking. It also gives the advantage of freedom in choosing and testing desired motion, such as circular rotation for homogenous heat transfer conditions inside the reactor [21]. Finally, the maintenance of the receiver is a lot easier due to its not being attached to the parabolic dish. This type of a solar reactor can be replaced with the receiver of a solar tower for the purpose of large amount of hydrogen generation. By direct cracking of natural gas via concentrated solar energy, hydrogen can be generated without any carbon dioxide emissions.

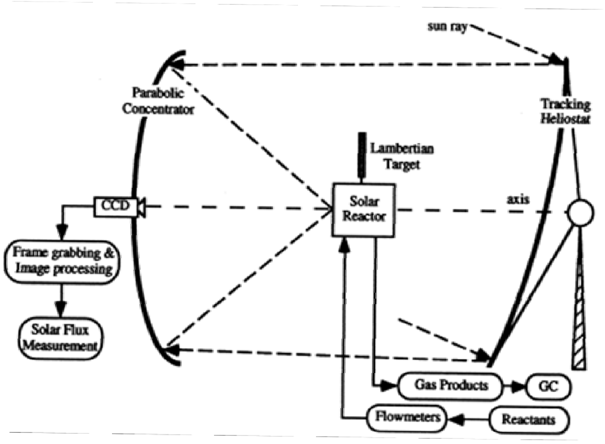

Figure 7 Optical setup of an example hydrogen generating facility composed of a dish, receiver and a heliostat [20].

There are also other very good laboratory scale hydrogen generation studies using concentrated solar energy [22-25], which demonstrate the feasibility of hydrogen production from commercially available solar concentrating systems.

INDUSTRIAL SCALE EXAMPLES OF POWER AND STEAM GENERATION VIA CONCENTRATED SOLAR

Currently, the largest solar electric generation station (SEGS) system in operation is a 330MW solar parabolic trough plant with 400,000 mirrors put on 4km^2 solar field in California [26]. Two solar trough power SEGSs of Spain has 50MW capacity, whereas "Plataforma" has the same 50MW capacity via solar central receiver system. Nevada commercial solar plant, "Solar One", has 64MW capacity using parabolic trough system. These plants are the largest representatives of commercial steam and power generation using concentrated solar radiation.

There are many ongoing projects throughout the world mostly either partially or fully subsidized by the local governments. For example, Spain is going to enlarge their steam and power generation from concentrated solar energy by investing on 12 new 50 MW solar power plants, which will make Spain to be the largest solar thermal power user in Europe. South Africa is planning to construct the largest central receiver type concentrated solar power plant with 100MW capacity. California and Nevada projects are also planned to be expanded to have larger capacity. Israeli Ministry of Natural Infrastructure and Solel are constructing 100MW solar power plant which will be on conventional steam cycle with hybrid fossil fuel firing. Algeria is going to have an Integrated Solar Combined Cycle System (ISCC) of 35MW solar capacity, whereas Greece is establishing a 50MW capacity steam cycle plant in Crete. The other countries that are in the process of installing ISCC systems are: Egypt, India, Iran, Morocco, and Mexico with solar thermal capacity between 17MW and 35MW. Government of Italy allocated substantial financial support for concentrating solar energy technologies. The first Italian solar power plant is planned to be installed in Sicily, which is planned to be integrated with a thermoelectric combined cycle plant using advanced parabolic troughs. Although Jordanian government had few plans to initiate concentrating solar energy technologies for steam and power generation, they have not come to an agreement with any company nor committed to fund. However, based on the earlier feasibility studies to explore possibilities of establishing a solar power plant, the government appears to be interested in utilization of solar energy. A brief comparison of trough, tower and dish systems is given in Table 1.

Table 1. Solar concentrating systems as comparison

	Trough	**Tower**	**Dish**
Concentration ratio	15 to 45 [27, 29]	100 to 1500 [27, 29]	100 to 1000 [27, 29]
Indicative temperature range	60 to 560 °C [27, 29]	150 to 3000 °C [27, 29]	100 to 1200 °C [27, 29]
Application	Process heat, electricity generation	Electricity generation	Electricity generation
Cost estimates for the investment of a 124 MW integrated solar combined cycle system	\$118.5M [28]	\$119.6M [28]	NA
CO_2 emissions from a 124 MW integrated solar combined cycle system	338,214 tons/a [28]	338,013 tons/a [28]	NA

CONCLUSIONS

An assessment of current solar radiation concentrating systems is given. Parabolic trough and solar tower systems are commercially used to generate high pressure steam for

Rankine cycle as in traditional cola fired or natural gas fired power plants, whereas parabolic shaped dish systems can hold a heat engine at the receiver port and produce power.

It is seen that there are many governments acknowledge solar technologies as a possible alternative way of steam and power generation. Although it looks promising, there are still no substantial investments on solar technologies by the governments -nor any policies being implemented- to see solar technologies as a strong competitor to conventional fossil fuel based technologies in the near future.

There are industrial scale steam, and power generating systems using various concentrated solar energy technologies. However, there is no industrial scale hydrogen generation using any of the existing solar concentrating technologies. If the current commercial solar power plants can reach to the point to replace fossil fuel power plants role, then they can also be used for the purpose of hydrogen generation in the case of it is needed. Alternatively, same structure can be constructed solely for the purpose of hydrogen generation. For example, a solar tower housing a receiver on top of it can be easily replaced with a solar thermochemical reactor generating hydrogen. There would not be any need in changing heliostats or the power generating unit. Therefore, solar concentrating technologies would offer not only steam and power generation without and/or significantly reduced amount of greenhouse emissions, but also they would offer hydrogen production. Hydrogen can be used as a commodity as well as it can be used as a fuel. For the countries which are suffering from clean water or dealing with a lot of desalination can utilize hydrogen combustion for their clean water need. This highlights the multiple aspects of solar concentrating systems, and therefore it also points out the importance of their development for further utilizing them for our energy need in an environmentally friendly fashion.

The benefits of concentrating solar power are not only limited by their compelling environmental protection, but also diversity of fuel supply and global potential for technology transfer and innovation. Since the solar energy is abundant and free, this is basically the major advantage of the solar concentrating systems over conventional power generating systems relying on fuels that are neither free, nor abundant. However, developments in the field of energy storage are of particular importance to the maturation of solar power technologies.

To sum up, considering the fact that all traditional energy technologies launched into market by the help of local governments, it is not unrealistic to expect the same subsidize from the current governments to support solar technologies so that they can actively be on the market. California, Nevada and Spain examples are very promising role models for the hope of seeing solar technologies as a substitute for fossil fuel energy technologies of the current world market. With a prioritized emphasis on supporting solar technology research and development may absolutely reduce the cost of electricity via solar concentrating systems so that they can compete with electricity generated via conventional technologies. Therefore, governments' subsidize to install new solar power plants should be considered as crucial as funding multidisciplinary solar energy research efforts. Solar power plants can also be used as a supportive unit to fossil fuel fired power plants during the peak demand times. Therefore, they can serve as a support or even as a backup during the course of transition from total dependency on existing fossil fueled plants to permanent dependency on a sustainable technology, which could be solar based eventually.

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