ENERGY STORAGE OPTIONS

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INTRODUCTION

To overcome the intermittence and low capacity factor of renewable energy systems such as wind and solar, backup systems as well as ingenious methodologies for energy storage are being suggested. The stored energy could then be used during the periods when the wind is not blowing or the sun is not shining, or wheeled to distant locations for consumption.

For high capacity systems such as nuclear and coal, the electrical energy produced in periods of low demand can be used for delivery in periods of high demand. An example is the charging of storage batteries during the night for vehicles to be driven during the day.

FREE HYDROGEN AS AN ENERGY CARRIER

ELECTROLYTIC ENERGY STORAGE IN HYDROGEN

Hydrogen as an energy carrier and storage medium can be generated through the electrical electrolysis of water:

$$2H_2O + \text{electricity} + \text{heat} \rightarrow 2H_2 + O_2 \qquad (1)$$

This reaction occurs in an electrolytic cell that is exposed to an electric Direct Current (DC) starting the process of the electrochemical separation of the water molecule into its two components, hydrogen and oxygen. The gases are emitted from the electrodes and are separated and captured in the cell. The gases go through a back flash valve, water trap and dehumidifier, before they are ready for distribution and use.

Hydrogen can be produced in small units near its intended point of usage, in a manner known as "distributed production." Distributed production may be the most viable approach for introducing hydrogen in the near term, in part because the initial demand for hydrogen will be low.

Hydrogen may also be compressed and stored as a metal hydride in cylinders or kept at low pressure in a gas tank. Compressed hydrogen can be used in a fuel to directly produce an electrical current at an efficiency of 60-70 percent.

A hydrogen economy requires an infrastructure to deliver hydrogen from where it is produced to the point of end-use, such as a dispenser at a refueling station or a stationary power site.

The required infrastructure includes the pipelines, trucks, storage facilities, compressors, and dispensers involved in the process of delivering the hydrogen as fuel.

Hydrogen production has been implemented in association with the HGenerators 3 kW Wind Turbine Electricity Generator. It can produce both electricity and hydrogen approximately at 600 kWhr per month using an average wind speed of 12 m/s and 210 hours of operation per month. The cost is just under $6,000 for the entire wind turbine.

Figure 1. HGenerators 3.4 kW electricity and hydrogen producer wind turbine.

Figure 2. Row of HGenerators 3.4 kW turbines along water shore.

Table 1. Technical Specifications of HGenerators turbine.

Peak power	3.4 kW
Wind wheel diameter	5 m
Start-up wind speed	2 m/s
Cut-in wind speed	2.5 m/s
Rated wind speed	10 m/s
Stop wind speed	25 m/s
Survival wind speed	45 m/s
Rated rotational speed	400 rpm
Protection level	IP54
Insulation level: B	B
Cooling Mode	IC0141
Operation Temperature	40-60 °C
Drive Mode	Direct, driven by wheel
Adjust Speed Mode	Automatic
Adjust Direction Mode	Manual/Automatic
Tower Height	9 m
Rated voltage	240 V
Insulation level	B
Proposed battery configuration	20 12 V 100 AH batteries

PHOTO CHEMICAL ENERGY STORAGE IN HYDROGEN

A catalyst composed of a 2 percent addition of antimony (Sb) to gallium nitride (GaN) into the semiconductor GaN-Sb alloy that acts as a catalyst for the Photo Chemical Decomposition of water into oxygen and hydrogen:

$$2H_2O + photons \rightarrow 2H_2 + O_2 \tag{2}$$

has been studied by Madhu Menon and Mahendra Sunkara at the University of Kentucky.

Gallium nitride alone is a semiconductor used to manufacture Light Emitting Diodes (LEDs). Antimony (Sb) has been used as a metalloid element in the microelectronics industry. This process may become a potential competitor to Photo Voltaics (PV) depending on its efficiency and economic considerations.

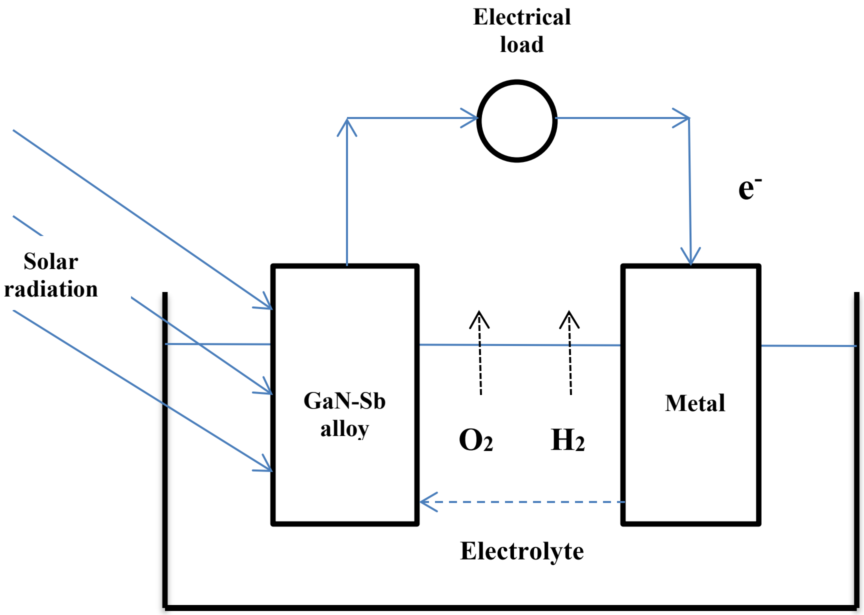

Figure 3. Photo Electro Chemical (PEC) energy storage in hydrogen by water dissociation.

THERMO CHEMICAL HYDROGEN ENERGY STORAGE

In Thermo Chemical (TC) hydrogen production renewable sources such as wind and solar as well as conventional non-carbon sources such as geothermal and nuclear can provide thermal heat sources for the production of hydrogen as an energy carrier for use in fuel cells in transportation systems.

Three processes using sulfuric acid as a catalyst are involved. A high temperature low pressure endothermic process involves the decomposition of sulfuric acid to produces water, oxygen and sulfur dioxide:

$$2H_2SO_4 \rightarrow 2H_2O + 2SO_2 + O_2 \tag{3}$$

The last reaction is carried out at about 800-1,000 degrees Celsius for efficient hydrogen production. The oxygen is separated and low and intermediate temperature steps follow.

In the Iodine Sulfur (IS) process, iodine is added in addition to water at low temperature to the sulfur dioxide after removing the oxygen:

$$2I_2 + 2SO_2 + 4H_2O \rightarrow 4HI + 2H_2SO_4 \tag{4}$$

This is followed by an intermediate temperature hydrogen-producing step as:

$$4HI \rightarrow 2H_2 + 2I_2 \tag{5}$$

If we add Eqns.3-5, we obtain the overall IS hydrogen producing reaction as:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{6}$$

This identifies sulfuric acid and iodine as catalysts since they appear on both sides of the equations but do not appear in the final overall equation.

BOUND HYDROGEN PRODUCTS

In the form of a gas, free hydrogen is highly reactive, and even explosive, as demonstrated by the Hindenburg experience.

Compressed hydrogen gas interacts with metal forming hydrides, which embrittles its containment vessels and causes explosions.

Being a small molecule it tends to readily diffuse and leak through its containers.

The safest and most manageable form of hydrogen is bound hydrogen whether confined in the lattice of a metal such as palladium, titanium, or uranium; as a hydride, or as a hydrocarbon.

Hydrogen bonds with carbon through alkane bonding producing isooctane, butane, and methane are relatively safe methods to bind hydrogen. If hydrogen is turned into methane, it could be distributed through the existing natural gas pipeline system, or used in fuel cells. It could also be turned into methanol as a liquid fuel.

POTENTIAL ENERGY, PUMPED STORAGE

Somewhere in North America, Europe and North Africa, the wind is blowing or the sun is shining, and all that is needed is to coordinate the balance between excess supply and demand. But computers alone are not sufficient. Instead, storage facilities are needed to collect the electricity, store it for days and weeks and release it as needed.

Compressed air reservoirs store compressed air in underground caverns. In Germany most of these reservoirs are already filled with natural gas. Hydrogen storage systems achieve only a moderate, 40 percent degree of efficiency. Lithium ion batteries are expensive and not very efficient. The idea of using the batteries of electric cars as a buffer suffers from the fact that there are very few electric cars on the road today.

Pumped storage is associated with hydroelectric power generation but has not been used with wind or solar power generation in spite of its promise. Water would be pumped to an elevated reservoir when the wind is blowing or the sun is shining and then used to drive a hydraulic turbine when energy is needed at a turn-around efficiency of 70 percent. The Dinorwig pumped storage project in the UK has an installed capacity of 1,890 MW.

Pumped storage hydroelectric power plants are considered as the most efficient energy storage alternative. The technology has been in use for 80 years at the Schluchsee, a reservoir in Germany's southern Black Forest region.

Up to 6,472 gallons or 24,500 liters of water flow down through a pressure shaft every second, coming from the Eggberg reservoir, which is about 400 meters above the Schluchsee.

The mode can be switched within only 90 seconds, so that hydroelectric power production can be stopped and water is pumped back up to the upper basin. No other system can be adjusted as quickly to whether electrical energy needs to be delivered to the grid, or has to be stored at any given time. In comparison, a coal power plant takes 12 hours to warm up to full capacity. This flexibility makes a pumped storage hydroelectric power plant quite valuable.

At the Schluchsee, the growing supply of wind energy benefits the plant. The water turbines are currently being switched between operating modes 60,000 times a year.

Another power plant is planned in the region, in the town of Atdorf. At a site where a hiking path now passes along a ridge, a reservoir will be dug and a tunnel will be excavated through gneiss and granite rocks, 600 meters down to a second reservoir on the Rhine River plain. About 272 acres or 110 hectares of land will have to be dedicated to the pumped storage hydroelectric power plant.

Figure 4. Dinorwig pumped storage system, UK. Source: BBC.

A Dutch engineer, L. Lievense proposed the linking of 1,000 wind turbines of 3 MW of rated power each to pump water into a 165 km^2 water basin. The wind turbines would pump the water to a higher level than the surrounding Ijsselmeer into the basin. The water would be later allowed to drive water turbines at peak electrical demand or at the times where there are no productive winds.

Germany has storage plants with a capacity of 6,400 MWs and is capable of expanding that by 2,500 MW. However, it needs 10 times more than that in new energy sources: 25,000 MW.

CHEMICAL BATTERY STORAGE

Electrical batteries or accumulators are regularly used in solar energy applications and can be charged by a coupled wind and solar energy system.

Lead acid batteries are a good choice since they are well suited to trickle charging. In terms of electrical output they have a high efficiency of 80-90 percent, and in terms of energy, their efficiency is 70-80 percent. Thick plates are used in special batteries for large installations. Small installations can use bank of ordinary automotive batteries. The main cause of deterioration is overcharging or being left for too long in a discharged state.

Nickel cadmium batteries are not usually used in wind and solar power applications since they have low efficiencies at low intensities and lower than lead acid batteries at all intensities. Their advantages are that they are not damaged by overcharging, nor by occasional over discharging, they do not self discharge, and not easily damaged by freezing temperatures compared with the lead acid batteries.

For automotive electrical hybrid vehicles, Li-ion and Nickel Metal Hydrid (NiMH) batteries are under consideration. A lithium-ion battery for the Mercedes S400 BlueHybrid design generates 120 Volts, a power output of 19 kWs with a weight of 26 kgs and a volume of 20 liters.

Table 2: Comparison of batteries for automotive power.

Battery Type	Generated Voltage [Volts]	Power output [kW]	Weight [kgs]	Volume [liters]	Cost [$]
Lithium-ion Mercedes S400 BlueHybrid	120	19	26	20	2,175
Nickel-Metal Hydride (NiMH) Toyota Prius Honda			160	120	800
Lead-Acid			500	400	100

Figure 5. All electrical cars and scooters at the 2010 Paris Auto show.

Automobile manufacturers appear to have realized that the future of mobility will not be the exclusive domain of cars. In Germany, both BMW and Daimler appear to be preparing to enter into the electric scooter market.

KINETIC ENERGY FLYWHEEL ENERGY STORAGE SYSTEM (FESS)

Wind energy using fast rotating flywheels can be used to store wind power. Around 1950, Oerlikon gyrobuses were deployed in Switzerland using the energy stored in a flywheel.

Composite metallic and polyester resin materials can be used in flywheels with an associated efficiency:

$$\eta = \frac{\text{Restored energy}}{\text{Consumed energy}} = 80\,\text{percent.} \tag{7}$$

With a flywheel rotating at 15,000 rpm on magnetic bearings in a vacuum chamber, it is theoretically possible to store 400 W.hr/kg for a period of 24 hours. A limitation shared with nuclear fuel enrichment centrifuges exists: beyond a certain critical rotational speed the centrifugal stresses would cause a catastrophic failure of the device.

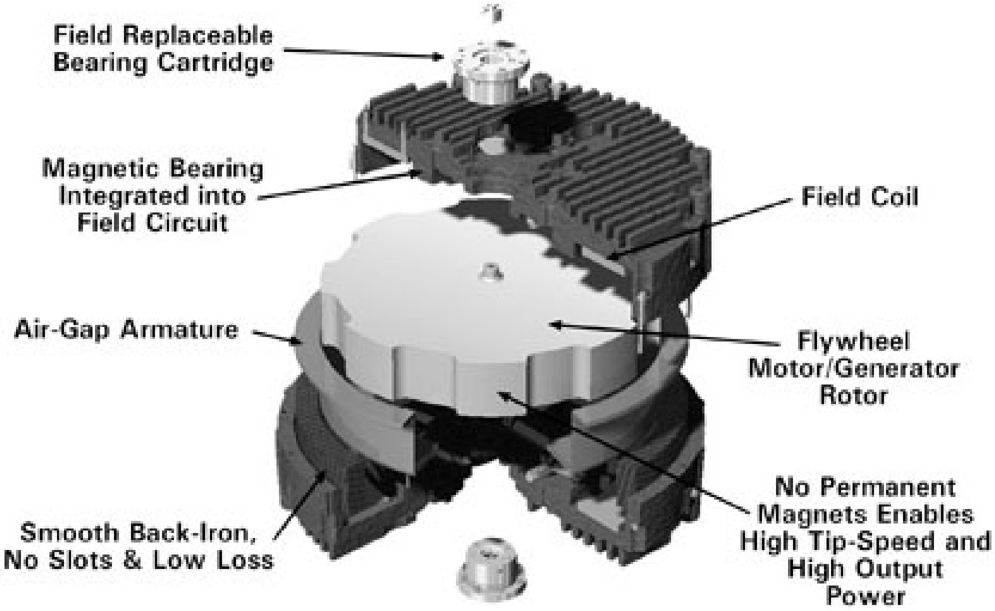

Figure 6. Flywheel motor-generator. Source: CleanSource.

Figure 7. Enercon Flywheel. Source: Enercon.

COMPRESSED AIR STORAGE

Wind turbines and solar collectors could compress air for storage in tanks or underground cavities. When needed, it can be used through its direct expansion in a compressed air motor.

Alternatively, the compressed air can be injected into an internal combustion turbine where the oxygen it contains can be burned with fuel, possibly hydrogen, in a combustion chamber to supply mechanical energy at an efficiency of 80 percent.

THERMAL STORAGE

Many alternatives exist for the thermal storage of wind and solar energy: water heating, heating of gravel or stones, or melting of a substance with a low melting point such as paraffin wax or lead. The molten substances would give back their latent heat when returned to their initial state. This approach would be useful for space heating application because of the low grade heat involved.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE, SMES

Superconducting coils or magnets can store energy in the form of a. magnetic field. Being superconducting, the Ohmic resistive losses can be minimal. The stored energy can be released in the form of an electrical current to power transportation systems such as automobiles or Magnetically Levitated (Maglev) trains. This could be coupled with a cryogenic hydrogen transmission system for a national efficient electrical grid and transportation system.

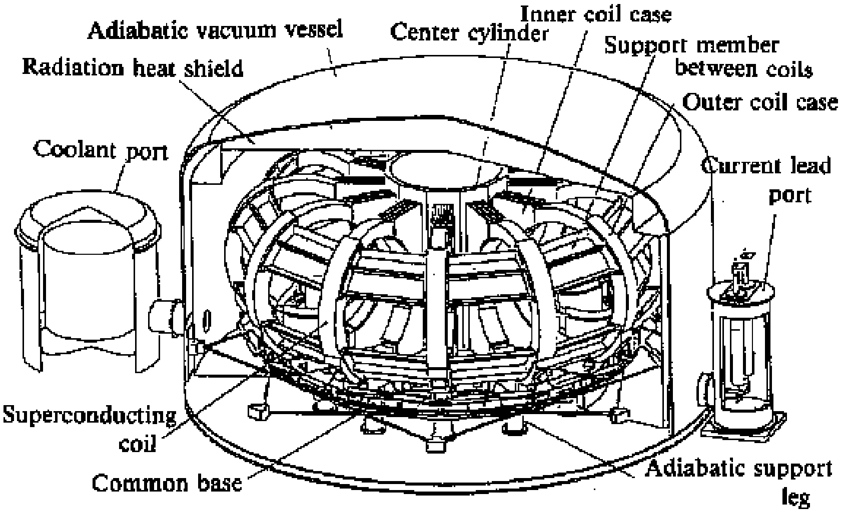

Figure 8. Conceptual design of a superconducting coil for the 100 kWhr small scale SMES, Japan.

Japan's International Superconductivity Technology Center (ISTEC) conducted a three year feasibility study starting in 1988 on SMES, under a program sponsored by MITI's Agency of Natural Resources and Energy.

Superconductors such as Nb-Ti and Nb_3Sn were the primary choice. Demonstration of a small-scale SMES, whose size is closely related to that needed for power system stabilization, would address many major technical issues facing the large-scale diurnal storage SMES, such as AC losses, power conditioning, and refrigeration.

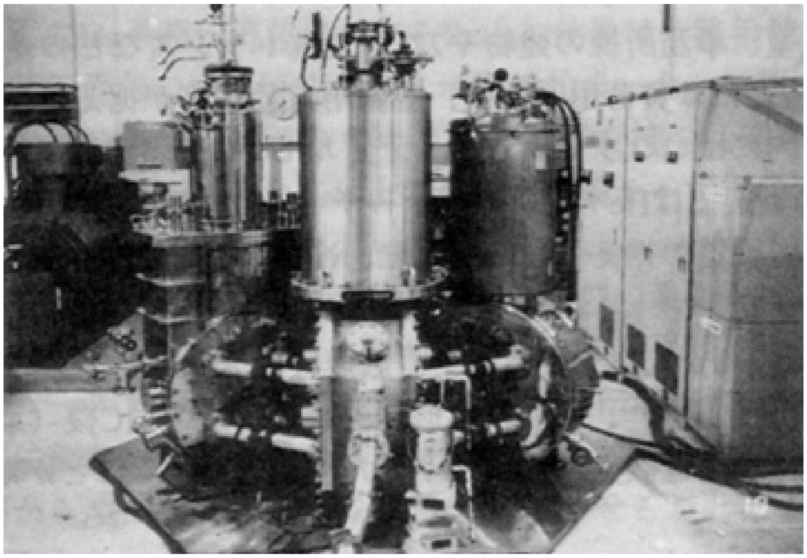

Figure 9. Kansai Electric Power Company (KEPCO) three coil torus with 400 kJ per coil. Source: Kepco.

A 100 kWh/20 MW system used a toroidal magnet with an outside diameter for the cryostat of ~12 m. A half size prototype coil was constructed by Toshiba. The test coil used a forced flow Nb-Ti cable in conduit conductor and demonstrated 20 kA at 2.8 T, which is the rated current for the basic design.

The initial testing was conducted at the Japan Atomic Energy Research Institute (JAERI), with further tests at Lawrence Livermore National Labs (LLNL) in the USA.

PHOTOCHEMICAL STORAGE

Photochemical decomposition can be used where solar radiation would decompose a material such as nitrosyl chloride is dissociated:

$$2NOCl + photons \rightarrow 2NO + Cl_2 \tag{8}$$

The reverse reaction can be carried out to recover the energy of the reaction. Storage in the system would be of the product materials in different containers [1].

BIOLOGICAL STORAGE

Algae can be grown whenever water and an energy source are available. Varieties of algae that contain oil can be grown for later extraction of the oil for conveyance to distant locations.

The increased use of biomass as a source of energy has led to big price hikes for agricultural produce. Some 2 million of the total 12 million hectares of agricultural land in Germany are already devoted to energy crops including biogas production from corn, fuel from rye, and diesel from rapeseed. In the USA, the brand name for rapeseed oil is "canola." Plans in the USA exists for a 13-17 fold increase in the use of biomass by 2050.

Figure 10. Rapeseed harvest in Eastern Germany. Source: DPA.

CO_2 REFORMING INTO DIESEL FUEL

Figure 11. Carbon Capture and Storage, CCS of liquefied CO_2 demonstration plant at Ketzin, Germany. Source: ddp.

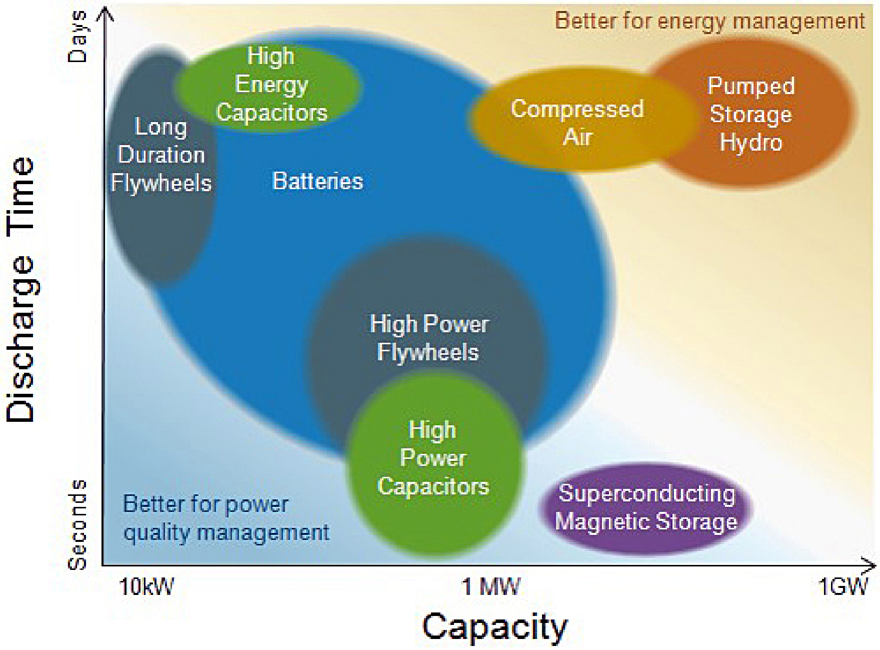

Figure 12. Ranges of application as of achievable discharge rate and installed capacity for different energy storage questions.

Carbon Capture and Storage (CCS), is a technology that proponents say will massively reduce CO_2 emissions from fossil fuel power plants. Instead of diluting the emissions into the sky, CCS technology would capture, liquefy and then pump the CO_2 into underground storage sites.

Researchers from the German Research Center for Geosciences (GFZ) in the town of Ketzin in northwestern Brandenburg, Germany reported success with a test facility where they have injected some 36,000 tons of CO_2 at a depth of 650 meters or 2,132 feet.

The International Energy Agency (IEA) estimates that widespread adoption of CCS would be the cheapest way to cut emissions by half by 2050, arguing that the technology could contribute nearly 20 percent of those cuts.

Critics, however, note that CCS technologies also require significant amounts of energy, particularly in liquefying the CO_2. The Intergovernmental Panel on Climate Change (IPCC) estimates that power plants would need between 11 percent and 40 percent more fuel once CCS technology is installed.

Critics of CCS suggest that if CO_2 leaks from a storage aquifer, it could contaminate the shallow aquifers drinking water supply or leak above ground through geological paths. Others concerned about such facilities suggest that they could negatively impact tourism. Some critics contend that it may cause enhanced seismic activity.

As an alternative to CCS, an alliance of industry, academic and government organizations, formed to commercialize technologies that will utilize concentrated solar energy to convert waste CO_2 into diesel fuel, was announced on June 1, 2010.

The team members include Sandia National Laboratories, Renewable Energy Institute International, Pacific Renewable Fuels, Pratt Whitney Rocketdyne (a United Technologies Division), Quanta Services, Desert Research Institute and Clean Energy Systems . Commercial partners have also signed on to advance work on the first round of commercial plants.

The solar reforming technology platform will be co-located next to industrial facilities that have waste CO_2 streams such as coal power plants, natural gas processing facilities, ethanol plants, cement production facilities and other stationary sources of CO_2.

A solar reforming system is currently being demonstrated in Sacramento, California, and demonstrations will continue both at Sandia's facilities in New Mexico and at a solar power plant project site in Bakersfield, California.

Planning for the first round of commercial plants is under way at several locations in the USA. The project team anticipates that deployment of the first commercial plants can begin in 2013. The project team has received a first phase of funding from the National Energy Technology Laboratory to demonstrate these technologies [2].

REFERENCES

1. John A. Duffie and William A. Beckman, "Solar Energy Thermal Processes," Wiley-Interscience, 1974.
2. "Status Report on Solar Thermal Power Plants," Pilkington Solar International, Report ISBN 3-9804901-0-6, 1996.