



RENU ENERGY



The sun showers the earth with **6,000 times** more energy than humans use at any moment in time.

# Firmenich, India

Plant Project #094-121100-00000-000-ASIAC

# S LAR POWER

# Conceptual Design

**Dahej, Gujarat, India**





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## EXECUTIVE SUMMARY

### Customer Requirements

Neal Zislin, Firmenich Director of Global Manufacturing Engineering, has defined the basis of design criteria for the electrical and steam power production needs for the new Firmenich-India plant as follows:

- The new Firmenich-India plant requires 3 MWe of electricity and 4 MWth of steam delivered at 20 bar, with a turndown capability of 4:1.
- The above quantity of steam and electricity is expected to be needed within 13 years after plant startup.
- Both industrial development areas have access to natural gas and electricity.

### Solar Power Solution for this location – Concentrating Solar Thermal Power

Given that there is no immediate access to geothermal power at this geographic location, concentrating solar thermal electric power is the next best source of renewable power to meet the power needs for this plant, at this geographic location.

Why? ***Once the solar plant is built, power production at this geographic location from a concentrating solar thermal power system is a reliable and economical source of steam and electric power - with negligible annual maintenance and operational costs.***

Additionally, since power output from solar thermal plants peaks during daylight hours as grid electric power peaks, excess power may be either stored for later use, or sold back to the grid when local grids experience the highest demand. The relatively low cost of thermal energy storage means that a solar thermal plant can be built to be "dispatchable", gathering energy during daylight hours to be stored for later use, or releasing it to be sold to the grid during times of peak demand. Based upon our analysis of the Firmenich-India plant needs, and land space available at the proposed plant sites for deploying solar collectors, a concentrating solar power array would provide the most efficient and cost effective source of alternative energy for this particular Firmenich plant, at this geographic location.

Although much like getting exact bids for the construction costs of a new chemical plant requires detailed construction engineering and plans to be drawn, likewise, complete solar engineering construction





plans would need to be completed prior to securing firm bids for construction of the heliostat power array, central receiver tower, and other equipment required for the new Firmenich chemical plant. That said, the initial installed capital investment for construction of the 25 acre solar array field, concentrating tower, steam turbine and related solar power equipment producing 7 megawatts of electricity and steam is estimated at \$37-\$42 million, based on current state of the art for this type of solar technology.

Assuming total projected plant production of 206,162 metric tons of product produced over the next 30 years at the new Firmenich-India plant, the approximate capital investment of \$40 million required for the construction of a solar thermal facility at this Firmenich plant would translate to approximately \$0.19/kilogram of product made. The implementation and use of solar energy at this new India facility would provide approximate energy savings of \$42.7 million from the reduced amount of natural gas required, PLUS new income from the sale of Renewable Energy Credits (REC's, or Carbon Credits) projected at \$6,817,500 (approx. \$227,250/yr or \$0.033/kilogram of product) during the first 30 years of plant operation. When calculating the economic benefit of the implementation and internal use of solar energy, but without including the additional income from the sale of excess energy produced from solar power over the amount actually needed over the first 13 years, operating energy expenses for the India plant are projected to be approximately \$0.29/kilogram using solar energy as the primary energy source.

Adding the annual cost of backup natural gas to the \$0.19/kilogram for the cost of constructing the solar thermal facility results in a total projected energy cost of \$0.48/kilogram from using solar energy as the primary energy source for the new India plant. By comparison, it's estimated that by using 100% natural gas for steam generation and buying electricity from the local grid would result in projected energy costs of approximately \$107 million, or approximately \$0.52/kilogram of product made at this plant over the first 30 years of plant operation.

Therefore, we estimate Firmenich could expect **net overall savings of approximately \$0.04/kilogram in plant energy costs over the course of the first 30 years of plant operation**, if the new Firmenich-India plant uses solar thermal energy as its primary source of power, with natural gas for backup power. In addition, future income from the sale of excess power produced from the solar array has not been included in the above numbers, which, if done, would further decrease the total cost of energy at this facility, resulting in additional savings over those shown above. When one considers the economic benefit described above, coupled with the potential for interruption of fossil fuel supplies and future uncertainty about fossil fuel price increases due to decline in global reserves, increases in global demand, and atmospheric pollution from fossil fuels, the investment in solar energy for this facility seems to be both a wise and prudent one for a far-sighted company whose business is wholly dependent upon a reliable and abundant source of energy. The environmental benefit of using solar energy rather than fossil fuels is well known and often documented, but therefore becomes just one more important benefit for consideration for use in this new Firmenich facility.



## CONCEPTUAL SITE PLAN WITH SOLAR POWER ARRAY

Solar concentrating technology consists of a number of solar clusters, each including a power tower surrounded by an array of heliostats. Heliostats are flat glass mirrors which track the sun and reflect sunlight onto a central receiver. The receiver is located on the top of the power tower. Power towers are linked together by pipelines to a central location where electricity is generated and sent to a power grid. The overall space requirement for the solar array is approximately 25 acres. State of the art solar concentrating technology heats water to superheated steam at pressures up to 160 bar and temperatures up to 565C. A high efficiency steam turbine converts the superheated steam to electricity, which is sent to a power grid. This technology is more than 40% efficient in thermal to electric conversion.

### The Power Tower

The height of the power tower is generally between 60 and 80 meters, but varies according to site and climactic conditions. The receiver is located on the top of the power tower. Heated water travels in pipes from the power tower to a central location. Process steam production efficiency from the solar array is close to 70%.

### The Heliostats

The heliostats are flat mirrors of standard glass with 7.3 m<sup>2</sup> of surface area. They reflect sunlight onto a receiver located on top of a power tower. Each heliostat is a sophisticated assembly, but all of its components are standard products readily available. Consequently, heliostat mirrors cost much less to manufacture than the parabolic mirrors used by most CSP (Concentrated Solar Power) thermal technologies. Each heliostat rotates in two axes (elevation and azimuth), enabling it to accurately track the sun and maintain the reflecting focus on the receiver. The aiming points are calculated by a computer program and updated every 15 minutes. The estimated number of heliostats required for this project are 2,000.

### The Receiver

The receiver is a radiant forced circulation, drum type, steam boiler. The solar boiler application is unique in its response to the daily and seasonal variations in solar flux distribution. However, the boiler is designed and built according to proven steam boiler design criteria using standard materials and components. Panel radiation heat flux is kept within levels standard in the boiler industry. The boiler's source of radiation is the sun reflected onto the receiver by fields of heliostats. The boiler can superheat steam at a pressure of 140 -160 bar and a temperature of 550-565 Celsius.

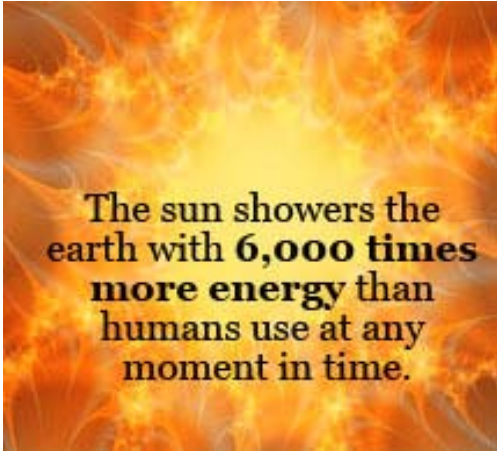
### Conversion to Electricity

Solar thermal power conversion to electricity is performed in a conventional Rankine steam cycle with reheat using steam turbine and generator set. The steam turbine is designed for inlet conditions of superheated steam from solar receiver/boiler at 140 bars and 565° Celsius steam. High inlet pressure and temperature provide high thermal efficiency like the conventional boiler/turbine combination. Low pressure, saturated steam will be extracted at 20 bar for process applications at an intermediate stage. Exhaust steam will pass through a condenser cooled by water. A step-up transformer and switch yard interconnect to the utility transmission lines will be required to bring power to grid level quality. The cycle thermal efficiency is in the range of 40%. This figure is the state of the art in the utility power plant market for similarly sized steam turbines. The overall efficiency rate for the conversion of solar thermal energy to electricity using this system will be about 28%.



**WHY USE SOLAR ENERGY FOR COMMERCIAL POWER NEEDS?**

**Solar Thermal Electric Power Economics, Emissions, and Employment Impacts**



The need for electric power generation is growing rapidly. The US Energy Information Administration projects ongoing growth in annual electrical energy use through 2025. This growth is occurring at a moment in time when scientists have recognized that preserving a climate on Earth similar to today's requires dramatic reductions in total emissions of greenhouse gases by mid-century. Our current electric power system emits over 40% of total human-caused emissions, and is the fastest growing source of emissions.

The business-as-usual scenario for power generation results in total atmospheric concentrations of CO2 far beyond the "point of no return" as described by James Hansen, NASA's chief climate scientist, who refers to our current situation as one of "imminent peril" and calls for 80% reductions in total emissions by 2050.

It is obvious that technologies which can deliver reliable power day and night are urgently needed to augment and supplant our current reliance on fossil-fired electric power generation. It would be preferable if these could be implemented without harming the overall economy or significantly increasing the cost of power.

Current renewable, zero-carbon sources of electric power include geothermal, photovoltaic solar, solar thermal, and wind. Of these, geothermal has limited total resources – the known locations for geothermal generation can provide only a fraction of the world's power needs. Wind and PV solar systems have large resources, but only operate roughly 20 to 30% of the time during windy or sunny hours, and since the hours of generation are not controlled by utilities – these sources are most often not "dispatchable", but generate on an as-available basis.

**Solar thermal electric power** is uniquely suited to meet much of the world's electric power needs. Solar thermal electric output peaks during the daylight hours when the grid need for power peaks, and the potential/projected low cost of thermal energy storage means that solar plants can be built to be "dispatchable", gathering energy during daylight hours and releasing it during times of peak demand.

Worldwide deployment of Solar Thermal Electric Power can displace 2-3 billion tons of carbon emissions annually.

This equals 50% of what's needed to solve the world's climate crisis.



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## Conceptual Design Process Description

### Customer Requirements

Client's engineer, Neal Zislin, and India plant project manager, Sanjay Kalyankar have described the client's expected power needs for the proposed Firmenich India plant as follows:

### Basis of design criteria for solar thermal power system

The basis of design criteria for electrical and steam power production at the proposed Firmenich India chemical plant is as follows:

- The new Firmenich-India plant requires 3 MWe of electricity and 4 MWth of steam delivered at 20 bar, with a turndown capability of 4:1.
- The above quantity of steam and electricity is expected to be needed within 13 years after plant startup.
- Both industrial development areas have access to natural gas and electricity.

### Purpose of Conceptual Design

It is our understanding that this document will be used by Firmenich senior management to determine the site requirements for Firmenich, India and to determine whether an investment in solar energy is warranted, so this document contains details regarding system costs, area required in order to finalize project scope, and thereby increase project certainty. This Conceptual Design Document outlines the best possible strategic direction for the company to take in the use of renewable solar energy by determining the technology type, design, and total costs that will be incurred in advance of commencing construction on the project. This document was prepared to enable Firmenich senior management to make an informed decision about the best implementation and use of renewable energy at the new Firmenich-India plant. Research for this document included an assessment of various types of alternative energy to determine the most reliable and suitable source of alternative energy for this geographic location. Further, this document includes projected cost and construction schedule information, equipment performance specifications, and an overview of system components for the recommended system.



## Economic Analysis

Along with a viable energy solution to the customer’s future energy requirements, this document includes a present value cost economic analysis that compares the selected system’s total cost over the system’s life expectancy with those systems using fossil fuels, and other solar power alternatives. Present value of the systems are calculated over the expected useful life of the system equipment, as well as including the combined totals of future annual costs of maintenance, and estimated costs of energy used. (note: Fortunately, India is one of the richest countries in terms of an energy source that is free, abundant, and nearly infinite – solar energy. The geographic area around Dahej, India receives an average of 5.28 kWh/square meter/day\* of solar energy, so the use of the sun for “free” energy is the most economical when the cost of construction is spread over the entire 30 year useful life of the system.)

				Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Ave.
Dahej	India	21 degrees 42’ N	72 degrees 35’E	5.22	6.03	6.66	7.05	6.77	4.59	3.54	3.40	4.72	5.39	5.15	4.80	5.28
LasVegas	NV	36 degrees 18’ N	115 degrees 16’W	3.02	4.13	5.05	6.57	7.25	7.69	7.37	6.42	6.08	4.26	3.18	2.60	5.30
Trenton	NJ	40 degrees 18’ N	74 degrees 46’W	1.71	2.39	3.43	4.04	5.26	5.67	5.39	5.14	4.18	3.00	1.98	1.48	3.63

\*Source: NASA Surface meteorology and Solar Energy Atmospheric Science Data Center

## Performance Criteria

1. The equipment selected for use meets or exceeds standard solar industry design principles and practice.
2. All solar power generating equipment selected for use shall meet or exceed client needs over 30 year period.

Note: Solar thermal technology has been in use for over two decades. For example, SEGS VIII and SEGS IX are the largest solar plants individually and collectively in the world, producing 160 MW of electricity. Composed of more than 400,000 mirrors and taking up 1,000 acres, and producing a combined total of 310 MW of electricity, the SEGS III-IX solar power plants are located in the Mojave Desert, an area where solar insolation is among the best available in the United States. These arrays have been functioning as planned since the 1980’s.



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## **SOLAR THERMAL POWER GENERATION – System Descriptions**

### **Background Overview of Solar Thermal Power Systems**

Portions of the following material are extracts from “Solar Thermal Power Systems” by Keith Lovegrove and Andreas Luzzi, Encyclopedia of Physical Science and Technology, 3rd Edition, Vol 15.

#### **1 Introduction**

Various devices for collecting solar radiation thermally have been devised. At the simplest level, a flat metal plate painted black and placed in the sun will heat up until it reaches a temperature where the heat that it loses to the air around it and also by radiating itself, exactly balances the amount of energy it receives from the sun. This “stagnation temperature” occurs at around 80°C for a simple flat plate. If water, for example, is passed through passages in the plate, then it will stabilize at a lower temperature and the water will extract some of the energy in being usefully heated up. This is the essence of solar thermal energy collection.

Greater levels of sophistication are aimed at reducing the amount of “thermal loss” from the collector surface at a given temperature. This allows energy to be collected more efficiently and at higher temperatures.

Starting with the flat plate, a cover layer of glass helps by cutting down the energy lost by the circulation of cold air. If metal tubes and glass cylinders are used instead of plates, then the space can be completely evacuated, so that air convection losses are completely eliminated. Clever use of coating materials to produce an optically selective surface that absorbs as much as possible of visible solar wavelengths whilst emitting as little as possible of thermal radiation from the plate helps to reduce radiation losses. Various combinations of these measures are used in the production of systems for the production of solar hot water that are used around the world for domestic and industrial applications. In principle, solar collectors of this nature could be used for electricity production. However the low temperatures achievable limit the conversion efficiencies possible to low levels.



Further increasing the temperature at which energy can usefully be recovered requires some method of optically concentrating the radiation so that the size of the absorbing surface and hence its thermal loss, is reduced. The conceptually simplest approach is to employ a series of flat mirrors (called heliostats) that are continuously adjusted to direct solar radiation onto the absorbing surface. This is illustrated conceptually in Figure 1. Large plants called "Central Receiver Systems" or "Power Towers" have been built based on this principle and are discussed in detail in section 2. The concept can also be adapted to linear absorbers and long strips of mirror to create a "Linear Fresnel" concentrator. Alternatively, the mathematical properties of a parabola can be exploited. The equation for a parabola in the x y plane is  $y=x^2/4f$

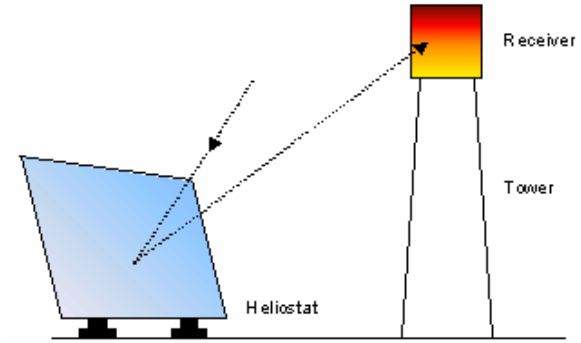


Figure 1. The central receiver concept; a field of plane mirror heliostats all move independently to each keep a beam of solar radiation focussed on a single central receiver (Figure H. Kreetz).

Rays of light parallel to the y axis of a mirrored parabola will all be reflected and focused at the focal point at a distance f from the vertex.

As illustrated in Figure 2, this effect can be used in a linear arrangement, where a mirrored "trough" with a parabolic cross section will focus solar radiation onto a line focus when it is pointed directly at the sun. The largest Solar Thermal Power plants constructed to date employ this principle, they are reviewed in section 3. Alternatively a mirrored dish with a parabolic cross section (a paraboloid) will focus solar radiation to a point focus (see figure 3). Dish systems are reviewed in section 4. Both dishes and troughs require continuous adjustment of position (or at least frequent readjustment) to maintain the focus as the sun moves through the sky.

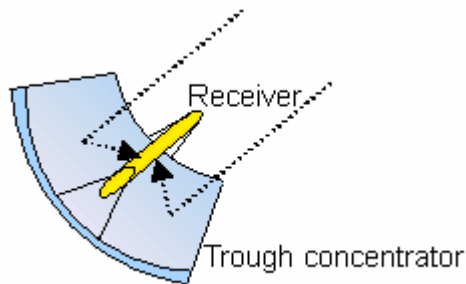


Figure 2. A parabolic trough concentrator focuses solar radiation onto a linear receiver when faced directly at the sun (figure from H. Kreetz)

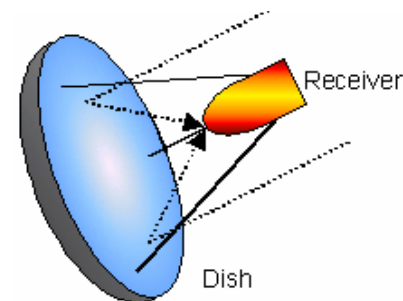


Figure 3. A paraboloidal dish concentrator focuses solar radiation onto a point focus receiver (figure from H. Kreetz).



Similar focusing effects can obviously be achieved with lenses of various kinds, and Ausra has employed a linear fresnel lens at their Australian demonstration project at the scale needed for solar thermal power systems.

Another alternative which potentially avoids the need to track the sun is to employ “non-imaging” concentration. As illustrated in Figure 4, this involves the construction of a mirrored “light funnel” of some kind. Such a device will be able to collect rays into its aperture over a range of incidence angles and cause them to exit via a smaller aperture via multiple reflections. Non-imaging concentrators have not found application as the “primary” means of concentration for Solar Thermal Power systems, but they are frequently applied as “secondary concentrators” at the focus of central receivers, dishes or troughs, where they serve to further reduce the size of the focal region.



Figure 4. (right). A non-imaging concentrator concentrates solar radiation without the need to track the sun.

The rays of light from the sun are not exactly parallel. This means that even a perfect optical system will produce an image of finite size, with an intensity distribution that is a maximum in the center and tapers off to zero at the edges. Imperfections in mirror shape and tracking accuracy have the effect of further spreading out the sun image.

Each of these approaches to concentration has a typical ratio of collected radiation intensity to incident solar radiation intensity, termed the “concentration ratio”. Table 1 summarizes the options discussed and lists typical concentration ratios, the resultant operating temperatures and the consequent thermodynamic limiting efficiency with which electricity could be produced. The limiting conversion efficiency arises from the second law of thermodynamics. The maximum efficiency for conversion of heat from a constant high temperature source is given by the equation:

$$\text{MCE efficiency} = 1 - T_{\text{cold}}/T_{\text{hot}}$$

This is the “Carnot limit”. A simple understanding of why there should be such a limit can be developed by realizing that empirically heat will not spontaneously flow from cold objects to hot ones. If all the heat flow from a hot object could be converted to electricity then this could in turn all be used to heat an even hotter object which we know to be impossible. In real Solar Thermal Power systems, conversion efficiencies around 40% or less of the ideal maximum are typically achieved. Clearly higher concentration ratios give higher efficiency, however they also lead to potentially higher complexity and cost. The design challenge with Solar Thermal Power systems is to produce the desired output as economically as possible. This often meant a trade off in the past between system efficiency and capital investment driving the design process.



Table 1. Typical temperature and concentration range of the various solar thermal collector technologies.

Technology	T [°C]	Concentration ratio	Tracking	Max Conv. Eff. (Carnot limit)
<i>Flat plate collector</i>	30 – 100	1	-	21%
<i>Evacuated tube collector</i>	90 – 200	1	-	38%
<i>Solar pond</i>	70 – 90	1	-	19%
<i>Solar chimney</i>	20 – 80	1	-	17%
<i>Fresnel reflector technology</i>	260 – 400	8 – 80	One-axis	56%
<i>Parabolic trough</i>	260 – 400	8 – 80	One-axis	56%
<b><i>Heliostat field + Central receiver</i></b>	<b>500 – 800</b>	<b>600 – 1000</b>	<b>Two-axis</b>	<b>73%</b>
<i>Dish concentrators</i>	500 - 1200	800 - 8000	Two-axis	80%

## 2 Central Receiver Systems

The central receiver concept was first proposed by scientists in the USSR in the mid 1950s. The first experiment was established in Sant' Ilario near Genova, Italy, in 1965 by Professor Giovanni Francia. He installed 120 round mirrors each the size of a 'tea-table', focusing on a small steam generator on top of a steel frame. The product was superheated steam (500 degrees Celsius, 10 Mpa). Central receivers have the advantage that all the energy conversion takes place at a single fixed point. This avoids the need for energy transport networks and allows investment to improve the efficiency and sophistication of the energy conversion process to be more cost effective. Associated disadvantages are that they must be built as single large systems, without the modularity benefits of distributed systems like troughs or dishes. The fixed position of the receiver also means that heliostats need to track the sun to work most effectively, so that the amount of collected solar radiation per unit area of mirror exceeds that of the other technologies. Major research over the past twenty years has focused on four heat transfer fluid systems; water/ steam, sodium, molten salt and air. An overview of the major demonstration grid connected power plants built to date is given in Table 2.





Table 2. Summary of Central Receiver demonstration power plants.

	<b>Eurelios ( Italy )</b>	<b>Sunshine ( Japan )</b>	<b>IEA-CRS ( Spain )</b>	<b>SolarOne ( USA )</b>	<b>SolarTwo ( USA )</b>	<b>CESA 1 ( Spain )</b>	<b>Themis ( France )</b>	<b>MSEE ( USA )</b>	<b>SES 5 ( CIS- USSR )</b>	<b>PS10 ( Spain )</b>
<b>Net electric power</b>	1MW <sub>e</sub>	1MW <sub>e</sub>	0.5MW <sub>e</sub>	10MW <sub>e</sub>	10MW <sub>e</sub>	1.2MW <sub>e</sub>	2.5MW <sub>e</sub>	0.75MW <sub>e</sub>	5MW <sub>e</sub>	11MW <sub>e</sub>
<b>Total reflector area</b>	6260m <sup>2</sup>	12,912m <sup>2</sup>	3655m <sup>2</sup>	71,095m <sup>2</sup>	81,344m <sup>2</sup>	11,880m <sup>2</sup>	10,740m <sup>2</sup>	7845m <sup>2</sup>	40,584m <sup>2</sup>	74,880m <sup>2</sup>
<b>Heat transfer fluid</b>	Water/steam	Water/steam	Sodium	Water/steam	Molten salt	Water/steam	Molten salt	Molten Salt	Water/steam	Steam
<b>Storage capacity</b>	0.06MWh <sub>e</sub>	3MWh <sub>e</sub>	1.0MWh <sub>e</sub>	28MWh <sub>e</sub>	107MWh <sub>th</sub>	3MWh <sub>e</sub>	15MWh <sub>e</sub>	2.5MWh <sub>e</sub>	1.5MWh <sub>e</sub>	0.46MWh <sub>e</sub>
<b>Period of service</b>	1980-1984	1981-1984	1981-1985	1982-1988	1996 -1999	1983-1984	1983-1986	1984-1985	1985-	2007-Present

To date, power generation in central receiver systems has been via conventional steam Rankine cycles at the base of the tower. In early systems, receivers were built to produce superheated steam directly, however thermal problems associated with the unsteady boundary between liquid water and steam in the tubes motivated a move to secondary heat transfer fluids. Liquid sodium provides good heat transfer behavior, but carries the disadvantage that all the transport piping must be heated above sodium’s melting point (slightly below 100 degrees Celsius). The possibility of leaks also provides a significant fire risk. Use of molten salt avoids the fire risk and is thus also well suited to storage in tanks to allow power generation when there is no sun. The nitrate salts used has a melting point of 260 degrees Celsius. They do however lead to corrosion problems if leaks occur. Air has also been used as a heat transfer fluid, and a 3MW<sub>th</sub> system has been demonstrated at the Plataforma Solar test facility in southern Spain.

Heliostat fields can either surround the tower or be spread out on one side. For a surround field, externally radiated circular cross-section receivers are employed; for one sided fields cavity receivers can be used. System designers have developed optimization strategies which determine the best arrangement for a given number of heliostats. These take into account the effects of shading between heliostats, the spread of the field and the optical inefficiency that increases as heliostats are further from the tower. Two general approaches to heliostat design have been used. The most obvious is a plane structure with rigid mirror facets mounted on it. The structure sits on top of a pedestal with a gearbox arrangement that allows for two axis tracking of the sun.



The other alternative is termed the “stretched membrane” approach. As the name implies a membrane is stretched across a circular frame in a similar manner to a drum skin. The membrane is then covered with mirrors. Thin stainless steel membranes with glass mirrors glued to the surface have been tried as have polymer films which are mirrored themselves. The stretched membrane approach allows the mirrored surface to be curved slightly by the application of a small internal vacuum. In this way heliostats can actually focus their own sun image on the tower receiver rather than just directing a plane beam at it. Figure 6 illustrates an example of a stretched membrane heliostat design. Development trends have suggested that larger heliostats are more cost effective, heliostat modules up to 200m<sup>2</sup> have been tested.



Figure 6. Stretched membrane heliostat.

The largest central receiver solar thermal power plant demonstrated to date is the “Solar Two” plant in Southern California. This plant is actually an updated version of the previously operated “Solar One” system. Extra heliostats were added and the receiver converted from direct steam generation to molten salt. Figure 7 shows the Solar Two plant in operation and figure 8 is a schematic illustrating the operating principles. When the solar field is operating, the molten nitrate salt moves from a cold (288 degrees Celsius) storage tank via the receiver at the top of the tower, where it is heated, to the hot storage tank (566 degrees Celsius). Independently of the solar energy collection process, salt from the hot tank is passed through a heat exchanger where heat is transferred to produce superheated steam, with the salt passing back to the cold storage tank. The steam is used in a conventional steam turbine power plant for electricity generation.

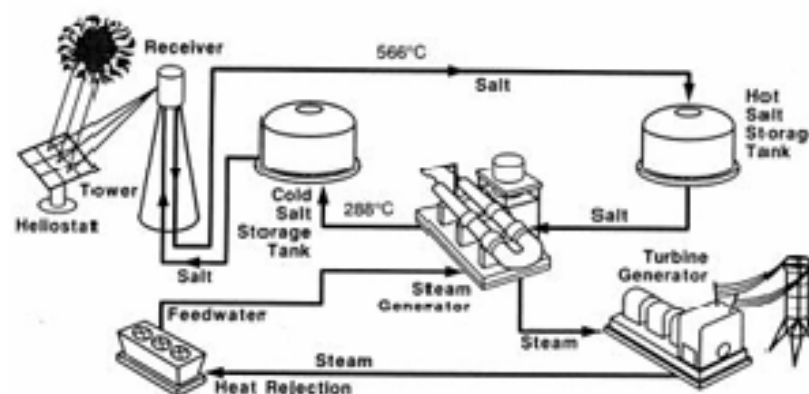


Figure 7. The Solar One (later Solar 2) central receiver power plant in operation. Figure 8. Schematic of Solar Two operation (figure from BechtelGroup).



The Solar Two plant has one thousand and eighteen 39.1m<sup>2</sup> heliostats plus a further one hundred and eight 95m<sup>2</sup> heliostats. Under nominal conditions, 48MWth is concentrated onto the receiver which sits at the top of a 91m high tower. Steam is produced in the heat exchangers at 10MPa and 538 degrees Celsius and the net electrical output is 10.4MWe.

One of the most recent developments in the Central Receiver area, is the “beam down” concept proposed by the Weizmann Institute in Israel. Rather than converting the energy at the top of the tower, a hyperbolically shaped secondary mirror directs it vertically downwards. At the bottom, a further non-imaging concentrator concentrates it further before it is captured by a volumetric receiver capable of heating air to very high temperatures needed for a Brayton cycle.

The LUZ II receiver is a radiant forced circulation, drum type steam boiler. The solar boiler application is unique in its response to the daily and seasonal variations in solar flux distribution. However, the boiler is designed and built according to proven steam boiler design criteria using standard materials and components. Panel radiation heat flux is kept within levels standard in the boiler industry. The boiler's source of radiation is the sun reflected onto the receiver by fields of heliostats. The boiler can superheat steam at a pressure of 140 -160 bar and a temperature of 545 degrees Celsius. One DPT 550 cluster is equivalent to one standard boiler. Boiler panels for steam generation and superheating are arranged in a circle around the top section of the Power Tower. One receiver is located atop each Power Tower.

### **3 Trough Systems**

Solar thermal power in the form of mechanical energy for water pumping was established for the first time near Cairo in 1914 (~ 40 kW). It incorporated a water/steam operated parabolic trough array (5 units, 4m x 62m) and a low pressure condensing steam engine. Solar electric trough development was re-activated by the U.S. Department of Energy in the mid-1970's. The first experimental system started operation in 1979. At the same time a private Research and Development company from Jerusalem, Israel, (LUZ) successfully designed and implemented commercial scale parabolic trough 'Solar Electric Generating Systems' (SEGS). This decision was strongly motivated by favorable power purchase agreements and tax credits offered in the state of California at that time.

The nine SEGS plants built by LUZ between 1984 and 1989, have a combined capacity of 354MWe. They all continue to operate on a commercial basis and together they represent by far the majority of operating solar thermal power station capacity in the world. During the early 1980s, small demonstration trough based solar thermal power systems were constructed in the USA, Japan, Spain and Australia. Table 3 lists the details of these plants. Specifications for the 9 SEGS plants are given in Table 4.



Table 3. Details of demonstration trough based solar thermal power plants.

	<b>Coolidge ( USA )</b>	<b>Sunshine ( Japan )</b>	<b>IEA-DCS ( Spain )</b>	<b>STEP-100 ( Australia )</b>
<b>Net electric power</b>	0.15MW <sub>e</sub>	1MW <sub>e</sub>	0.5MW <sub>e</sub>	0.1MW <sub>e</sub>
<b>Total aperture area</b>	2,140m <sup>2</sup>	12,856m <sup>2</sup>	7,622m <sup>2</sup>	920m <sup>2</sup>
<b>Heat transfer fluid</b>	Synthetic oil	Water/steam	Synthetic oil	Synthetic oil
<b>Effective Storage capacity</b>	5MW <sub>th</sub>	3MW <sub>e</sub>	0.8MW <sub>e</sub>	117MW <sub>th</sub>
<b>Duration of service</b>	1980 -1982	1981 - 1984	1981 -1985	1982 -1985

Table 4. Details of the California SEGS plants.

	<b>SEGS I</b>	<b>SEGS II</b>	<b>SEGS III</b>	<b>SEGS IV</b>	<b>SEGS V</b>	<b>SEGS VI</b>	<b>SEGS VII</b>	<b>SEGS VIII</b>	<b>SEGS IX</b>
<b>Net electric power</b>	13.8 MW <sub>e</sub>	30 MW <sub>e</sub>	30 MW <sub>e</sub>	30 MW <sub>e</sub>	30 MW <sub>e</sub>	30 MW <sub>e</sub>	30 MW <sub>e</sub>	80 MW <sub>e</sub>	80 MW <sub>e</sub>
<b>Total aperture area</b>	83,000 m <sup>2</sup>	199,000 m <sup>2</sup>	230,000 m <sup>2</sup>	230,000 m <sup>2</sup>	251,000 m <sup>2</sup>	188,000 m <sup>2</sup>	194,000 m <sup>2</sup>	464,000 m <sup>2</sup>	484,000 m <sup>2</sup>
<b>Duration of service</b>	1984 - present	1985 - present	1986 - present	1986 - present	1987 - present	1988 - present	1988 - present	1989 - present	1989 - present



Figure 9 shows one of the SEGS plants and figure 10 illustrates the operating principles schematically. A synthetic heat transfer oil is pumped through the trough array and heated to up to 400oC. This oil is then used to produce steam in heat exchangers before being circulated back to the array. The steam is used in a conventional steam turbine based electricity generating plant. Although some hot oil based energy storage was provided in the first plant, the SEGS systems overall rely on natural gas firing to provide continuous operation when the sun is not available.



Figure 9. View of SEGS trough based solar thermal power plant in southern California.

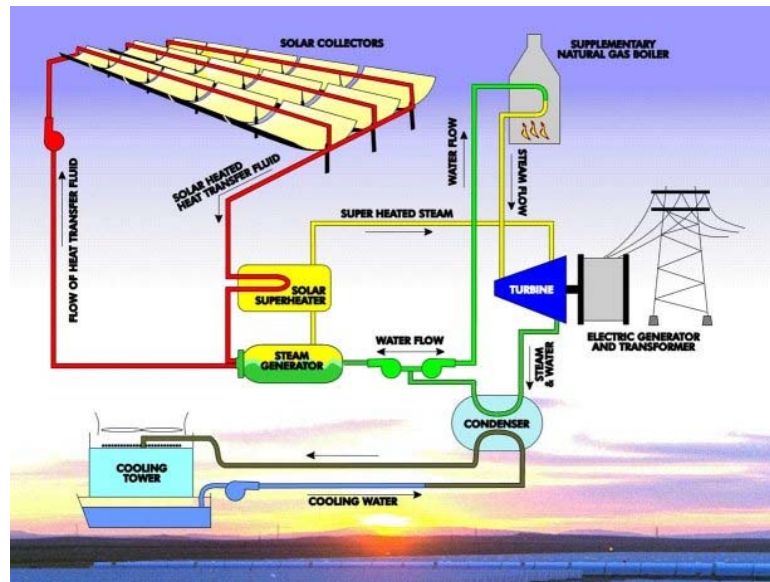


Figure 10. Schematic representation of SEGS plant operation (figure from ABB).

The LUZ troughs were built using a galvanized steel space frame. This frame supports 4mm thick glass mirror segments which are shaped by heating and molding to match the parabolic profile, before silvering. Each mirror facet is supported only at 4 points of attachment. The most recently constructed systems (termed LS-3) are 5.76m wide and 95m long giving a total aperture of 545m<sup>2</sup>. 224 glass mirror segments are used and a concentration ratio of up to 80:1 is achieved. The trough units are lined up in north south rows and track the sun from East to West during the day. During the winter when midday sun elevation is lower some radiation is lost from the end of each trough, but because they are long, this is only a small fraction of the total. Each trough has its own positioning and local control system.

The receiver units of the LUZ troughs consist of a stainless steel tube 70mm in diameter, covered by a Pyrex glass envelope which is sealed to the tube via metal bellows at the ends. The space between the steel and glass is evacuated to minimize thermal losses. The surface of the stainless steel absorber tubes is coated with a black chrome selective surface which absorbs 94% of the solar radiation incident whilst minimizing the amount that is radiated at thermal wavelengths. The combination of trough and receiver is capable of operating at temperatures in excess of 400oC. However the heat transfer oil becomes chemically unstable and begins to

degrade at temperatures above 300 degrees Celsius. Approximately 350m<sup>3</sup> of oil circulates in one of the 30MWe plants. Depending on the operating regime this can need replacing at rates of up to 8% per year as a result of chemical breakdown. The latest SEGS



plants each employ an Asea Brown Boveri steam turbine with reheat cycle and multiple extraction. With steam inlet conditions of 10MPa and 370 degrees C, thermal to electric conversion efficiencies of approximately 37% are achieved, giving overall peak solar to electric efficiencies of 24%.

Regular maintenance is required for all solar thermal power systems. For the SEGS plants, routine cleaning and replacement of broken mirror facets and receiver modules forms a major part of the maintenance program. Research and Development on trough systems has been continued by both Ausra and Solel since the LUZ plants were completed. A major area of investigation has targeted the replacement of the heat transfer oil with direct generation of steam in the receivers. Direct steam generation by Ausra's linear fresnel reflectors allows collection of energy at higher temperatures, and improves the efficiency of the steam turbine. Direct generation of steam also avoids the need to replace the costly oil and eliminates the inherent fire risk. The challenge is managing the rapidly changing thermal stresses induced in the receiver tube by the unsteady movement of liquid and vapor water when boiling is taking place.

This variation of linear focusing technology was originally created by Ausra's co-founder, David Mills, and a group based at the University of Sydney, who developed the concept known as the "Compact Linear Fresnel Reflector". This operates rather like a linear version of a central receiver system. Fixed linear receivers are illuminated by a series of long narrow mirrors which track the sun individually. If several receiver rows are installed side by side, then the individual mirror units can switch from one receiver to another depending on the relative optical efficiencies at different times of the day. A demonstration system based on this technology was built by Ausra as an addition to the existing Liddell coal-fired power station in New South Wales' Hunter Valley. (Australia) Another 177 megawatt plant using this technology is under construction in southern California.

### **Solar Thermal Trough Case study:**

- Daggett SEGS 1 & II – 165 MW capacity located at Daggett, California about 155 miles northeast of Los Angeles
- Kramer Junction SEGS III, IV, V, VI, VII – 165 MW capacity located in the Mojave Desert at Kramer Junction, California
- Harper Lake – SEGS VIII and IX. 165 MW capacity located at Harper Lake in San Bernardino County, California

Longstanding, field proven experience has helped reduce the cost of kWh produced to competitive levels by renewable market standards.

### **System Description**

Solar thermal technology converts sunshine into useful thermal energy, and subsequently into electricity, by way of parabolic mirrors that concentrate the solar energy onto solar thermal receivers containing a heat transfer fluid. The heat transfer fluid is circulated and heated through the receivers, and the heat is released to a series of heat exchangers to generate super-heated steam. The steam powers a turbine/generator to produce electricity delivered to a utility's electric grid. In state of the current art solar thermal trough collectors such as those being manufactured by Ausra and Solel, a central computerized tracking facility enables optimal absorption of the sun's energy by automatically adjusting the alignment of the parabolic mirrors. From the moment the sun rises until it dips over the horizon, its rays can be captured and converted into usable energy.



Aerial photo of existing 310 MWe SEGS Power Generating System in California's Mojave Desert

## Solar Thermal Trough Power System – Basic Description

- | Stage | Description   |
|-------|---|
| 1     | Solar collectors with curved reflectors cover large areas and are used to capture and concentrate sunlight.   |
| 2     | Sunlight then heats a material such as oil or salt which then heats water to create steam.  |
| 3     | The steam is piped to an onsite turbine-generator to produce electricity. The steam is then condensed and reused as the cycle begins again. After the electricity leaves the generator, it goes to a step up transformer so that the voltage can be increased, allowing the power to be transmitted via the electrical transmission system. |
| 4     | On cloudy days, the plant has a supplementary natural gas boiler which can burn natural gas to heat the water, creating steam to generate electricity.  |



## 4 Paraboloidal Dishes

The first realization of dish concentrator / engine system design was in 1864. The Frenchman Augustin Mouchot built a variety of 'thermo-piles' and 'solar engines' using conical mirrors. Currently, there are many designs and states of development of paraboloidal dishes.

Paraboloidal dish concentrators must point directly at the sun for proper operation. This necessitates two axis tracking mechanisms. There are two approaches to this, "altitude / azimuth" tracking or "polar / equatorial" tracking. In the first, the dish is mounted with a horizontal axis pivot (to allow altitude adjustment) plus a vertical axis pivot (to allow azimuth adjustment). A polar / equatorial system has a main axis of rotation, the angle of which is adjusted on a daily basis so that it is at a right angle to the sun's noon elevation. With the polar axis correctly adjusted, tracking during the day involves following the sun from sunrise to sunset with this single axis of movement. Altitude / azimuth arrangements have the disadvantage that both actuators must work throughout the day and the azimuth adjustment must be very rapid near midday for high sun elevations. Despite this, it is sometimes used for pragmatic structural design reasons.

Dish based solar thermal power systems can be divided into two groups. Those that generate electricity with engines at the focus of each dish, and those that use some mechanism to transport heat from an array of dishes to a single central power generating block. From a research and development perspective, dish systems have a major advantage over central receivers in particular, in that a single dish prototype can be constructed and tested relatively economically. Furthermore, for the dish / engine approach, a single module on its own can demonstrate the operation of the full system. Consequently there have been well over 30 dish prototypes developed to date, both by research institutes and private companies.

The variations in structural design of dish concentrators are very similar to the different types of heliostats used with central receivers. Possible different approaches include;

- A space frame structure that supports a number of rigid mirror elements held in a paraboloidal orientation.
- A single rigid paraboloidal surface covered with mirror elements.
- A single mirrored stretched membrane that is pulled into a paraboloidal shape on a drum like structure.
- A space frame supporting a series of small stretched membrane mirror elements.

The high concentration ratios achievable with dish concentrators allow for efficient operation at high temperatures. Stirling cycle engines are well suited to construction at the size needed for operation on single dish systems and they function with good efficiency with receiver temperatures in the range 650oC to 800oC. To achieve good power to weight ratios, working gas pressures in the range 5 – 20MPa are employed and use of either the high conductivity gases hydrogen or helium gives improved heat transfer. The Advanco corporation and McDonnell Douglas have produced 25kWe dish Stirling units which have achieved solar to electric conversion efficiencies of close to 30%. This represents the maximum solar to net electric conversion efficiency achieved by any solar energy conversion technology.

Figure 11 shows a series of Stirling dish systems constructed by the German company Schlaich Bergermann and Partner. The array is at the Plataforma Solar de Almeria test site in southern Spain and has been operating since 1991. Each unit consists of a 44.2m<sup>2</sup> stretched membrane dish fitted with a 9kWe 2 cylinder kinematic Stirling engine. The membranes are made from a sheet of 0.23mm thick stainless steel sheet which has been plastically deformed to form a parabolic shape and is then kept in place by a slight internal vacuum. 1mm thick back silvered glass mirror tiles are bonded to the membrane and elastically deformed to follow its shape. The dishes use a polar equatorial tracking system. The first 3 dishes were installed in 1991 and a further 3 dishes added in 1996. In the period up to 2000 an accumulated total of 30,000 MWh of electricity was generated and fed into the local grid.





The biggest distributed array / central plant solar thermal power system that has been trailed is the "Solarplant 1" system built in Southern California by the "Lajet" consortium in 1983/84. A photograph of this system is in Figure 12. It consisted of 700 dishes with a total collecting area of 30,590m<sup>2</sup>. The dishes generated steam in their cavity receivers, with 600 of the dishes producing saturated steam and others taking the saturated steam and superheating it to 460 degrees Celsius. The steam was transported through an insulated pipe network to a central steam turbine based generating plant which produced a nominal output of 4.9MWe. As can be seen from figure 12 the dishes were constructed with multiple stretched membrane mirror elements. The membranes were made from aluminized acrylic film. Unfortunately, this film proved not to be very durable, which was a major factor in the plant ceasing operation in 1990.



Figure 12. Solar Plant 1, 700 dishes producing steam.

The Australian National University's large dish prototype (designated Solar Generating System 3 – SG3) is intended for use in distributed systems similar to Solarplant 1. The first prototype was completed in 1994 and is shown in figure 13. A similar unit has been built at the Sde Boquer Desert Research Center in Israel. At 400m<sup>2</sup> aperture, they are the biggest dishes built so far. The SG3 unit in Canberra Australia, has 54 triangular mirror panels supported on a hexagonal aperture space frame structure. Altitude azimuth tracking is employed, with the horizontal axis near the base of the dish so that it can be parked in a horizontal position relatively close to the ground. This helps to reduce wind resistance and so improve storm survivability. The SG3 dish has a cavity receiver based on a single helical winding of stainless steel tubing. This receiver serves as a "once through" boiler which produces superheated steam at 5MPa and 500 degrees Celsius. Although intended for operation in large arrays, the SG3 prototype is currently connected to a small reciprocating steam engine which is capable of generating 45kWe and is connected to the local grid. The thermal efficiency from solar to steam is approximately 85% and in a large steam turbine based system production of electricity at a rate of approximately 100kWe per dish would be expected.

Figure 13. The 400m<sup>2</sup> SG3 dish prototype at the Australian National University.



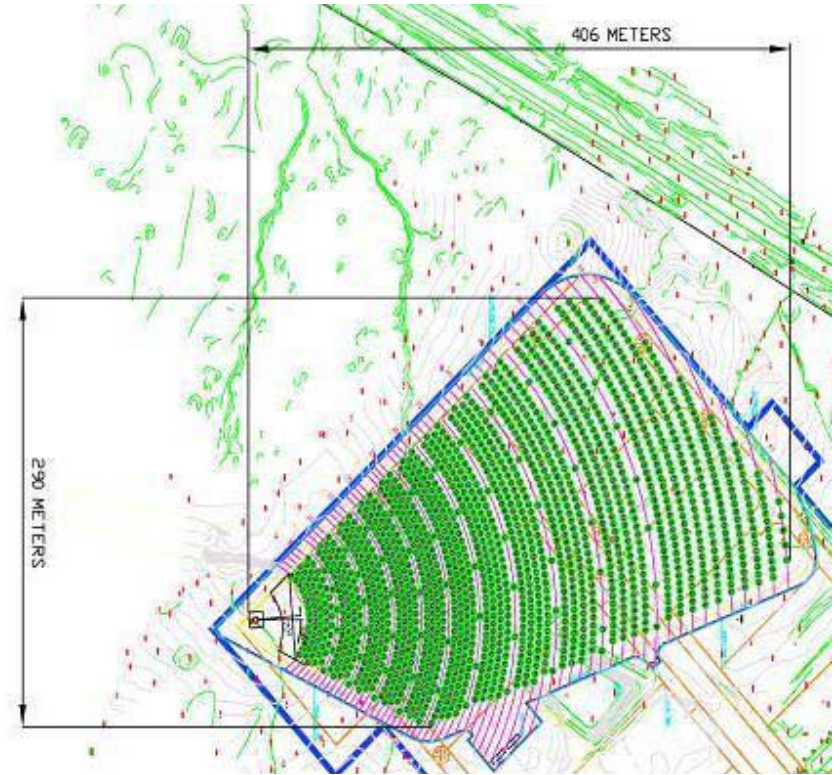
Research and development on dish systems around the world, looks at improving and developing dish designs to bring the cost down and at improving the reliability and efficiency of conversion systems. A number of groups are investigating using small solar driven gas turbines at the focus of dishes (dish / Brayton systems). These offer the potential for high efficiency operation but with less maintenance than Stirling engines.

Chemical conversion systems are also investigated. High temperature reversible chemical reactions such as methane reforming or ammonia dissociation can be used to store energy in chemical form in products which are stored and transported at low temperature and then recombined to provide the heat for power generation on a continuous basis.



## Firmenich Campus - Dahej, India

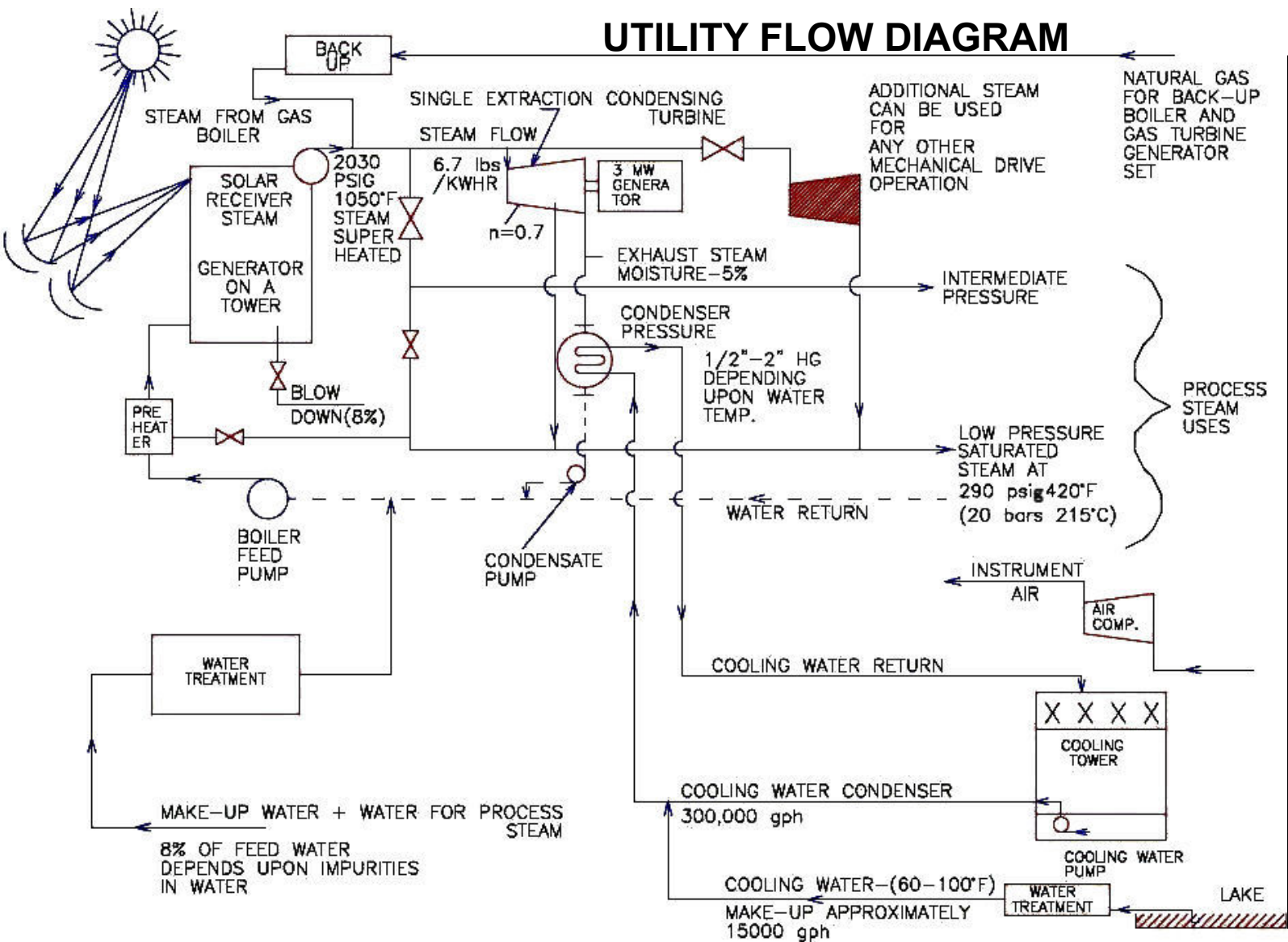
Proposed Site Plan with 7 Megawatt Solar Power Plant



Site Design by Larry Bestor

The sun showers the earth with **6,000 times more energy** than humans use at any moment in time.

## UTILITY FLOW DIAGRAM



This utility flow diagram is based on the following data:

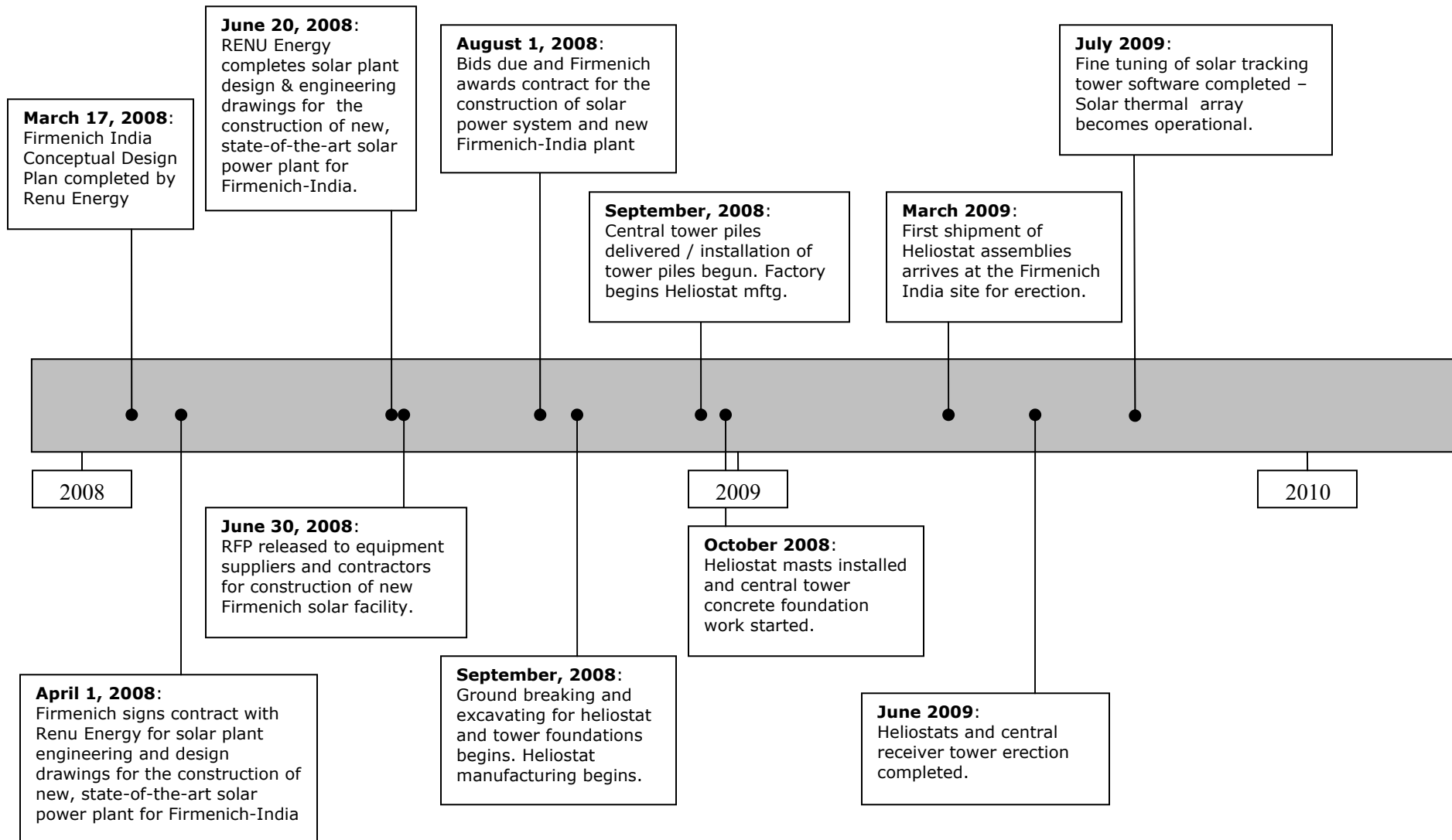
1. Thermal efficiency of the cycle: 40%
2. Solar Thermal Heat Rate: 8532 Btu/kwh
3. Turbine throttle steam rate: 6.7 lb/kwh
4. Steam throttle pressure: 140 bars-2030 psig
5. Steam temperature: 565 C (1050 F)
6. Turbine efficiency: 70 percent
7. Site water temp: 7C - 28C
8. Condenser pressure: 1.5 " HG
9. Exhaust Steam moisture content: 5%
10. Summer wet bulb temperature: 28 C
11. Total mass flow rate: approx. 28,000 lb/hr.

UTILITY FLOW DIAGRAM FOR FRMENICH  
CHEMICAL PLANT IN -GUJRAT-INDIA- 7 MW-CAP.

DW	UTILITY FLOW
BY	TUSHAR GOSWAMI



## CONCEPTUAL ENGINEERING and CONSTRUCTION SCHEDULE





## ECONOMIC ANALYSIS

Estimate of solar thermal power system costs – see also Appendix ‘A’

Factored Total Installed cost based on equipment category & prior experience. Factors based on Indian craft man-hour rates and productivity.

Size of the solar thermal generating plant	7 Megawatt
Engineering and equipment costs	\$ 30 million
Installation labor	<u>\$ 7- \$12 million*</u>
Total Capital investment	\$ 37-\$42 million

\*Installation labor is based on the following Indian labor rates supplied by Sanjay Kalyankar and an exchange rate of Rs to US\$ at 40Rs./\$1.00:

- 1) Skilled electricians - Rs. 100/Hr.
- 2) Skilled process pipe workers - Rs. 100/Hr.
- 3) Skilled Plumbers - Rs. 80/Hr.
- 4) Skilled manufacturing assembly workers - Rs. 125/Hr.
- 5) Semi-skilled construction workers - Rs. 75/Hr.
- 6) Day laborers - Rs. 50/Hr

30 yr estimated operating expense of natural gas backup	\$ 64 million
30 yr estimated cost of solar equipment maintenance	\$ 3 million
Total 30 yr estimated operating energy expense	\$ 67 million
Projected income from annual sale of 9,090 REC's (Carbon Credits) for 30 years	\$ 6,817,500
Net projected annual operating expense assuming use of solar as primary energy	\$ 60,182,500
Total 30 year estimated production	206,162 metric tons
Net operating cost of energy per kilogram of product	\$0.29/kilogram



## APPENDIX A

### COMPARATIVE POWER COSTS of SOLAR and FOSSIL FUELS

#### ANNUAL ENERGY COST COMPARISONS (1) COST ANALYSIS

Location	Power Generating Source	Per kWh (cents)	Estimated Annual	Environmental	Cumulative 30 YR
			Cash Cost (2009)	Annual Cost (3b) (tons of CO <sub>2</sub> )	Cost (FY2009- 2039)
Mundra, India (2)	Natural Gas for electricity (4a)	\$ 0.12	\$ 1,126,955	7,353	\$ 50,385,149
	Natural Gas for steam (4b)	\$ 0.05	\$ 931,000	8,170	\$ 56,331,786
	Solar thermal w/CNG backup (5)	\$ 0.05	\$ 1,228,773	6,433	\$ 64,030,161
	Oil (6)	\$ 0.15	\$ 4,172,053	16,566	\$ 170,648,825
	Coal	\$ 0.12	\$ 3,337,643	27,287	\$ 136,519,060
Dahej, India (3)	Natural Gas for electricity (4a)	\$ 0.12	\$ 1,126,955	7,353	\$ 50,385,149
	Natural Gas for Steam (4b)	\$ 0.05	\$ 931,000	8,170	\$ 56,331,786
	Solar thermal w/CNG backup (5)	\$ 0.05	\$ 1,228,773	6,433	\$ 64,030,161
	Oil (6)	\$ 0.15	\$ 4,172,053	16,556	\$ 170,648,825

#### NOTES:

- (1) Assumes projected demands for electricity and process steam per numbers from Sanjay Kalyankar.
- (2) Annual costs reflect comparative commercial general electric service rates in Mundra from Paschim Gujarat Vij Company Ltd.
- (3) Annual costs reflect comparative commercial general electric service rates in Dahej from Dakshin Gujarat Vij Company Ltd.
- (3b) Environmental costs are based upon volume of CO<sub>2</sub> added to the atmosphere annually from an energy source
- (4) Natural gas prices are based on current proposed pricing quoted for Firmenich-India per Herman Mihalich
- (4b) Natural gas prices are based on current prices quoted for Firmenich-India per Neal Zislin.
- (5) Solar power production is based on average annual solar insolation in Mundra and Dahej, India of 5.28 kWh/m<sup>2</sup>/day = 1674.3 Btu/ft<sup>2</sup>/day
- (6) Commercial electricity rates for industrial uses in India from conventional sources are among the highest in the world.

The electricity sector remains a bottleneck in India with most states (except a select few cities) facing electricity supply cuts on a regular basis. As a result, most of the large successful Indian companies tend to have captive infrastructure facilities. Tariffs charged in India are among the highest in the world. The distribution setup leaves much to be desired and cross subsidization to residential customers and farmers results in a large burden of the cost of producing electricity being passed to industrial customers.

Typical CO<sub>2</sub> emissions rate (coal based electric): 0.89 lbs CO<sub>2</sub> per kWh - Typical CO<sub>2</sub> emissions rate (oil based electricity): 0.54 lbs CO<sub>2</sub> per kWh

Typical CO<sub>2</sub> emissions rate (natural gas based electricity): 0.43 lbs CO<sub>2</sub> per kWh

CO<sub>2</sub> emissions rates shown above were calculated from stoichiometry by Neal Zislin

**Dahej Energy Subsidy** - Per Herman Mihalich; electricity quoted for the local SEZ in Dahej will be 5rs(\$0.12)/kwhr for 2 yrs, then 3.5rs(\$0.084)/kwhr afterward.

Natural Gas Price for Dahej, India site quoted to Neal Zislin and used above was 20 rupees/m<sup>3</sup> = \$15/MM BTU = \$14.17 per 292.80kWh = \$0.048/kWh.

Electricity costs assume exemption from electricity duty, and any other tax or levy on sale of electricity for both self-generated & purchased power.



## APPENDIX A (cont'd)

### ANNUAL ELECTRIC POWER COST COMPARISONS COST ANALYSIS

Location	Power Generating Source	Per kWh (cents)	Estimated Annual Energy Costs		
			FY2019	FY2029	FY2039
Mundra, India (2)	Natural Gas for electricity (4a)	\$ 0.12	\$1,743,700	\$1,812,273	\$1,812,273
	Natural Gas for steam (4b)	\$ 0.05	\$1,975,551	\$2,053,242	\$2,053,242
	Solar thermal w/CNG backup (5)	\$ 0.05	\$2,231,551	\$2,319,309	\$2,319,309
	Oil (6)	\$ 0.15	\$5,839,200	\$5,956,754	\$5,956,754
	Coal	\$ 0.12	\$4,671,360	\$4,765,403	\$4,765,403
Dahej, India (3)	Natural Gas (4a)	\$ 0.12	\$1,743,700	\$1,812,273	\$1,812,273
	Natural Gas Steam (4b)	\$ 0.05	\$1,975,551	\$2,053,242	\$2,053,242
	Solar thermal w/CNG backup (5)	\$ 0.05	\$2,231,551	\$2,319,309	\$2,319,309
	Oil (6)	\$ 0.15	\$5,839,200	\$5,956,754	\$5,956,754

\*Note\* - All figures in Appendix "A" above are expressed in 2008 US Dollars



## APPENDIX B

### COMPARATIVE OPERATING ENERGY COSTS of FIRMENICH PLANTS<sup>1</sup>

<b>Plant Location</b>		<b>\$/kg PRODUCT</b>
FIRMENICH-INDIA <sup>2</sup>	Planned	\$0.48
FIRCAL	Existing	\$0.34
FIRCHEM	Existing	\$0.40
FIRCHINA	Existing	\$0.12
FIRHARBOR	Existing	\$0.11
FIRINC	Existing	\$0.10
FIRMING	Existing	\$0.27
FIRSA-LP	Existing	\$0.29
FIRSA-MS	Existing	\$0.11
FIRULM	Existing	\$0.08

- 1) The above energy costs are expressed as the price per kilogram of plant production.
- 2) Assumes use of solar thermal energy as primary source of power with CNG backup.