

DESIGN & PERFORMANCE OF THE AMONIX HIGH CONCENTRATION SOLAR PV SYSTEM

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ABSTRACT

Amonix has designed, manufactured, installed, and tested over 500 kW of high concentrating PV systems based around a concentrating silicon cell that set a new world efficiency record in 1992. This paper describes the development of this product as well as the physical and operating characteristics of the system. The operating characteristics that make this system attractive for grid, distributed, and off-grid are discussed. Data is presented that demonstrates the high daily power generating capability and the energy performance of the concentrating PV system. Other attributes of the system are also discussed such as the automatic/unattended operation, the short installation time, etc. An array installed at Pomona, CA is described, it has operated unattended for over 3 years and is still producing power today.

INTRODUCTION

An Electrical Power Research Institute (EPRI) study [1] indicated that a high concentrating PV system could

potentially generate power at a lower cost than flat plate PV systems. EPRI, working with Stanford University [2,3], developed a high concentrating silicon cell. Amonix was formed in 1989 to commercialize high concentration PV systems. The initial development of a solar concentrator was based upon the EPRI/Black & Veatch design concept. The system has evolved through several major design iterations that have greatly changed the basic design in order to reduced the manufacturing cost, increased the performance, and increased reliability. It has also resulted in one of the largest tracking structures for concentrating solar systems. Amonix is currently manufacturing these systems in Torrance, California and has installed systems at sites belonging to Arizona Public Service (APS), Southern California Edison, Pacific Gas & Electric, Nevada Power Company, and Central & South West Texas. A 100 kW plant installed in Glendale, Arizona in 2001 is shown in Fig 1. The high concentrating PV system has gone through several generations of development and testing. As each generation was installed and tested, information



Figure 1. 100 kW of 25 kW arrays installed in Glendale, Arizona in 2001.

obtained from the testing was incorporated into the next generation. A 12 kW 4th generation array was installed in Pomona, CA in 1998 as part of a Southern California Edison program. This unit has operated for the last three years completely unattended. It continues to unstop and tracks the sun each day and produce power. Up to the year 2000, 115 kW have been manufactured, installed, and tested for various utilities. Starting in mid-2000, 240 kW of the 5th generation system have been manufactured, installed and are currently producing power. Another 250 kW are scheduled to be manufactured and installed before the end of 2002, and an additional 500 kW in 2003.

SYSTEM DESCRIPTION

The integrated high concentration photovoltaic (IHCPV) system uses a Fresnel lens to concentrate the sun's energy on a silicon cell as illustrated in Fig. 2. Four cells are mounted on a patented design metal strip. Each solar cell has a secondary optical element (SOE) placed around the cell to reflect any beam dispersion. Each cell on the strip also has a by-pass diode. Since a number of cells are connected in series (referred to as a string), the by-pass diode ensures that a single bad cell in the series will not interrupt the flow of current in the string. Six strips are mounted on an aluminum plate with a heat sink mounted on the backside of the plate opposite the cell strip as shown in Fig. 3. There is no active cooling because the back plate and heat sink are designed to transfer the waste heat to the ambient air. Therefore none of the generated power is used as parasitic power for cooling. The Fresnel lens is a circular Fresnel lens (circular facets) that is 7-inch by 7-inch with a 21-inch focal length (see Fig. 2). Twenty-four lenses are manufactured as a single unit or parquet. The parquet lens and cell plates are integrated with a support structure to form a 5 kW MegaModule™. The support structure aligns the Fresnel lens with the solar cell, positions the cell at the focus point of the Fresnel lens, and provides an enclosed space for environmental

protection of the solar cells. The MegaModule™ is a rectangular box 44 ft long, 11 ft wide, and 2.5 ft deep as shown in Fig. 3. It has been designed to fit on a standard truck for transporting from the factory to the installation site.

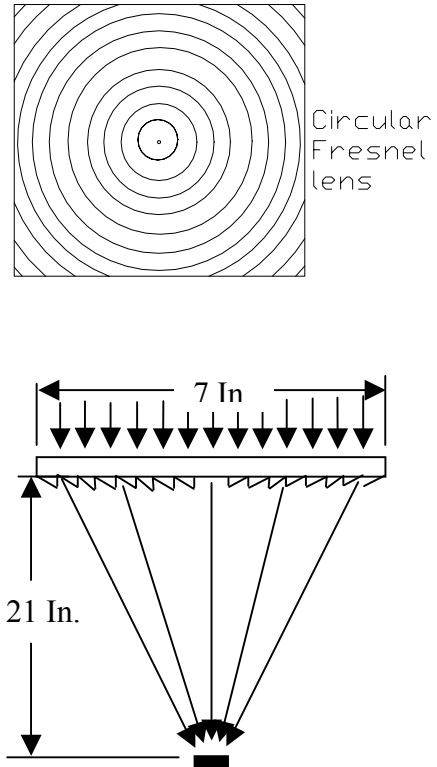


Figure 2. Fresnel focuses sunlight on solar cell.

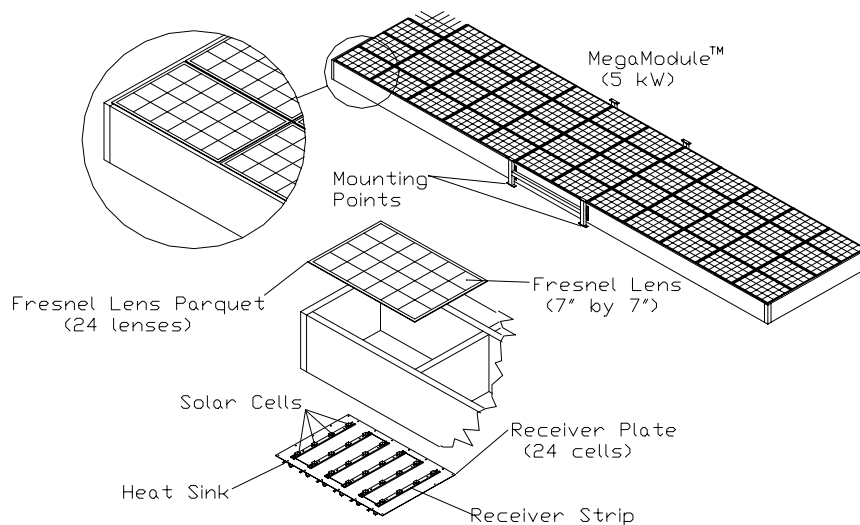


Figure 3. Major components of a 5 kW MegaModule™.

There are 48 parquets and cell plates in a single MegaModule™, which will produce 5 kW ac of power at a solar insolation of 850 W/m² and 25 deg C. The general characteristic of an individual and a 25 kW system are summarized in Table 1.

The MegaModule™ requires a sun tracking accuracy of less than 0.1 degree. For this purpose, it is mounted on a tracking structure as shown in Fig. 4. The 5 kW MegaModule™ was designed as the basic building block for 5 kW to 35 kW power systems. Different tracking structure configurations are used to mount anywhere from a single MegaModule™ to 7 MegaModules™. Array configurations of 15 kW, 20 kW, and 25 kW have been designed, manufactured, installed, and tested.

Table 1. System characteristics

Individual MegaModule™ configuration	
Rated power output	5 kW @ 850 W/m ² , 25 C
Width x length x depth	11 ft x 44 ft x 2.5 ft
Weight	5,528 pounds
Number of cells	1152
Aperture lens area	392 ft ² (36.4 m ²)
Average efficiency	18 %
25 kW MegaModule™ configuration	
Rated power output	25 kW ac @850 W/m ²
Collector size	55 ft x 44 ft x 2.5 ft
Aperture lens area	1960 ft ² (182m ²)
Operating voltage	277/480 volts ac
Stow wind speed	30 mph
System efficiency	dc=18% , ac=16%

The total surface area of the 25 kW array is 2475 ft² (224 m²). To handle this amount of area, a patented gearless hydraulic drive was developed. The hydraulic fluid used in the drive is a biodegradable fluid that does not have any negative impact upon the environment. The elevation drive is a single hydraulic linear actuator and the azimuth drive is composed of two hydraulic linear actuators and an offset cam. The two azimuth actuators apply force to a cam to achieve the commanded position. Elevation rotation is from 10 deg to 95 deg and azimuth is a full 360 deg. A single hydraulic pump is used to pump the fluid from the reservoir into a pressure vessel. When the upper operating pressure limit is reached, the pump turns off and remains off until the pressure drops to the lower pressure limit. The hydraulic drive system was first tested in 1998 and currently there are over 10 systems operating. Minor changes have been made over the years to increase the reliability and lower the cost.

The elevation drive system has a high slew rate capability as well as a low track rate for sun tracking. The high track rate is used to move the array to a safe position in the event of a fast-moving wind front or dust devils. The array can move from any position to a face-up wind stow position in less than 15 seconds.



Figure 4. A five MegaModule™ tracking structure.

The drive system is designed to survive a 90 mph wind and operate up to an average wind speed of 29 mph. The system also has a fail-safe wind stow mode: in the event of the loss of power to the array, the array will automatically move to a face-up stow position using the pressure stored in the pressure tank.

The electronic control system has open loop control algorithms with a sun detector adjustment. The sun detector provides a signal to the controller when the sun image moves beyond a threshold limit. Incremental encoders on the elevation and azimuth gimbal angles provide feedback information to the controller as to the actual position. A position error is determined by comparing the actual position to the calculated position. When this error is above a threshold value, the electronic controller activates the proper valves to move the array in the direction to reduce the error.

The electronic controller is completely autonomous but can be monitored or controlled remotely. The electronic controller has a built-in GPS signal to obtain universal time. Using universal time and the array position, the controller calculates the sun's position. When the sun's elevation reaches a data base value in the morning, the controller moves the array to the sun position. As the sun's irradiance increases, the inverter will connect to the grid and start producing power automatically. The controller maintains the array pointing at the sun over the day. In the event of heavy cloud cover, the inverter will automatically disconnect from the grid but the array will continue to track the sun. When the cloud intensity decreases, the system will reconnect to the grid and start producing power again within minutes. When the sun's elevation reaches the lower preset elevation limit, the array is moved to a night stow position.

An anemometer is mounted on each array. When the wind reaches a data base level, the controller moves the array to a face-up stow position. It stays in the wind stow position until the wind speed stays below a threshold for a preselected time period. The

array then returns to tracking the sun and power generation.

The power generator-wiring configuration is shown in Fig. 5. Each MegaModule™ has two strings. To provide a high reliability, the cells are wired in a series string of 576 cells. Each string is wired in parallel to the other strings. If a

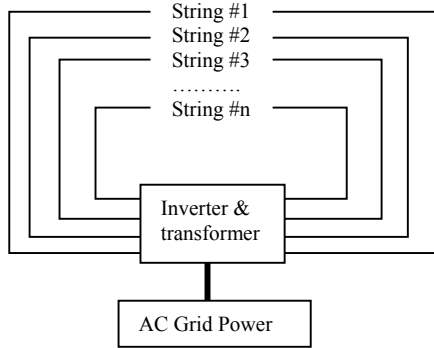


Figure 5. Power generator wiring configuration

problem occurs with a string, the power from that string is lost but the power generation of the other strings is not affected. In addition, as discussed above, each cell has a by-pass diode that prevents a bad cell from interrupting the power production of the string. In the event of a bad cell, only the power of that cell and the drop across the diode are lost, approximately 14 watts. These features greatly increase the system reliability because of the reduced number of single point failures that would reduce the power level to zero. The inverter, transformer, and drive control system are the only major single-point failures that would take the array off-line. Other failures only result in reduced power.

OPERATION AND MAINTENANCE (O&M)

As discussed above, the system operates completely autonomously but the system can be monitored or controlled from a remote site if required. Currently the 4 arrays located at Glendale, AZ are monitored from the APS STAR facility in Tempe, AZ.

The array has not only been designed to achieve a high reliability but to minimize maintenance operation in the field. In the 25 kW array configurations, there are 24 plates connected in series to form a string. When a problem occurs in a string, it can normally be isolated to a plate by simply measuring the open circuit voltage. The array does not need to be moved to a stow position for this operation but only off-sun. Once off-sun, the plate can easily be removed and replaced with a new plate. The plate can be returned to a repair location where the plate can be repaired. The plate consists of six cell strips (four cells per strip) and interconnecting wiring. If the cell strip is the problem, it can easily be replaced.

When a problem occurs with most single pedestal azimuth drives, a crane must be used to disassemble the unit or to lift the tracking structure up while a second crane is used to lift the old drive out and replace it with a new drive. In this gearless drive, the majority of the drive components can be replaceable without any disassembly of the array. The hydraulic actuators, valves, cam, and all of the bearings except for the main rotational bearing can be replaced without the removal of the array structure. Only when there is a problem with the main structure is a crane required for repair.

The control electronics, control valves, inverter, grid interface, and transformer are modules that are all located at ground level for easy servicing. They are all separate modules that can be replaced with a minimum of interface with other modules, minimizing disconnecting and connecting operations.

Washing the lenses is the only periodic maintenance task. The frequency of washing for optimum power generation will depend upon the location. It should be less than for glass concentrators or heliostats because of the single light passage through the lens versus double through a glass reflector. There are two bearings in the azimuth drive that have grease fittings. These presently require greasing about once a year but with future design improvements will result in a longer service life. Except for a few startup problems, hydraulic fluid leaks have not been a problem. From the limited amount of operating time in the field, the design time for replacement of hydraulic fluid of more than a year appears to be achievable. The control system monitors the state of the hydraulic fluid and will set an alarm when it is low. All other maintenance items are as performed as required.

INSTALLATION

The system is manufactured in three main subassemblies of pedestal, drives and torque tube, and MegaModule™. First the foundation is installed in



Figure 6. Installation of a MegaModule™. the ground. A 48-inch diameter hole is drilled approximately 15 feet into the ground, depending upon the soil conditions. The pedestal is positioned

vertically in the hole and concrete is poured around the pedestal pipe. The drives and torque tube are shipped to the site as a single unit. After the foundation has set, the drives and torque tube are lifted up and mounted on top of the pedestal. The power wiring, control electronic, control lines, and inverter are connected and checked out. The MegaModules™ are shipped 2 on a truck. A crane lifts the MegaModules™ off the truck and they are mounted on the array tracking structure as shown in Fig. 6. Presently it takes 3 to 4 hours to mount 5 MegaModules™.

Since the operation of each array is independent of the other arrays, it can start producing power once installed and checked out, thus power production does not have to wait until the last array is installed in a large field before revenue can start to be generated. This is a distinct advantage over conventional power plants such as a gas turbine plant, which takes a year and half to two years before revenue can be generated or a steam power plant which takes three to five years [4] from the initial funding point.

SYSTEM PERFORMANCE

The array will start operating automatically in the early morning producing power when the sun's insolation reaches 300 to 400 W/m². The power will continue increasing as the sun's irradiance rises as shown in Fig. 7. After solar noon, the generated power will start decreasing as the sun's irradiance falls. The array will continue to operate until the sun's irradiance reaches the operating limit in the evening. The output power as a function of the direct normal irradiance (DNI) is shown in Fig. 8 for one of the 20 kW array installed at APS in 2000. Power production starts at approximately 300 W/m², and at a DNI of 850 W/m², the power production is 20 kW. The output power shown is gross power. The gross power

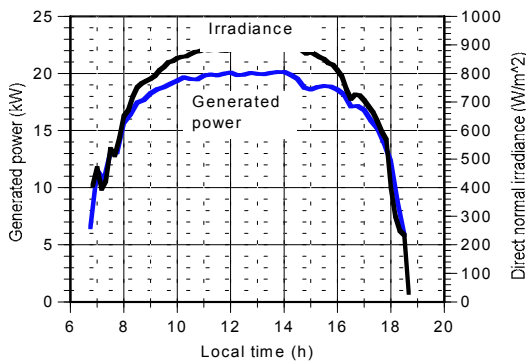


Figure 7. Typical generated power for the array.

and net power are nearly the same since no power is required for cooling and the parasitic power for tracking over the day is small, less than 100 W average over the day. At a DNI of 1000 W/m² the array would generate a gross power output of 18.6 kW or a net power output of 18.1 kW.

The daily net generated energy performance for the current design configuration is shown in Fig. 9. The line shown represents the maximum daily energy

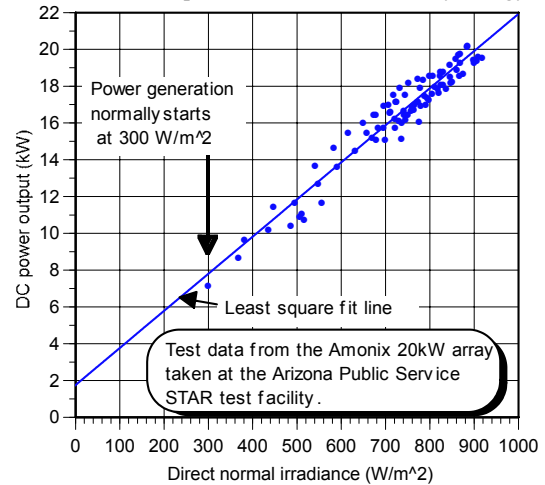


Figure 8. Power production of a 20 kW array.

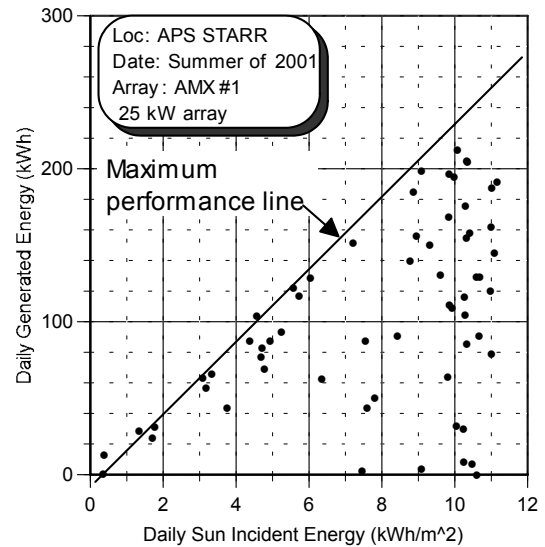


Figure 9. Test data of the net dc daily energy

performance of the array. The dispersion of the data points below the performance line are mainly the result of lens soiling, wind, field tests, and operating problems. Soiling is the major reason for the dispersion of the data at this site and is caused by construction in the area and proximity to major highways. The array was also taken off-sun to conduct specific field tests to characterize the performance, thus reducing daily energy generated. Since Fig. 9 represents data gathered early in the maturity of the 5th generation, some design problems remain to be corrected. When the fine-tuning has been completed, it is expected that the slope of the maximum performance line will increase. The total energy generated by the 5th generation system since

installation started is shown in Fig. 10. The upward slope of the data is because of the additional arrays that have been installed.

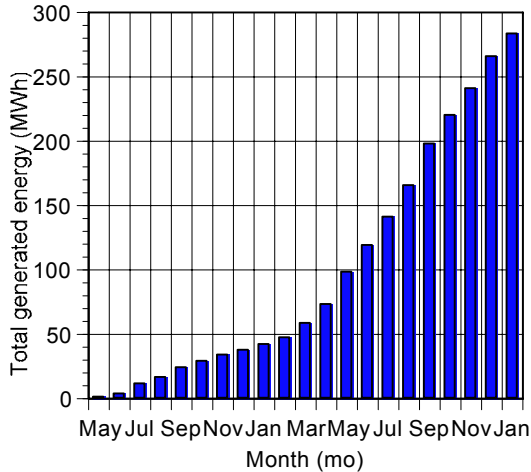


Figure 10. Accumulated energy produced.

MANUFACTURING

A manufacturing facility has been set up to manufacture approximately 1 MW or 200 MegaModules™ per year as shown in Fig. 11. The cell are manufactured, mounted on a strip subassembly, and mounted on plates. After on-sun acceptance tests are conducted on each plate, it is ready for assembly on the support structure. A four-point flange structure in the center of each MegaModule™ serves as the structural interface with the drive torque tube. C-shape channel sections are set up in a tooling fixture as shown in the right side of Fig. 11. End and bulkhead C-shape channel sections are then installed as shown in the center of Fig. 11. Next the cell plates are installed on the structure. A small crane (center of Fig. 11) is used to lift the structure and rotate the assembly such that the cell plates are on the bottom. The 48 Fresnel lenses are then installed on the top face of the structure. This



Figure 11. MegaModules™ manufacturing facility.

completes the assembly of the MegaModule™ and it is stacked on top of other modules waiting to be loaded on a truck for shipment to the site (far left of Fig. 11).

MARKET APPLICATION

This system has been designed to operate with conventional utility grids, distributed applications, and off-grid or remote markets. The system is well suited for plants sizes of 1, 5, 10, 100, or 1000 MWs. Plants of this size would result in the lowest levelized energy cost because of economy-of-scale both in manufacturing, installation, and plant maintenance. Large-scale production would allow special tooling for mass installation and reduced operating and maintenance (O&M) cost per kWh. The plant will have very high reliability and availability. Since each array operates independently of the other arrays, a failure with one array would only result in the loss of that array's power. Since an array can be taken off-sun at any time without affecting any others, there would not be a need for an annual maintenance outage period as there is with most conventional utility power plants.

The system characteristics also make it applicable for distribution along transmission lines to boost the power; near industrial parks; at high end users such as mining, telecommunication, and radar installations; or at the end of a transmission line where the community is outgrowing the capability of the transmission line.

The autonomous operating feature of this system makes it well suited for off-grid application. Since it has a very low parasitic power requirement, a remote system will not require significant power storage. The controller is designed such that stored hydraulic pressure is always available for emergency wind stow, or it can be used to move the array to a sun tracking position. The high reliability resulting from no moving parts in the power conversion system and low number of single-point-failure in the power conversion system, make the system well suited for remote application.

A clear advantage to the end usage is not only the independence from fuel price fluctuations but also the ability to add to the generating capacity in small increments in a very short period of time.

SYSTEM COST

The present cost of the installed system is decreasing with time as design changes are made, the production rate increases, and production processes are improved. An estimate of the cost of the current system is less than \$5.50/W at a production rate of 5 MW per year. According to a Solar Electric Power Association report [5], the average cost for flat plate PV systems (at much higher production levels) was \$8.10/W in 1999-2000.

CONCLUSION

Amonix has developed and is currently manufacturing a high concentration PV system. Over 350 kW have been installed at major US utilities and

have operated for many years. Amonix has continued to refine the design to lower manufacturing cost and to improve system performance. The system has high reliability because of designed-in fault isolation, no moving parts in the power conversion system, and minimum single-point failures. The system requires no operator because it was designed to operate and is operating unattended. Maintenance is very low because the system was designed for easy module replacement. These features make it applicable for both grid power generation and remote power generation. The factory currently has the capability to manufacture 1 MW per year and the ability to expand to meet future markets.

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