Concentrating PV Systems

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Science Applications International Corp (SAIC): 20+ years

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- Overview:
  - Theory of PV Cells and Sunlight
  - Why Look at Concentration?
  - Example Systems and Technologies
  - Competitiveness

Concentrating PV Systems

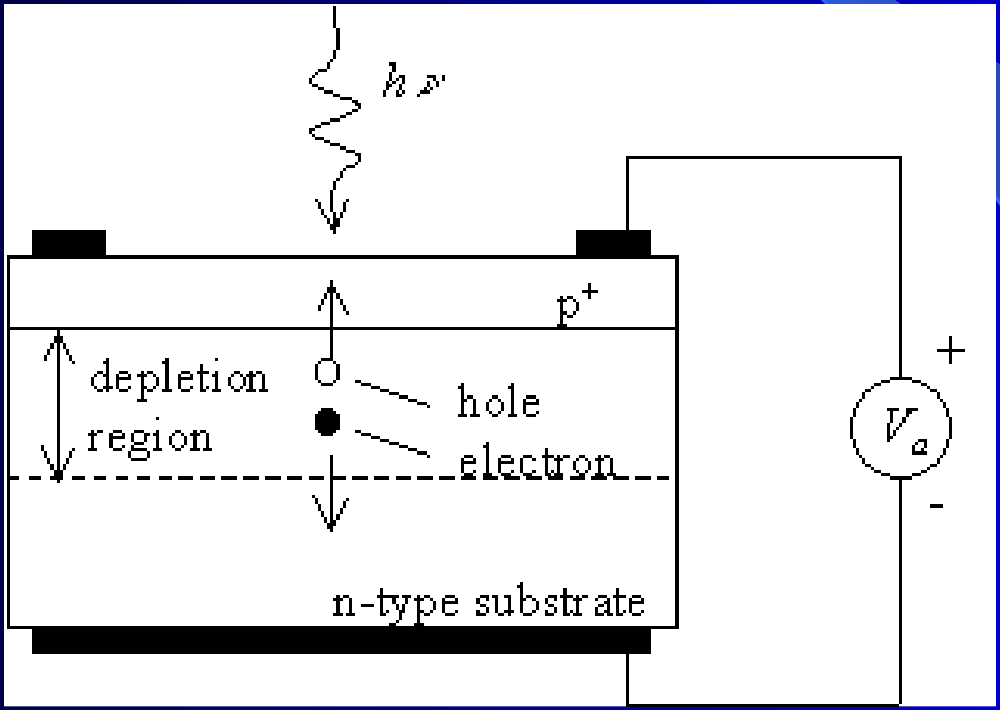
- How a Photovoltaic (PV) Cell Works
  - PV Physics (Silicon example):
    - Silicon forms a crystal lattice with its four free electrons bonding to each of four nearby atoms
    - Phosphorus can replace Silicon in the lattice but has 5 free electrons so one is “extra” (p-type material – electrons)
    - Boron also replaces Silicon but only has 3 free electrons so one is “missing” (n-type material – holes)

Concentrating PV Systems

- How a Photovoltaic (PV) Cell Works (cont.)
  - Putting a p-type material in contact with a n-type material forms a p-n junction that establishes a static electric field (bandgap Voltage) across the junction
  - When a photon of sufficient energy is absorbed in the p-type material, it “pumps” an electron across the junction
  - An electrical connection between the p-type and n-type material completes the circuit and allows the electron to “get home” while doing external work across a resistance.

Concentrating PV Systems

- How a Photovoltaic (PV) Cell Works (cont.)



Concentrating PV Systems

- How do PV Cells Interact with Sunlight?
  - The energy needed to get an electron across the p-n junction is 1.1eV for silicon (different for each semiconductor material)
  - A photon with lower energy (too far in IR) doesn't produce a free electron
  - The excess energy from a higher-energy photon (e.g., UV) gets lost as heat.

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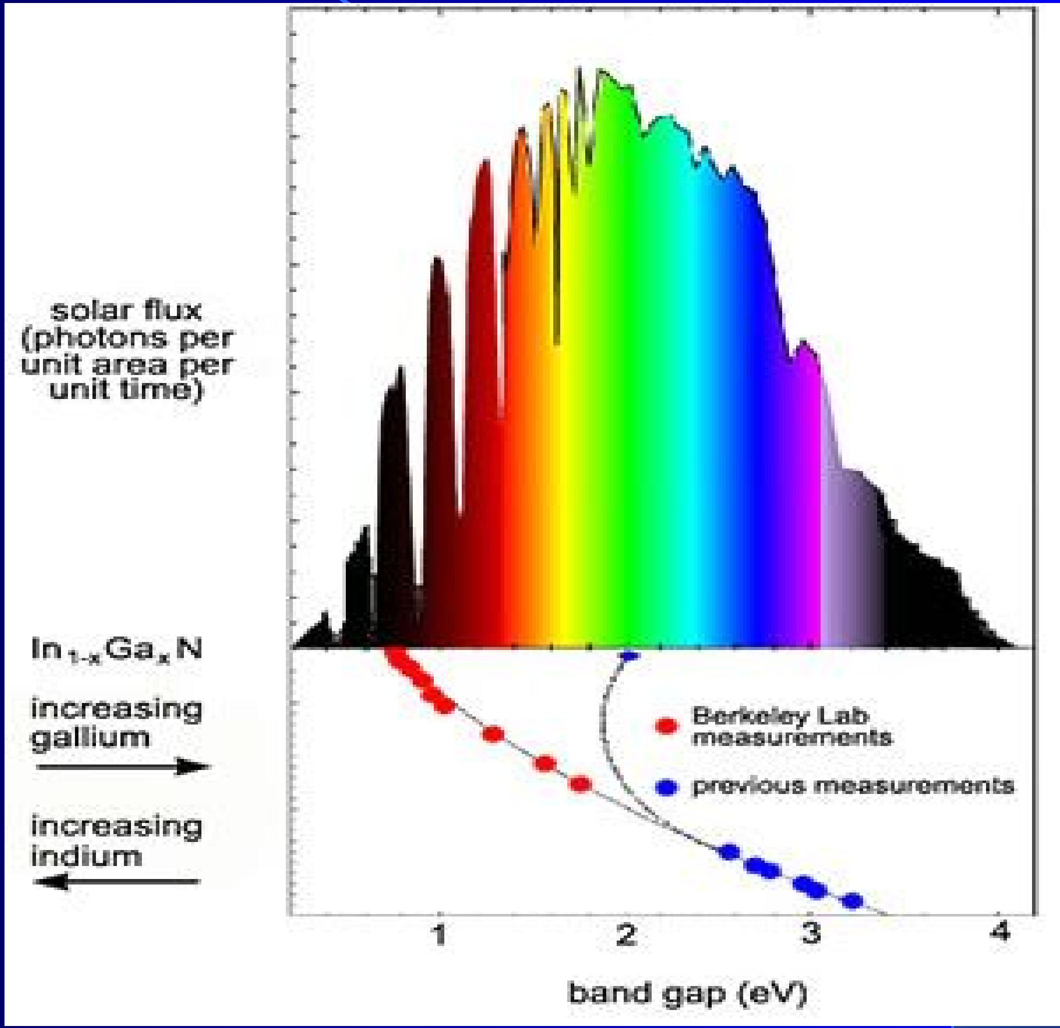
- Solar Spectrum

Semiconductor	Bandgap (eV)
Ge	0.66
In	0.7
Si	1.11
GaAs	1.43
CdTe	1.44
GaP	2.25
ZnO	3.2
ZnS	3.6



Concentrating PV Systems

- Solar Spectrum
  - The solar spectrum has photons ranging up to about 4eV. A single-material PV cell can only convert about 30% of the available energy to useful electrical power.
  - To improve this, we can use multiple cells with different bandgaps, but the cells/receivers are more complex and therefore cost more.
    - Examples of Spectrolab, United Technologies

Concentrating PV Systems

- Multi-Junction PV Cell Approach
  - Spectrolab is the world's largest producer of space solar cells, starting in 1959
  - Spectrolab has developed 2-, 3-, and even 4-junction high-efficiency cells
  - A Spectrolab cell has demonstrated 40.7% efficiency (Dec 2006)
  - Spectrolab is producing cells for commercial applications. (Example characteristics of Spectrolab cell from data sheet…)

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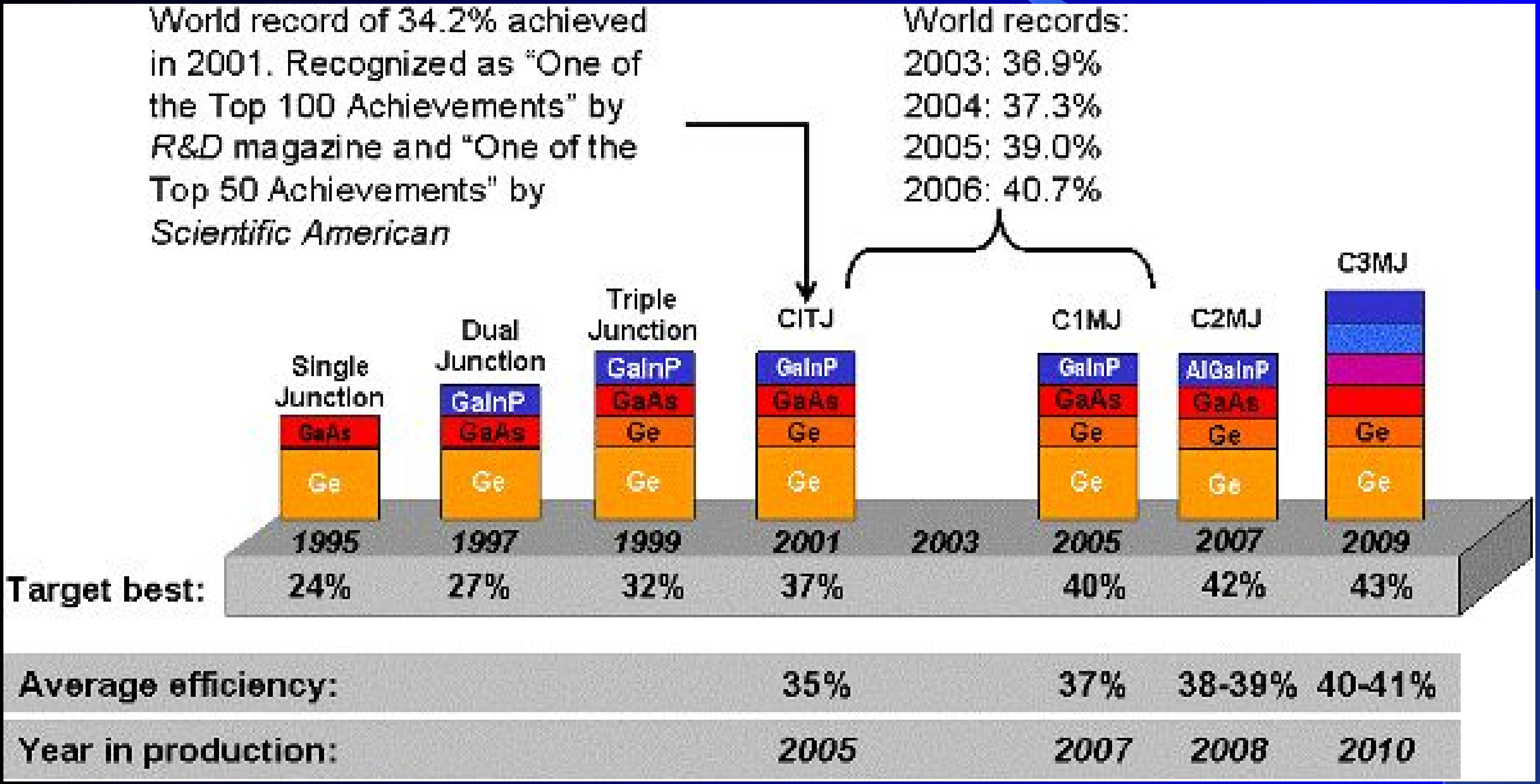
- Spectrolab Cell Development Records



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- United Technologies Approach
  - Stacked cells require matching current from each cell in the stack. This is difficult with varying spectral light during the day.
  - Instead of stacking cells, UT places many single-junction cells of different types in an "integrating sphere"
  - "Rugate filters" are used to reflect light away that doesn't match each cell's bandgap
  - This allows each cell to operate in the narrow spectral band where it is most efficient

Concentrating PV Systems

- Both these approaches to high-efficiency PV receivers are expensive and complex
  - Although some flat panels of multi-junction cells have been used for space power, you wouldn't want to build a terrestrial flat-plate panel of multi-junction cells or UT receivers because of the expense
- To mitigate the expense of the high-efficiency PV receivers, we consider concentrating the sunlight onto the cells to make Concentrating PV (CPV) systems

Concentrating PV Systems

- What Concentration Does For You
  - Good Things
    - Replaces solar cell (silicon, GaAs, exotics) area with lower cost materials (e.g., glass mirrors, steel, aluminum, and plastic)
      - This reduces the total solar cell area so you can afford more efficient and more complex cells
    - Solar cells are more efficient at high concentration (up to 400-1000 suns)
    - Solar production can start earlier and extend later in the day due to tracking

Concentrating PV Systems

- What Concentration Does For You
  - Bad Things
    - Cells heat up and lose efficiency, so they must be cooled (cell voltage goes down with temperature)
    - Concentrating systems only use direct sunlight – no help from diffuse light (as opposed to flat plates, which can use all light)
    - System must track the sun; the higher the concentration, the more accurately it must track. E.g., for 500X concentration, errors can't be more than a milliradian (0.06 degrees) or so.
    - Concentrator systems are more complex than fixed flat-plate PV panels – more failure points, lower reliability
    - Potential for danger from focused solar flux in some systems

Concentrating PV Systems

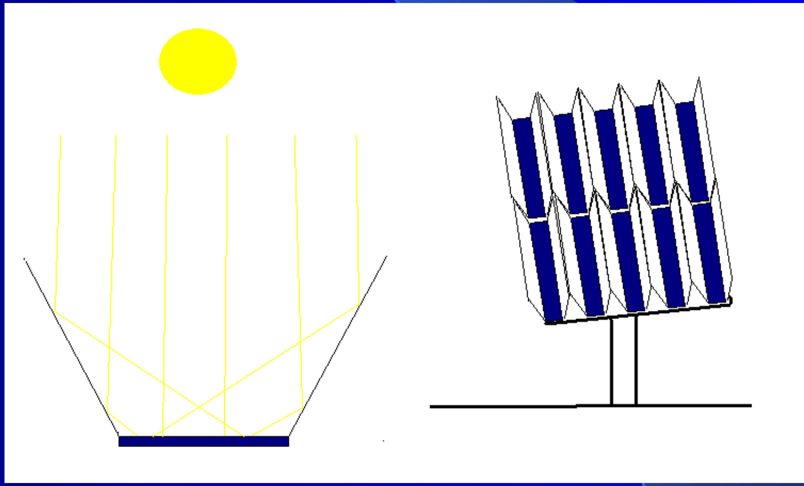
- What Concentration Does For You
  - As a result, all CPV system designs are a delicate balance of cost, efficiency, and complexity
    - System cost is traded off against precision and complexity for accurate tracking
    - Efficiency is traded off against tracking accuracy and thermal management complexity/cost
    - System size is traded off against production, shipping, and installation costs
  - Available systems demonstrate different approaches to these trade-offs

Concentrating PV Systems

- Approaches to Concentrating PV (CPV) Systems
  - Enhanced flat plate (mirrors on sides) – Carrizo Plains
  - Hybrid PV/thermal trough – Davenport (1979)
  - Single-axis trough – Entech
  - Single-lens, single cell - Amonix
  - Single mirror, single cell – CT Dish
  - Dish with monolithic receiver – SSL, SAIC, EdTek, United Innovations
  - Central Receiver CPV - SSL

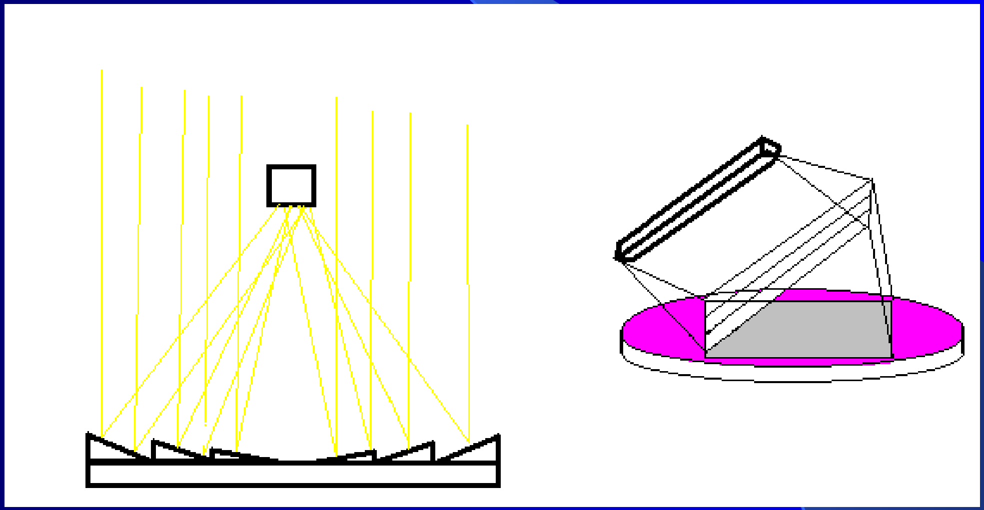
Concentrating PV Systems

- Enhanced flat plate (mirrors on sides) – e.g., Carrizo Plains
  - A step above flat plates and tracking flat plates
  - About 2 suns illumination
  - No thermal control – panels heat up significantly
  - Materials problems led to degradation of output over time



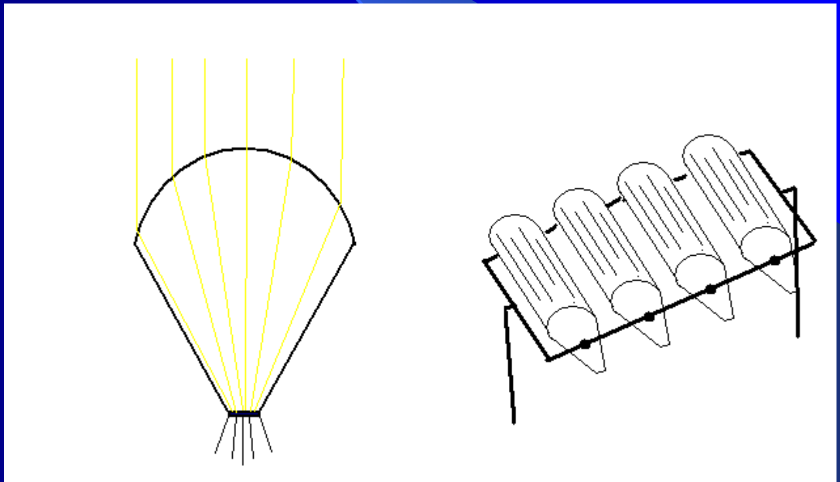
Concentrating PV Systems

- Hybrid PV/thermal trough – Davenport (1979)
  - Proposed to CA Energy Commission
  - Fresnel mirrors on floating turntable
  - Cooling water pumped behind cells
  - PV electricity and hot water to be used for household use
  - ~1kW in size
  - Not funded….



Concentrating PV Systems

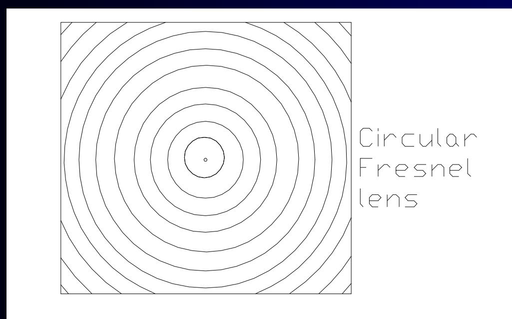
- Trough Fresnel Lens– e.g., Entech
  - Curved plastic Fresnel lens with 1-dimensional focus onto PV cells
  - Passive cooling
  - Often ganged on trackers to reduce cost
  - Low concentration (~40X)

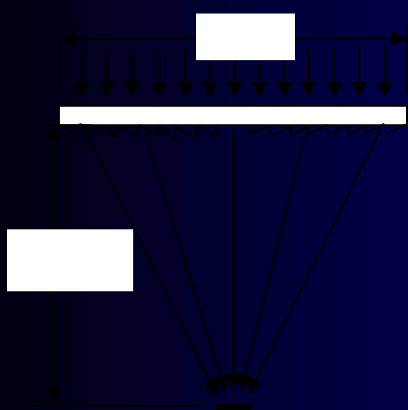


Concentrating PV Systems

- Single-lens, single cell – e.g., Amonix Corp.

SYSTEM OPTICAL PRINCIPLE

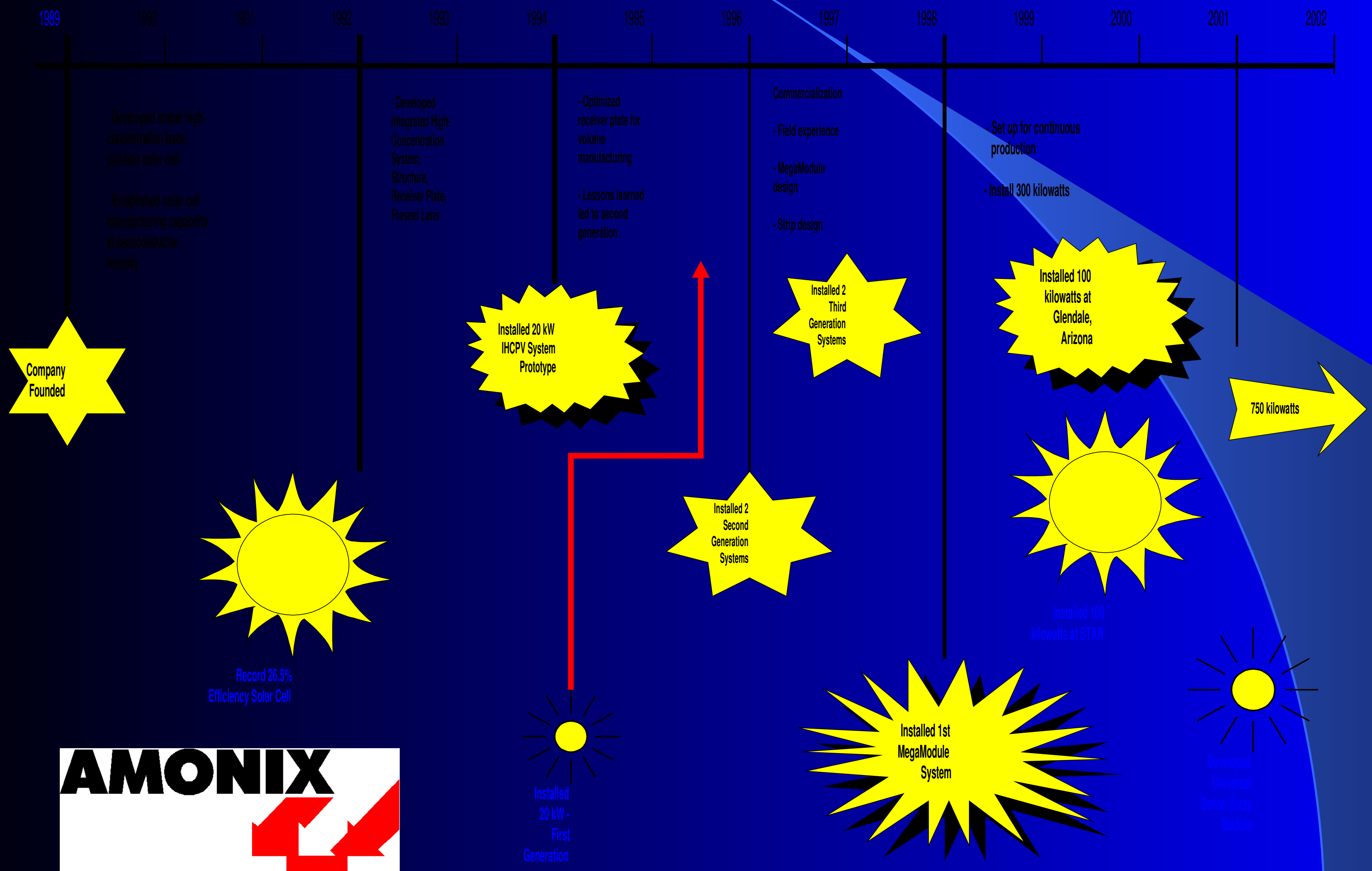




- Circular Fresnel lens designed to refract sunlight onto single cell at the focus
- Secondary optical element around cell captures any “spillage” and allows for some tracking error
- Solar concentration of 250 suns
- Lens about 18 cm square
- Cell about 1cm square

BACKGROUND DEVELOPMENT

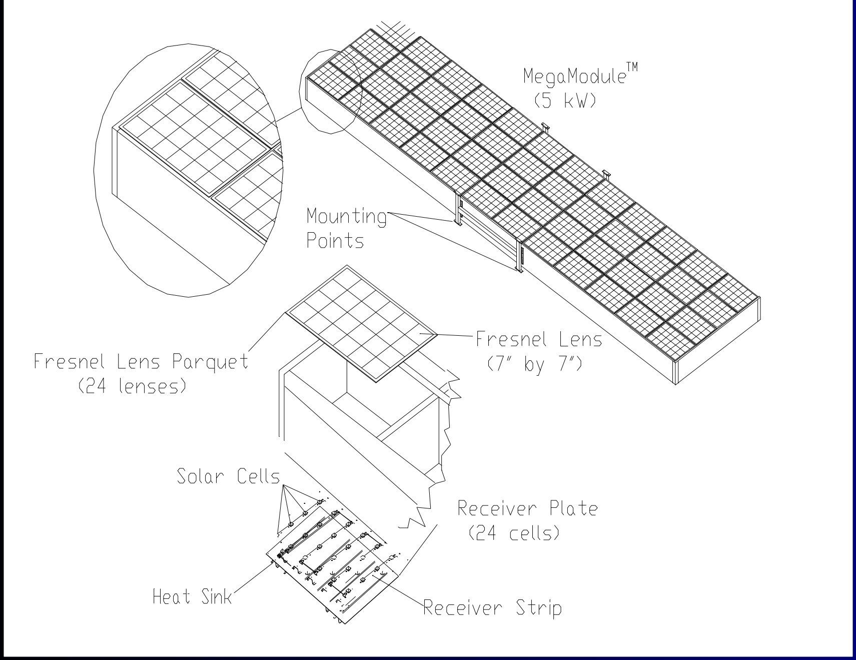
Key Milestones



THE ARRAY IS COMPOSED OF FOUR MAJOR SUBSYSTEMS

- MegaModule
- Drive, torque tube, pedestal/foundation
- Power conditioning system
- Tracking control System

MegaModule™ - BASIC BUILDING BLOCK



- Produces 5 kW at rated conditions
- Composed of 1152 cells & lenses
- 24 cells per chamber
- 48 chambers per MegaModule
- Cells connected in series
- Two cell strings per MegaModule
- Length ……….. 44 ft
- Width ………… 11 ft
- Weight ………. 5,200 lbs
- Passive heat removal via fins on back of module
- Next-generation mega-module is both lighter and simpler

DRIVE, TORQUE TUBE, & PEDESTAL/FOUNDATION

- Hydraulic drive (patented by Amonix)
  - Elevation is single linear actuator
  - Azimuth uses dual linear actuators
  - Wind stow in under 45 seconds
  - Wind stow without electrical power
  - Survival winds of 90 mph
- Pedestal/foundation
  - Single pipe pedestal to foundation
  - Concrete poured around pipe
- Torque tube is single pipe with mounting flanges for Megamodules

POWER CONDITIONING AND TRACKING CONTROL SYSTEM

- Power conditioning
  - Converts DC to AC power
  - Peak-power tracking
- Tracking control
  - Automatic, unattended operation
  - Remote or local control
  - Closed-loop tracking

DESIGNED FOR MASS PRODUCTION AND FAST FIELD INSTALLATION

- Manufactured in Torrance, CA
- Factory assembled & tested
- Shipped by truck to site, no permits needed
- After pedestal/controls are installed:
  - Array installed in less than half a day
  - Power production can begin the next day

HIGH RELIABILITY & LOW FIELD MAINTENANCE TIME

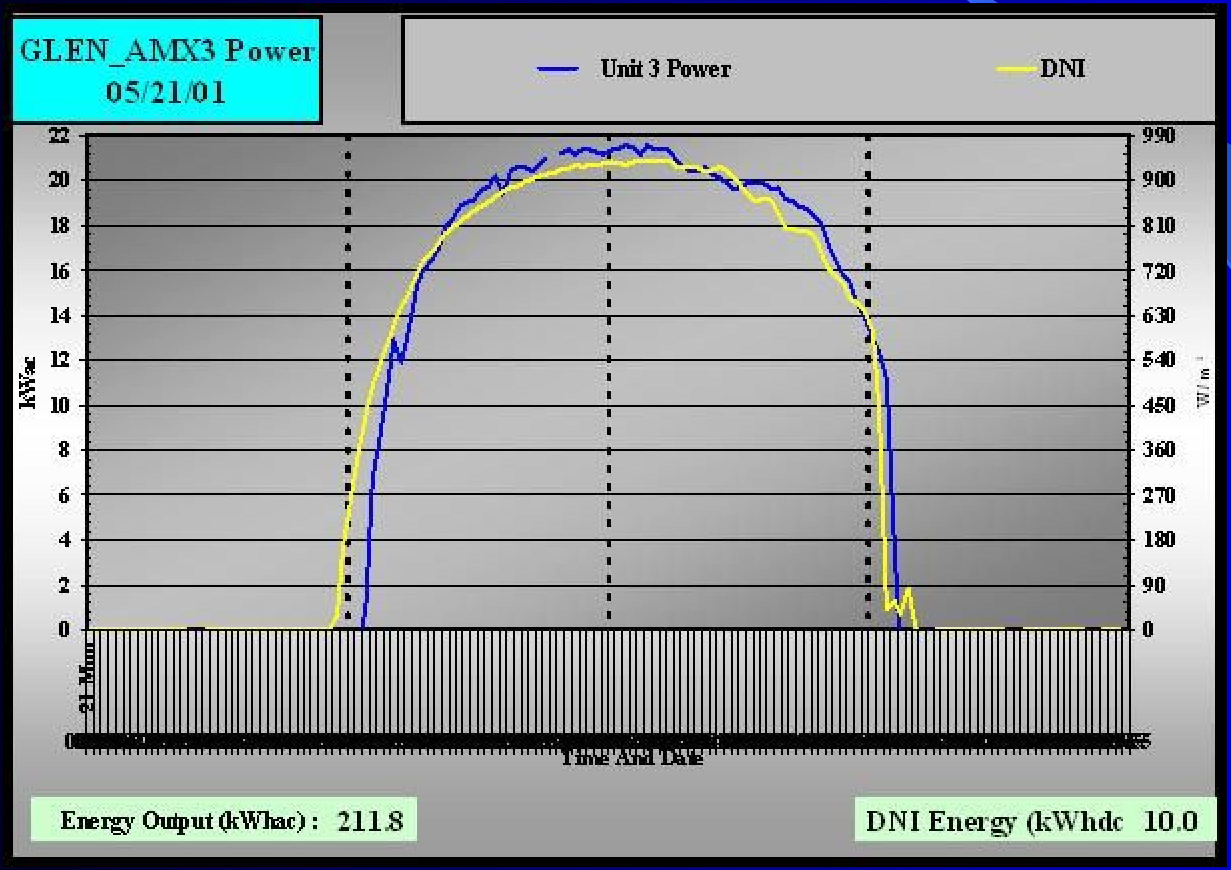
- Major components at ground level
- Field module change out
- Access ladder to upper components
- Drive component replacement without requiring a crane
- Passive cooling, no moving parts
- High system reliability

  - Cells connected in parallel strings

  - Bypass diodes prevent loss of string

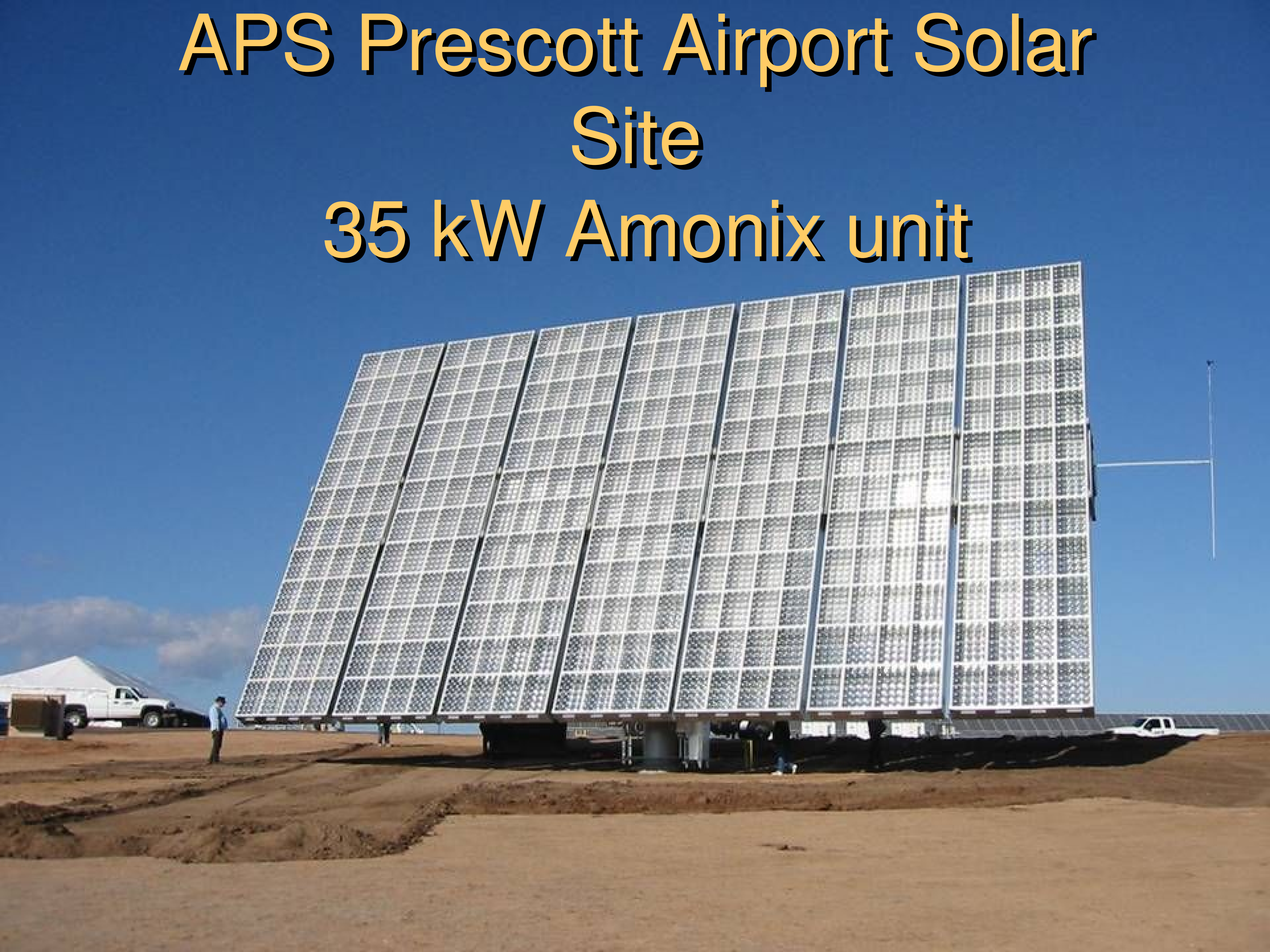
DAILY POWER GENERATION

- Power generation follows the solar insolation
- Fast power response after passing of a cloud



Amonix at APS STAR Site

APS Prescott Airport Solar Site
35 kW Amonix unit



AMONIX: Over 600kW Installed and in Operation

➢ **Over 4.7 GWh of grid energy produced since May of 2000**

APS STAR West Field Site

- 145kW (3 x 25kW, 2 x 35kW)
- 75 months of operation
- 1,490 MWh

UNLV Site

- 25kW (one system)
- 43 months of operation
- 190 MWh

APS Prescott Site

- 140kW (5 x 35kW)
- 55 months of operation
- 1,075 MWh

APS STAR East Field Site

- 125kW (5 x 25kW)
- 60 months of operation
- 923 MWh

APS Glendale Site

- 100kW (4 x 25kW)
- 79 months of operation
- 831 MWh

Nevada Power Corp. Site

- 75kW (3 x 25kW)
- 17 months of operation
- 192 MWh

Concentrating PV Systems

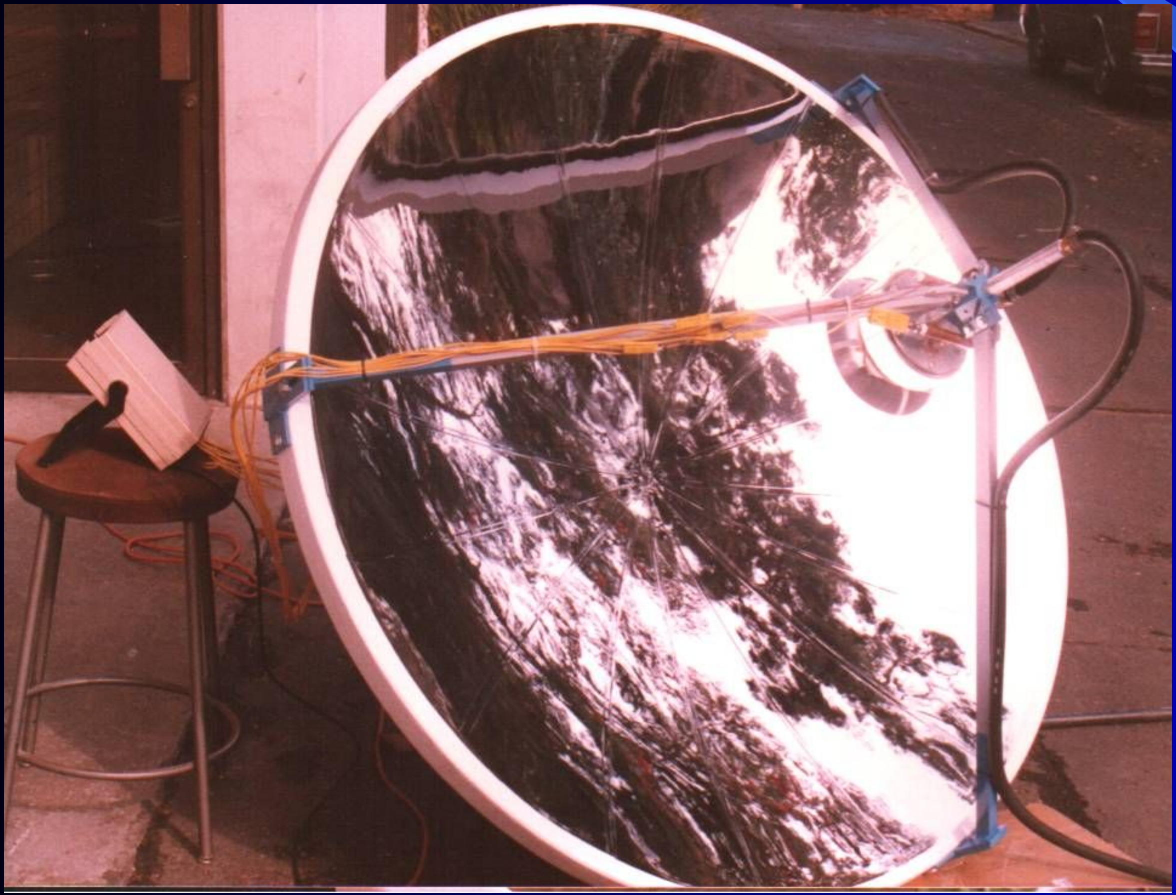
- Single mirror, single cell – CT Dish
  - Each module has heat-pipe radiator
  - R&D – No large-scale deployment yet

Concentrating PV Systems

- Dish reflectors with monolithic receiver
  - Usually large in size to make economies of scale for tracker/drive
  - None deployed in the US yet except as R&D prototypes
  - Active pumped-water cooling of receiver with radiators or ground-coupling for heat rejection
  - Receivers are close-packed cells, usually with back contacts

Concentrating PV Systems

- Dish reflectors with monolithic receiver

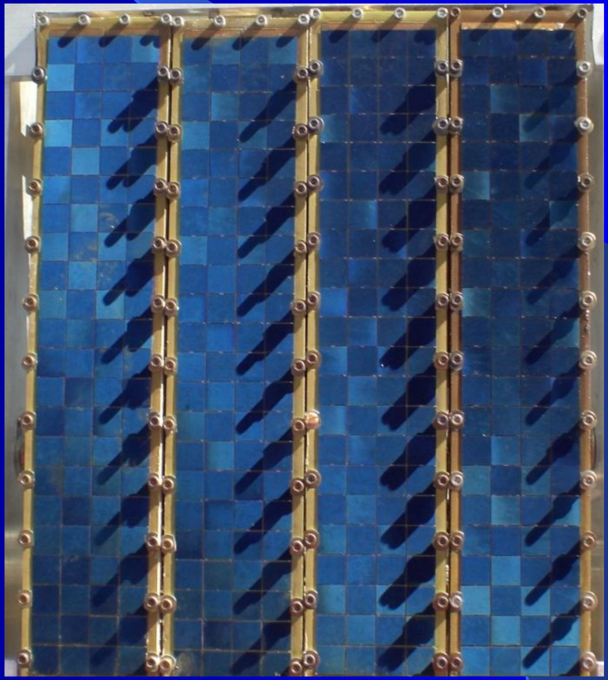


- Proof of concept test
- PV cells were at a low level of development (not yet ready for prime time)
- SAIC built composite dish, receiver cooling plate

SAIC 300W Small Dish/PV System (1990)

Concentrating PV Systems

- Dish reflectors with monolithic receiver



SAIC 20kW Dish/PV System at UNLV (2007)

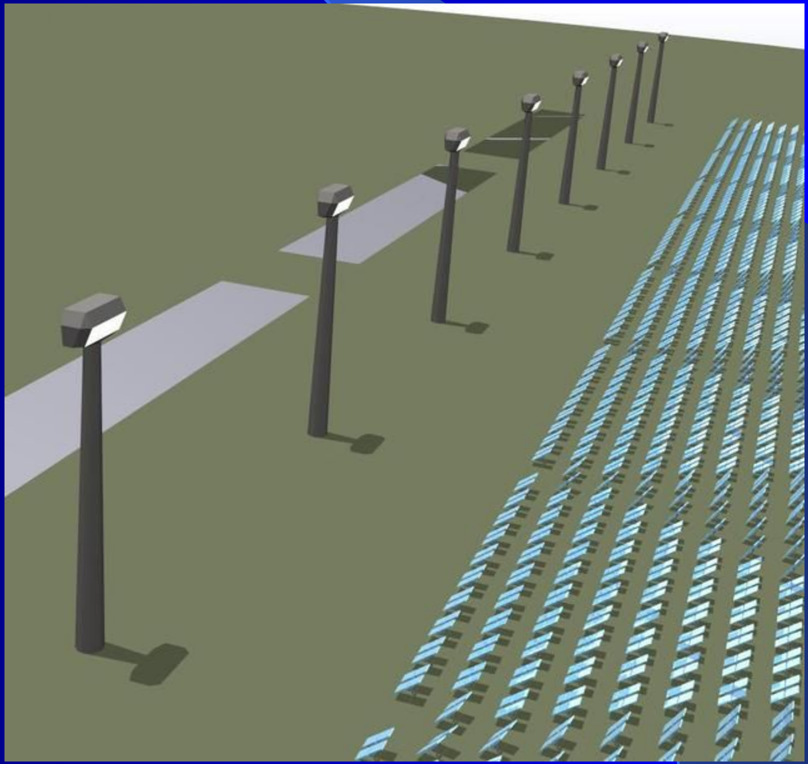
Concentrating PV Systems

- Dish reflectors with monolithic receiver

Solar Systems Limited 20kW Dishes in Australia

Concentrating PV Systems

- Central receiver CPV (e.g., SSL)
  - SSL now building a 154MW plant in SE Australia
  - Monolithic receiver allows quick upgrade
  - Cost expected to be 10 cents per kWh
  - 95 million (AUS$) funding from Australian government



Concentrating PV Systems

- What About the Competition?
  - Solar Thermal Power Systems
  - Other PV Technologies
  - Between CPV Technologies

Concentrating PV Systems

- How Does CPV Compare to Solar Thermal Technologies?
  - A CPV system at 15% peak efficiency can out-perform a dish/Stirling system at 25% peak efficiency
    - Lower parasitic energy requirement leads to more hours of operation per year
    - Efficiency actually improves at partial load and in cold weather (opposite of thermal systems like Stirling engine)
  - PV cells are pushing 40% efficiency, which is much higher than any solar thermal converter; cost projections are <$1/W in large-scale production
  - CPV has fewer moving parts and no high-temperature parts, giving the potential for higher reliability than any solar thermal technology
  - Solar thermal can be stored and hybridized, making it more valuable to utilities (peak-matching, dispatchability)

Concentrating PV Systems

- CPV Compared to other PV Technologies:
  - CPV is expected to compete mainly in large systems due to economies of scale and cost of tracker/controls
    - But single-lens/single-cell systems have small basic building block (~10W) so a clever design might be cost-effective at smaller scale
  - Because of smaller cell production requirements, CPV is cheaper to scale up to large-scale implementation, so costs should come down faster than for flat plate PV
  - Flat plate PV systems have the advantage of providing power on the customer side of the meter => higher value power

Concentrating PV Systems

- Which CPV Technology Will Win?
  - Single-Lens/Single-Cell
    - Advantages
      - Simple design – no moving parts except for tracker
      - Flux profile not critical; just need to get sunlight on each cell
      - Fabrication and alignment done in factory
      - Inherently safe design – no more than a few 10's of Watts of power focused in any spot; all focused energy within the cavity of the unit
    - Difficulties
      - Degradation of lenses over time
      - Need to be careful to get good cell cooling – high-efficiency cells help with this

Concentrating PV Systems

- Which CPV Technology Will Win?
  - Dish/PV
    - Advantages
      - Reduced wiring losses for a given output
      - Easier receiver changeout or upgrade
      - Potential for “better” thermal management
    - Difficulties
      - Danger of 1000’s of Watts of power focused in space and on the receiver, and multiple failure points
      - Flux on receiver must be uniform – difficult to achieve in design without large losses; systems require alignment in field

Concentrating PV Systems

- Which CPV Technology Will Win?
  - Central Receiver CPV
    - Advantages
      - Integration into huge receivers reduces parts count
      - Heliostats are cheaper to build than dishes
      - Potential for even better thermal management than dishes due to fixed, large receivers
    - Difficulties
      - Multiple failure points; not as modular as dishes
      - Heliostats not as materials efficient as dishes (cosine effects)
      - Only suitable for utility power