ABENGOA SOLAR

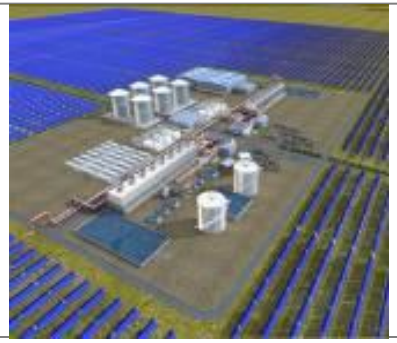
A New Generation of Parabolic Trough Technology

SunShot CSP Program Review 2013

Phoenix, April 2013

Content

Abengoa Solar is a leader in CSP with around 1.6 GW operational by 2014

Europe 681 MW	▪ PS10 & PS20 (11 and 20 MW), the first two commercial solar power towers in operation worldwide ▪ 11 parabolic trough plants in operation (50 MW each) ▪ 2 parabolic trough plants under construction (50 MW each)	
U.S. 560 MW	▪ Solana (AZ): 280 MW gross parabolic trough plant with six hours of storage under construction ▪ Mojave (CA): 280 MW gross parabolic trough plant under construction	
Rest of the world 400 MW	▪ Algeria: 150 MW hybrid plant (20 MW solar) in operation ▪ Shams-1 (Abu Dhabi): 100 MW parabolic trough plant under construction ▪ South Africa: 150 MW (50 MW tower, 100 MW parabolic trough plant) under construction	

For Abengoa the innovation and the R&D pilots are in the roots of the technology competitive advantage and CSP future

R&D | Pilot plant | Commercial project

- +100 in-house researchers
- R&D center in Denver, US
- R&D center in Seville, Spain
- Abengoa Research
- Collaboration with key research institutions and companies worldwide

Content

Over 25 years of operational experience

- Solar Electric Generating Systems (SEGS)
  - 9 plants, 14 to 80 MW, 354 MW total
  - Built between 1984 - 1990
  - 3 sites: Daggett, Kramer Junction, and Harper Lake
  - 30-year power purchase agreements with Southern California Edison
  - Hybrid plants 75% solar, 25% natural gas
  - Luz LS-1, LS-2, and LS-3 parabolic trough collector technology
- SEGS demonstrated commercial nature of parabolic trough technology
  - All plants still operating, many will likely operate past 30 year lifetime
  - Demonstrated exceptional annual and on-peak performance record
- Extensive data has been shared from plants
  - Encouraged global CSP market
  - Enabled improvements in the technology.
  - Reduced financial risk of technology

SEGS III-VII, Kramer Junction, CA

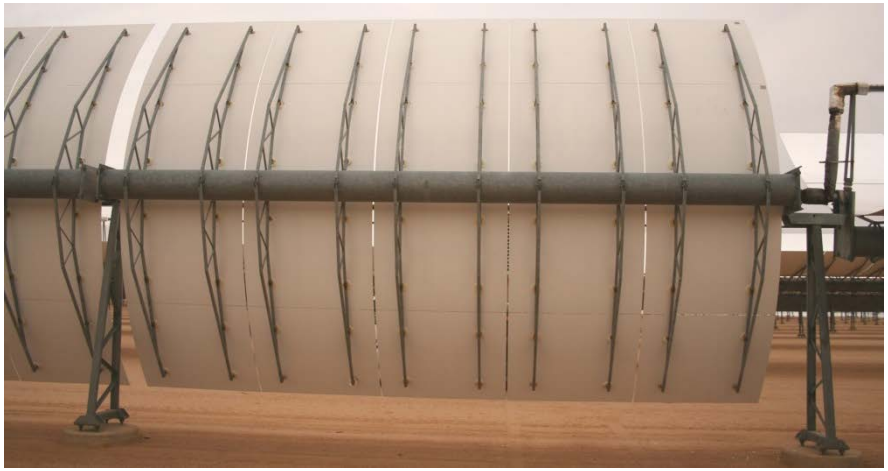
Benefits from 25+ years of operational experience

- Demonstrated Commercial Nature of Technology
  - Numerous problems identified and resolved as development progressed
  - Significant advances in the technology
- New Concentrator Structures
  - Reduced Cost
  - Improved Optical Accuracy
  - Optimized Assembly
- Improved Receiver Technology
  - Reduced Failure
  - Improved Performance
- Thermal Energy Storage
  - Indirect molten-salt TES systems
  - Allow solar dispatch
  - Higher solar capacity factors
- Ball joint assemblies
  - Improved reliability and lower pumping parasitics
- New tools developed by industry and labs
  - Optimize collector operation, cost and performance

LS-2 Parabolic Trough Collectors, Kramer Junction, CA

Luz Concentrator Structures

- LS-2
  - Torque tube design
  - Able to achieve good optical accuracy
  - Easy to assemble
  - Expensive to manufacture due to high tolerance on torque tube & mirror arms
  - ➢ **Good optical performance**
  - ➢ **High cost**



Luz System 2 (LS-2)

- LS-3
  - Space frame truss design
  - Larger aperture (15%)
  - 2x as long (100 meters)
  - Lower tolerance pieces (lower cost)
  - Alignment jig required for assembly
  - Inadequate torsion stiffness
  - ➢ **Cost savings not demonstrated**
  - ➢ **Lower optical performance**

Luz System 3 (LS-3)

1985 1989

LS-2 ⇒ LS-3

EuroTrough Concentrator

- EuroTrough
  - Torque box space frame design
  - Reduced steel content
  - Improved torsional stiffness
  - LS-3 aperture, 100 - 150m length
  - Alignment jig required for assembly
  - Significant labor to assemble
  - Consortium of European companies (including Abengoa)
  - ➢ **Performance similar to LS-3**
  - ➢ **Cost higher than desired**

Abengoa's ET II - Repow PS10

1985	1989	2000	2005
LS-2 ⇒	LS-3 ⇒	ET-I ⇒	ET-II

Abengoa ASTR0

- ASTR0 150
  - Torque box design
  - Redesigned to use low cost steel profiles
  - Eliminates welding in frame
  - Optimized factory assembly to reduce labor for assembly
  - Mirror alignment jig required
  - Collector assembly building required
  - Used in Abengoa plants in Spain and North Africa
  - ➢ **Reduction in installed cost**
  - ➢ **Performance similar to EuroTrough**

ASTR0 Collector

ASTR0 Solar Fields – Solnova 1 & 3

1985	1989	2000	2005	2007
LS-2 ⇨	LS-3 ⇨	ET-I ⇨	ET-II ⇨	ASTR0

Development of Next-Generation Parabolic Trough Collectors
DOE FOA (DE-FG36-08GO18037)

Patrick Marcotte, Ken Biggio, Kerry Manning, Diego Arias

- Objective
  - Develop the technology that is needed to build a competitive parabolic trough industry for the US utility market.
- Near-term
  - Focus on collector technologies that could be deployed in the 2010 – 2013 time frame.
  - deployed cost <$235/m2, commercial-quality optics
- Medium-term
  - Develop the next generation of lower-cost parabolic trough technologies that can compete on an equal footing with conventional power generation.
  - deployed cost <$190/m2 (>20% savings), improved optics (>2%)
  - Optimized for molten salt & DSG HTFs

Near-term Collector Development

- Phoenix Gen 2.0 (Cameo)
  - Extruded aluminum spaceframe
  - 5.75m Aperture, 150m length
  - Unique hub design, rim drive
  - No alignment Jig
  - Rapid module assembly (4.5 man hours)
  - ➢ **Optical performance target not achieved**

Phoenix Gen 2.0 – Abengoa Lakewood Test Site

- Phoenix Gen 3.2 (Solnova)
  - Aluminum spaceframe w/steel torque arms
  - Improved purlins, jig aligned mirrors
  - Improved receiver supports
  - Designed for Mojave seismic loads
  - Significantly improved optical perf.
  - 4 collector loop test in Spain end of 2012
  - ➢ **~10% reduction in cost from ASTR0**
  - ➢ **Good optical performance**

Phoenix Gen 2.0 – Xcel Cameo Coal Hybrid Plant

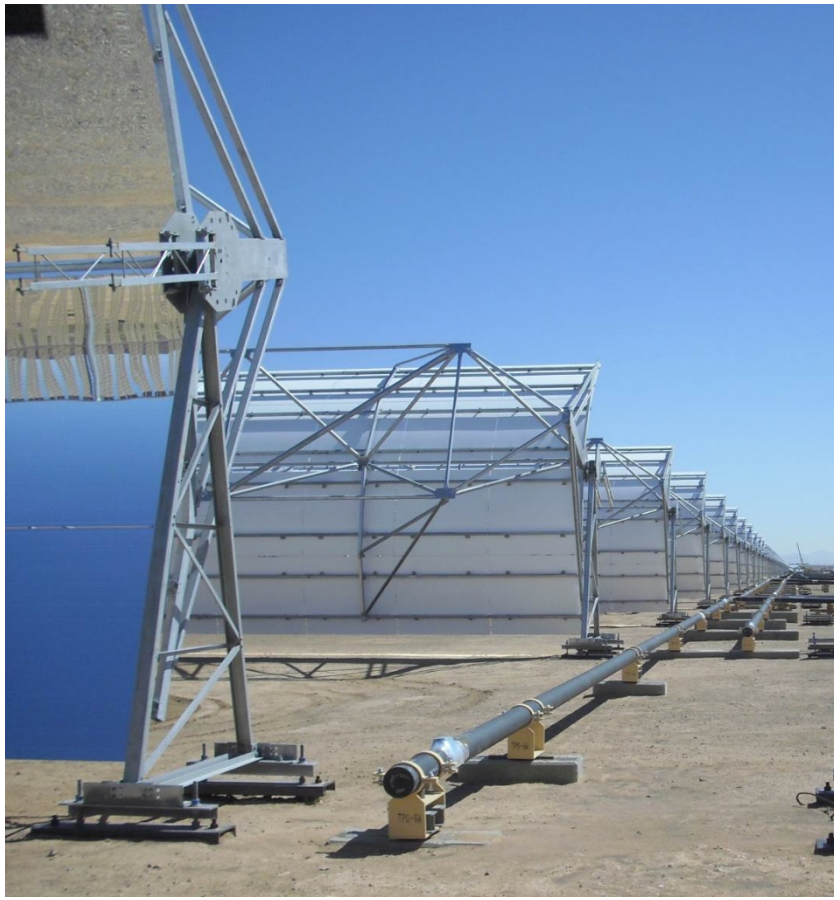
1985	1989	2000	2005	2007	2009
LS-2 →	LS-3 →	ET-I →	ET-II →	ASTR0 →	Phoenix

Near-Term Collector Development

Abengoa E2 Collector

- E2 (Eucumsa)
  - Steel spaceframe variation of Phoenix design
  - 5.75m Aperture, 125m length
  - New crimped steel members & hubs
  - Standard ASTR0 torque transfer connection
  - Requires jig alignment of mirrors
  - Optimized collector assembly factory
  - ➢ **~10% reduction in cost from ASTR0**

Solana Solar Field (Arizona)

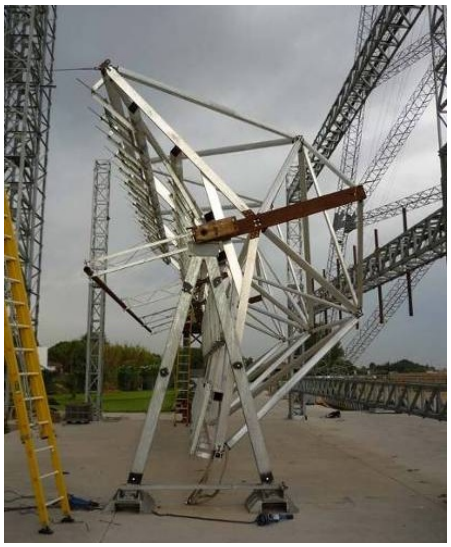


E2 Collectors – Solana Solar Field (Arizona)

1985	1989	2000	2005	2007	2009	2011
LS-2 ➡	LS-3 ➡	ET-I ➡	ET-II ➡	ASTR0 ➡	Phoenix ➡	E2

Near-term Collector Development

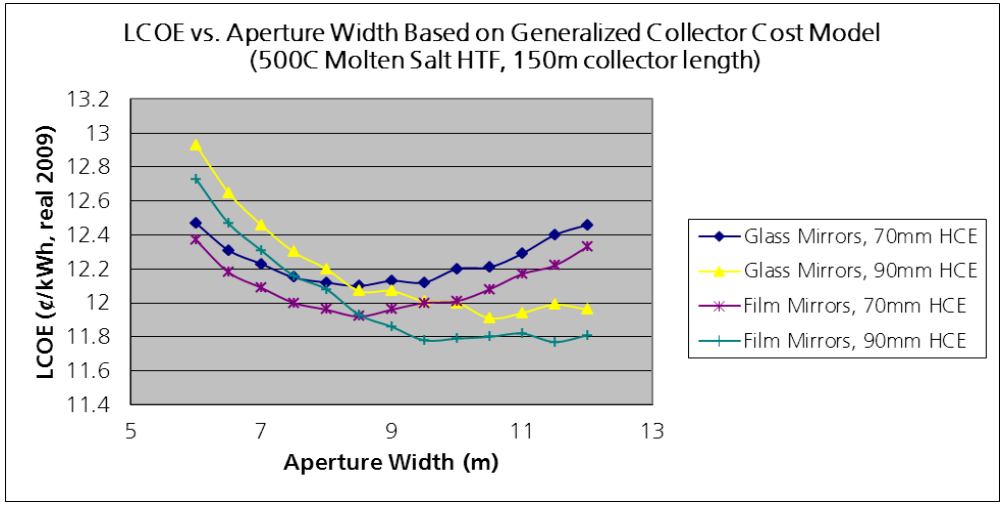
- Project achievements
  - Met some, not all, of project goals
  - Launched two new frame technologies
  - Showed feasibility of lower assembly cost
    - 4.5 m-h @Cameo (vs ~21 m-h ASTR0)
  - 60% higher torsion stiffness vs ASTR0
  - Developed expertise & several new tools



Final Structural and Optical Acceptance Testing of Gen 3

Mid-term Collector Development

- Phoenix project results drove R&D toward new design concept
  - Larger aperture, streamlined assembly are keys to further cost reductions



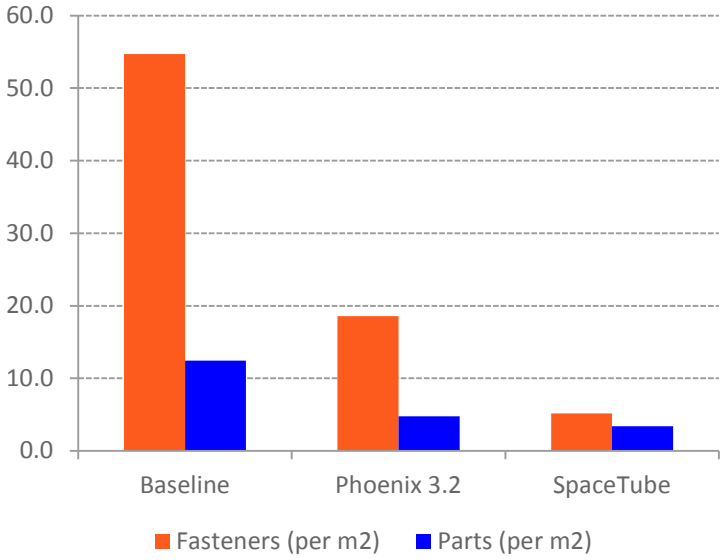
TRNSYS parametric opt. output for baseline optics case
LCOE vs. aperture width, Hitec XL 500C outlet temp

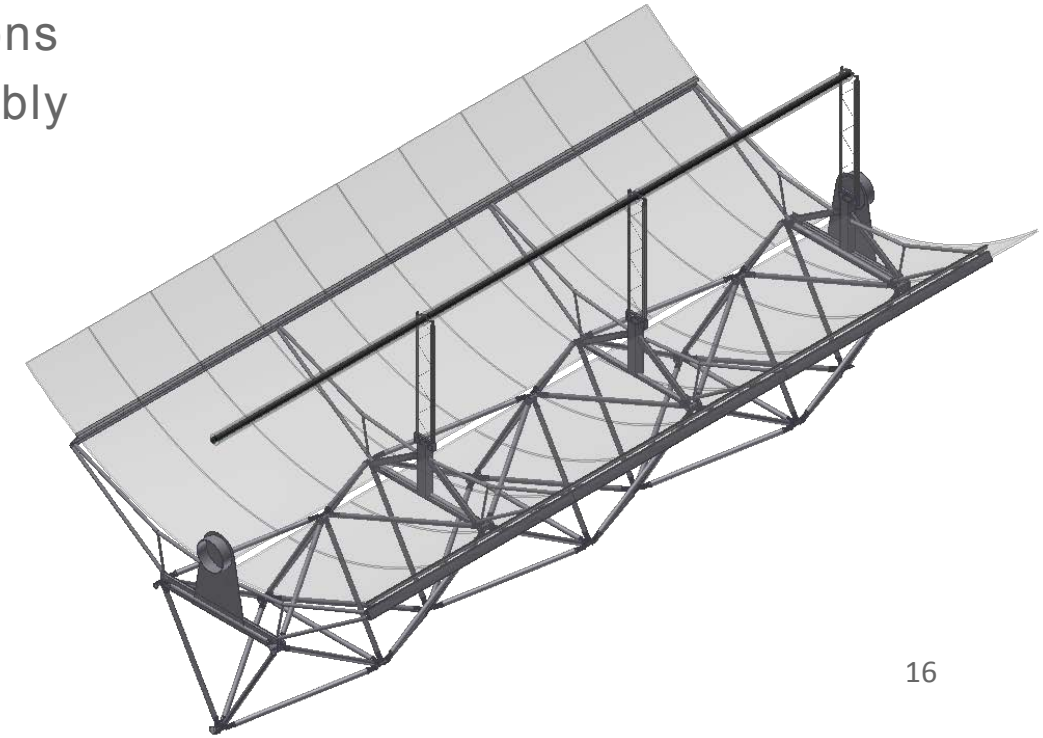
Assumptions:
- Larger SCA cost scaled to reflect higher wind loads
- Typical commercial optics (2.6mrad conc. slope error)
- 2008 Schott PTR

- New designs must promote better optical control, practical fabrication
  - Parabolic structures to support parabolic mirrors
  - Stiffer HCE supports and torque structures, roller bearings
- Need better corporate integration

Mid-term Design Concept

- 8m SpaceTube concept
  - 8m x 14.2m module, 80mm and 89mm HCE options
  - Helical center truss for high bending & torsion efficiencies
  - Stiffer interconnect axle, HCE support, mirror supports
    - Design driven by optics, not vice-versa
  - Film and glass mirror options
  - Designed for jig-less assembly





Mid-Term Collector Development

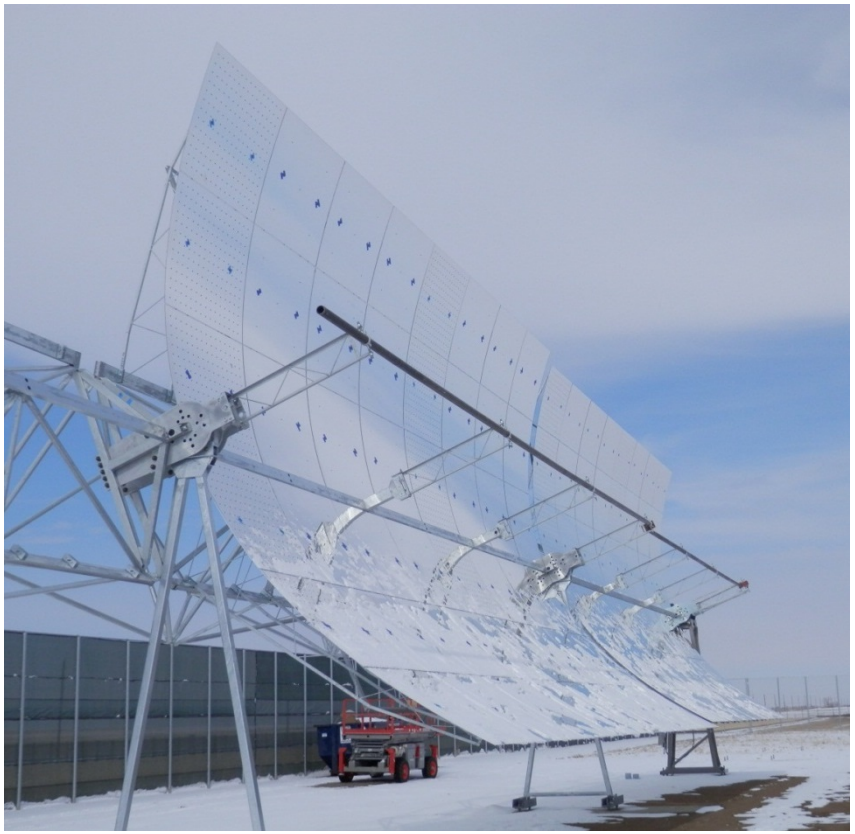
ST8g – 8m Spacetube with Glass Mirrors

ST8c – 8m Spacetube with Composite Panels

1985	1989	2000	2005	2007	2009	2011	2013
LS-2 ⇒	LS-3 ⇒	ET-I ⇒	ET-II ⇒	ASTR0 ⇒	Phoenix ⇒	E2 ⇒	ST8

SpaceTube Advantages

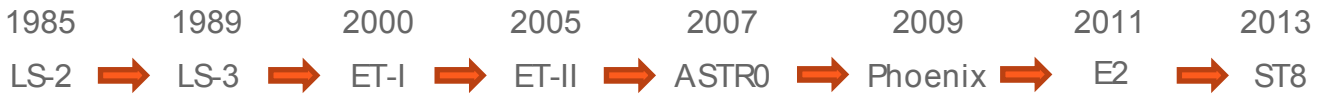
- Low cost – both film & glass
  - >20% reduction from near-term
  - Low on-site labor requirements
- Good thermal performance
  - High torsional stiffness
  - Good optical performance
- Low part count
- High degree of standardization
  - 1 hub, 2 struts in space frame



8 m SpaceTube Collector at SolarTAC

Outcomes from Abengoa Collector Development FOA

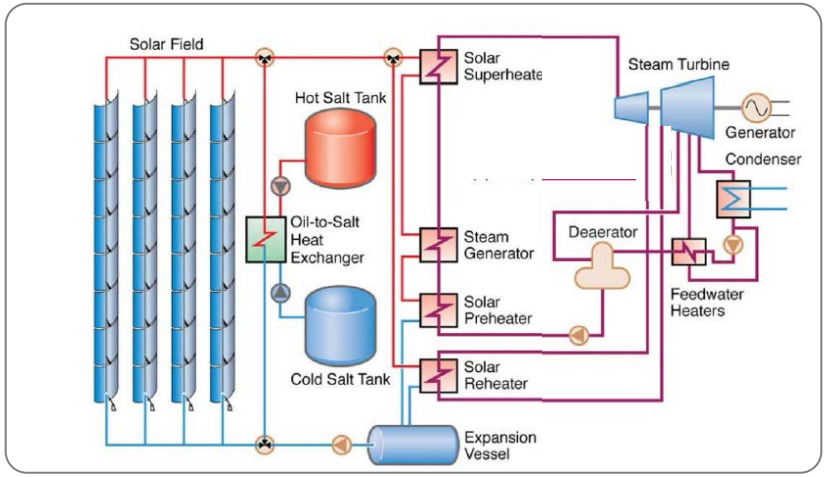
- Near-term Collector
  - Phoenix spaceframe design - reduced solar field cost by ~10%
  - Aluminum and steel versions allow commodity hedge against metal prices
  - Development effort created new design, analysis and testing capabilities
- Mid-term Collector
  - SpaceTube space frame design – reduced solar field cost by additional 20%
  - Larger 8m aperture
  - Glass and reflective film/composite panel versions
  - Optical performance better than near-term designs
  - Optimized for higher temperature HTF



Content

Solana: The world's largest parabolic trough plant

Solana Solar Power Plant Overview



- Solana
  - 280 MWe
  - Parabolic trough solar field
  - 6 hours of thermal energy storage (TES)

Solana

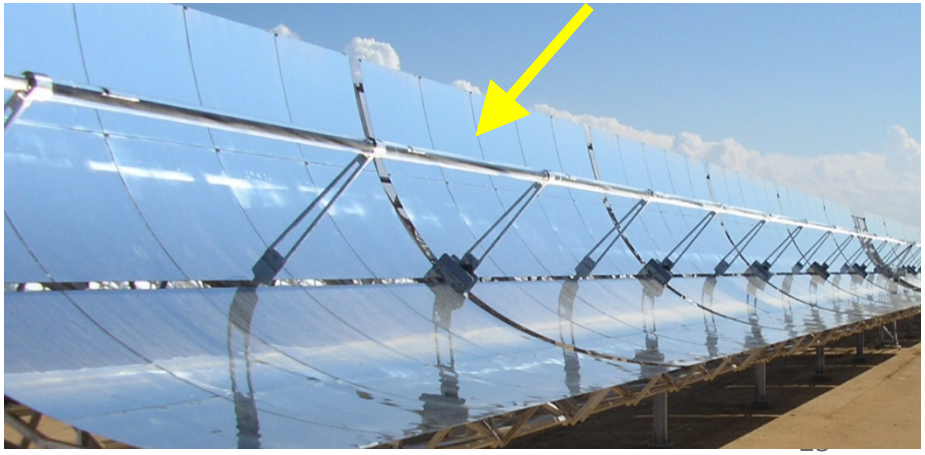
- Has a 30-year power purchase agreement (PPA) with Arizona Public Service (APS)
  - 2007 APS renewable solicitation
  - Will generate enough electricity to serve 70,000 APS customers
  - PPA allows APS to dispatch the plant.
- Plant located on agricultural land 70 miles southwest of Phoenix, near Gila Bend, Ariz.
  - ~ $2 billion in total investment
  - 1,500 construction jobs over 2 years
  - 75 full time jobs to operate and maintain the plant
- Benefited from the 30% ITC/grant and Federal Loan Guarantee Program financing.
- Will use 1/10 the amount of water of previous crop usage.
- Will generate ~50x as much revenue per acre as crops

Solana Design

Plant Size:	280 MW gross generation, 2 x140 MW turbines (~250 MW net after station parasitic loads)
Land Area:	3 square miles
Collector Type: Collector Area:	Abengoa E2 parabolic trough 2,200,000 m^2
Heat Transfer Fluid	Solutia Therminol VP-1
Thermal Energy Storage:	6 hours of full load operation 2-tank, indirect, molten-salt TES Uses six parallel TES trains
On-Peak Generation:	95% capacity factor hours noon – 8 pm June – September
On-Line Date:	2013

Receiver Technology

- Schott receivers
  - Manufactured in Albuquerque NM factory
- Improvement in receiver thermal performance
  - Current receivers ~30% better thermal performance than Luz
- Improved receiver technology
  - Improved glass to metal seal design – Reduced breakage
  - Reduced bellows shadowing
  - Hydrogen problem addressed



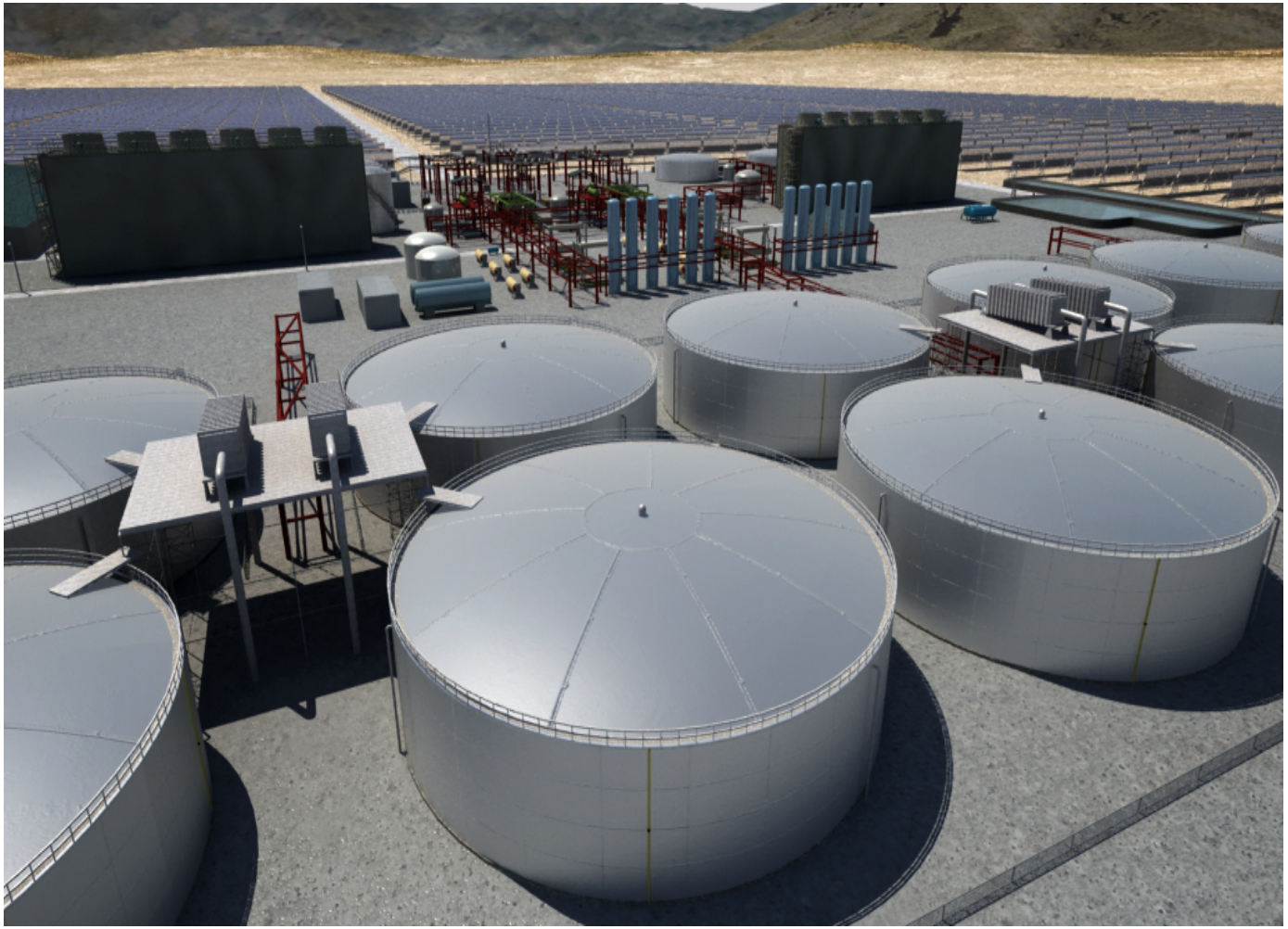
Mirror Technology

- Rioglass mirrors
  - Manufactured in Surprise AZ factory
- Improved mirror technology
  - Mirrors made with more environmentally friendly manner
  - Improved automated manufacturing of mirrors
  - Reduced glass breakage because mirrors are made with tempered glass

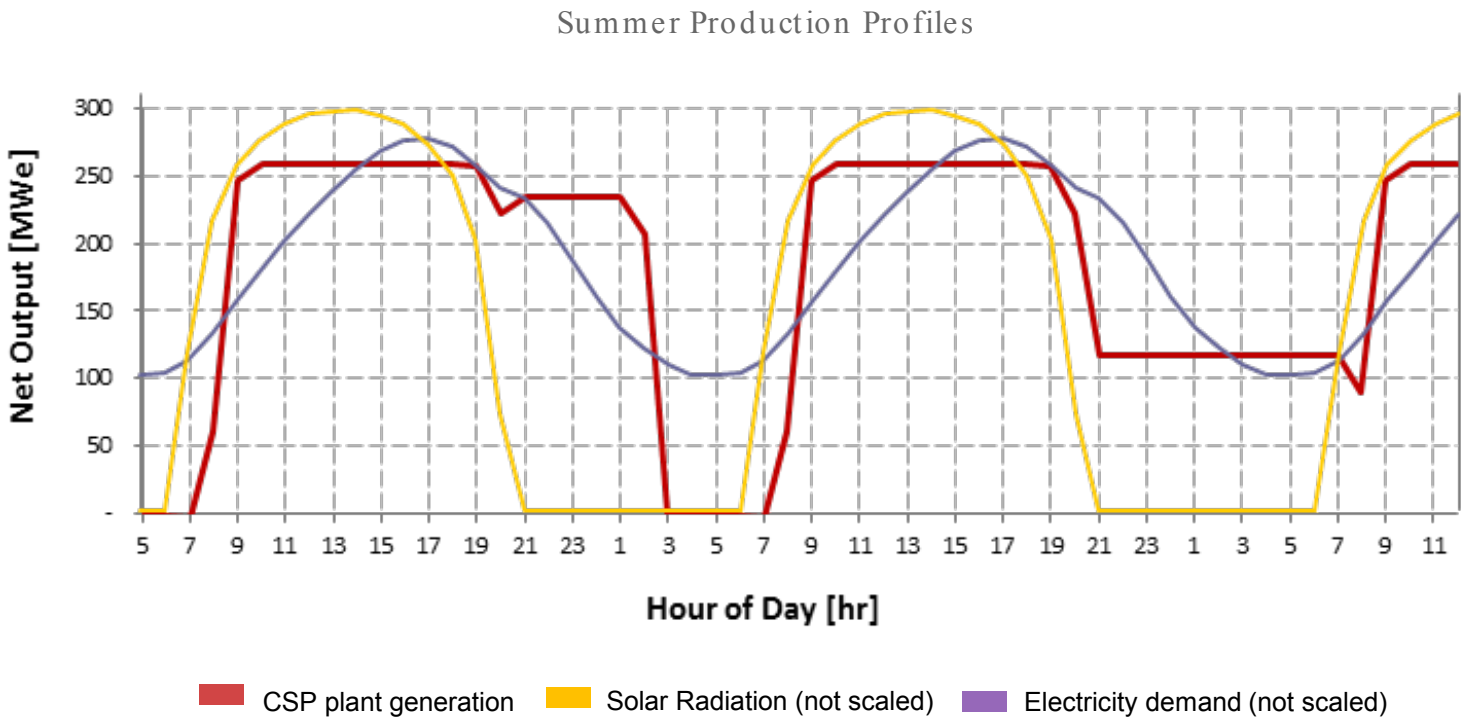
Parabolic Trough Collector Technology

- Abengoa E2 structure
  - LS-3 aperture 125 m long
  - Galvanized steel design
  - Optimized factory assembly process
  - QC testing of structure alignment during assembly process
- Hydraulic drive
  - Accumulator for defocusing during power failure
- Improved control system
  - Fiber optic communications
- Ball joints used for collector interconnect
- Micro pile collector foundations

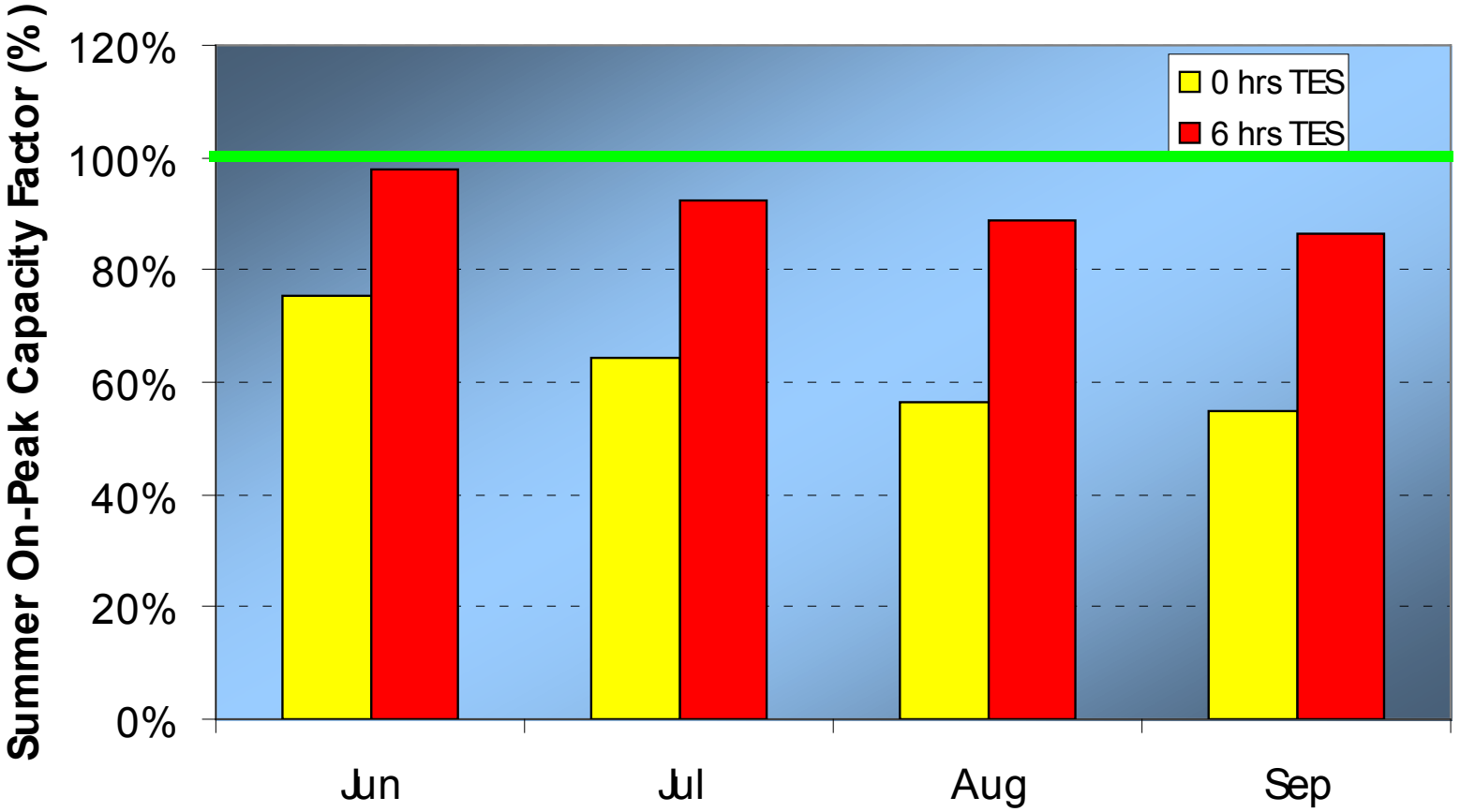
Thermal Energy Storage (TES)



- Storage allows improved operational flexibility to meet utility peak loads. APS system peaks:
  - Summer Peak: 12 Noon to 8pm, June - September



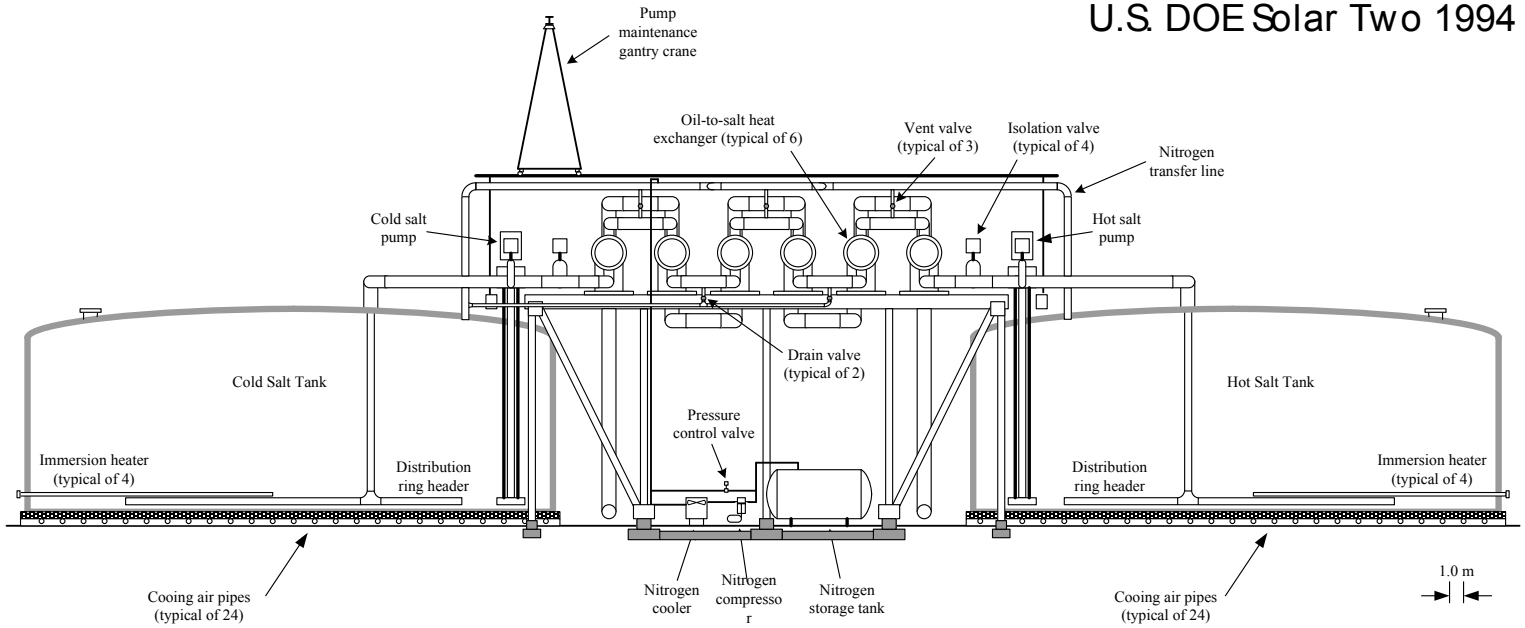
Summer On-Peak Generation
0 & 6-hours of Thermal Energy Storage



TES for Parabolic Trough Plants

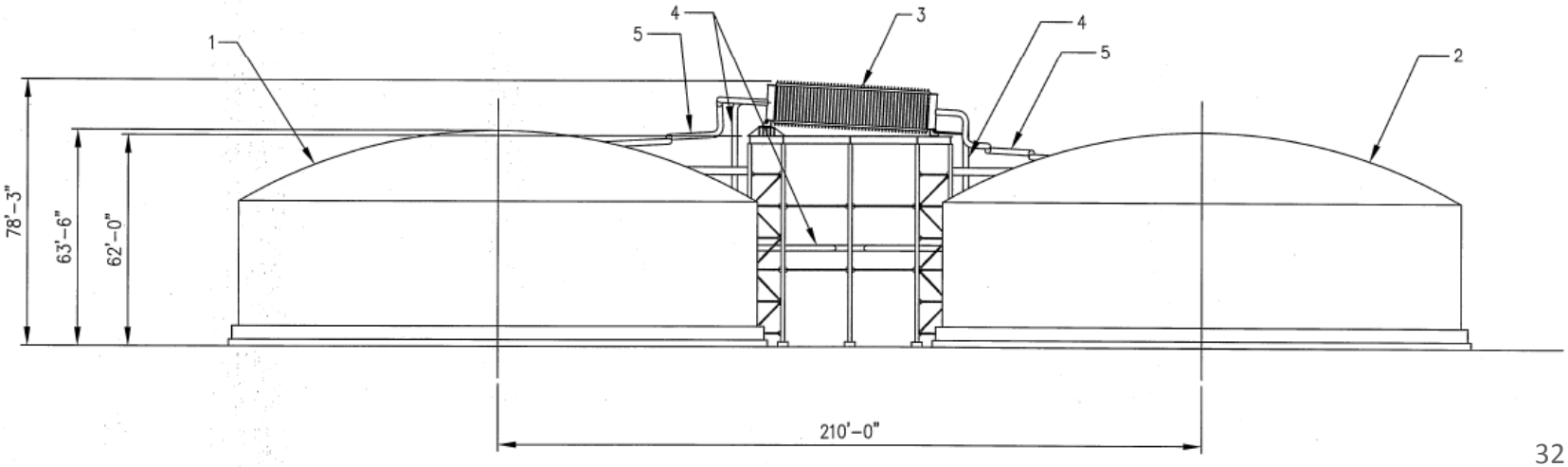
- Indirect 2-tank molten-salt design for parabolic trough plants
  - Based on Solar Two molten-salt power tower experience.
  - Uses oil to salt heat exchangers to transfer energy to and from storage

U.S. DOE Solar Two 1994



Indirect 2-tank TES configuration used for non-Abengoa parabolic trough plants in Spain

- Improved heat exchanger design
  - Alfa Laval plate and frame heat exchanger
  - Reduces the number of separate salt heat exchangers
  - Reduces salt valves and piping
  - Reduces pressure drop through heat exchangers,
  - Improves temperature approach between salt and HTF
- All salt equipment located above tanks for emergency drain back.
- Long-shafted molten-salt pumps mounted above tank
- Recirculation system for HTF & TES freeze protection & improved TES start-up



Arial View of Solana

Power Block and TES is located at the center of the solar field

ABENGOA SOLAR

Innovative technology solutions for sustainability

Henry Price, PE
VP Technology

Abengoa Solar LLC
Lakewood, CO

hank.price@solar.abengoa.com