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A New Energy Infrastructure: Building Blocks for the Next Industrial Revolution

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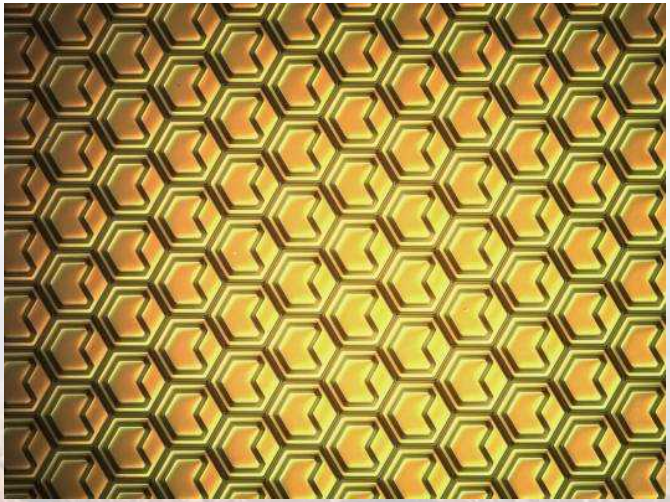
August 8, 2011



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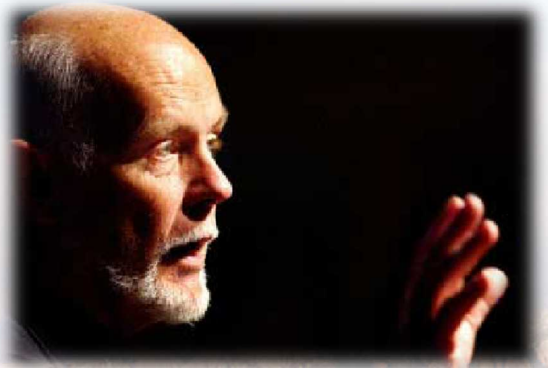
Historical Perspective

“ I'd put my money on the sun and solar energy. What a source of power!...I hope we don't have to wait until oil and coal run out before we tackle that.”

Thomas Alva Edison to Henry Ford - 1931



“Energy is the single most important challenge facing humanity today”

Richard Smalley, Nobel laureate, 2002 1st Sandia Truman lecture

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News item #1 “We don't want the West to go and find alternatives, …”, June 2011

In an interview broadcast Sunday on "CNN's Fareed Zakaria GPS," the grandson of the founding king of modern Saudi Arabia said the oil price should be somewhere between $70 and $80 a barrel, rather than the current level of over $100 a barrel.
"We don't want the West to go and find alternatives, because, clearly, the higher the price of oil goes, the more they have incentives to go and find alternatives," said Talal, who is listed by Forbes as the 26th richest man in the world.

News item #2 “Saudi Arabia to invest $100 Billion in renewables”, March 2011

"Fuel supply is one of the major challenges facing the power sector and the nation," Saleh Al-Awaji, Saudi Arabia’s deputy minister for electricity at the Ministry of Water, said at a recent conference in Abu Dhabi. "The policy is to work intensely on saving energy and making sure every barrel of oil that can be saved is, and is made available for export."

Logical course of action for holders of non-renewable resources : maximize value of recoverable assets

David Hume (1752) “Of commerce”

“commerce with strangers… rouses men from their indolence”
“international diffusion of technology” and “comparative advantage to different geniuses, climates, and soils” → only way to advance (stay ahead) is to invent the future

1st Industrial Revolution : Steam engine (coal)

2nd Industrial Revolution : Oil and gas

3rd Industrial Revolution : Electricity (largely based on coal, oil, gas)

4th Industrial Revolution : IT/communications (microelectronics - silicon)

5th Industrial Revolution : Distributed Electricity generation/storage and trade (pending) (silicon, storage technologies, microelectronics/IT)

along with AC vs. DC, this was part of the battle between Tesla and Edison

democratization of energy – individuals, smaller groups no longer dependent on large institutions to meet daily energy needs

Two of the Building Blocks

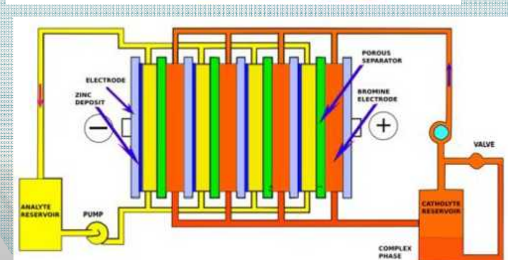
Microsystems Enabled Photovoltaics
(Distributed, embedded, low cost power generation)

MEPV

Storage (many new technologies)

Flow batteries

Redflow



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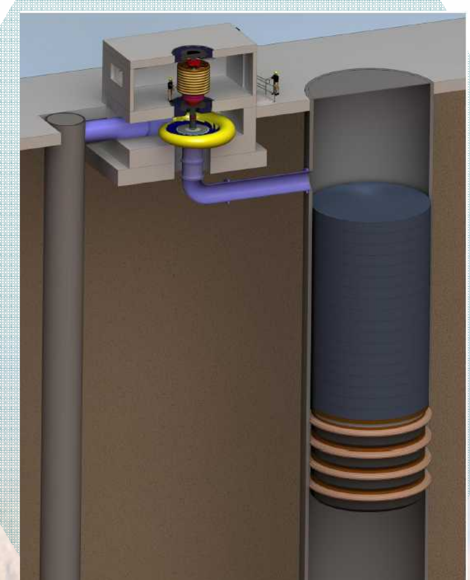
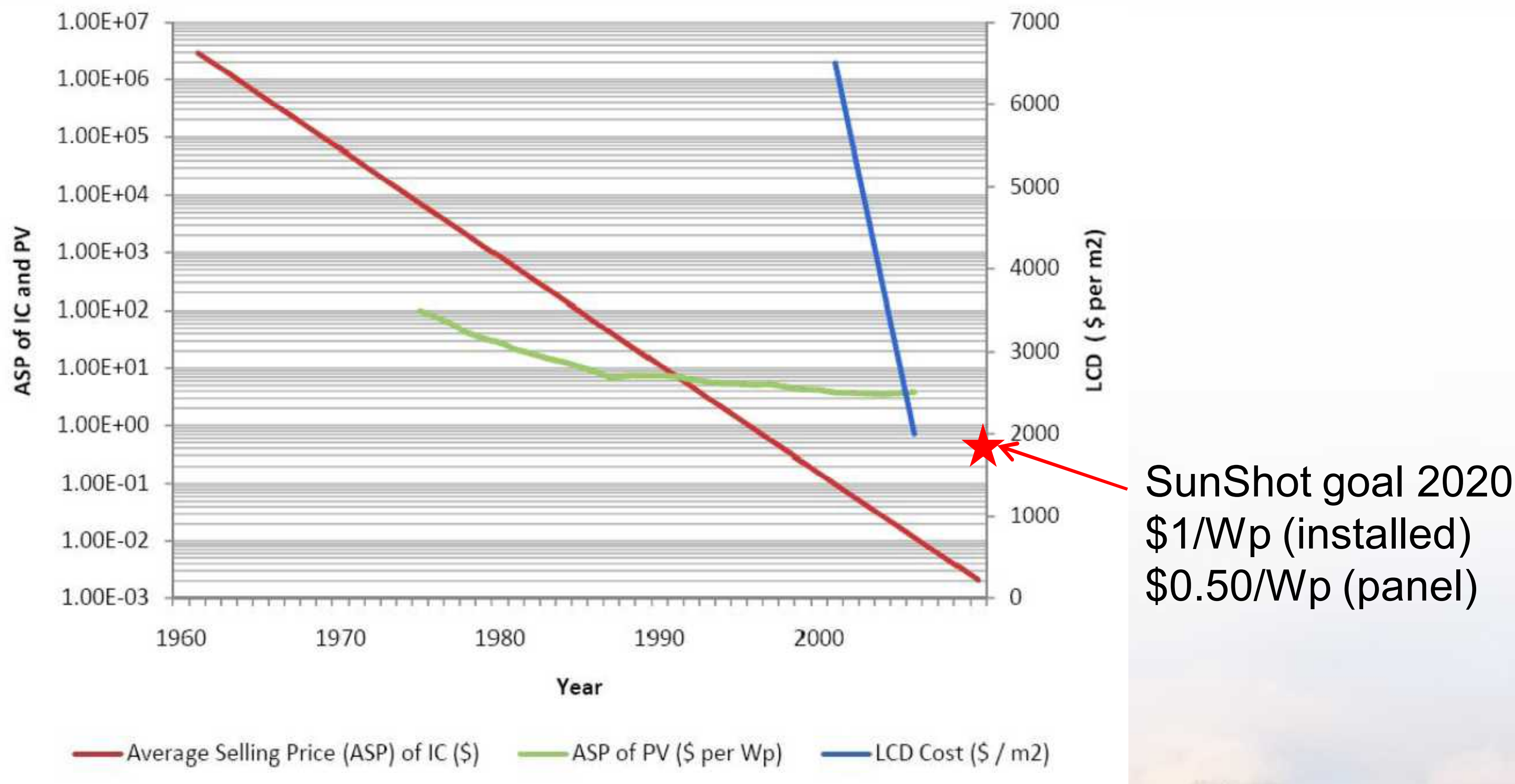
Non-traditional pumped hydro



Gravity Power

Building Block #1 - MEPV

Manufacturing Cost Reductions



Rajendra Singh, "Why silicon is and will remain the dominant photovoltaic material," Journal of Nanophotonics, vol. 3, 032503 (2009), p. 4.

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Leveraging Existing Microelectronics (Si – III-V) Infrastructure

Established Polysilicon supply (9-9s purity)

2010 >100,000 metric tons (Hemlock, Wacker, REC, MEMC)

2011 >120,000 metric tons

2012 - OCI (S.Korea) – 62,000 metric tons
GCL Poly (China) – 65,000 metric tons

200 MW_p/year unit line

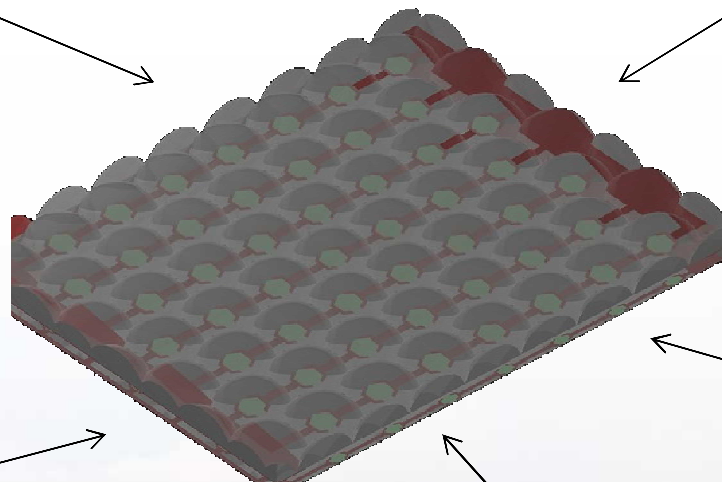
- Small IC Fab: 5,000 8'' wafers/week
- 10 pick-and-place tools: 130,000 parts/hr (Source: Universal Instruments)
- 2,900 m^2 PV modules produced per day
- 200W x 2,900 = 0.58 MW_p/day

Standard Si wafered PV
~ 5-6 grams Si/W_{peak}

MEPV - < 0.1 gram Si/W_{peak}

10x thinner cells
no kerf loss (usually 50% for standard Si PV)
>10x optical concentration

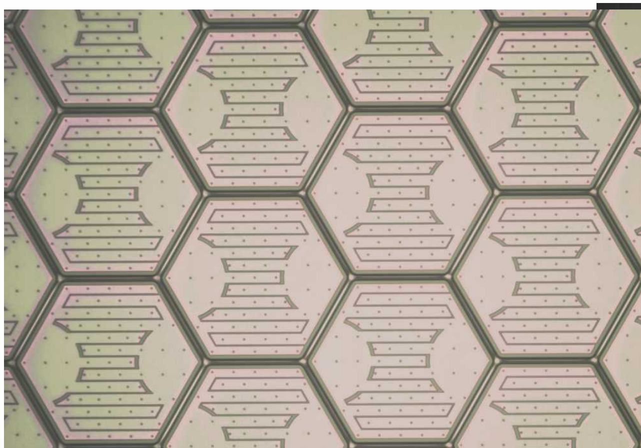
High-Efficiency, High-Functionality, Low-Cost Photovoltaic Modules

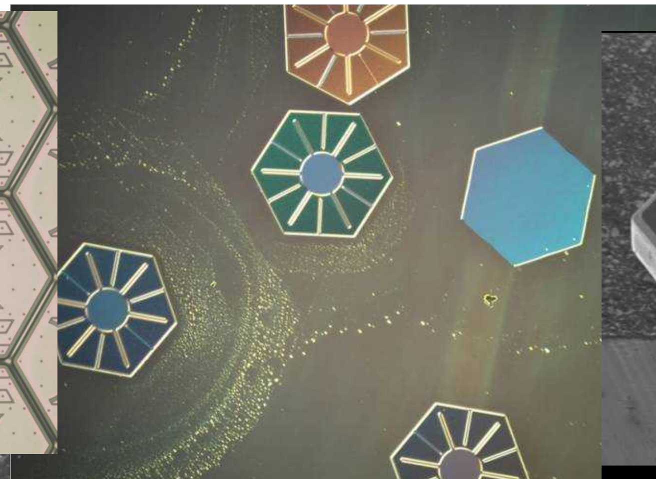


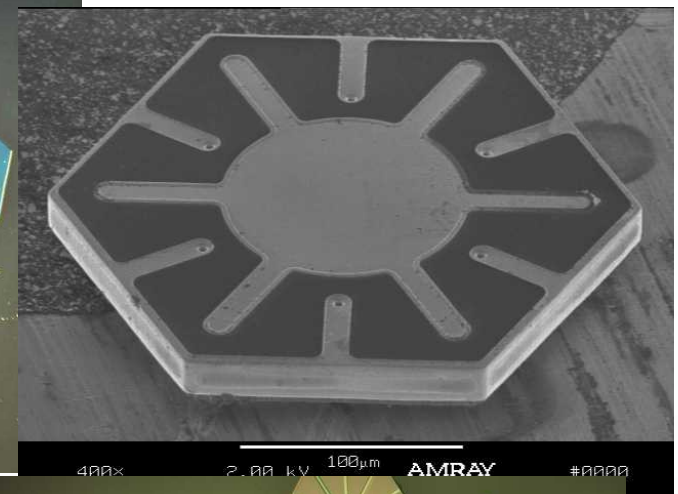
Potential for energy payback on the order of 3-4 months

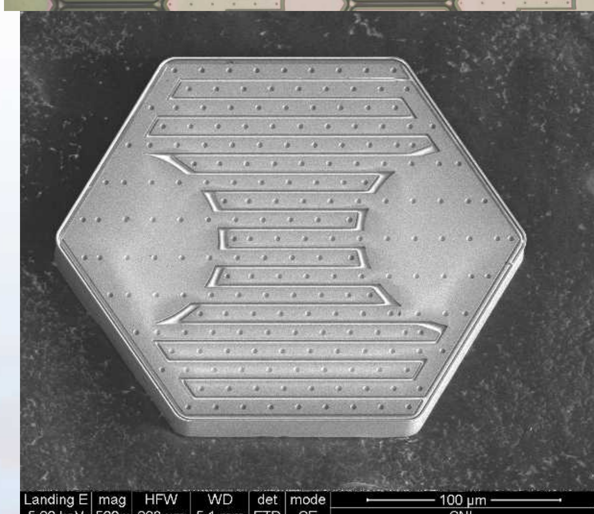
Thin c-Si PV Cells

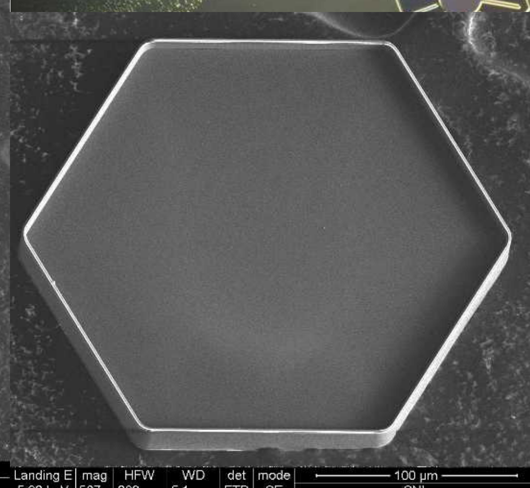
14 to 20 μm thick; 0.25 to 1 mm across



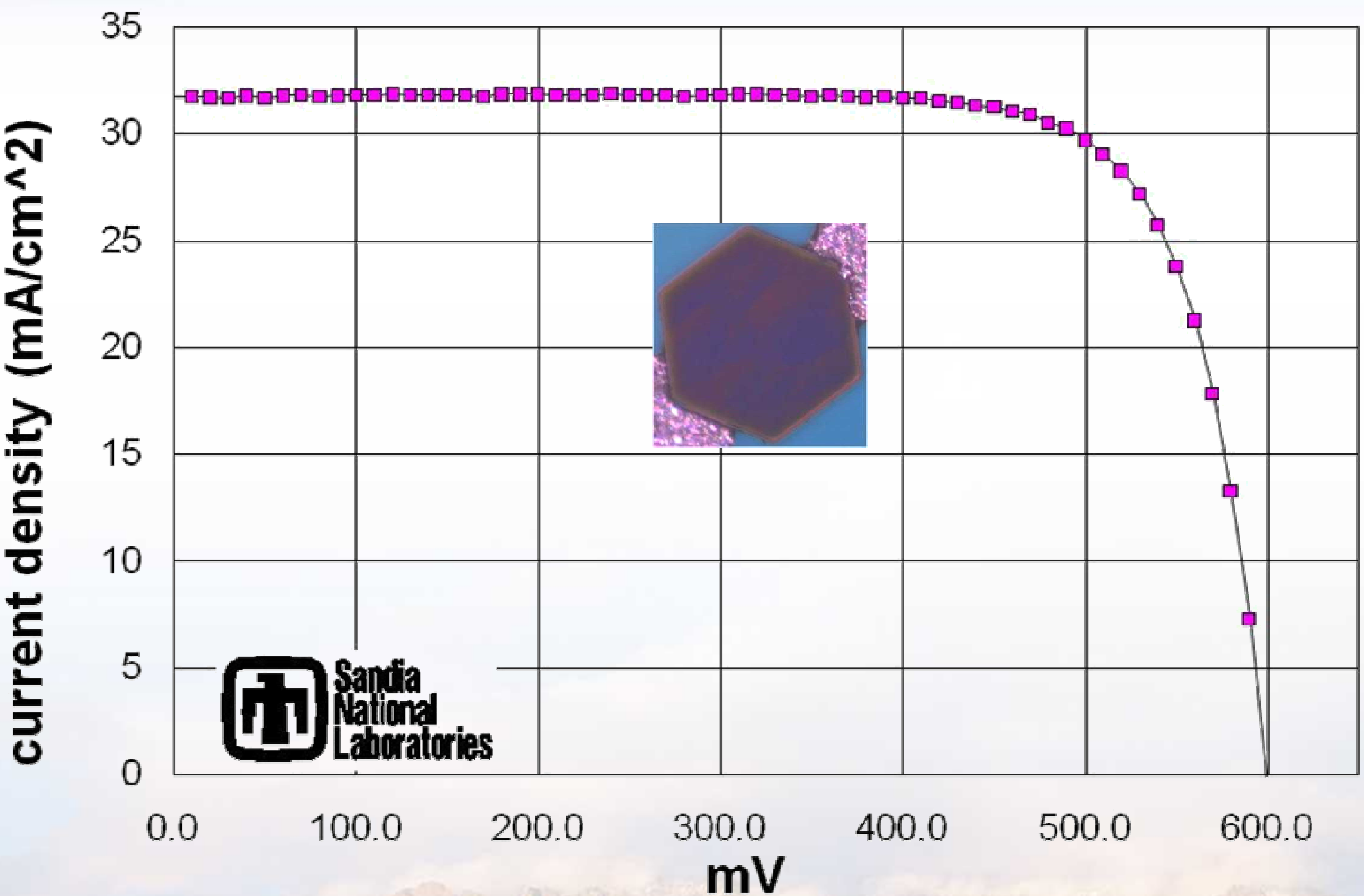








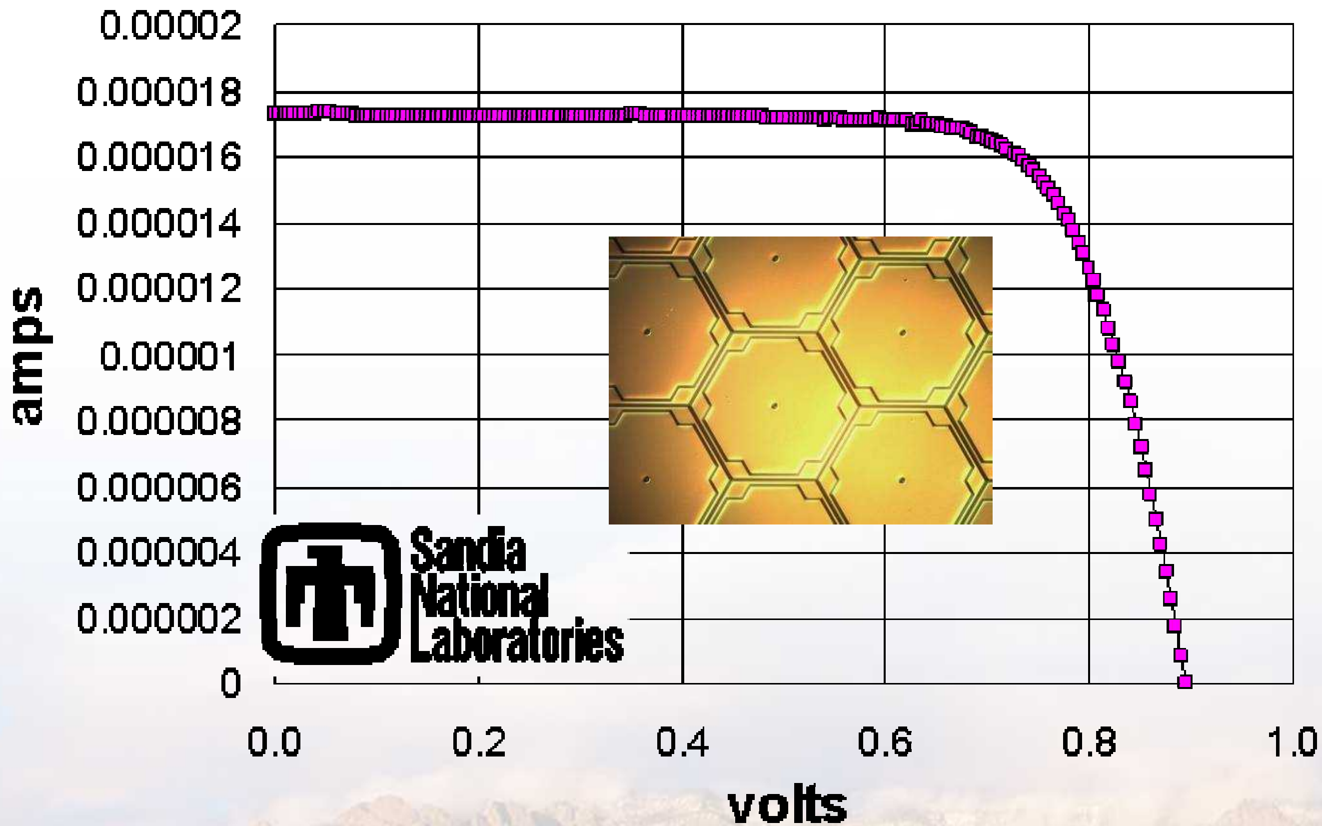
Thin c-Si PV Cell Performance



08/20/09 2:18 PM	25.0 °C	0.0003763 cm^2	31.75 $J_{sc}(mA/cm^2)$	0.784 FF	AM1.5G
LN3_2_250k	1.0000 M*	597.3 $V_{oc}(mV)$	11.946 $I_{sc}(uA)$	14.86 % Eff	1.00 Suns
	1.0000 S*	501. $V_{mp}(mV)$	11.161 $I_{mp}(uA)$		

Thin III-V Cell Performance

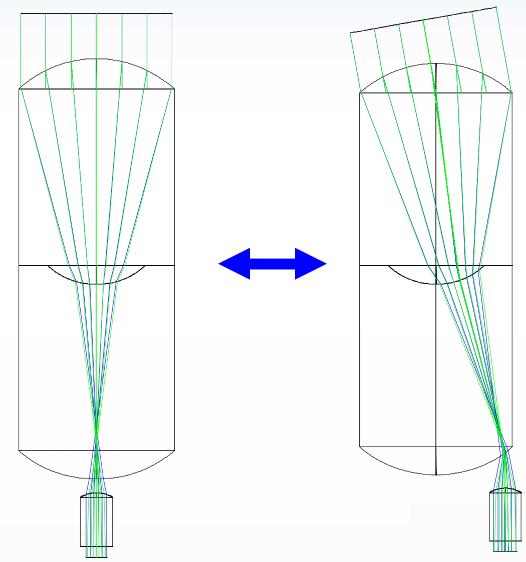
Best GaAs back contact solar cell (1sun) Efficiency 10.03% +/-0.4%



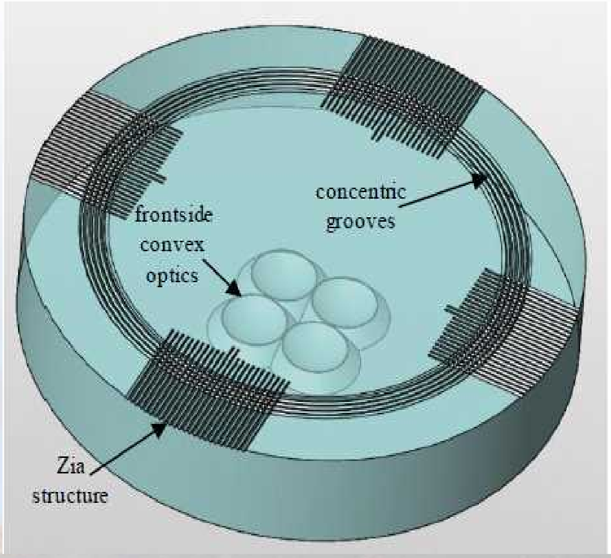
10/06/09 1:54 PM	24.9 °C	0.001164 cm^2	14.86 J_{sc}(mA/cm^2)	0.754 FF	AM1.5G
GaAs slide 2 500um AR coat cell2	1.0000 M*	894.8 V_{oc}(mV)	17.300 I_{sc}(uA)	**10.03 % Eff**	1.00 Suns
	1.0000 S*	723.6 V_{mp}(mV)	16.127 I_{mp}(uA)		

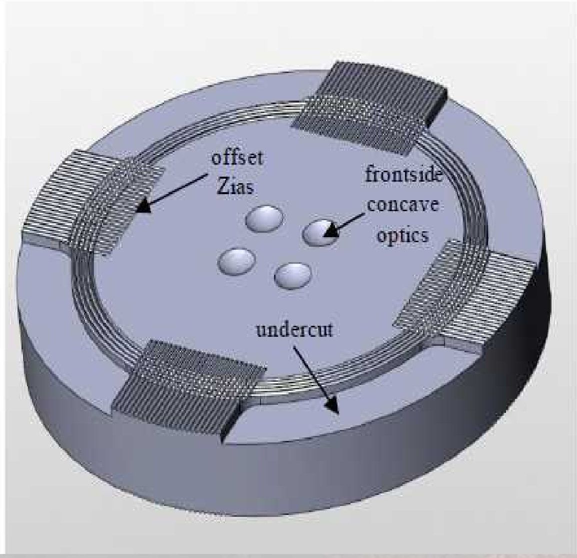
Microlens Concentrator Design

- Optical design and manufacture of first lens elements complete
- Provides 49X concentration
- ± 10° tracking in both axes
- Presents light as a normal plane wave to PV cells (optimal for AR coating performance)

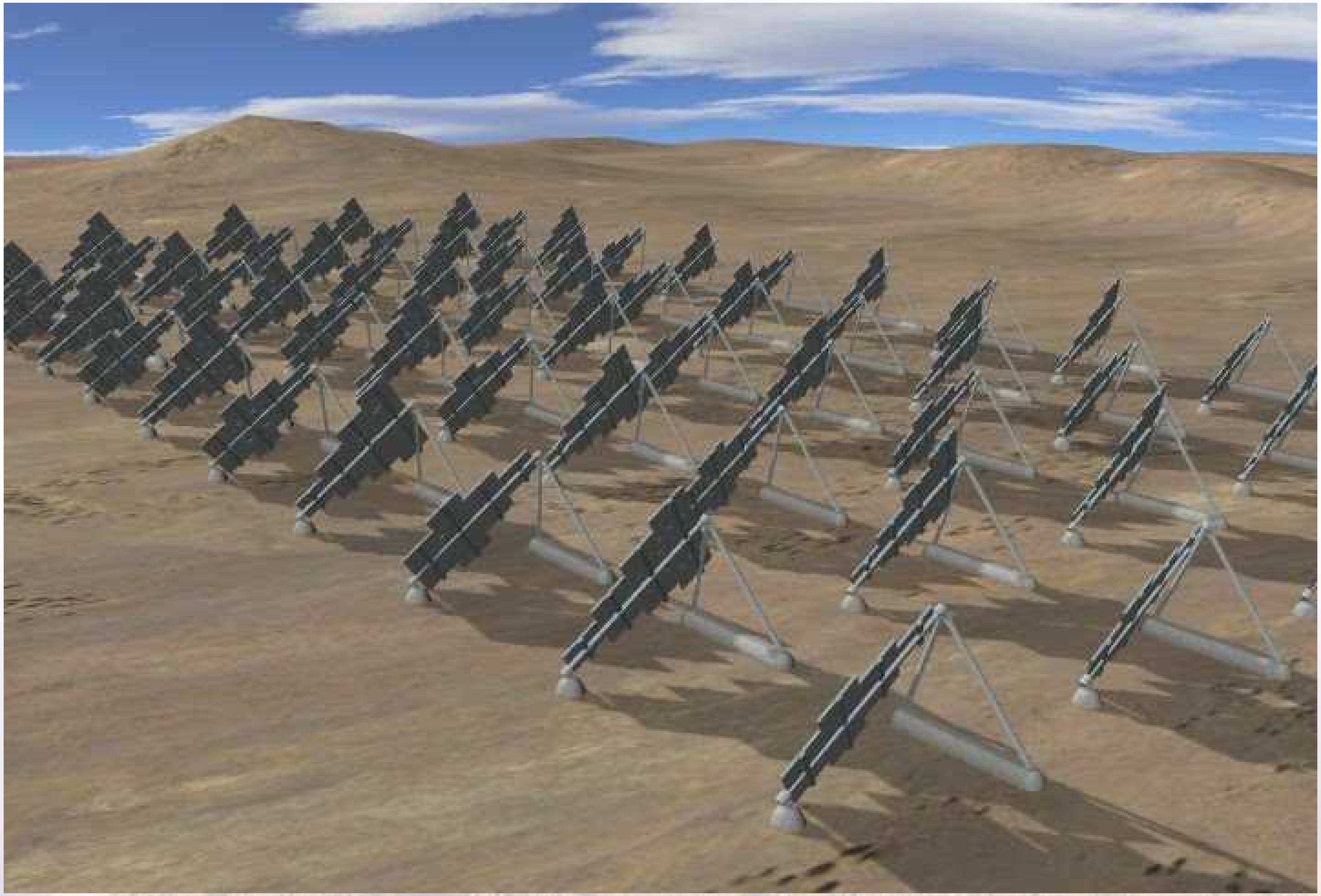


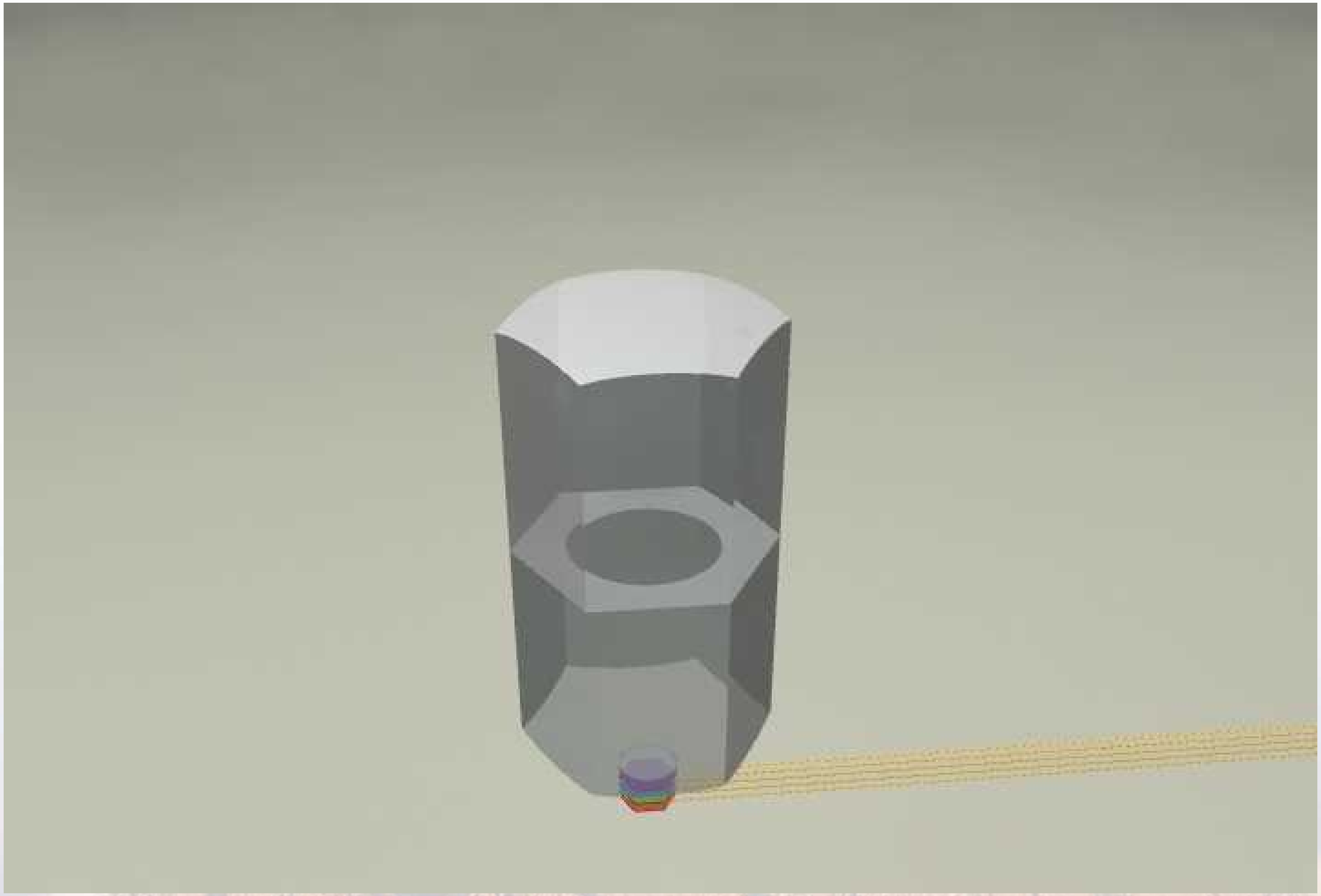
Simulations of optical elements demonstrating tracking





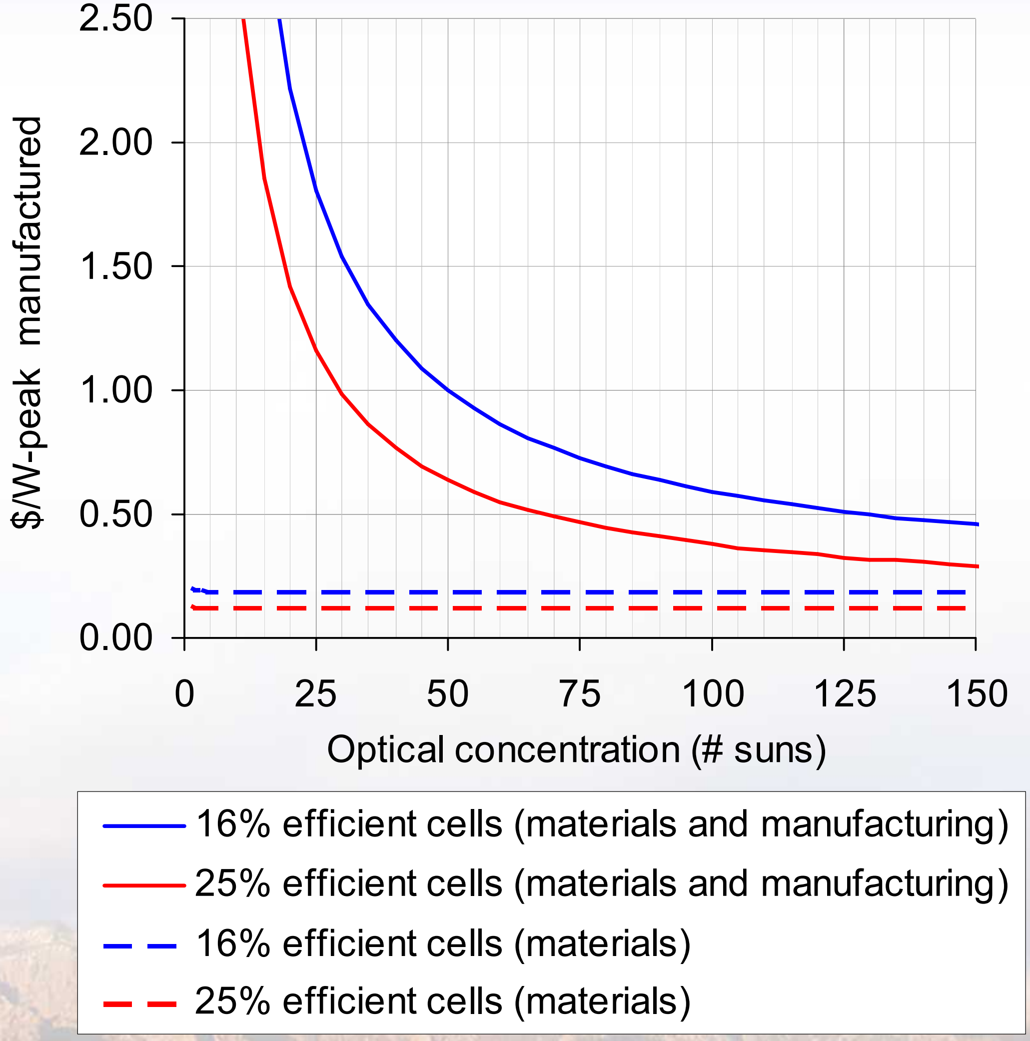
CAD drawings of top two lens elements showing alignment features.





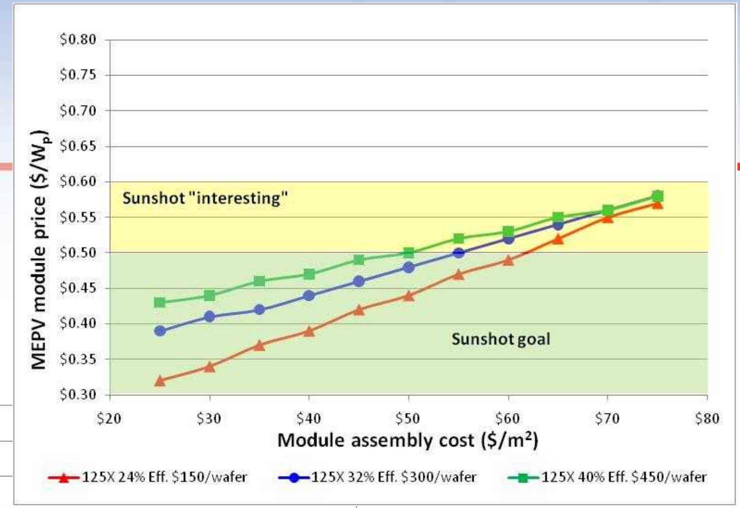
Economic Analysis: Module $/W$_{peak}$ Manufacturing Costs

- The promise of the roll-to-roll self-assembly technology is negligible assembly cost per part.
- Current challenges in self assembly are with speed and assembly yield.
- With current high speed (130,000 parts/hr) pick-and-place assembly, modules that are ~20% efficient with manufacturing costs below $0.50/Watt are possible.
- Cost model assumes $150 cell process costs for an 8” silicon wafer, $25/m^2 material costs for module materials, negligible cost for module assembly, and optical losses of 20% (~15% indirect light, ~5% optical system loss).

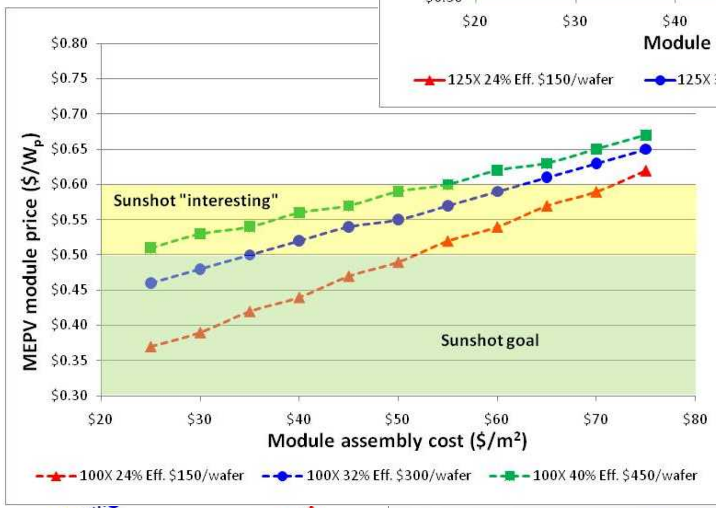


Cost Models

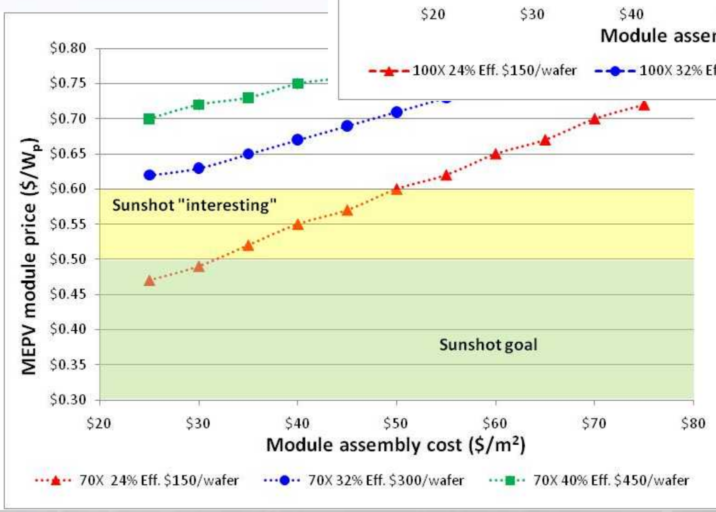
including 18% margin



125x



100x



70x

BOS costs are another $0.50/W$_p$ – our approach has the potential to reduce those costs as well (integrated power management, easier install, etc.)

Building Block #2 - Storage

Baseline Electrical Storage Technologies

Lead-acid

- ~$200/kW.hr
- extremely large production base
- very well recycled
  (environmental reasons)
- >100 yr. old chemistry
  - new developments with carbon foam electrodes

Li-ion

- large volume quotes @ $450/kW.hr
- rapidly increasing production volume
- currently recycling is not economical
  (cheaper to buy new lithium)
- many new developments

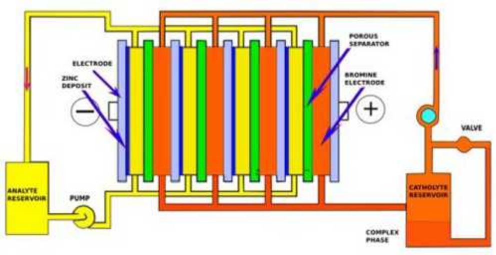
NaS

- In use by utilities
- 1GW battery farm project in progress (across the border from San Diego, in Mexico)

Flow Batteries

Redflow

UNSW



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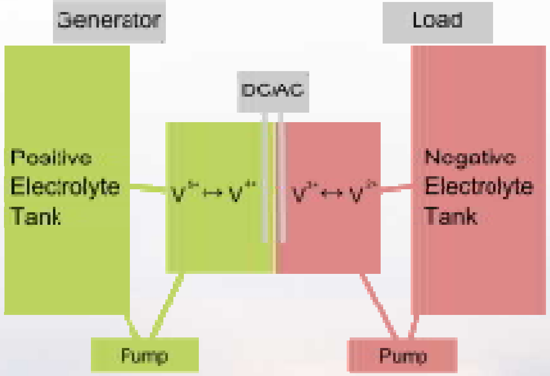
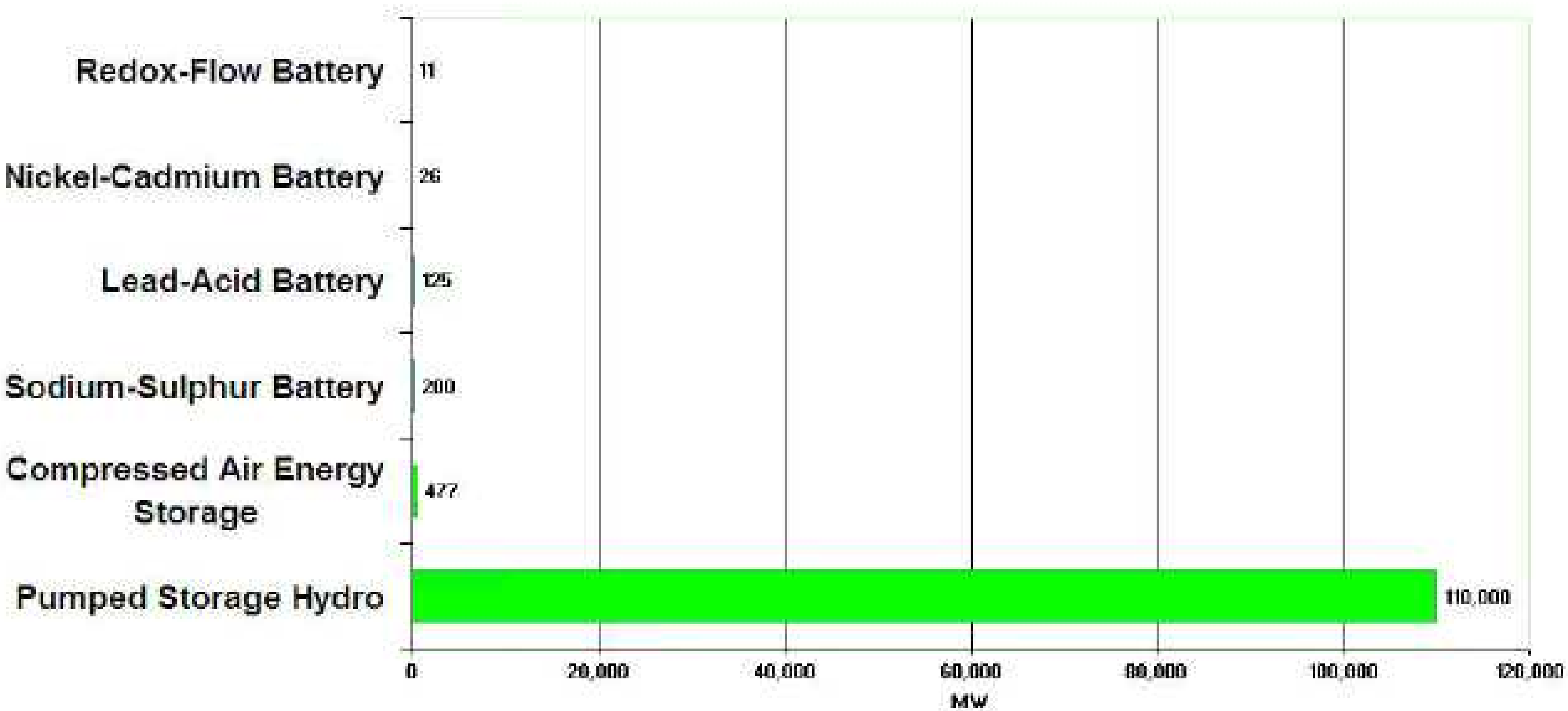


Zinc-Bromine

Vanadium redox

Worldwide Energy Storage Capacity



gravitypowerstorage.com

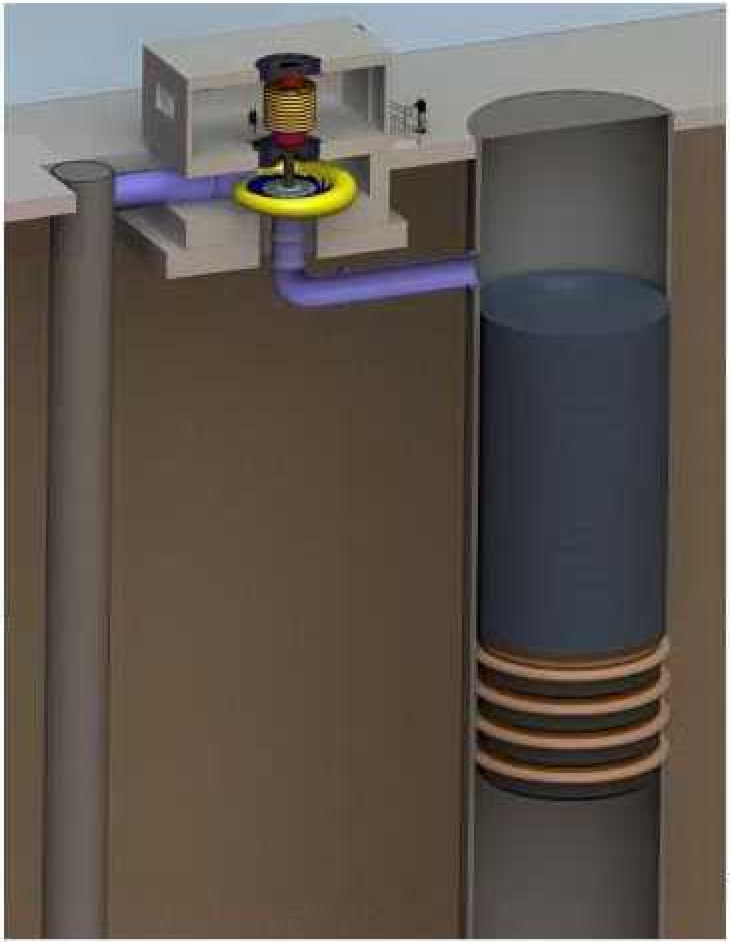
Initial Product: Ancillary Service Plants

A-GPM Parameters

- 6m storage shaft, 2m return pipe
- 500m deep
- 8000-tonne storage mass
- ~25 MW with 8.5 MWh per module initially, more energy later

Market

- ~50 GW in U.S.
- ~2000 GPMs @ ~$25M each
- Performs better than thermal plants
- System payback time: ~5-10 years
- System lifetime: 30+ years



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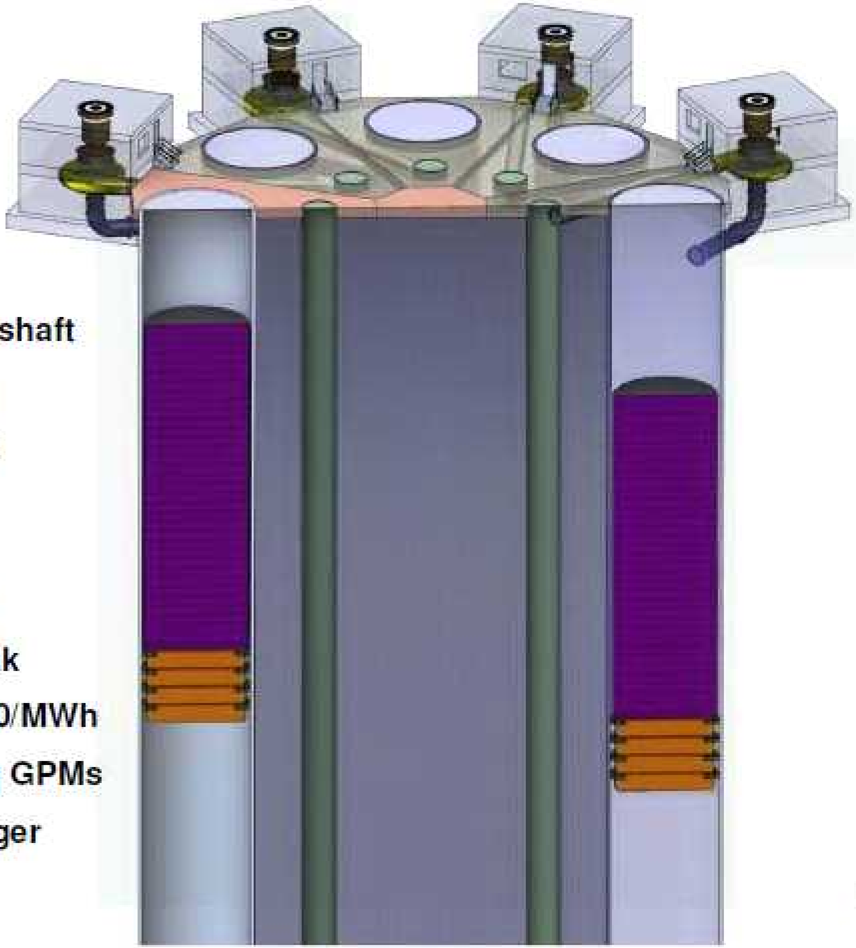
GRAVITY POWER

Second Product: Peaking Plants



B-GPM Parameters

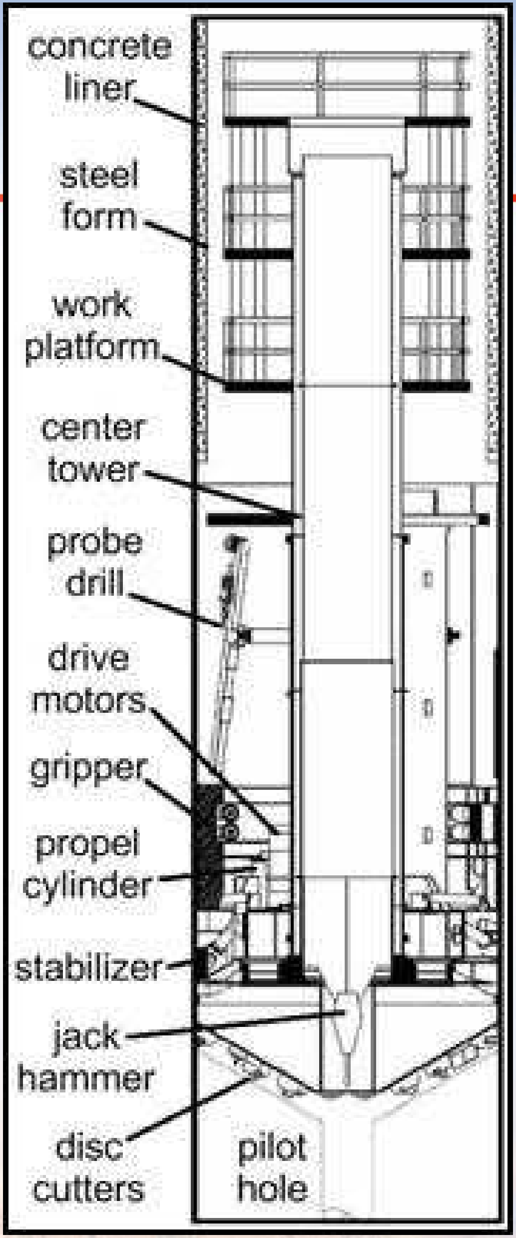
- Bulk energy storage
- 10m storage shaft
- 3m return pipe
- 1000-2000m deep
- Up to 150 MW for 4 hrs per shaft
- Up to 210,000 tonnes/shaft
- Up to 2400 MW in 2.5 acres

Market

- Buy cheap energy off peak
- Sell valuable energy on peak
- Differential can exceed $100/MWh
- ~200 GW in U.S. = 4000 big GPMs
- Foreign market is much larger

TBM ⟹ SRM

Tunnel boring machine that was used at Yucca Mountain



"Shaft Reaming Machine"

gravitypowerstorage.com

Building Block #3 – Smart Grid

Building Block #4 – Demand response

Building Block #5 – CCS

Building Block #6 – Solar thermal + natural gas

Building Block #7 – New nuclear (LFTRs, travelling wave reactors)

⋮

Extremely exciting times –
possibility of enabling a new energy economy,
addressing many of the challenges facing humanity.

Many building blocks, many possible pathways.

Future is shaped by our imagination and our desires.
(subject to boundary conditions imposed by nature, physics, biology, etc...)

“May you live in interesting times” – ancient Chinese curse

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