From Nano-Structured PV Materials to PV Concentrators and Beyond

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About PARC

Founded as Xerox PARC, a corporate laboratory

Became PARC Incorporated in 2002, cross-industry center for innovation

170 researchers

4 research divisions

- Computing Science, Electronic Materials and Devices Hardware Systems, Intelligent Systems

Industry-focused research

- Xerox Sponsored Research: 50%
- Client Sponsored Research: 25%
- Licensing: 10%
- Government Sponsored: 15%

1800 patents and patents pending

- Average 100+ new patents per year 2000-2006

150+ peer reviewed publications per year

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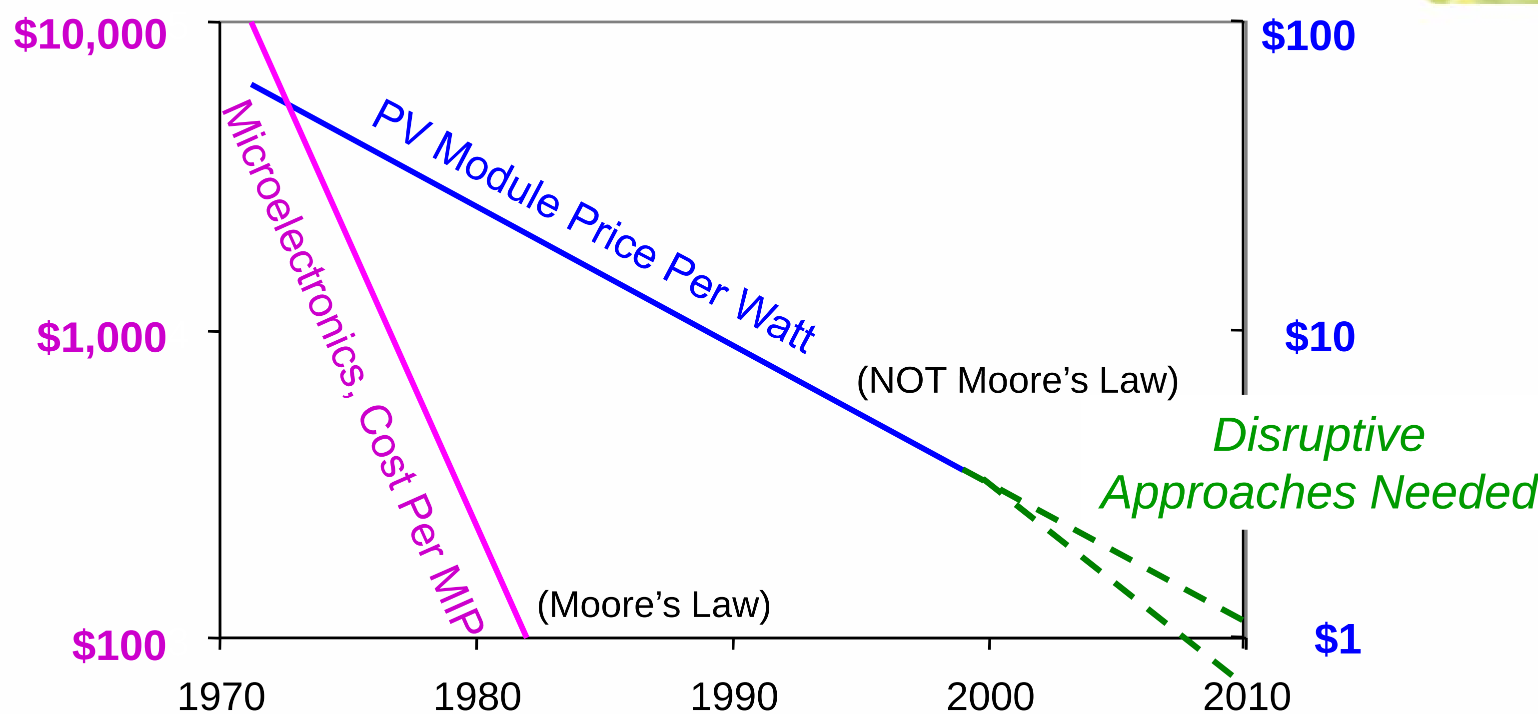
PV: A Long, Slow March Toward Lower Cost



Disruptive Cost Performance:
Materials Deposited From Solution

Organic devices
- Dye sensitized
- Polymer blends

Organic/Inorganic blends
Inorganic/Inorganic devices

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PARC Approach

Look only at materials that are:

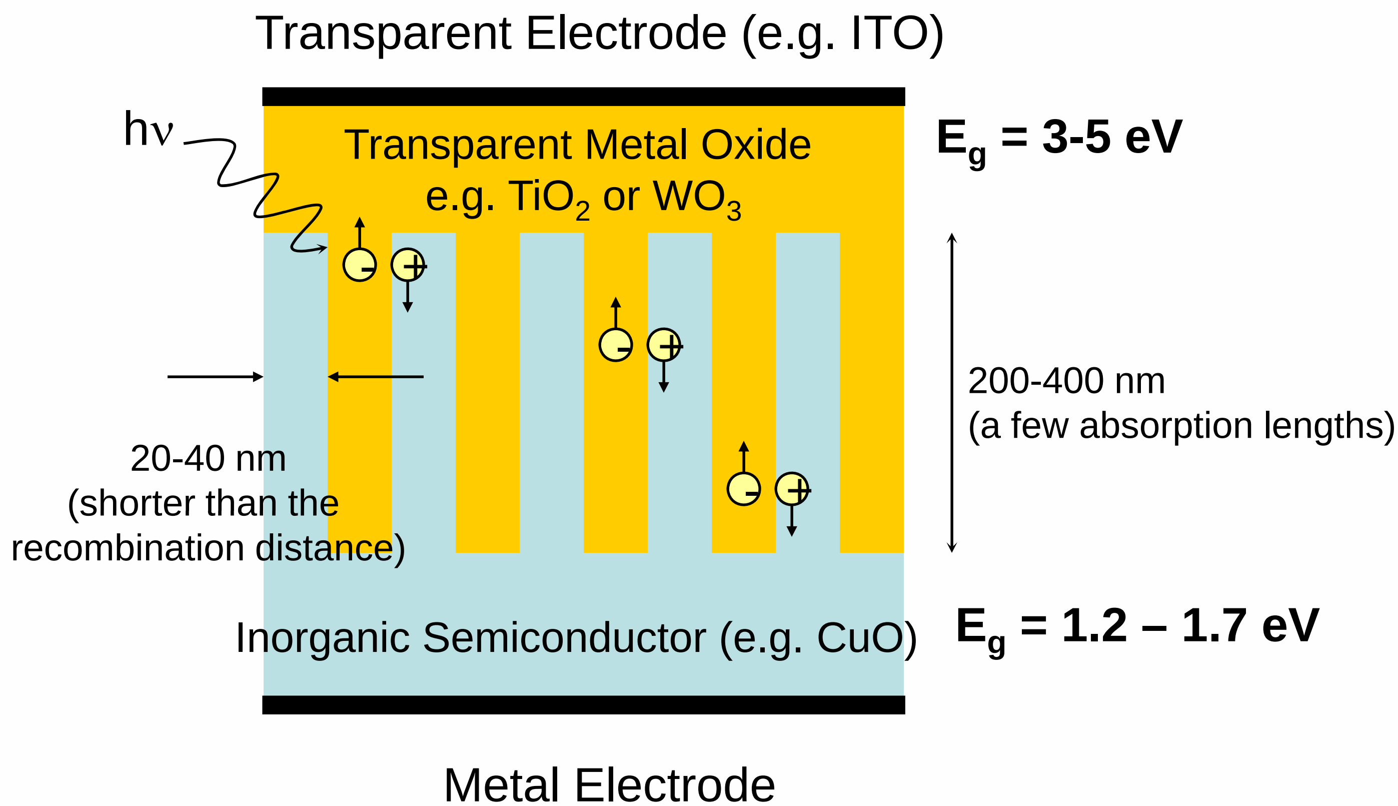
- Abundant and low cost (e.g. transition metals: Zn, Cu, W, Fe)
- Environmentally friendly (i.e. not Cd, As, Se)
- Processed below 600C (to enable glass substrates or possibly roll-to-roll)

Low cost manufacturing process

- plating, anodization, dip coating, evaporation, thermal oxidation, sputtering
- probably not CVD

Use nano-structuring to mitigate effects of imperfect material quality (e.g. low $\mu\tau$)

Idealized Nanostructure



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Figures of Merit for Si and Some Binary Compounds

Material	Band Gap (eV)	Material A	log(Availability Material A)	Material B	log(Availability Material B)	Gap Deviation Factor	Availability Factor	Figure of Merit
Si	1.12	Si	1.4			-1.8	1.4	-0.4
CuP2	1.46	Cu	-2.4	P	-1.0	-0.6	-2.4	-3.0
Zn3P2	1.23	Zn	-2.2	P	-1.0	-1.0	-2.2	-3.2
Cu2S	1.56	Cu	-2.4	S	-1.7	-1.3	-2.4	-3.7
MoS2	1.41	Mo	-3.9	S	-1.7	-0.3	-3.9	-4.2
GaAs	1.42	Ga	-2.9	As	-3.8	-0.3	-3.8	-4.2
CuO	1.65	Cu	-2.4	O	1.6	-2.0	-2.4	-4.4
ZrS2	1.78	Zr	-1.9	S	-1.7	-2.8	-1.9	-4.7
Bi2S3	1.42	Bi	-4.8	S	-1.7	-0.4	-4.8	-5.2
SnS	1.17	Sn	-3.8	S	-1.7	-1.4	-3.8	-5.2
ZnP2	1.81	Zn	-2.2	P	-1.0	-3.1	-2.2	-5.3
Ag2O	1.35	Ag	-5.2	O	1.6	-0.1	-5.2	-5.3
WS2	1.12	W	-3.7	S	-1.7	-1.8	-3.7	-5.5
K3Sb	1.25	K	0.3	Sb	-4.8	-0.8	-4.8	-5.6
GeS	1.62	Ge	-3.9	S	-1.7	-1.7	-3.9	-5.6
CdTe	1.50	Cd	-4.8	Te	-4.3	-0.9	-4.8	-5.7
FeS2	0.80	Fe	0.7	S	-1.7	-4.0	-1.7	-5.7
Zn4Sb3	1.20	Zn	-2.2	Sb	-4.8	-1.2	-4.8	-6.0
AlSb	1.71	Al	0.9	Sb	-4.8	-2.4	-4.8	-7.2
Cs3Sb	1.81	Cs	-3.6	Sb	-4.8	-3.1	-4.8	-7.9
Cu2O	2.19	Cu	-2.4	O	1.6	-5.8	-2.4	-8.2
Sb2S3	1.92	Sb	-4.8	S	-1.7	-3.9	-4.8	-8.7
SnS2	2.36	Sn	-3.8	S	-1.7	-6.9	-3.8	-10.7

Using: Ideal Gap = 1.37 eV; Net Availability = Lowest of the Pair

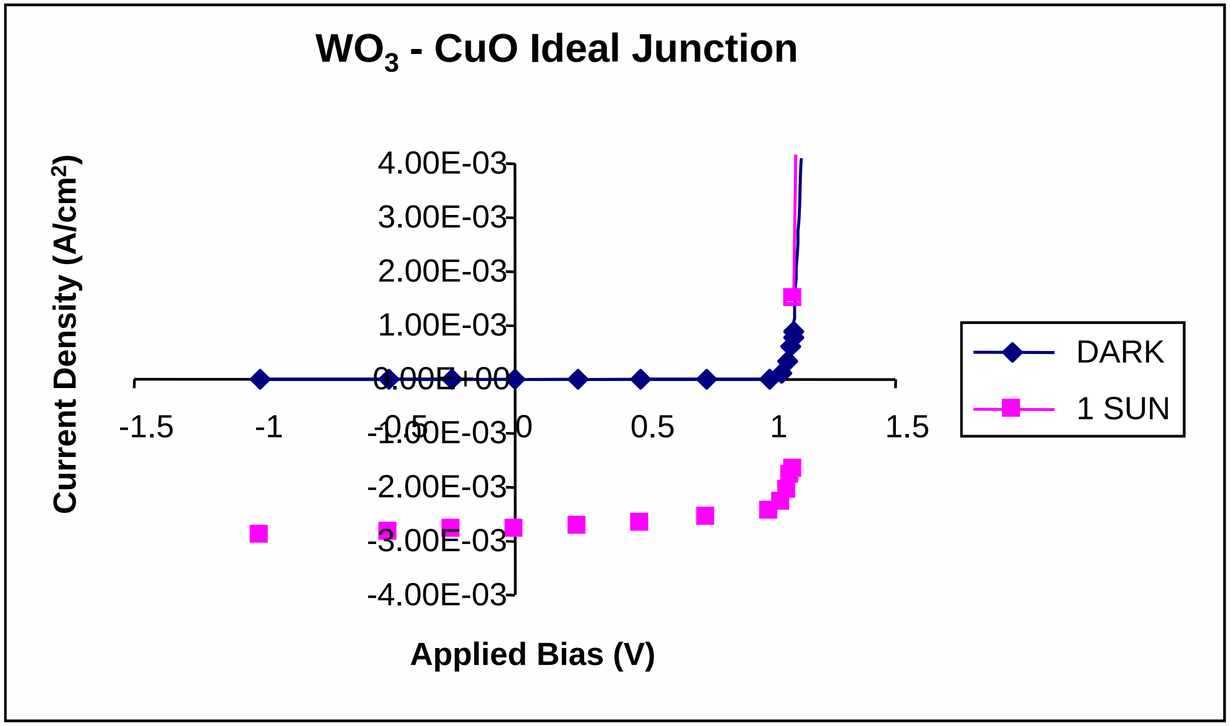
Prediction of I-V Curves for Ideal WO_3+CuO Devices

Planar devices to understand basic materials issues

Emphasis on CuO and Cu_2O as optical absorber

Simple hot plate annealing

Mixed metal oxide heterostructures (e.g. CuO + WO_3)



SimWindows was used for device simulation

device thickness: 80 nm WO_3 + 80 nm CuO

best available materials parameters used

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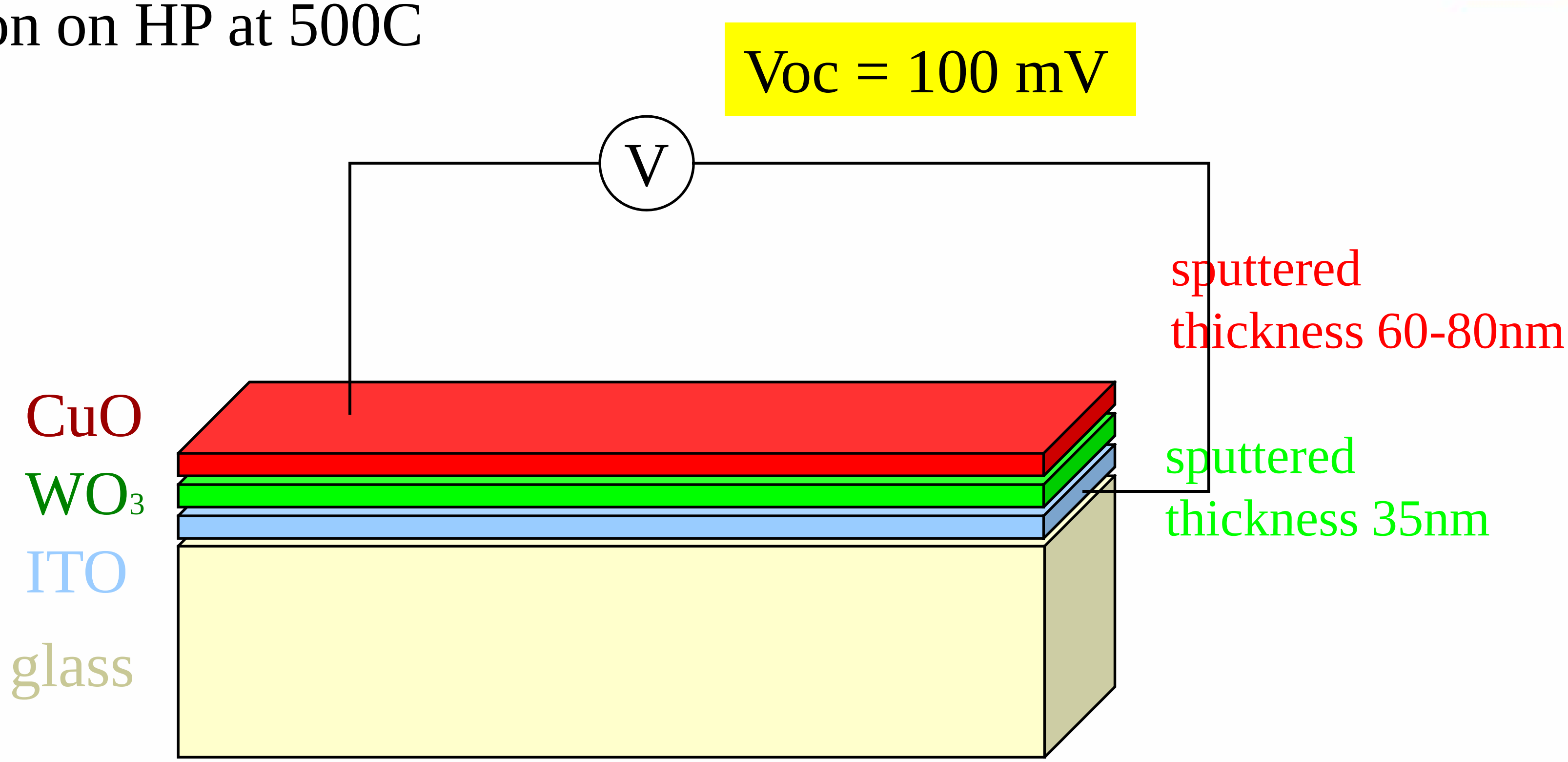
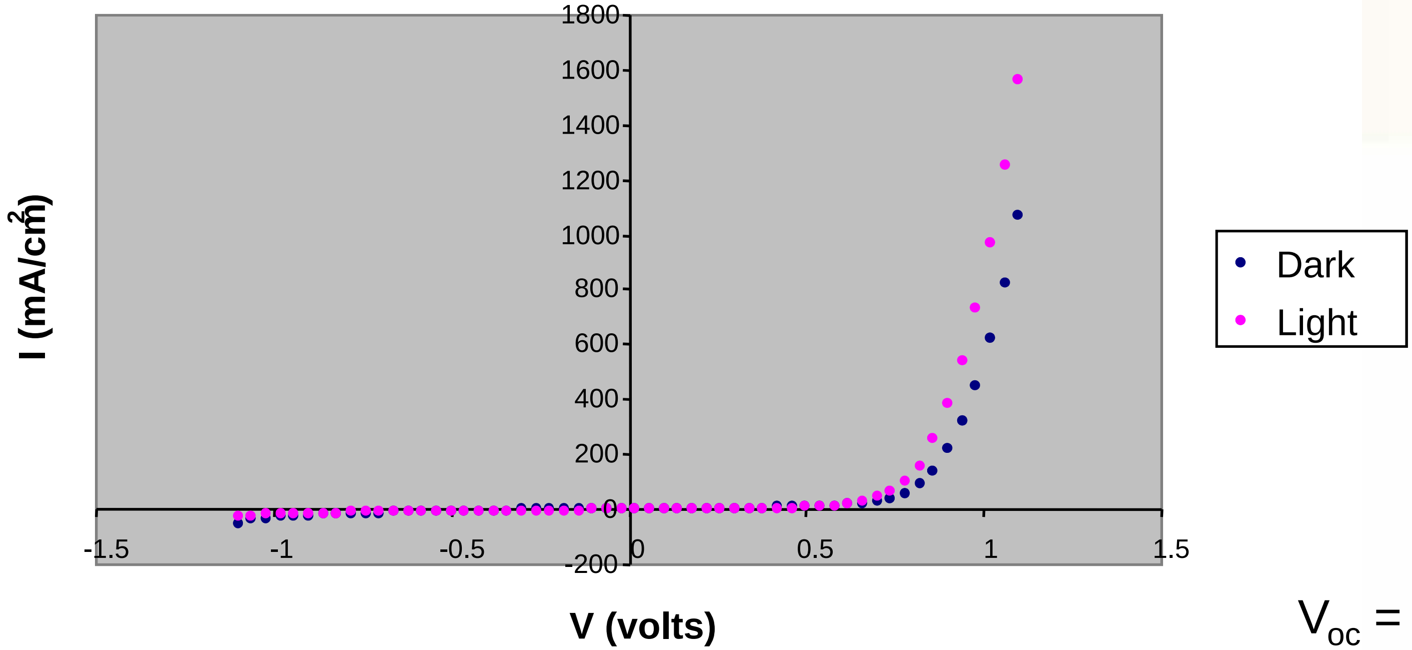
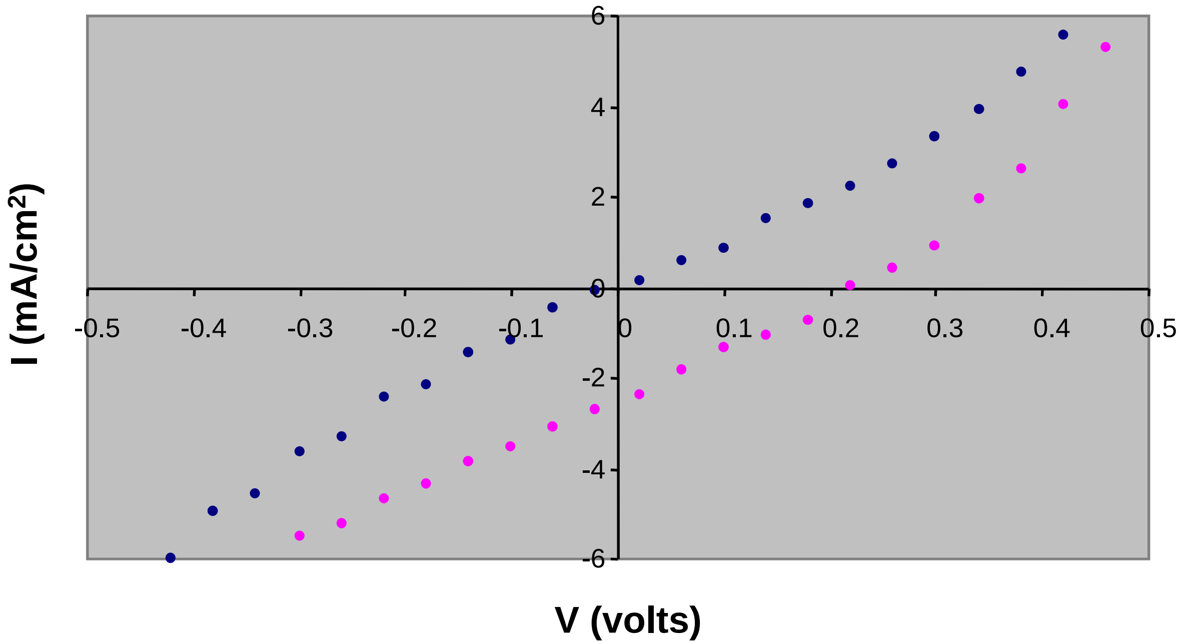
Solar Cells I

Oxidation on HP at 500C







V_{oc} = 0.2 – 0.3 V

I_{sc} = 2.5 mA/cm^2

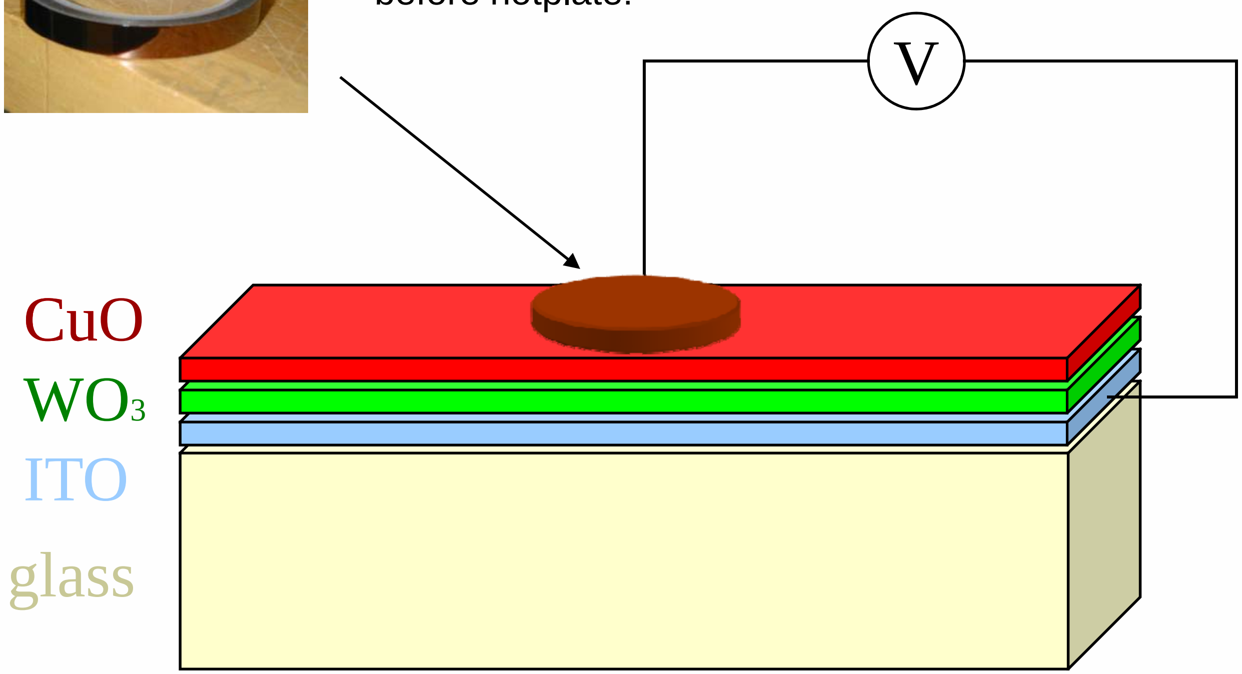
FF = 25%

Eff = 0.1%

Solar Cells II

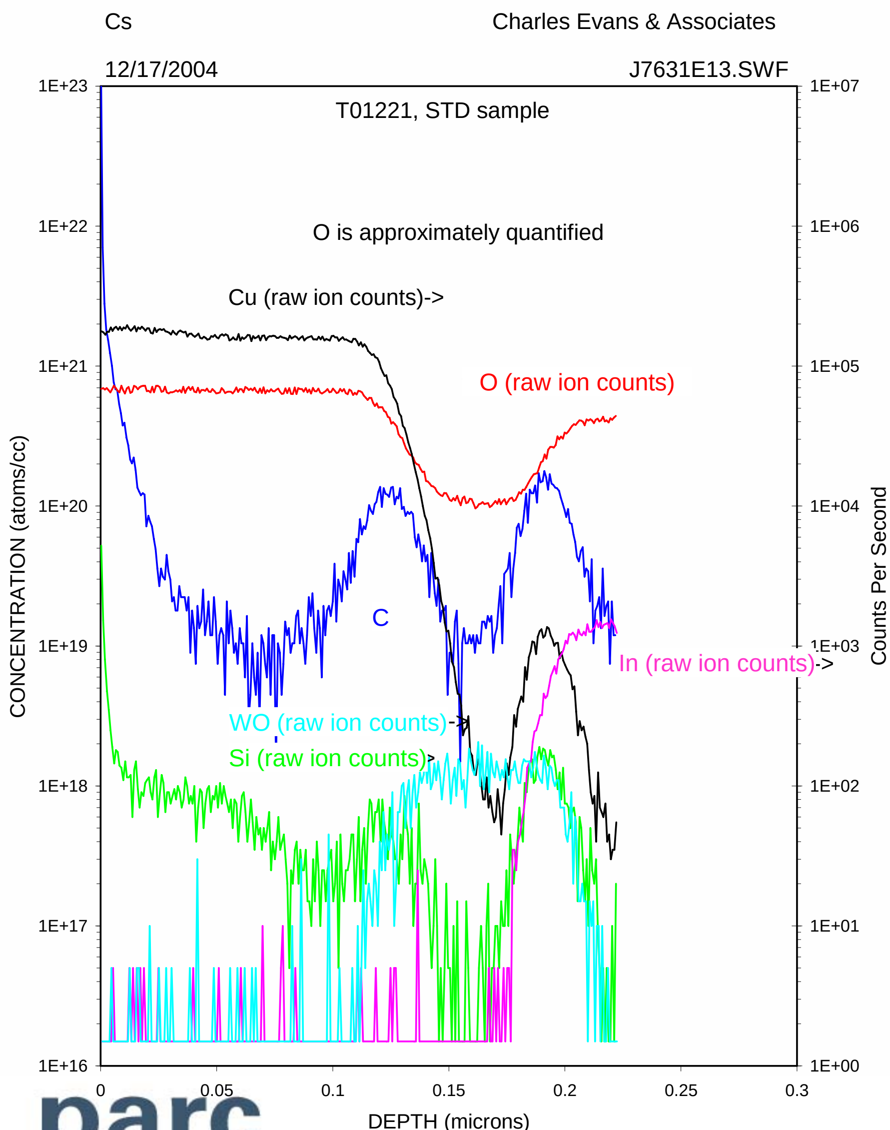
Oxidation on HP at 500C

Voc = 300 mV

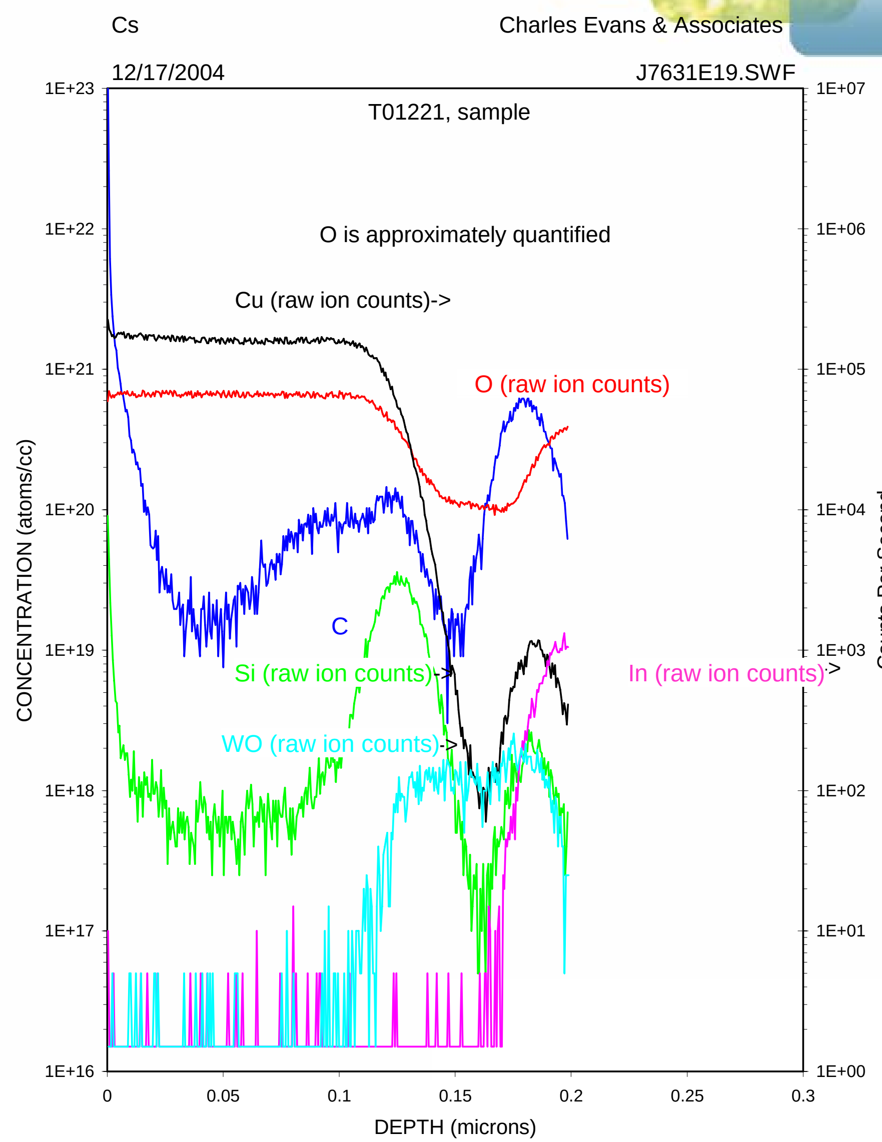


SIMS

No Tape



With Tape



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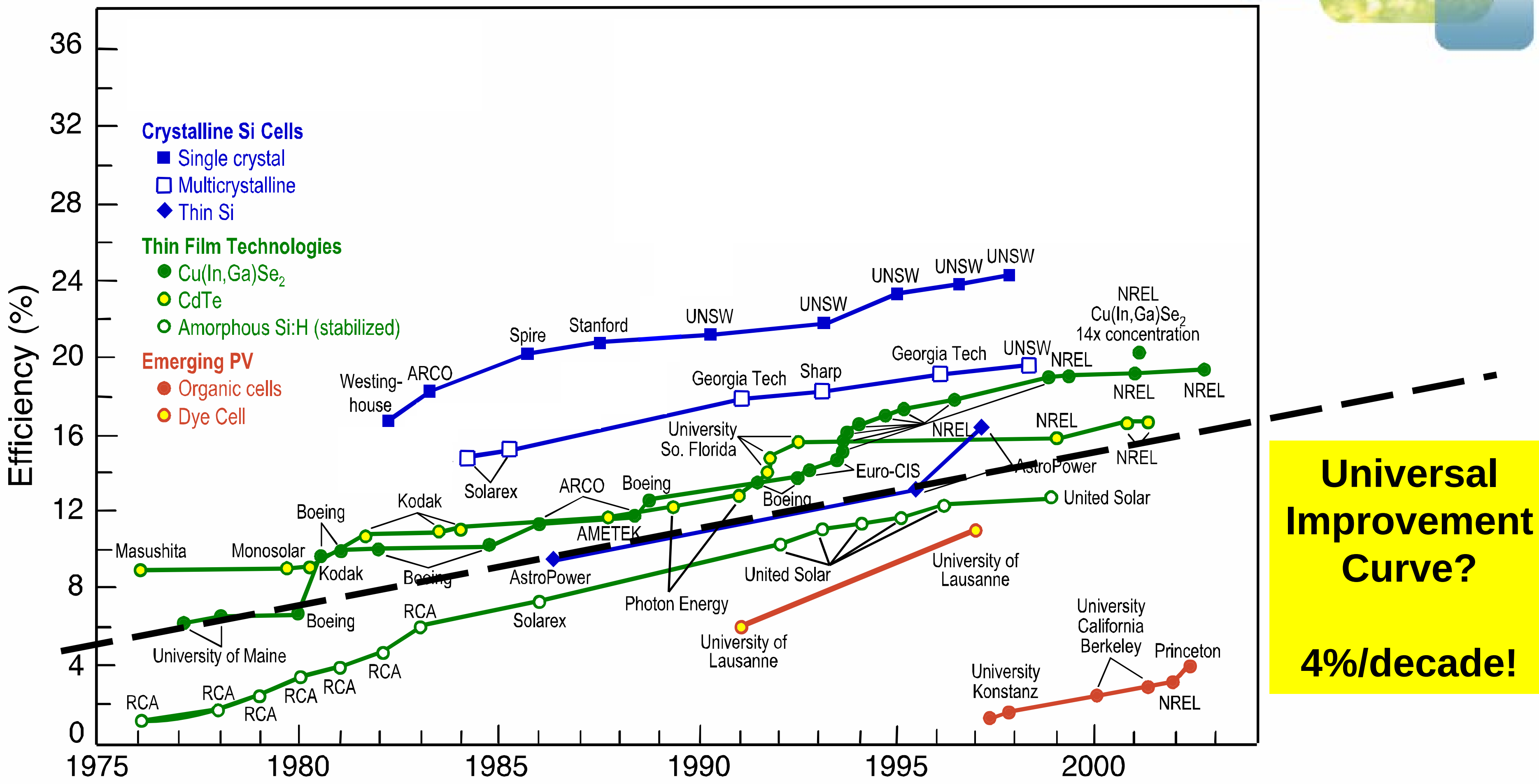
Is this really the right path for a commercial R&D lab?

Present and Next-Generation Best Cell Efficiencies



Source: NREL

Conclusion

If you start out at 1-2% in 2006, it might take you until 2026 to reach 10%....

Alternate Plan

Develop technologies that could have a near-term impact on PV cost reduction:

- Concentrator PV
- Printing approaches to Si solar cells

Cleantech Entry

- Cleantech entry was a bottoms-up, researcher driven activity (with management support)
- Researchers organized a speaker series
- Many valuable connections were made

Connecting to a Startup

Oct, 2004: Trip to visit Professor Roland Winston at UC Merced

- He mentioned the work being done by Solfocus

Dec, 2004: Met Gary Conley (CEO) & Steve Horne (CTO) of Solfocus

- Learned about their 1st generation concentrator

Jan, 2005: Invented a Gen2 concept for a PV concentrator

- Used PARC know-how in optical systems to propose a much lower cost design

Jan, 2005: Initial discussion about a possible license

Dec, 2005: Signed license and research collaboration agreement

Feb, 2006: Solfocus moves into PARC

Aug, 2006: Solfocus closes $32M A-round

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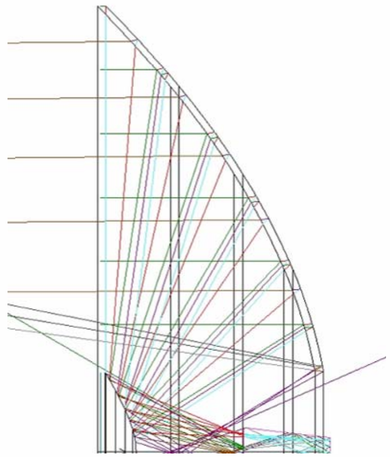
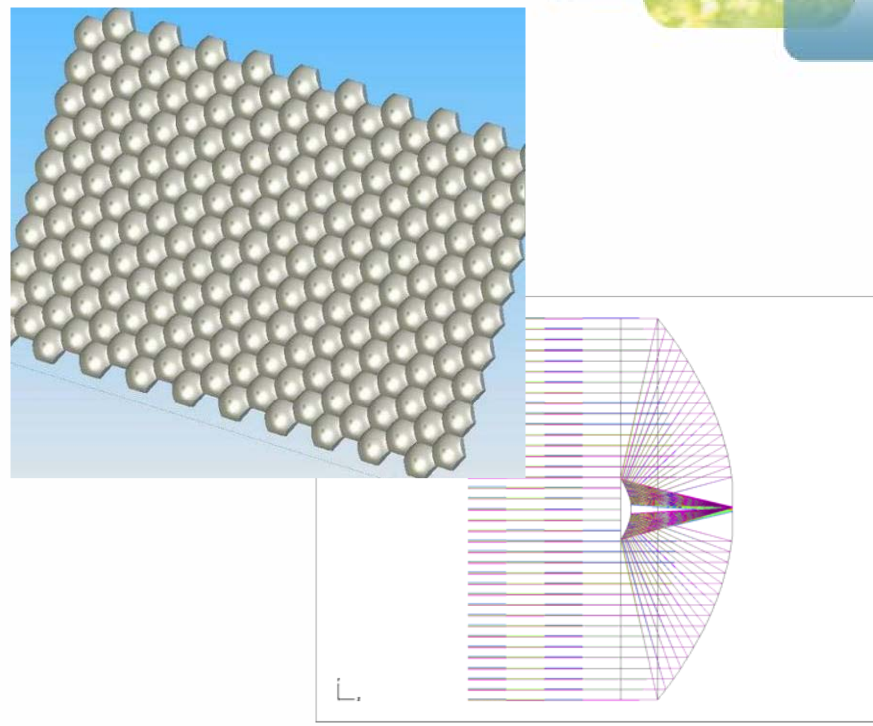
1st Generation → 2nd Generation





Tailored Imaging Concentrator

- Cassegrain geometry
- 500 suns on 1cm^2 Spectrolab cells
- Passive cooling

F-0.25 is the theoretical limit for imaging

Solid Concentrator

- stamped glass – on to rolled process
- 8mm thickest point, 4mm average
- 280 x 430mm tiles – 160 elements
- 30W/tile = 258W/m^2 = **26% efficiency**

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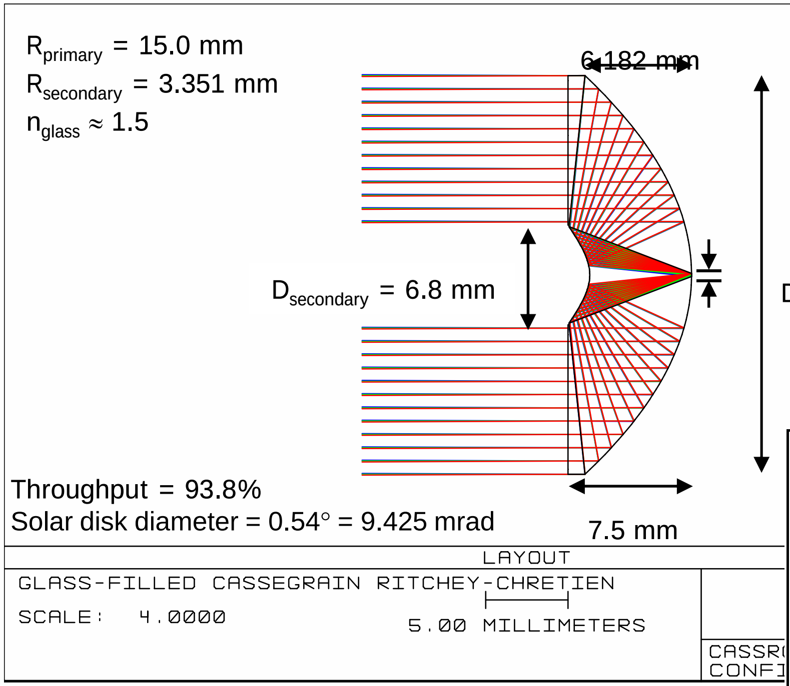
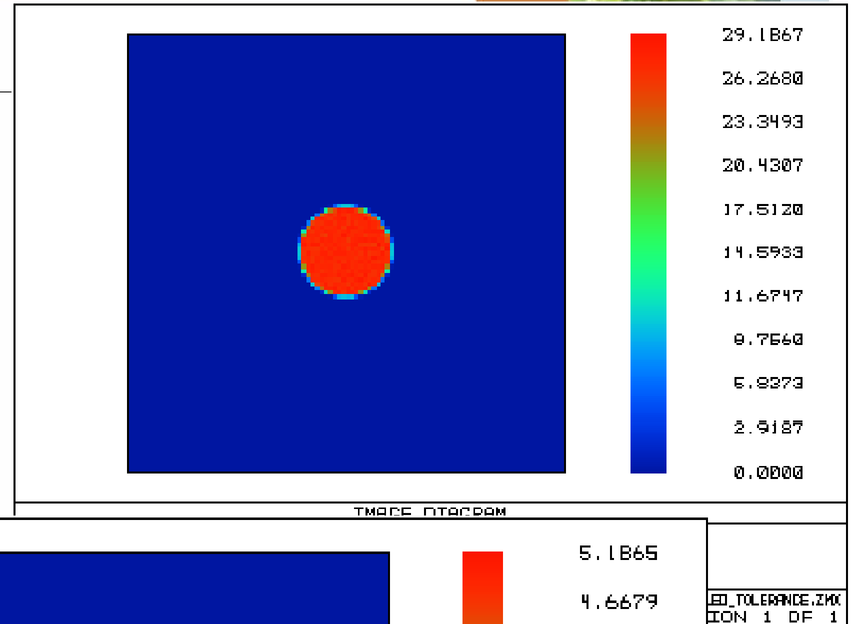
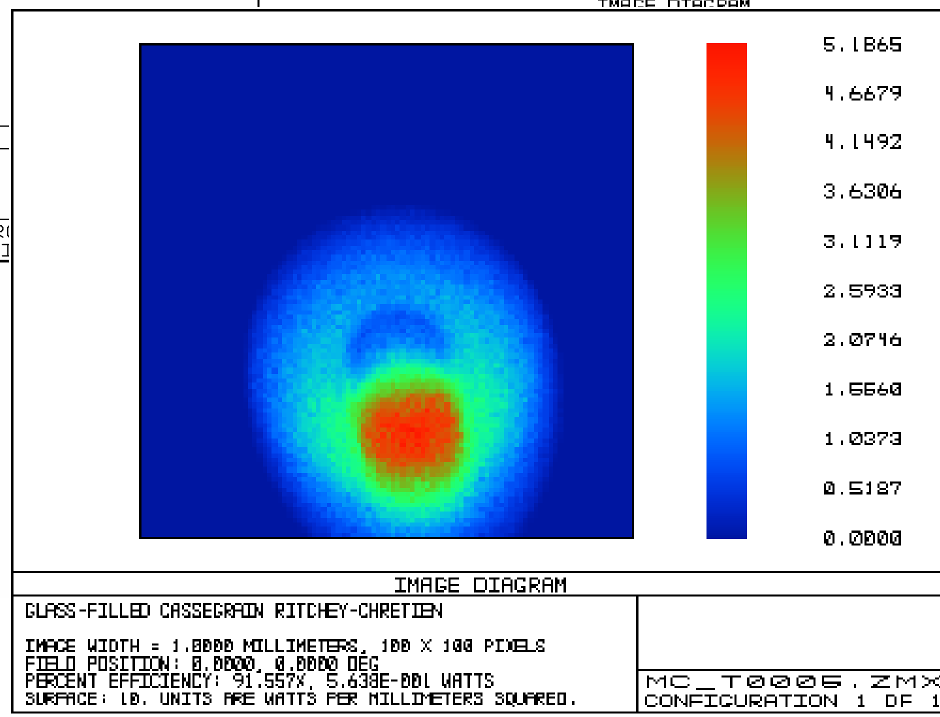
PARC Optical Modeling for Manufacturing Tolerance Analysis







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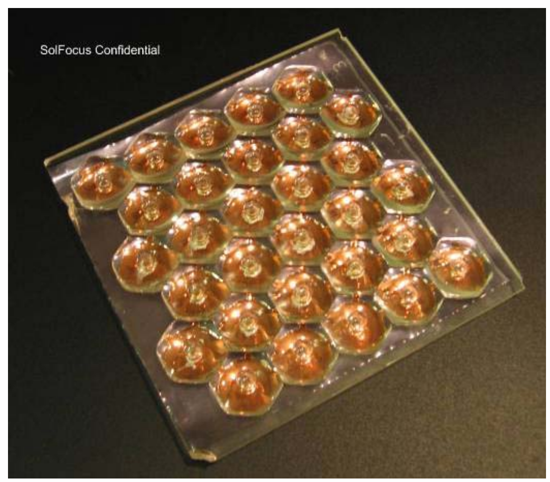
PARC Design for Gen 2

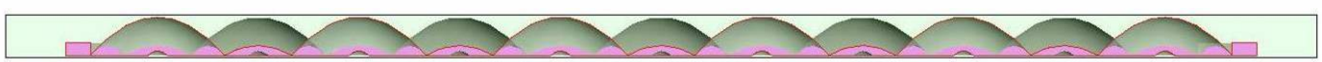
Single glass-molded optic

Purely Reflective, light enters at normal incidence, no chromatic aberration

No: Coverglass, seals, spacers, liquid cooling…



10mm



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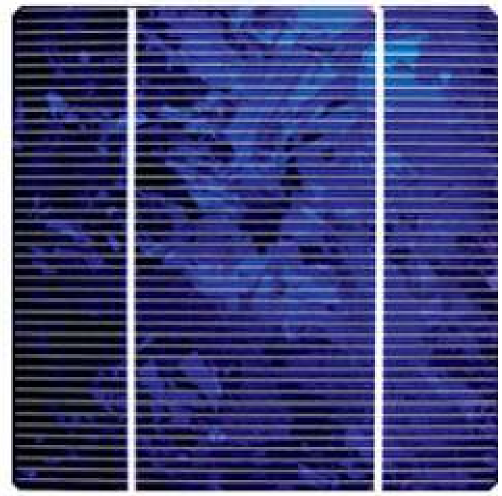
Other PV Projects

- Made initial Cleantech bet on concentrator PV with Solfocus
- Wanted to create new projects to address flat-plate silicon (still 95% market share in PV)
- Goal would be to improve efficiency and/or reduce manufacturing cost using PARC competencies (for example printing)

Initial Focus of PARC effort

- Diffusion
- Edge Isolation Etch
- Antireflection Coating
- Front Silver Gridline Print
- Back Silver Print
- Back Aluminum Print
- Firing in Furnace



Technical Objectives:

- 1 to 5% absolute efficiency increase
- Machines pay for themselves in months
- Non-contact, direct write systems
- No wet baths
- 1 to 2 seconds per wafer
- 24/7 operation, limited downtime
- Produce features of 10-50 microns
- Self alignment for device feature registration

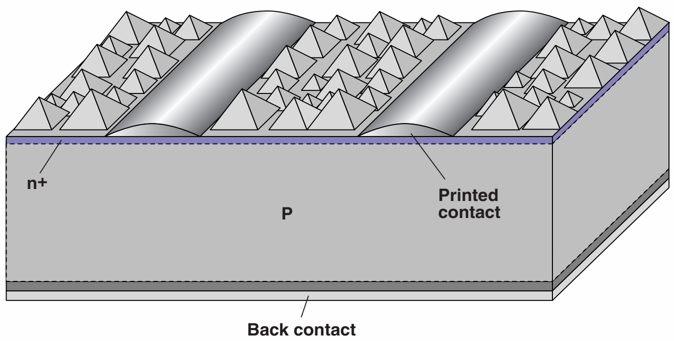
Leverage Existing PARC Competencies

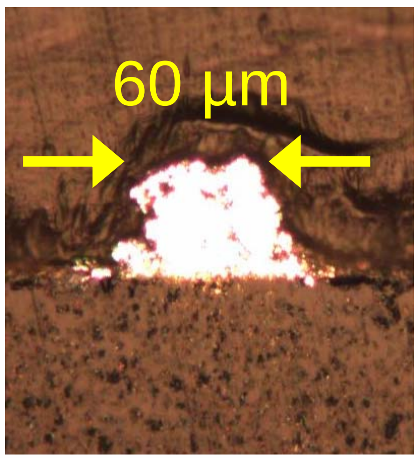
PARC innovations support
high speed, very low cost printing
(DocuTech @ 180ppm)

New Printing Method

- Current gridlines are screen printed and have an aspect ratio of 1:10
- Opportunity to reduce shadowing and increase efficiency by 6-8% relative with higher aspect ratio gridlines
- First generation lines from PARC printing approach are 1:1 aspect ratio
  - Uses standard Ag ink fire-through process

Screen printed





PARC technique

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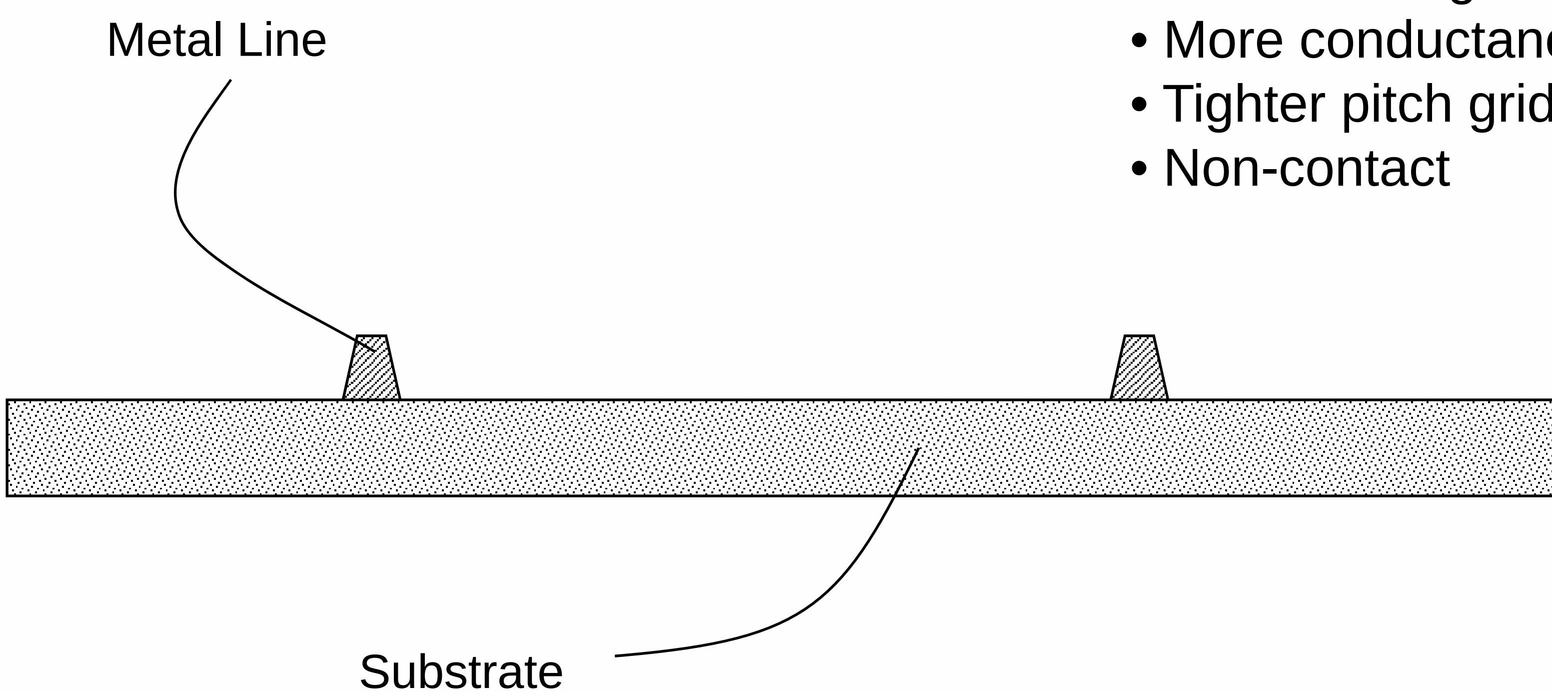
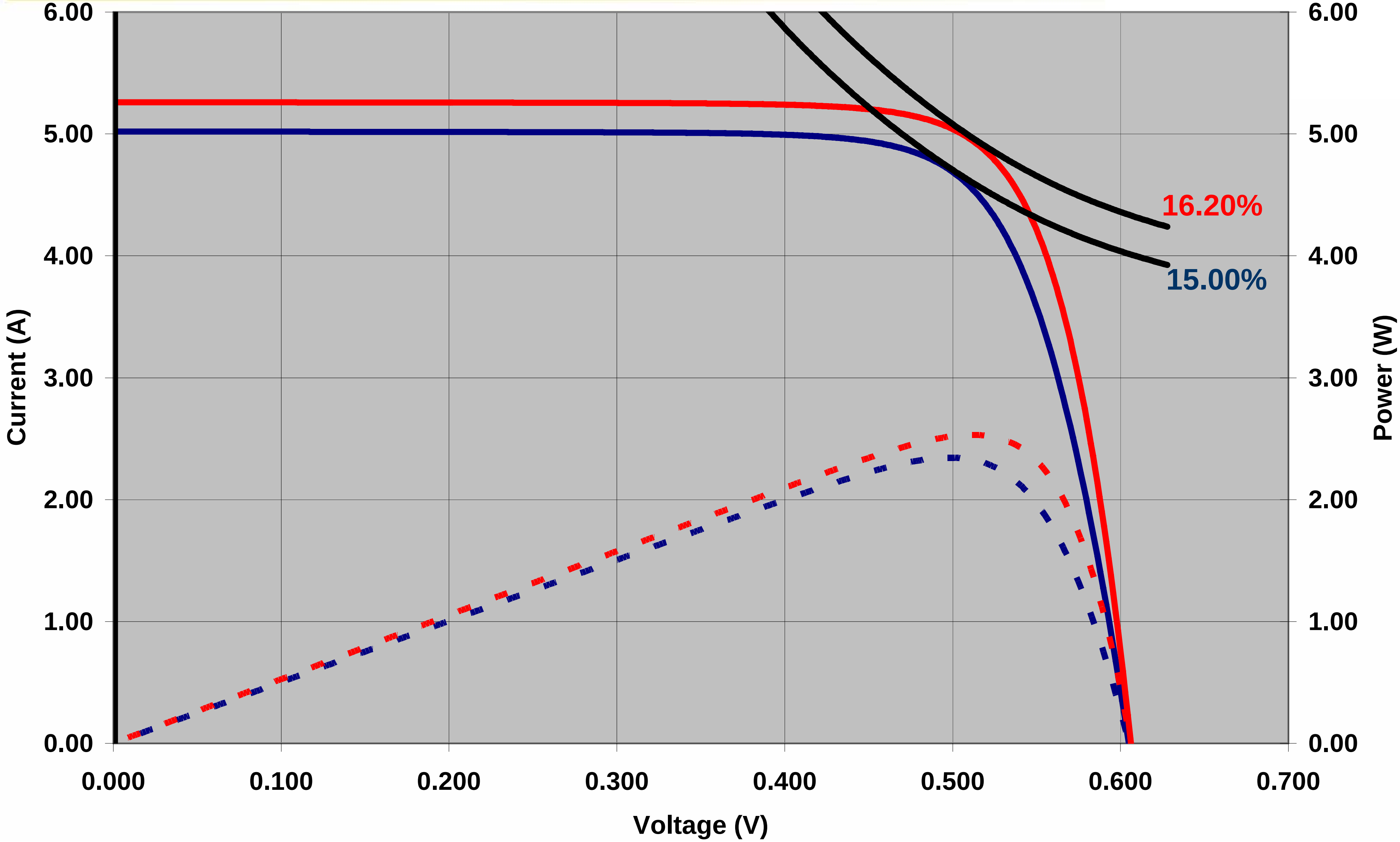
1st Generation Gridline

Advantages:
- Less shading
- More conductance
- Tighter pitch gridlines
- Non-contact



Target Dimensions:
50 micron height, 50 width
Efficiency increase: ~6% relative for cast multi

I-V and Power Curves for Baseline (15.0%) and PARC printing (16.2%) Solar Cells



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Solar Fuels

Addressing the Needs of 21st Century Energy Storage

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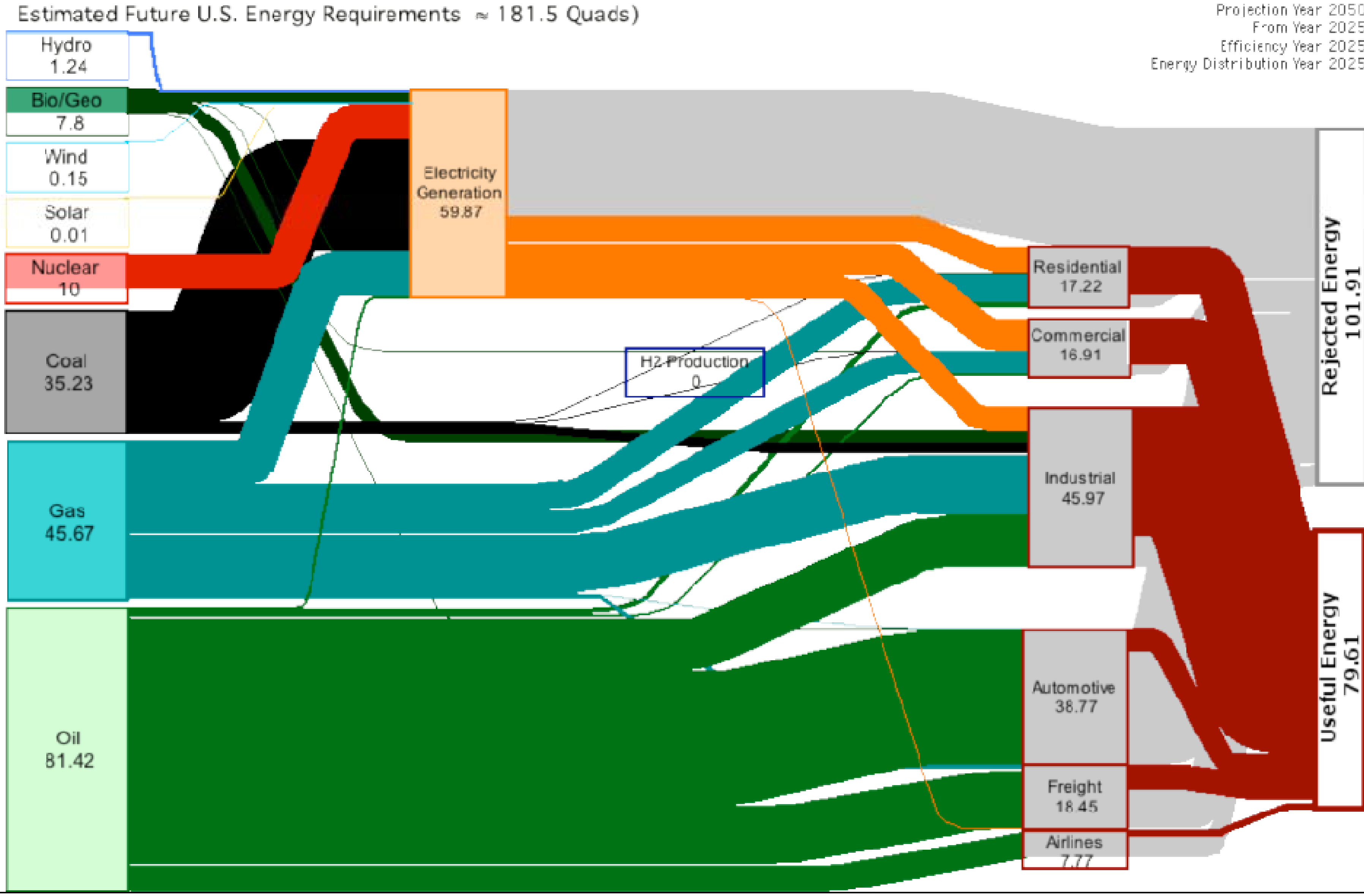
US Energy Flow 2050

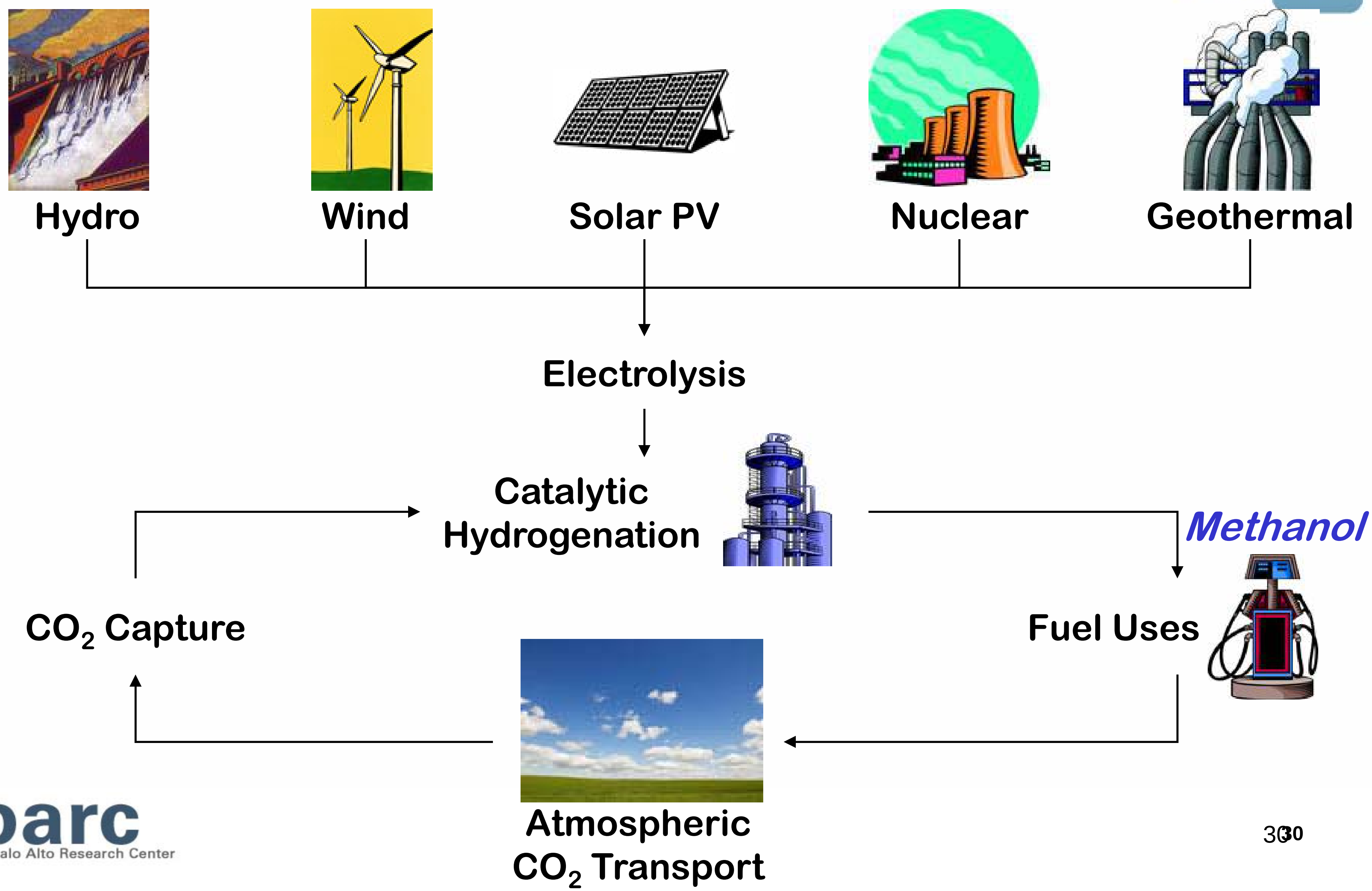


Scenario 3. Linear extrapolation of *Annual Energy Outlook* projections for 2020-2025 out to 2050. A driving age population of 318 million, averaging 19,500 miles driven per year in 20 mpg vehicles, requires 39 Quads of petroleum or 18 million bbl/day.

Solar electricity -> fuels

- Solar PV industry already producing modules with 10 – 20+ % efficiency
- Electrolysis units can produce H_2 at 80% energy efficiency
- H_2 can convert CO_2 to methanol at efficiencies of 70% (>99% yield)
- 50% efficiency from electricity to fuel is possible today
  - Overall efficiencies of sunlight to fuel of >10%
  - Area to "fill" one tank of gas/week ~100 m^2
  - Requirements:
    - cheap "carbon free" electricity
    - cheap CO_2 extraction

Solar / Renewable Fuels Flowchart



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Cost

Electricity (retail)	12 ¢/kW-hr	$3.50 /gge
Electricity (wholesale)	$36 /MW-hr ($20 – $80+)	$1.25 /gge
Gasoline (excluding dist. mrktng. & taxes)	$2.00 /gal (~$2.80 /gal retail)	$2.00 /gal
Natural gas (retail)	$1.33 /therm	$1.75 /gge
Natural gas (wholesale)	$0.75 /therm	$1.00 /gge
Coal (2005)	$31 / short ton	$0.20 /gge
Wind	3 ¢ - 6 ¢ /kW-hr	$1.00 /gge
Solar PV (flat plate)	$6/W (installed)	$4.25 /gge

Gasoline is one of the most expensive forms of energy

Cost

Carbon free electricity is close to the required cost today

- Solar is too expensive today but costs are dropping…
  - Cost reduction and higher efficiency for direct DC off grid solar
    - – Eliminates 5 – 10 % inverter losses
    - – Avoids inverter / grid costs
      - » ~$1.00 / W reduction
- Wind 3 – 6¢ /kW-hr -> $1.00 - $2.00 /gge
- Nuclear $50 /MW-hr -> $1.75 /gge
- Govt. incentives or technological development can bridge the gap.
- Addresses some renewable resource problems
  - Intermittency
  - Not dispatchable

Methanol from "carbon free" sources as low as $2.30 gge

w/o CO_2 capture, distribution, marketing and taxes

How to get CO_2?

Conversion to fuel requires relatively pure CO_2

- CO_2 in the atmosphere only at 0.038%

Energy Cost of >500 kJ /mol CO_2 with technology available today

- Too inefficient, Too Slow -> Too expensive – about $1.50 /gge

However, the thermodynamic minimum energy required is only 20 kJ/mol

- 5 ¢ /gge

Atmospheric CO_2 Gas separation membrane technology >30 years old

- Best electrochemical systems < 10% efficient
- PARC experience in large area MEMS, thin films, microfluidics, and printable electronics applicable to membrane applications
- Highly structured fuel cell membranes with high ionic conductance have been designed – similar requirements to CO_2 membranes
- Printing technology can be applied to mass produce gas separators

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Conclusion

- Solar to fuel conversion closer than it first appears
- Cost effective CO_2 neutral fuels could be a reality with improved carbon dioxide concentration
- Wind or nuclear generated electricity plus efficient concentration and methanol conversion could be economical in the near future
- Ultimately reduction in the cost per Watt of solar PV will enable a complete system generating clean liquid fuel from sunlight.

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Thank you

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