Ellen D. Williams, Director of ARPA-E
MIT Solar Day
Sept 10, 2015

http://www.arpa-e.energy.gov/
U.S. Energy

Atmospheric CO₂ concentration
1960: 320 ppm
2010: 390 ppm
Desired maximum by 2100: 450 ppm

Source: EIA AER Table E1 and MER Tables 1.1 and 10.1
ARPA-E

**Mission:** To overcome long-term and high-risk technological barriers in the development of energy technologies

**Goals:** Ensure America’s

- Economic Security
- Energy Security
- Technological Lead in Advanced Energy Technologies

**Means:**

- Identify and promote revolutionary advances in fundamental and applied sciences
- Translate scientific discoveries and cutting-edge inventions into technological innovations
- Accelerate transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty
ARPA-E Goal: Disruptive technologies

transformational potential

cost / performance

time

Steam-powered Cugnot (1769)
Benz Motorwagen (1885)
Ford Model T (1914)

existing learning curve

new learning curve – disruptive technology
If it works... *will it matter?*
Transitions Toward Market Adoption

- **R&D**
- **Prototype**
- **Demonstration**
- **Commercialization**

**Valley of Death #1:** Public Funds

**Valley of Death #2:** Follow-on Development Funds

**Valley of Death #3:** Venture Capital/Private Equity

Time

Investment
Mission
To provide disruptive new solar energy conversion and storage options to enable a much higher penetration of solar energy generation into the US energy mix.

Goals & Opportunities
Develop two distinct technology options to deliver low-cost, high-efficiency solar energy on demand:

1. **New hybrid solar energy converters** to turn sunlight into electricity for immediate use, while also producing heat that can be stored at low cost for later use (using the entire solar spectrum more efficiently than PV or CSP technologies)

2. **New hybrid energy storage systems** that accept heat and electricity from variable solar sources to deliver electricity when needed

<table>
<thead>
<tr>
<th>Year</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projects</td>
<td>12</td>
</tr>
<tr>
<td>Total Investment</td>
<td>$30 Million</td>
</tr>
</tbody>
</table>
Pathways For High Penetration Solar Energy

Concentrating solar power (CSP):
• Light to heat at $\eta \approx 60$-80% $\Rightarrow$ ~20% net efficiency
• Offers dispatchability with low-cost thermal storage
• **Challenge:** LCOE high relative to PV

Photovoltaics (PV):
• Light to electricity at $\eta \approx 40$-60% just above PV band edge (1-2 eV bandgaps work best)
• **Challenge:** requires low-cost electricity storage

**FOCUS:** Create hybrid PV + CSP systems that use the full spectrum efficiently and produce low-cost electricity (PV) with low-cost thermal storage (CSP).

Hybrid solar converters for maximum exergy and inexpensive dispatchable electricity

H. M. Branz,*ab W. Regan,a K. J. Gerst,a J. B. Borakac and El. A. Santoría

Options For Hybrid Collectors

- **Combined cycles:**
  - PV topping cycle (400°C or higher)
  - Send subgap and thermalization losses to storage, heat engine
  - **Challenge:** high temperature PV

- **Spectral splitting:**
  - Send matched wavelengths to PV
  - UV and IR to thermal cycle
  - (Optional) Capture low-grade heat on PV for preheat
### Hybrid solar converters (spectral splitting)

<table>
<thead>
<tr>
<th>Category</th>
<th>Value (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exergy efficiency of converter with output heat temperature of $T_h$ ($^\circ$C)</td>
<td>$&gt; 30 + [(T_h-200)/40]$ (%)</td>
</tr>
<tr>
<td>Fraction, $f_{th}=x_{th}/x_{tot}$, of delivered exergy as heat</td>
<td>$0.50 &lt; f_{th} &lt; 0.90$</td>
</tr>
<tr>
<td>Temperature of heat provided by converter, $T_h$</td>
<td>$150 – 600 ^\circ$C</td>
</tr>
<tr>
<td>Collection area of prototype converter</td>
<td>0.5 to 25 m$^2$</td>
</tr>
<tr>
<td>Cost per unit of delivered exergy from converter</td>
<td>$&lt; $1/W</td>
</tr>
<tr>
<td>Field life of manufactured converter</td>
<td>25 years</td>
</tr>
<tr>
<td><em>Intermediate-scale application unit area</em></td>
<td>$&lt; 1000$ m$^2$</td>
</tr>
</tbody>
</table>

### Topping Devices

<table>
<thead>
<tr>
<th>Category</th>
<th>Value (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature of solar topping device</td>
<td>$&gt; 400^\circ$C</td>
</tr>
<tr>
<td>Sunlight-to-electricity efficiency of topping device</td>
<td>$&gt; 25%$</td>
</tr>
<tr>
<td>Cost per unit area of sunlight intercepted</td>
<td>$&lt; 20 \times C ($/m^2$) $100 &lt; C &lt; 1000$</td>
</tr>
<tr>
<td>Field lifetime of device</td>
<td>25 years</td>
</tr>
</tbody>
</table>
FOCUS Portfolio

**combined cycles**
- dual junction InGaN on InP
- InGaP/(In)GaAs dual junction on GaAs
- (Al)InGaP/GaAs dual junction on GaAs
- thermoacoustic engine for use with topping PV

**spectrum splitting**
- diffuse light capture in Si PV with spectrum-splitting CSP “PV mirror” trough
- PV splitting/topping secondary on trough
- retrofit troughs with dichroic splitter + PV
- aerogel-insulated thermal receiver for linear Fresnel
- Cassagrainian trough with dichroic and 500X PV
- nanoparticle spectrum-splitting thermal fluid

**co-storage of heat and electricity**
- supercritical CO₂ turbo-generator using dry ice and molten salt

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11
High-Temperature PV: 26% at 400°C, 500x

- 26% efficient 2-junction III-V PV (InGaP/(In)GaAs)
- Epitaxial lift-off (with MOCVD growth) lowers cell cost
- Accelerated lifetime testing for 25-year lifetime
Re-Envisioning The Solar Thermal Trough

PV Mirror: capture diffuse (PV) and direct (PV + thermal) light with spectrum-splitting dichroic film and PV on traditional trough
Close-Up of PV Mirror Trough Surface

- Planar Si PV cells and dichroic mirror replace silver mirror
- PV cells convert 1-sun direct and diffuse visible components
- Reflection heats fluid with concentrated direct-beam UV/IR

On track for ~50% (relative) gain in trough efficiency
MOSAIC
Micro-scale Optimized Solar-cell Arrays with Integrated Concentration

Program Director: Dr. Mike Haney

Mission
Develop novel solar conversion devices that deliver the increased performance of concentrated photovoltaic (CPV) but are similar in profile and cost to traditional non-concentrated “flat-plate” (FP) PV.

Goals & Opportunities
Solar-to-electrical power conversion efficiency (as measured against total annual incident solar radiation) of > 30% across a wide range of geographic locations with varying amounts of direct and diffuse insolation.

- Micro-scale design reduces size, weight, & cost with efficient concentration, tracking, and thermal management: Many small repeat units have benefits based on physics, modularity, optimization and customization.

<table>
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<th>Year</th>
<th>2015</th>
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<td>11</td>
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<td>$24 million</td>
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</table>
Challenge: High DNI* vs Low DNI Regions

Global insolation and percentage of diffuse radiation as a function of geographical location in the U.S.; data adopted from National Solar Radiation Data Base (1961-1990), 1992

*Direct normal irradiance
PV Technology Pathways

**Flat Plate**

Discrete FP (1-sun) modules
- Harvesting eff. ~20%
- Lower Cost
- Wider Geographical and Market Domains

**Macro-scale CPV**

Discrete CPV module
- Harvesting eff. ~40%
- Higher Cost
- Limited Geographical and Market Domains

**Integrated \(\mu\)-CPV cell array**
- Harvesting eff. ~40%
- Low Cost, FP form factor
- Expanded Geographical and Market Domains

Exploit developments in commercial large-area integrated *micro-*optical/electronic systems
Goal: Take CPV Technology from Discrete to Integrated

Challenges:
• Pixilated cell array fabrication, integration, and packaging techniques;
• Micro-scale optics with high performance, robustness, and manufacturing scalability;
• System fabrication costs commensurate with current FP PV.
# Programs Set Stretch Goals - MOSAIC

<table>
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<th>Target</th>
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<td>Solar Energy Harvesting Efficiency</td>
<td>≥ 30% at module output</td>
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<tr>
<td>Production Cost</td>
<td>&lt; $125/m²</td>
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<td>Array height</td>
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<tr>
<td>Projected system degradation</td>
<td>&lt; 1%/year</td>
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**High DNI system with macro-tracking**

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**Low DNI system with macro-tracking**
MOSAIC Portfolio

Category 2: Systems for Low DNI regions

- MIT: Integrated Micro-Optical Concentrator
- Caltech: Micro-optical tandem luminescent solar concentrator
- SHARP: High-efficiency flat plate PV with integrated micro-PV
- SEMPRIUS: Micro-scale ultra-high efficiency CPV
- ATm: Waveguiding solar concentrator
- GLINT PHOTONICS: Stationary wide-angle concentrator PV system

Category 1: Systems for High DNI regions

- PennState: Wide angle planar microtracking microcell CPV
- University of Rochester: Planar Light guide concentrated photovoltaics
- Panasonic: Low Profile CPV Panel with Sun Tracking

Category 3: Innovative Partial Solutions

- MIT: Wafer level Integrated Concentrating Photovoltaics
- parc: Micro-Chiplet Printer
Energy Context - World

CO₂ emissions, 18.3 Gtonne/yr, 32.3 Gtonne/yr, 45.5 Gtonne/yr

Energy Consumption, QBtu


* Includes both traditional and modern uses of biomass
Energy and Emissions – Changing What’s Possible

U.S. CO₂ emissions (Gtonne/yr)

- 4.8
- 6.0
- 5.5 (2025 target: 4.3)

U.S. Energy Consumption, QBTu

- 1980
- 1990
- 2000
- 2010
- 2020
- 2030
- 2040

* Includes both traditional and modern uses of biomass

EIA AEO Figure MT-9 (Reference Case), 2013 updated for Actual
EIA 2014 AEO Tables A2 and 17, and IEA World Energy Outlook 2014, Table 2.1
Note: EIA biofuels projection moved to “Bioenergy” to match IEA categorization
ARPA-E Fellows

FELLOWS’ Roles & Responsibilities:

- Independent Study
- Program Director Support
- Organizational Support

ATTRIBUTES

- Ph.D. in science or engineering
- Record of demonstrating analytical and research capabilities
- Ability to work independently and as a team member
- Strong communication skills
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www.arpa-e.energy.gov

Join us at our 2016 Summit
February 29 – March 2, 2016
Gaylord National Convention Center
just outside Washington, DC.
ARPA-E Impact

- TECHNICAL OPPORTUNITIES
- PATH TO COMMERCIALIZATION
- EVOLVING PORTFOLIO
- OPTIONS FOR THE FUTURE
Backup
Two Application Domains

Macro-tracking (Utility/Commercial)

Micro-tracking (Residential): space-constrained

Fixed-tilt installation

These two domains have common technical challenges, but fixed-tilt domain must also have embedded micro-tracking integrated into micro-optical layer.
The Good and the Bad of Solar Photovoltaics

- **Good:** Near/below grid parity
  - $100 billion/year and growing
  - ~5% of CA electricity (2014)
  - Will double by 2020

- **Bad:** Daytime oversupply
  - Germany already experiencing oversupply on bright days
  - California (below) and US southwest on similar path

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**Graphs**

- **Left:** R. Swanson, 47th IEEE PV Specialists Conference
- **Right:** California ISO “duck curve” (2013)