Trends in Solar Photovoltaics (PV): From Rooftops to Gigawatt Arrays to Microgrids

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Outline

Research activities and capabilities at IEC

Status of World PV installation and generation

Cell and module technologies with >1 GW manufacturing

Fixed tilt vs tracking

Too much PV on the grid? Need for self-consumption

Microgrids: integrating renewables and storage for on-grid and off-grid reliability

Wrap-up
Institute of Energy Conversion (IEC)

44 years of RESEARCH, INNOVATION, EDUCATION and SUPPORT for US Govt PV programs and the PV industry

Multidisciplinary R&D team of scientists, engineers, faculty, postdoctoral fellows, visiting scholars, and graduate and undergraduate students from physics, materials science, chemical and electrical engineering

Research facility at U of Delaware funded from federal and industrial contracts

Since 2000, direct support from >20 companies to develop PV technologies or materials
IEC Historical Highlights

1970’s and 1980’s

- Established at the University of Delaware in 1972
- First thin film solar cell with greater than 10% efficiency (flexible Cu$_2$S/CdS)
- First deposition of semiconductor on flexible moving substrate (Roll-to-Roll R2R)
- R&D initiated on CuInSe$_2$, CdTe, a-Si:H thin-film solar cells, all >10% by 1990

1990’s

- Designated as DOE University Center of Excellence for PV Research and Education
- DARPA consortium with IEC and 6 companies develop flexible R2R PV product
- Significant collaborations supporting >12 US PV manufacturers: a-Si, CIGS, CdTe

2000 – present

- Installed three industrially relevant deposition systems: moving substrates, ~1 ft
- Merged 2 leading concepts for hi eff c-Si: first heterojunction IBC cell, Eff ~ 20%
- Developed process for single crystal growth of CZTS for fundamental studies
- Worked with >20 companies to develop PV technologies or materials
IEC: Integrated Photovoltaic Laboratory

- More than 20 deposition systems: semiconductor, metallic and oxide thin films
- Material characterization: electrical, optical and structural
- Device characterization: solar cell performance, modeling and diagnostics
- Accelerated environmental exposure: moisture, heat, light
- Develop and optimize device fabrication processes
- Modeling, design, construction and operation of experimental systems
- Monolithic module design, fabrication and characterization
Trends in PV
Status of Worldwide and US PV

Compound Annual Growth Rate (CAGR): 44% from 2000-2014

- Not sustainable (35% in 2015)

Cumulative installed capacity: 240 GW (US=26)

- If all 240 GW installed in US, would generate ~ 10% annual electricity

Compare 240 GW PV to thermal power plants

- Power: capacity ~ 240 coal/nuclear
- Energy: generates ~ 30 coal/nuclear

%PV Gen: Europe 3.5%, Japan 2%, US 1%

US 2015: Install 7.7 GW (84,000 module/day)

Energy payback time: 1.0-1.5 years, with lifetime ~ 25-30 years, very high net energy
PV module and system price

Barbose et al Prog in PV 2014

Installed price of residential and commercial photovoltaic (PV) systems and Global Module Price Index over time.

2015:
- System ~ 3.0-3.5 $/W
- Module ~ 0.70 $/W

Module ~ 1/2 of system
Module ~ 1/5 of system
PV Cell Technology
Silicon PV Manufacturing: 90% of today’s modules

**Polysilicon**
- Purify SiO2
- React to obtain Si
- 400 kg ingots
- High energy use

**Cz ingot & wafering**
- Crystallize Si
- Cut ingots bricks
- Slice into wafers
- ~50% kerf loss

**Cells**
- Chemical processing
- Form pn junction
- AR coating, grids
- 60% : same process
- Industry differentiation
- Cost and efficiency

**Modules**
- Low tech
- Standardized
- Reliability!

Goodrich et al SolMat 114 (2013)
Commercially viable PV cell technology options

**BAU Si:**
- today’s multicrystalline p-Si wafers with minor improvements (PERC)
- >60% of production
- standardized, commodity
- lowest risk and cost
- module eff ~16-17%

**Advanced Si:**
- innovative high performance junction and contact, n-Si, improved passivation, no grids
- higher risk and cost
- 6% of production
- module eff ~21-22%

**Thin Film technology**
- 2-4 µm, radical different production stream
- CdTe or CuInGaSe₂
- Different challenges
- 8% of production
- Module eff ~ 14-16%
**Worlds 2nd Largest PV System: 290 MW_{AC}
Agua Caliente (AZ), First Solar Thin Film CdTe**

- 5.2 million CdTe thin film modules on 3.8 sq miles in AZ
- Designed to “Ride through” grid disturbances
- Large area minimizes impact rapid change cloud transients
- 1st PV connected to transmission grid at 500 kV
Trends in PV Applications

- Tracking
- Battery storage for self-consumption
- Microgrids
PV can be installed anywhere, any scale
Before 1995: PV demand driven by off-grid apps (telecom, water, lights)

After 1995: Innovative policy in Japan, Germany stimulated market for grid-connected residential+comm (kW subsidies, kWhr FIT)

2008-2010: Large utility scale (10-100 MW) accelerating > 50%

2014: China surpasses US, ROW for installed PV (already #1 manufacturing)
Tracking the sun: 1 or 2 axis

1 axis tracking (horizontal)  
2 axis tracking
Tracking: gains over fixed tilt installation

Daily power profile for 600 kW arrays:
fixed tilt, 1 axis, 2 axis tracking

- 1 axis tracking widely found to be most cost effective for utility scale
- 20-25% more energy for 5-10% higher installation cost

<table>
<thead>
<tr>
<th>Location</th>
<th>1 axis</th>
<th>2 axis</th>
</tr>
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<tbody>
<tr>
<td>Nairobi</td>
<td>24%</td>
<td>33%</td>
</tr>
<tr>
<td>Sydney</td>
<td>27%</td>
<td>38%</td>
</tr>
<tr>
<td>Madrid</td>
<td>22%</td>
<td>33%</td>
</tr>
<tr>
<td>Miami</td>
<td>23%</td>
<td>28%</td>
</tr>
<tr>
<td>Phoenix</td>
<td>26%</td>
<td>37%</td>
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Two problems with too much PV

California load profile with projected PV generation (March 31)

PV does not reduce peak

~ 5 GW/hr ramp up due to PV decreasing as load increases
Solution: PV with battery storage

Battery backed grid connected system also helpful with unreliable intermittent grid
Residential PV with storage: increase self-consumption, reduce impact on grid
What is a microgrid?

Network of energy generators, storage, power and load control

- Diverse renewable energy sources: PV, wind, fuel cell, hydro
- Fossil fuel generator back-up for reliability (<5% of energy)
- Local control of energy flow AND load (turn-off sub-critical loads)
- Fast response, constant optimization, complex interface/sensors

Can be grid connected or off-grid

- Single point of grid connection: can be rapidly islanded
- High fraction of self-consumption
- Add significant renewables without adding to grid congestion or instability
- Off-grid operation allows higher power and reliability than single source

Applications: hospitals, campus, military base, remote village or industry
Typical PV system for rural off-grid home

- Very limited PV
- Insufficient energy to both meet load and charge battery
- Reduces battery life
- Single source: less resilient
- No infrastructure for repair, maintenance
Microgrid for village-scale reliable rural power
Advanced microgrid with storage, load control
Wrap-up

Strong technology base, phenomenal growth for 20 years

Both mature and emerging PV technologies: delivering lower cost or higher efficiency

Module cost reduction slowing, focus on system costs

Broad and diverse applications at wide scale: 50 W to 500 MW

PV can contribute to energy resiliency and reliability without C emissions or enviromental damage

Self-consumption (storage) critical for grid-connected and off-grid
Back up
**IBC vs Standard Si: Quantum Efficiency**

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Current Density (mA/cm²)</th>
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<tbody>
<tr>
<td>6x6 inch Standard Multicrystalline Si</td>
<td>82%</td>
<td>42</td>
</tr>
<tr>
<td>5x5 inch IBC Single Crystal Si</td>
<td>91%</td>
<td>38</td>
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</table>

Captures 82% of available photons vs. 91% of available photons.
**Thin Film Multilayer CdTe Solar Modules**

Lowest cost PV due to equipment costs, high dep rate, simple device

- Vapor Transport Dep (IEC) on glass
- T~500°C, 2-4 µm
- Glass in, module out: 2.5 hr
- Single manufacturer First Solar
- > 10 GW installed
- **THIN FILM SUCCESS STORY**

Best laboratory cell efficiency over 22%,

Best module eff~18%

Avg module eff~16%

3-5% more energy in hot climates vs c-Si

Ginley et al. MRS 2007