Principles and Varieties of Solar Energy (PHYS 4400) and Fundamentals of Solar Cells (PHYS 6980)

Prof. Randy J. Ellingson, Physics and Astronomy
Prof. Mike J. Heben, Physics and Astronomy, and Chemistry

The University of Toledo

Wright Center for Photovoltaics Innovation and Commercialization (PVIC – www.pvic.org) and

School for Solar and Advanced Renewable Energy (SSARE)

Course Website: http://astro1.panet.utoledo.edu/~relling2/teach/6980.4400/spring2011_phys_6980.4400.html
Energy for Planet Earth: The Role of “Carbon-Free” Energy Sources

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PHYS 4400, PHYS 6980
January 11, 2011
### Humanity’s Top Ten Problems for next 50 years

<table>
<thead>
<tr>
<th>Problem</th>
<th>Year</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>ENERGY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. <strong>WATER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. <strong>FOOD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. <strong>ENVIRONMENT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. <strong>POVERTY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. <strong>TERRORISM &amp; WAR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. <strong>DISEASE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. <strong>EDUCATION</strong></td>
<td>2006</td>
<td>~ 6.5 Billion</td>
</tr>
<tr>
<td>9. <strong>DEMOCRACY</strong></td>
<td>2050</td>
<td>~ 10 Billion</td>
</tr>
<tr>
<td>10. <strong>POPULATION</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Slide from R. Smalley, Rice University**

http://www.agci.org/library/presentations/about/presentation_details.php?recordID=16950
On watch: global temperatures, atmospheric CO$_2$


Keeling curve, data from Mauna Loa, Hawaii.
How Ohio’s Electric Power Generation Stacks Up

CONTRIBUTIONS OF FUEL SOURCES TO TOTAL ELECTRIC GENERATION

Data Source: Energy Information Administration
U.S. Department of Energy

Graphs prepared by B. Martner,
Lafayette, CO

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Need for clean energy

**Growth**
- Growth in global energy consumption predicted to average ~1.6-1.7% per year.
- Includes for 1%/yr. efficiency improvement
- 28 TW global power consumption by 2050
- Population growth primarily in less-developed countries → increased C-intensity.

**Health**
Coal-fired power plants:
- 59% of total U.S. sulfur dioxide pollution
- 18% of total nitrous oxides every year
- largest polluter of toxic mercury pollution

All U.S. power plants: release over 40% of U.S. CO₂

[Sources – U.S. DOE and U.S. EPA]
A Power and Energy Primer

Dealing with energy and power in:

<table>
<thead>
<tr>
<th></th>
<th>Standard International Units</th>
<th>Everyday Life*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Joule</td>
<td>kW·hr</td>
</tr>
<tr>
<td>Power</td>
<td>Watts (1 W = 1 J/sec)</td>
<td>Watts</td>
</tr>
</tbody>
</table>

Energy is the amount of work that can be completed by a force. Power is the rate at which the energy is converted (dE/dt).

A toaster is a good benchmark for power → typically at the 1,000 W (1 kW) power level.

Leave a toaster on for an hour continuously → 1 kW·hr. Same as a 100 W bulb left on for 10 hrs. Cost is about $0.12/ kW·hr, but leave one on for a year?

How much energy is used to light this room for 10 hours?

* Average cat generates ~5 W during sleep, and ~24 W walking briskly

1 kW·hr = 3.6 x 10^6 J

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Earth’s key natural resources: water and air

Volume of Earth: $1.1 \times 10^{12}$ km$^3$
Volume of water: $1.4 \times 10^9$ km$^3$
Volume of atmosphere: $4.2 \times 10^9$ km$^3$
420,000+ years of atmospheric CO₂ levels

from N. Lewis, Cal Tech
Earth’s energy consumption

2008 Global energy use ≈ 15 TW
US’s share ≈ 25% of total

http://en.wikipedia.org/wiki/World_energy_resources_and_consumption

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China has emitted 8.2% of cumulative emissions, as compared to 27.5% emitted by the US (3 times that of any other country).

China became the emissions leader in 2006.

China’s population is more than 4 times that of the US, so per capita emissions were roughly 1/4 of the US’s.

Per capita emissions from China could double or triple in coming decades.

From China Sustainable Energy Program: http://www.efchina.org
Energy Consumption and GDP

From: Wikimedia Commons
Earth’s energy problem

Global power consumption is current ~15 TW; projected need by 2050 of ~30 TW.

Carbon-free power required by 2050 to stabilize atmospheric CO₂ at 450 ppm ~15 TW

By 2100, carbon-free power requirement jumps to ~40 TW.

"Gasoline was great."

-- from R. Smalley’s energy talk (2003)
The Need to Produce Fuel

“Power Park Concept”

Fuel Production

- Fuel Processor or Electrolyzer

Distribution

Stationary Generation

- Fuel Cell

From N. Lewis, CalTech
Oil: The Haves and the Have-nots

<table>
<thead>
<tr>
<th>Nations that HAVE oil</th>
<th>Nations that NEED oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>(% of Global Reserves)</td>
<td>(% of Global Consumption)</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>U.S.</td>
</tr>
<tr>
<td>26%</td>
<td>26%</td>
</tr>
<tr>
<td>Iraq</td>
<td>Japan</td>
</tr>
<tr>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>Kuwait</td>
<td>China</td>
</tr>
<tr>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Iran</td>
<td>Germany</td>
</tr>
<tr>
<td>9%</td>
<td>4%</td>
</tr>
<tr>
<td>UAE</td>
<td>Russia</td>
</tr>
<tr>
<td>8%</td>
<td>3%</td>
</tr>
<tr>
<td>Venezuela</td>
<td>S. Korea</td>
</tr>
<tr>
<td>6%</td>
<td>3%</td>
</tr>
<tr>
<td>Russia</td>
<td>France</td>
</tr>
<tr>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Mexico</td>
<td>Italy</td>
</tr>
<tr>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Libya</td>
<td>Mexico</td>
</tr>
<tr>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>China</td>
<td>Brazil</td>
</tr>
<tr>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Nigeria</td>
<td>Canada</td>
</tr>
<tr>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>U.S.</td>
<td>India</td>
</tr>
<tr>
<td>2%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Source: EIA International Energy Annual 1999

*From Sam Baldwin’s contribution to “Basic Research Need to Assure a Secure Energy Future”, A Report from DOE’s Basic Energy Sciences Advisory Committee*
Sustainable Paths to Hydrogen

Solar Energy

- Heat
- Mechanical Energy
  - Thermolysis

- Biomass
  - Conversion
    - Electrolysis
    - Photolysis

Hydrogen

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H₂ Energy Cycle with Fuel Cells

Inputs:
• Solar Energy
• Water
• Nuclear Energy
• Fossil Fuel

Outputs:
• Electricity
• Heat
• Water
• Nuclear Waste
• CO₂ with Fossil

Adapted from John Turner, NREL

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Integrated Large- and Small-Scale Systems
(*distributed energy systems*)

World energy resources and consumption
From Wikipedia, the free encyclopedia
(Redirected from World Energy)

In 2008, total worldwide energy consumption was 474 exajoules \((5 \times 10^{20} \text{ J})\) with 80 to 90 percent derived from the combustion of fossil fuels.\(^{[1]}\) This is equivalent to an average power consumption rate of 15 terawatts \((1.504 \times 10^{13} \text{ W})\) or a yearly energy consumption of 133 Petawatt•hr \((132.8 \times 10^{15} \text{ Wh})\). \[snip\]

Most of the world's energy resources are from the sun's rays hitting earth.

Tough Reality

The Good News

In 2009, world energy consumption decreased for the first time in 30 years (-1.1\%), a result of the financial and economic crisis (GDP drop by 0.6% in 2009). Coal posted a growing role in the world's energy consumption: in 2009, it accounted for 27% of the total.

http://en.wikipedia.org/wiki/World_energy_resources_and_consumption
### Potential Sources for Significant Carbon-Free Energy

<table>
<thead>
<tr>
<th>Source</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroelectric</td>
<td>1.5 TW</td>
</tr>
<tr>
<td>(1.5 TW technically feasible – 0.777 TW generated in 2006)</td>
<td></td>
</tr>
<tr>
<td>Geothermal (installed capacity in 2007)</td>
<td>10 GW</td>
</tr>
<tr>
<td>Tides/Waves</td>
<td>1 TW</td>
</tr>
<tr>
<td>Wind</td>
<td>65 TW</td>
</tr>
<tr>
<td>Solar</td>
<td>600 TW*</td>
</tr>
<tr>
<td>(120,000 TW solar energy striking Earth globally)</td>
<td></td>
</tr>
</tbody>
</table>

* Renewable only as long as our Sun shines

* 50 TW – 1500 TW, depending upon land fraction, etc., and assuming today’s typical solar-to-electricity conversion efficiency of 10%.
Hydroelectric Power

- eliminates cost of fuel;
- long-lived power production compared to fuel-fired plants;
- operates without CO$_2$ emissions;
- no nuclear waste
- sizeable hazard (dam failures among largest human-created disasters);
- siltation ultimately limits “economic” life;
- environmental impacts: spawning, downstream river environment, anaerobic decay of plant material – methane
- population relocation
- flow reduction (global warming)

Power produced depends on factors such as the density of water ($\rho = 1000$ kg/m$^3$), the “hydraulic height” ($h$), the flow rate in cubic meters per second ($r$), the gravitational constant ($g$), and the efficiency factor ($k$):

$$P = \rho hr g k$$
Pixii’s dynamo (1832), built by Hippolyte Pixii (1808–1835), an instrument maker from Paris, France.

\[ \varepsilon = -\frac{d\Phi_B}{dt} \]

\( \varepsilon \) is the electromotive force (volts); \( \Phi_B \) is the magnetic flux (webers). 1 weber/m\(^2\) = 1 tesla

750 MW water turbine being installed at Grand Coulee Dam (Columbia River).

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### Hydroelectric Power – Big Players

<table>
<thead>
<tr>
<th>Country</th>
<th>Annual Hydroelectric Energy Production(TWh)</th>
<th>Installed Capacity (GW)</th>
<th>Capacity Factor</th>
<th>Percent of all electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>140.5</td>
<td>27.528</td>
<td>0.49</td>
<td>98.25[^24]</td>
</tr>
<tr>
<td>Brazil</td>
<td>363.8</td>
<td>69.080</td>
<td>0.56</td>
<td>85.56</td>
</tr>
<tr>
<td>Venezuela</td>
<td>86.8</td>
<td>-</td>
<td>-</td>
<td>67.17</td>
</tr>
<tr>
<td>Canada</td>
<td>369.5</td>
<td>88.974</td>
<td>0.59</td>
<td>61.12</td>
</tr>
<tr>
<td>Sweden</td>
<td>65.5</td>
<td>16.209</td>
<td>0.46</td>
<td>44.34</td>
</tr>
<tr>
<td>Russia</td>
<td>167.0</td>
<td>45.000</td>
<td>0.42</td>
<td>17.64</td>
</tr>
<tr>
<td>China (2008)[^25]</td>
<td>585.2</td>
<td>171.52</td>
<td>0.37</td>
<td>17.18</td>
</tr>
<tr>
<td>India</td>
<td>115.6</td>
<td>33.600</td>
<td>0.43</td>
<td>15.80</td>
</tr>
<tr>
<td>France</td>
<td>63.4</td>
<td>25.335</td>
<td>0.25</td>
<td>11.23</td>
</tr>
<tr>
<td>Japan</td>
<td>69.2</td>
<td>27.229</td>
<td>0.37</td>
<td>7.21</td>
</tr>
<tr>
<td>United States</td>
<td>250.6</td>
<td>79.511</td>
<td>0.42</td>
<td>5.74</td>
</tr>
<tr>
<td>Paraguay (2006)</td>
<td>64.0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Potential capacity of 1.5 TW; ultimately driven by the Sun.**

**Reminder: We need 15 – 40 TW total CfP**
What: thermal energy “in the Earth” from:
• original formation of the planet (hot springs, geysers)
• radioactive decay of minerals
• solar energy absorbed at the surface

How much: 10 GW of electricity generated in 2007;
28 GW of direct thermal heating capacity.

Notes:
• Earth’s heat content = $10^{31}$ J
• Thermal conduction to surface at rate of 44 TW ($44 \times 10^{12}$ J/s)
• Additional heat generated by radioactive decay, 30 TW
• Average thermal power at Earth’s surface: $\sim 0.1$ W/m$^2$

Reminder: We need 15 – 40 TW total CfP
Origins of Wind

Wind results from pressure differentials in the atmosphere; local effects include variations in heating and cooling (e.g., land vs. a body of water).

Air subsequently moves to alleviate these pressure differences; since air has mass, it’s movement (wind) carries with it kinetic energy that can be converted to electricity through the use of turbines (electrical generators).

The two dominant causes of wind in Earth’s atmosphere are:

1. the differential solar heating between the equator and the poles, and
2. the rotation of the planet.

Land is often warmer than water (A) during the day, and cooler than water (B) at night.
“Humans have been using wind power for at least 5,500 years to propel sailboats and sailing ships, and architects have used wind-driven natural ventilation in buildings since similarly ancient times. Windmills have been used for irrigation pumping and for milling grain since the 7th century AD.”

http://en.wikipedia.org/wiki/Wind_power

... growth in the forecasts can be attributed to the increasingly common use of very large turbines that rise to almost 100 meters. Wind speeds are greater at higher elevations. Previous wind studies were based on the deployment of 50- to 80-meter turbines.


Global potential for wind-generated electricity
Xi Lu, Michael B. McElroy,, and Juha Kiviluomac
www.pnas.orgcgidoi10.1073pnas.0904101106

Reminder: We need 15 – 40 TW total CfP
Wind Power

This map shows the annual average wind power estimates at a height of 50 meters. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential W/m²</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
</tr>
<tr>
<td>5</td>
<td>Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.6 - 17.9</td>
</tr>
<tr>
<td>6</td>
<td>Outstanding</td>
<td>600 - 800</td>
<td>8.0 - 8.8</td>
<td>17.9 - 19.7</td>
</tr>
<tr>
<td>7</td>
<td>Superb</td>
<td>800 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.8</td>
</tr>
</tbody>
</table>

*Wind speeds are based on a Weibull k value of 2.0*
Wind farms are under consideration and/or planned along the shores of, or out on the open water of, Lake Erie.
The Sun

“Why Does the Sun Shine?”
by They Might Be Giants

The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

Yo ho, it's hot, the sun is not
A place where we could live
But here on Earth there'd be no life
Without the light it gives

We need its light
We need its heat
We need its energy
Without the sun, without a doubt
There'd be no you and me
# The Sun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean diameter</td>
<td>$1.392 \times 10^6$ km</td>
</tr>
<tr>
<td>Equatorial radius</td>
<td>$6.955 \times 10^5$ km</td>
</tr>
<tr>
<td>Equatorial circumference</td>
<td>$4.379 \times 10^6$ km</td>
</tr>
</tbody>
</table>

109 times the Earth’s diameter, radius, circumference

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidereal* rotation period (at equator)</td>
<td>25.05 days</td>
</tr>
</tbody>
</table>

*Sidereal* means: “Of or relating to the stars”

(http://en.wiktionary.org/wiki/sidereal)
The **photosphere** of an astronomical object is the region from which externally received light originates. It extends into a star's surface until the gas becomes opaque, equivalent to an optical depth of approximately 2/3. In other words, a **photosphere** is the deepest region of a luminous object, usually a star, that is transparent to photons of certain wavelengths.

http://en.wikipedia.org/wiki/Photosphere
The Sun’s Hydrogen

\[ E_n = -\frac{13.6}{n^2} \text{eV} \]

approximation

\[ E_n = -\frac{13.6057}{n^2} \text{eV} \]

more sig figs

\[ E_n = -\frac{13.5983}{n^2} \text{eV} \]

with reduced mass

Balmer Series: H-atom transitions for which final state is \( n = 2! \)

\[ E_{\text{photon}} = E_n - E_2 = -13.5983 \text{eV} \cdot \left(\frac{1}{n^2} - \frac{1}{2^2}\right) \]


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Earth’s Solar Resource

- Theoretical: $1.2 \times 10^5$ TW solar energy potential (1.76 $\times 10^5$ TW striking Earth; 0.30 Global mean albedo)
- Energy in 1 hr of sunlight $\leftrightarrow$ 14 TW for a year
- Practical: > On-shore electricity generation potential of $\approx 600$ TW (10% conversion efficiency).
- *Photosynthesis*: 90 TW
Green line marks bandgap of Si

Radiation at Sea Level

5250°C Blackbody Spectrum

Spectral Irradiance (W/m²/nm)

Wavelength (nm)

UV Visible Infrared

Sunlight at Top of the Atmosphere

H₂O H₂O H₂O

O₂ O₃

Image created by Robert A. Rohde / Global Warming Art

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Solar spectra at Earth

http://pvcdrom.pveducation.org/APPEND/Am1_5.htm
The Solar Resource in the US

3 TW

PV covering area of square ~110 miles x 110 miles could satisfy all of US energy needs.
PV electricity at $1/Watt

Solar PV is a booming global industry

But U.S. market share has fallen to about 5% of global output – from more than 40% in the mid-1990s

Worldwide production of solar photovoltaics – in Megawatts

http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf

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Properties of light

Energy of a photon:

\[ E = \frac{hc}{\lambda} \]

Convenient relation:

\[ E = \frac{1.24}{\lambda(\mu m)} \]

1 eV = 1.602 x 10^{-19} J

Definition of photon flux:

\[ \Phi = \frac{\text{# of photons}}{\text{sec} \cdot \text{m}^2} \]

Spectral irradiance:

\[ F = \left( \frac{W}{m^2 \mu m} \right) = q\Phi \frac{1.24}{\lambda^2(\mu m)} = q\Phi \frac{E^2(eV)}{1.24} \]

F is the spectral irradiance in Wm^{-2}µm^{-1}; Φ is the photon flux in # photons m^{-2}sec^{-1}; E and λ are the energy and wavelength of the photon in eV and µm respectively; and q, h and c are constants.

An excellent resource:

http://www.pveducation.org
Basic silicon photovoltaic (solar) cell operation

**Key functions of a solar cell**

- absorbs sunlight efficiently
- separates charge (electrons from “holes”)
- creates an electrical current and voltage when illuminated
- acts like a battery under sunlight

http://www.emeraldinsight.com/fig/0870210205001.png
Conventional p-n junction photovoltaic cell

For Si (E\textsubscript{g} = 1.1 eV) at T = 300 K, AM1.5G

\[ \eta_{\text{max}} = 32.9\% \]

Losses
- transmission = 18.7%
- heat = 46.8%
- radiative em. = 1.6%

1 e\textsuperscript{-}h\textsuperscript{+} pair/photon
“Generations” of photovoltaic cells

- **1st generation:** crystalline silicon
- **2nd generation:** thin films
  e.g. amorphous Si, CdTe, CuInGaSe$_2$ (CIGS)
- **3rd generation:** nanostructures, organic materials, and advanced concepts.
Economics of solar conversion cost and efficiency

To provide the level of CO₂-free energy required for electricity and fuel:
Power cost needs to be 2-3 cents/kWh (module cost of $0.20 – $0.30/W)

BOS = Balance of System, incl. inverter, installation, etc.

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Many different solar cell technologies are being developed, for various applications (rooftops, solar power plants, satellites, backpacks or clothing, etc.).
1st gen.
single crystal Si

2nd gen.: thin film amorphous Si and CdTe

Xunlight

First Solar

polycrystalline Si

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The biggest PV power plant (so far)

The Olmedilla Photovoltaic (PV) Park uses 162,000 flat solar photovoltaic panels to deliver 60 MW of electricity on a sunny day. The entire plant was completed in 15 months at a cost of about $530 million at current exchange rates. Olmedilla was built with conventional solar panels, which are made with silicon and tend to be heavy and expensive. So-called "thin-film" solar panels, although less efficient per square meter, tend to be much cheaper to produce, and they are the technology being tapped to realize the world's largest proposed PV plant, the Rancho Cielo Solar Farm in Belen, N. Mex., which is expected to cost $840 million, cover an area of 700 acres (285 hectares), and produce 600 MW of power.

http://www.scientificamerican.com/article.cfm?id=10-largest-renewable-energy-projects
3rd Generation Solar Cells

Polymer solar cell

Nanocrystal solar cell

Dye-sensitized solar cell

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Toledo reinvents itself as a solar-power innovator

By Judy Keen, USA TODAY

TOLEDO — This city is trying to swap its Rust Belt image for a new identity as a hub of solar-energy research and production.

The mission is being led by an unusual partnership of business, academia and government that could be a model for other aging industrial cities. "We are ready to do anything, we are ready to try anything," says University of Toledo President Lloyd Jacobs.

Like many manufacturing cities, Toledo has struggled with the loss of jobs and tax revenue, but it has taken pieces of its past as the glass capital to create a new future in solar energy.

The payoff so far: At least 6,000 people work in the area's solar industry. First Solar (FSLR), which makes solar panels, was founded here and employs more than 1,000 at its 900,000-square-foot plant here. There are more than a dozen solar-related start-up companies in the area. The University of Toledo is home to top solar researchers and has a business incubator that provides business services to solar entrepreneurs. It has graduated four solar companies and is working with six more. Owens Community College, which had 13 students in its first solar class in 2004, has trained 255 solar installers.

"In the solar world, Toledo is a hot spot," says Xunming Deng, a physics professor on leave from the University of Toledo. He's developing Xunlight, the company he founded here in 2002 to produce thin, flexible solar panels. It has about 100 employees.
Science and Technology has given us solutions in the past.

With the right government policies, it will come to our aid in the future.

-- Energy Secretary, Steve Chu
In 1990, Carl Sagan convinced NASA engineers to turn Voyager for one last, homeward look before leaving the solar system.

“Look again at that dot. That's here. That's home. That's us. On it, everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives .... Every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, ... every saint and sinner in the history of our species lived there--on a mote of dust suspended in a sunbeam.”

“....The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate ... Like it or not, for the moment the Earth is where we make our stand.”

-- Energy Secretary, Steve Chu

$1 per Watt Workshop held Aug. 11-12, 2010 [ http://www1.eere.energy.gov/solar/dollar_per_watt.html ].

http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf