Introduction to Fundamentals of Photovoltaics

Lecture 1 – Introduction
MIT Fundamentals of Photovoltaics
2.626/2.627 – Fall 2011
Prof. Tonio Buonassisi
Why Solar?
Energy: Fuel for Development

Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, Physics Today (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Livermore National Laboratory rep. no. UCRL-ID-140773.

Source: David Roland-Holst, based on World Bank and IEA data

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2011: 7 Billion People  
2050: 7.5–11 Billion People
Solar Resource

Image courtesy NASA Earth Observatory.

http://neo.sci.gsfc.nasa.gov/Search.html
Solar Supply Well Matched to Future Energy Demand

Image courtesy NASA Earth Observatory.

http://eosweb.larc.nasa.gov/sse/
Solar Resource Base

Solar Energy Resource Base
1.5x10^{18} \text{kWh/year}
1.7x10^5 \text{TW}_{ave}

Solar Resource on Earth’s Surface
5.5x10^{17} \text{kWh/year}
3.6x10^4 \text{TW}_{ave}

Wind Energy Resource Base
6x10^{14} \text{kWh/year}
72 \text{TW}_{ave}

Human Energy Use (mid- to late-century)
4x10^{14} \text{kWh/year}
50 \text{TW}_{ave}

References:
Potential of Solar Energy

The Sun is able to support TWs of demand:
Average $9 \times 10^4$ TW incident on Earth; 450 TW practical to recover.

18 TW = 6 Dots at 3 TW Each

http://www.answers.com/topic/solar-power-1

Image by Mino76. License: CC-BY
Residential Installations

- Solar Panels
- Inverter
- Existing Circuit Breaker Panel
- Utility meter

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Photovoltaics: Historical Perspective and Current Challenges
Rich History of Innovation

1839: Discovery of photovoltaic effect


http://pvcdrom.pveducation.org/MANUFACT/FIRST.HTM

Courtesy of PVCDROM. Used with permission.


Rich History of Innovation

1877: Photoelectric effect in solid system


1883: Photovoltaic effect in sub-mm-thick films

C.E. Fritts, "On a new form of selenium photocell", *Proc. of the American Association for the Advancement of Science* **33**, 97 (1883)

1927: Evolution of solid-state PV devices


Images from: [http://pvcdrom.pveducation.org/MANUFACT/FIRST.HTM](http://pvcdrom.pveducation.org/MANUFACT/FIRST.HTM)
Photovoltaic Device Fundamentals

(1) **Charge Generation**: Light excites electrons, freeing them to move around the crystal.

(2) **Charge Separation**: An electric field engineered into the material (pn junction) sweeps out electrons.

**Advantages**: There are no moving parts and no pollution created at the site of use (during solar cell production, that’s another story).

**Disadvantages**: No output at night; lower output when weather unfavorable.

(3) **Charge Collection**: Electrons deposit their energy in an external load, complete the circuit.

Courtesy of [PVCDROM](http://pvcdrom.pveducation.org). Used with permission.
How Solar Has Evolved Since Your Parents First Heard of It


Large PV cost reductions over the past few decades were driven by (1) innovation in technology, manufacturing, and deployment, (2) increased scale, and (3) lower-cost materials.
Innovation: Driving Force in PV Cost Reduction


Source: Behind the learning curve. G. Nemet, UC Berkeley

*Assumes annual production grows at 35%. Projected costs based on 18% learning curve.*

Courtesy of G. F. Nemet. Used with permission.
Convergence Between PV and Conventional Energy

Source: US Department of Energy (ca. 2006)
Convergence Between PV and Conventional Energy

Figure 8: PV market deployment and competitiveness levels

Assumptions: Interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); O&M costs 1%.

Convergence Between PV and Conventional Energy Scale


Plot on previous page: “The coming convergence.” Data sources used:

- World primary energy usage: [http://www.eia.gov/totalenergy/data/annual/index.cfm#international](http://www.eia.gov/totalenergy/data/annual/index.cfm#international)
- For PV, $TW_{peak}$ to $TW_{ave}$ conversion assumes 1/6 PV capacity factor.
Solar Energy Technology Framework
Motivation, explanation, and rationale of framework
Motivation:

Several hundreds of technologies exist to convert solar radiant energy into other usable forms that perform work for humanity.

To make sense of this technology space, and to produce meaningful technology assessments and projections, a technology framework is helpful.

Please see lecture video for example images of each type of solar panel.
Framework for the Solar Energy Technology Universe

Design Principles for the Technology Framework:

*Exhaustive categorization*
Our technology framework must provide a meaningful framework to categorize 90+% of solar energy technologies today.

*30 years challenge*
The framework should be time-immutable, useful also in 30 years (within which time solar may “come of age”).

*Useful analysis tool*
The framework must provide a tool to economists and social scientists, to divide the solar space into meaningful units that can be analyzed independently.

Please see lecture video for example images of each type of solar panel.
**Division 1: According to Conversion Technology**

<table>
<thead>
<tr>
<th>Solar Energy Conversion Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar to Electricity</td>
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**Rationale:**

*Output-oriented*
Focus on the delivered product (electricity, heat, fuels) naturally lumps similar technologies together.

*Exhaustive categorization(?)*
There are only a limited number of known energy products useful to humanity. Barring unexpected discoveries and harnessing of other energy forms (e.g., the “gravity wave” scenario), this framework should continue to be useful in 30 years.
### Division 2: According to Moving Mechanical Parts

#### Solar Energy Conversion Technology

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**Rationale:**

**Input-oriented**
Focus on the method that solar energy is captured and converted into a usable form.

**Moving parts**
Tracking systems imply moving parts, which add to the complexity, cost, and maintenance of solar systems, while increasing the output.

**Why not “concentrating / non-concentrating”?**
“Tracking” and “concentrating” are non synonymous. While concentrator systems add extra capital equipment expenditure (capex), tracking systems add both extra capex and operating expenses (opex).
on to the assessment...
## Solar Energy Conversion Technology

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**Embodiments:**
- Photovoltaic device (solar cell).
- Thermoelectric device
Photovoltaic Device Fundamentals

(1) Charge Generation: Light excites electrons, freeing them from atomic bonds and allowing them to move around the crystal.

(2) Charge Separation: An electric field engineered into the material (pn junction) sweeps out electrons.

Advantages: There are no moving parts and no pollution created at the site of use (during solar cell production, that’s another story).

Disadvantages: No output at night; lower output when weather unfavorable.

(3) Charge Collection: Electrons deposit their energy in an external load, complete the circuit.

For animation, please see http://micro.magnet.fsu.edu/primer/java/solarcell/
### Technological Diversity

Please see lecture video for example images of each type of solar technology.

<table>
<thead>
<tr>
<th>Kerfless Silicon</th>
<th>Multijunction Cells</th>
<th>Copper Indium Gallium Diselenide (CIGS)</th>
<th>Amorphous Silicon</th>
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<tbody>
<tr>
<td>Dye-sensitized Cells</td>
<td>Silicon Sheet</td>
<td>Cadmium Telluride</td>
<td>Hybrid (nano)</td>
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<td>Monocrystalline Silicon</td>
<td>Multicrystalline Silicon</td>
<td>High-Efficiency silicon</td>
<td>Organics</td>
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#### Two Sub-Groups:

1. Non-concentrating
2. Concentrating

Please see lecture video for example images of each type of solar technology.
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### 1. Non-concentrating, non-tracking

- **a. Roof-mounted**
- **b. Ground-mounted**

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#### 2. Concentrating, non-tracking

##### a. External (mounted) reflectors

Please see lecture video for example images of each type of solar technology.
2. Concentrating, non-tracking
   b. Internal reflectors

Please see lecture video for example images of each type of solar technology.

Sliver Cell (A.N.U.)

Solyndra
### Solar Energy Conversion Technology

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#### 2. Concentrating, non-tracking

c. Photon conditioning, internal reflectors

![Luminescent Concentrator](image)

Image by MIT OpenCourseWare.
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#### The Basics of Tracking Systems:

**One Axis Tracking**
- Axis allows east-west rotation

**Two Axis Tracking**
- Primary axis allows east-west rotation
- Secondary axis allows north-south rotation

Image by MIT OpenCourseWare.
### Solar Energy Conversion Technology

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#### Two Sub-Groups:

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2. Concentrating

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1. Not concentrating, tracking
   a. Photovoltaics

Please see lecture video for example images of each type of solar technology.
## 2. Concentrating, tracking

a. (Frenel) Lenses

Please see lecture video for example images of each type of solar technology.
Current embodiments

1. **Heat Engines***: Sunlight heats a fluid (e.g., pressurized water, nitrate salt, hydrogen), which moves a turbine or piston, either directly or via heat exchanger.
2. **Heat Exchangers***
3. **Thermoelectrics*****: Visible sunlight converted into heat; temperature difference between leads drives an electrical current.
4. **Long-λ PV**: Visible sunlight converted into heat, which powers IR-responsive photovoltaic devices.

* Hybrids Possible (e.g., combined cycle power plant): The above, in tandem with another fuel (e.g., natural gas).
** Hybrids Possible (e.g., with solar cells)
## Solar Energy Conversion Technology

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### Non-tracking and Concentrating

**Solar Updraft Tower**

Please see lecture video for example images of each type of solar technology.
# Solar Energy Conversion Technology

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## Tracking and Concentrating

a. Reflectors (Parabolic Troughs)

Please see lecture video for example images of each type of solar technology.
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**Tracking and Concentrating**

b. Parabolic Dish / Sterling Engines

Please see lecture video for example images of each type of solar technology.

http://www.stirlingenergy.com/technology/suncatcher.asp
## Tracking and Concentrating

c. Solar Towers (a.k.a. “Power Towers”)

Please see lecture video for example images of each type of solar technology.

PS10, 11 MW Solar Tower (Sanlucar la Mayor, Seville)
## Solar Energy Conversion Technology

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### Current embodiments

*Use heat to...*

1. Heat water.
2. Desalinate water.
3. Cook food.
## Solar Energy Conversion Technology

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### 1. Non-tracking and Non-concentrating

**Solar Hot Water Heaters**

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2. Non-tracking and Concentrating

Solar Hot Water Tubes

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## Solar Energy Conversion Technology

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**Tracking Solar to Heat**

**Solar Oven**

Please see lecture video for example images of each type of solar technology.
**Current embodiments**

**Enthalpy**
1. **Solar catalysis:** Use sunlight to split (stable) molecules into more volatile species (e.g.: $2\text{H}_2\text{O} + \text{Energy} \rightarrow 2\text{H}_2 + \text{O}_2$).
2. **Photosynthesis:** Use sunlight to combine (stable) molecules into long-chain hydrocarbons (e.g.: $6\text{CO}_2 + 6\text{H}_2\text{O} + \text{Energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$).

**Entropy**
1. **Separation of phases:** E.g., desalination.
Example of a Renewable Solar Fuels Cycle

1. Starting Compound(s)
2. Sunlight
3. Intermediate Compound(s) (Solar Fuels)
4. Energy Extraction
5. Final Compound(s)
Example of a Renewable Solar Fuels Cycle

Sunlight

### Solar Energy Conversion Technology

| Solar to Electricity | Solar to Heat Electricity | Solar to Heat | Solar to Fuels |

**Reducing Entropy**

Solar Desalination

---

Please see lecture video for example images of each type of solar technology.

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Footnote: Some discussion occurred on 6/30 as to whether this should fall under “solar to fuels”, or “solar to heat”.

Buonassisi (MIT) 2011
Balance of Systems
(Infrastructure Beyond Conversion Devices)
Today’s typical centralized installation typically exceeds 500 kWp.
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<tr>
<td><strong>Energy Production Centralized</strong></td>
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Please see lecture video for example images of each type of solar technology.
Today’s typical distributed installation is typically less than 10 kW, but can be 675 kW or larger.
Please see lecture video for example images of each type of solar technology.
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Zero energy homes, Rancho Cordova, CA


Please see lecture video for example images of each type of solar technology.
Systems

Energy Production Centralized

Energy Production Distributed

Solar Panels

Inverter

Existing Circuit Breaker Panel

Utility meter

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What about energy storage?

Energy storage, current embodiments

1. **Chemical**: Batteries (Pb, NiMH, Li), redox flow, fuels...
2. **Electromagnetic**: Capacitors, supercapacitors, SMES...
3. **Mechanical**: Fly-wheels, pneumatic, elastic, gravitational...
4. **Thermal**: Storage tanks...
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Please see lecture video for example images of each type of technology.

Fuel cells (x2)

Batteries (lead acid)
### Systems

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Please see lecture video for example images of each type of technology.

“Utility-scale” energy storage


The Grid*

*non-dispatchable storage solution!
## Solar Energy Conversion Technology

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<td>Solar to Fuels</td>
<td>Non-Tracking</td>
<td>Tracking</td>
<td>Non-Tracking</td>
<td>Tracking</td>
</tr>
</tbody>
</table>
CO$_2$, Energy, and Climate Change
Greenhouse Gasses and Mean Global Temperature

For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

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See also:
Greenhouse Gasses and Mean Global Temperature

For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

For the last 12,000 years, global temperatures have been stable, coincident with the rise of human civilizations.

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See also:
Greenhouse Gasses and Mean Global Temperature

For over 600,000 years, a strong correlation between greenhouse gasses and global temperature exists.

For the last 12,000 years, global temperatures have been stable, coincident with the rise of human civilizations.

Recently, greenhouse gas levels have greatly exceeded naturally-occurring watermark – in some cases, by >2x.

What recently disrupted this natural cycle?
The past two centuries experienced a rapid rise in human population, concomitant with a rise in atmospheric CO$_2$ levels. Shortly thereafter, average global temperatures began to rise.

**Does the coincidence between population and CO$_2$ levels imply causality?**

Energy and Greenhouse Gasses

Please see lecture video for relevant interaction with graph.

- >85% global energy from fossil fuels
- Energy, GDP, and CO$_2$ are strongly correlated.
- Global energy needs are predicted to steadily increase.
- Business as usual: CO$_2$ levels will continue to increase.
- >20% increase in atmospheric CO$_2$ content!
The Magnitude of Global Warming

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (Wm⁻²)

- Greenhouse gases
- Halocarbons
- N₂O
- CH₄
- CO₂
- Tropospheric ozone
- Sulphate
- Organic carbon from fossil fuel burning
- Biomass burning
- Mineral Dust
- Black carbon from fossil fuel burning
- Aviation (Contrails, Cirrus)
- Solar
- Stratospheric ozone
- Land use (albedo only)

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

Aerosol indirect effect

LEVEL OF SCIENTIFIC UNDERSTANDING

- High
- Medium
- Medium
- Low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low
- Very low

http://www.ipcc.ch/present/graphics/2001syr/large/06.01.jpg

Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.
Scientific Consensus re: Global Warming

“Consensus as strong as the one that has developed around this topic is rare in science.”

“Human activities … are modifying the concentration of atmospheric constituents … that absorb or scatter radiant energy. … [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations” p.21

“Greenhouse gases are accumulating in Earth’s atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise.” p.1

928 [peer-reviewed] papers were divided into six categories: explicit endorsement of the consensus position, evaluation of impacts, mitigation proposals, methods, paleoclimate analysis, and rejection of the consensus position. Of all the papers, 75% fell into the first three categories, either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position… [or argued] that current climate change is natural.

“One of the reasons scientists consider the evidence so compelling is that it draws on such a broad range of sources. In addition to climate specialists who use sophisticated computer models to study climatic trends, researchers from an array of disciplines, including atmospheric scientists, paleoclimatologists, oceanographers, meteorologists, geologists, chemists, biologists, physicists, and ecologists have all corroborated global warming by studying everything from animal migration to the melting of glaciers. Evidence of a dramatic global warming trend has been found in ice cores pulled from the both polar regions, satellite imagery of the shrinking polar ice masses, tree rings, ocean temperature monitoring…” p.29
Anthropogenic Forcing

Comparison between modeled and observations of temperature rise since the year 1860

(a) Natural forcing only

(b) Anthropogenic forcing only

(c) Natural + Anthropogenic forcing

IPCC: [http://www.ipcc.ch/present/graphics/2001syr/ppt/05.18.ppt](http://www.ipcc.ch/present/graphics/2001syr/ppt/05.18.ppt)

Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.
Future Predictions

Current trends predicted to continue.

http://www.census.gov/ipc/prod/wp02/wp-02003.pdf

Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.

IPCC: http://www.ipcc.ch/present/graphics.htm
The Renewable Energy Imperative

Emissions, concentrations, and temperature changes corresponding to different stabilization levels for CO₂ concentrations

(a) CO₂ emissions (Gt C)

(b) CO₂ concentration (ppm)

(c) Global mean temperature change (°C)


Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Figure 2-2; Figure SPM-2; Figure SPM-10b; Figure SPM-10a; Figure SPM-6. Cambridge University Press.
2.626/2.627 in perspective
Recap

Why Solar?
1. Energy is a necessary ingredient for human development.
2. The solar resource is abundant.
3. The solar resource distribution is well matched to growing human energy demand.
4. Solar is renewable, and is a 5-10x lower-carbon energy source than fossil fuels. [1]

How Solar?
1. Solar is on a rapid path to convergence with conventional fossil-fuel-based energy sources, both in cost and scale.
2. Many challenges inhibiting wide-scale solar adoption are identified.
3. Solutions to these challenges are rooted in PV technology, manufacturing, and deployment innovations.
4. To train future leaders to develop these solutions, a solid fundamental understanding of the science, technology, and cross-cutting themes is necessary.

2.626/2.627 Roadmap

You Are Here

Fundamentals
Every photovoltaic device must obey:

\[
\text{Conversion Efficiency } (\eta) = \frac{\text{Output Energy}}{\text{Input Energy}}
\]

For most solar cells, this breaks down into:

\[
\eta_{\text{total}} = \eta_{\text{excitation}} \times \eta_{\text{drift/diffusion}} \times \eta_{\text{separation}} \times \eta_{\text{collection}}
\]