Photovoltaic Systems
- the term “photovoltaic” refers to the direct generation of electricity by solar irradiation

photo = light
voltaics = electricity
photovoltaics = electricity from light
abbreviated as “PV”
Types of Silicon Solar Cells
- the three types of silicon cells are:
  - mono-crystalline
  - poly-crystalline
  - amorphous

Mono-crystalline
- consists of silicon in which the crystal lattice of the entire solid is continuous, unbroken (with no grain boundaries)
- efficient and expensive
- cut from cylindrical ingots and do not completely cover a square solar cell module without a substantial waste of refined silicon

Source: Alternative Energy Systems and Applications, B.K. Hodge
**Poly-crystalline**

- consists of multiple small crystals and recognized by visible grain (metal flake effect)
- made from cast square ingots (large blocks of silicon carefully cooled and solidified)

- less expensive, less efficient

Source: Alternative Energy Systems and Applications, B.K. Hodge
Amorphous
- non-crystalline allotropic form of silicon (continuous random network)
- vacuum silicon (thin film), can be deposited at low temperatures, less expensive, less efficient (compared to other two), more flexible in applications (can deposit on class, plastic, etc.)

Source: Alternative Energy Systems and Applications, B.K. Hodge

Photovoltaic Cell Fundamentals
- photovoltaic cells are made of a semiconductor material
- the most common semiconductor used is silicon
- the two layers of silicon that constitute a silicon-based PV cell are modified (doped) to more likely:
  1) loose electrons
  2) produce holes in the molecular structure where electrons can reattach
Photovoltaic Cell Fundamentals

- the $p$-$n$ junction is the boundary in the semiconductor material where the region of electron depletion neighbours the region of electron surplus; right at the junction, the $n$-type and $p$-type do mix (creating an electric field) and form something of a barrier, making it harder and harder for electrons on the $n$ side to cross over to the $p$ side.

- as an example, in one PV cell design, the upper or $n$-type layer is doped with phosphorus with 5 valence electrons while the lower or $p$-type layer is doped with boron, which has 3 valence electrons (recall that the silicon atom has 4 valence electrons in its outer shell).

- if the incident photon is energetic enough to dislodge a valance electron (from the depletion zone / electric field), the electron will jump to the conduction band and initiate a current flow.
Band Gap Energy
- solar radiation and the band gap of silicon

![Normalized power spectral density for 5760 K](image)

Insufficient energy to dislodge an electron

1.12 μm

Wavelength, microns


I-V Characteristics of a (Ideal) Solar Cell
- the I-V (current-voltage) characteristics of a solar cell can be obtained by drawing an equivalent circuit of the device
- a solar cell array is represented by a voltage source and two internal resistances, $R_j$ and $R_L$
I-V Characteristics of a (Ideal) Solar Cell

- the maximum power $P_{\text{max}}$ produced by a solar cell is reached when the product $I-V$ (current * voltage) is maximum

- this can be shown graphically where the position of the maximum power point represents the largest area of the rectangle shown

Current Density Ratio and Power Ratio vs. Voltage

- I-V Characteristics Curve
Standard Test Conditions and Temperature and Irradiance Effects

- the efficiency $\eta$ of a solar cell is defined as:

\[
\text{the power } P_{\text{max}} \text{ produced by the cell at the maximum power point under standard test conditions}
\]

\[
\text{the power of the radiation incident upon it}
\]

- most frequent conditions are: irradiance 100 mW/cm$^2$, standard reference AM1.5 spectrum, and temperature 25°C

- in practical applications, however, solar cells do not operate under standard conditions

- the two most important effects that must be allowed for are due to the variable temperature and irradiance

Temperature Effect

- temperature has an important effect on the power output

- the most significant is the temperature dependence of the voltage which decreases with increasing temperature

- $P_{\text{max}}$ decreases as T of cell

- the voltage decrease of a silicon cell is typically 2.3 mV per °C

- the temperature variation of the current is less pronounced (usually neglected in PV design)

Source: Solar Electricity, Tomas Markvart
Irradiance Effect

- solar cell characteristics vary under different levels of illumination
- the light generated current (flowing of electrons) is proportional to the flux of photons with above-bandgap energy
- increasing the irradiance increases, in the same proportion, the photon flux, which in turn, generates a proportionally higher current
- therefore the short circuit current is directly proportional to the irradiance
- the voltage variation is much smaller and is usually neglected

Cell Operation

- as an example, this figure shows the power characteristics of a cell at lower irradiance and at an elevated temperature
Optimal Running Condition

- although it is desired to operate the cell at the maximum power point, this may not easily be realized in practice
- a simpler but less efficient solution is to operate the cell at a constant voltage below the voltage of maximum power point
- if the operating voltage remains in the linear part of the I-V characteristic, temperature will have little effect on the power output
- the power delivered to the load will therefore be proportional to the short circuit current and thus also irradiance

Source: Solar Electricity, Tomas Markvart

Photovoltaic Components

- the basic building block of a PV system is the individual solar cell
- individual cells are assimilated into ‘strings’ which make up a module; modules are then assembled in arrays
- modules are constructed by placing PV cells in series and parallel arrangements

- glass cover to protect cells
- various frame and backing materials to facilitate mounting
Photovoltaic Components

- series and parallel configurations of solar cells follow the same rules as series and parallel DC circuits
- for identical components placed in **series**, the **voltages add at constant current** (multiple cells in series to increase operating voltage)
- for identical components placed in **parallel**, the **currents add at constant voltage** (multiple strings in parallel increase current – used to power up to several MW)

**EXAMPLE**

Photovoltaic cells are to be arranged to provide an output of 12 V and a power of 120 W. If the voltage and current at maximum power are 0.493 V and 5.13 A (V*I = 2.53 W), recommend an arrangement that meets the specifications.

**SOLUTION**

- the number of cells required for 120 W is
  \[
  \text{number of cells} = \frac{120 \text{ W}}{2.53 \text{ W/cell}} = 47.2 \text{ cells}
  \]
- to provide the correct voltage 12 V, the number of cells in series are
  \[
  \text{cells in series} = \frac{12 \text{ V}}{0.493 \text{ V/cell}} = 24.3 \text{ cells}
  \]
- the number of cells in series can be rounding up to 25; two rows of 25 cells in parallel will required 50 cells with a total power of 126.5 W

Source: Alternative Energy Systems and Applications, B.K. Hodge
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Multijunction Photovoltaic Cells

- developed for higher efficiency, multijunction cells consists of multiple thin films; semiconductors are carefully chosen to absorb nearly all of the solar spectrum

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Absorption Coefficient of Semiconductor Materials
Multijunction Photovoltaic Cells
- developed for higher efficiency, multijunction cells consists of multiple thin films; semiconductors are carefully chosen to absorb nearly all of the solar spectrum.
The price of solar photovoltaic cells has dropped 99% in the past quarter century. So in an increasing number of markets around the country, solar is at or very close to grid parity, (http://thinkprogress.org)

More and more countries and regions will reach residential grid parity. Denmark, Germany, Spain, Italy, Portugal, Australia and Hawaii were among the first to do so.
Renewable Energy Technologies
How do we get “connected”?
Utility-Scale Grid-Connected PV

Harnessing the power of the sun

A solar farm is being developed in Canada, thanks to the subsidized prices developers receive for the power they generate. As the cost of photovoltaic panels continues to fall, however, solar power will become more competitive with other forms of generation, opening the way for large-scale developments in other sunny provinces.

THE FARM
An average solar farm in Canada generates about 10 megawatts of power – enough to power about 2,000 homes – and covers around 100 acres, although some can be as large as the size.

FROM THE FARM TO THE END USER

POWER CONVERTED
The direct current generated by the solar panels is moved through underground cables to inverters, which convert the power to usable alternating current.

HOW A SOLAR CELL WORKS
Two layers of positively and negatively charged semiconducting silicon are layered together. As sunlight photons allow the cell, the silicon releases electrons from its atoms. Hand-conducting strips attached to the two sides complete the circuit resulting in an electrical charge that can be harvested.

TO USERS
The solar-generated electricity travels on power lines to a substation, where it joins the existing grid to supply local or distant users.
Grid Connected Photovoltaics Energy Systems for buildings

Installations: e.g., Parking Lot Structures
PV Thermal (PVT) and Building Integrated PV (BIPV) and BIPVT

PV versus Solar Thermal – Why not PV & Thermal Combined in ONE panel, i.e. PVT (like CHP on a cell)

**Physics: Where Does the Energy Go?**

**PV**
- 10 – 15% Electricity
- 10% Optical loss
- 75 – 80% Waste Heat

**Thermal**
- 15% Optical loss
- 45% Useful Heat
- 40% Heat Losses
Hybrid Photovoltaic – Thermal Systems
Thermoelectric modeling of PV/T systems at Queen’s

Figure 2: Layers of a PV/Thermal collector surface

PV/T

Solar Roofs Take the Heat
Photovoltaic panels can act like a solar cooler, generating intense heat on a roof. Atlantis, a photovoltaic module manufacturer, has devised a way to capture this excess heat and use it inside the house.

1. Fresh air enters the space beneath the solar panels.
2. The rising air cools the solar panels, which become less efficient when overheated.
3. In summer, the heated air can escape through a vent to the roof.
4. Alternatively, the heated air can be directed to an air-to-water heat exchanger to provide hot water. It can be blown into ductwork to heat the house.
BIPV/T roof construction in Maisons Alouettes factory as one system

Based on research and simulation models developed at Concordia Univ.

PV added to a Solar Air Preheat
The photovoltaic/thermal system is fully integrated into the mechanical room façade

~ 300 sq. m.
~ 25 kWe, 75 kW heat

Integration: with the envelope, architectural and with HVAC (fresh air preheat)

Partners: Concordia University, Conserval, Day4 Energy, SET

The JMSB solar system will generate enough electricity over a year to light 1250 light bulbs and thermal energy to heat seven Canadian homes

Up to 15000 cfm fresh air =
Up to 75 kW heat (planned)
Measured: 90 kW

25 kWe
Key Features

• It consists of specially designed photovoltaic panels optimally combined with perforated wall cladding through which much of the ventilation air of the building is drawn as solar-heated fresh air.

Building Integration

• Essentially, from one building surface with an area of about 300 square metres, we generate both solar electricity (up to 25 kilowatts) and solar heat (up to 75 kW of ventilation fresh air heating).
• The system also forms the exterior wall layer of the building i.e. it is NOT an add-on, and that is why we call it building-integrated.
Kingston Building subsidized under Ontario’s Feed-in-tariff that incentivizes the installation of PV systems by guaranteeing to by-back PV power a high market rate for 20 years. Unfortunately the PV was not well integrated into building.

FIT program! (or unfit Program?)

EcoTerra™ EQuilibrium House
– an example of Integrated PV Roof plus Passive solar and conservation

2.8-kW Building-integrated photovoltaic-thermal system

Passive solar design:
Optimized triple glazed windows and mass

Ground-source heat pump

Prefabricated home Partners: NRCan, CMHC
designed to have close to net-zero annual energy consumption
BIPV/T PROTOTYPE in Montreal
2 kW system (completed in May 2006)

4 kW heat recovery from BIPV/T; Passive solar design; floor heating in direct gain zone; geothermal 2.2 ton system.

Case Study

Goodwin Hall Queen’s
Retro-fit Case

-Analysis and Solution to PV panel overheating
Example: Building Retro-fit of PV Solar Cells (Goodwin Hall @ Queen’s)

Building Retrofit of Solar Cells: Construction
Expensive and disruptive process
Use of Solar PV Awnings for summer Shade

- shading affecting daylight and view
- figure shows complete shading and unimpeded sky view from typical sitting position

Solar PV Awnings: Thermal Analysis

- sun heats cells
- cells heat air
- hot air rises
- where does it go?
Revised Baffle/flashing Design to allow air circulation and minimize module temperature
The End
Thank you!