Unit 6
Photovoltaics

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Appendix A - Electrical Basics: A Brief Introduction
1. Introduction

Photovoltaics [photo-volt-AY-iks] is the art and science of turning sunlight directly into electricity. The word comes from "photo" meaning light, and "voltaic" referring to electricity or voltage. Internationally, photovoltaic (PV) technology is growing rapidly in importance. As a means of providing electrical energy, it is unequaled in terms of its versatility, its technological elegance and its future potential. There are currently dozens of applications for which PV provides the most economical power supply solution. Australia has a large domestic market of many thousands of remote homesteads and small communities, and a potentially huge market in Asia where electricity demand is growing faster than anywhere in the world, and where there is a widely spread population with little existing infrastructure.

These notes provide an introduction to PV technology. A basic description of the structure and methods of manufacture of commercially available PV cells is given, followed by an explanation of their electrical characteristics, as single cells and as interconnected combinations.

After a description of multi-cell characteristics such as arrays of cells in series and parallel, the notes then briefly detail the sequence of steps required to correctly size a PV array. A short section on PV Pumping is also included together with a glossary and bibliography for reference works and further reading.

Appendix A provides a brief review of basic electrical theory.

1.1 PV Applications

Applications of photovoltaic systems are growing worldwide, as is the production of PV modules themselves. In 1995, the worldwide production of PV modules totalled more than 80 MW, worth around half a billion dollars. By 1999 this had risen to 200 MW (refer to Figure 1). Two PV manufacturers are located in Sydney, producing several MW per year. Japan has passed legislation requiring the installation of 400 MW by the year 2000 and 4600 MW by the year 2100. Both of these targets will require a huge increase in manufacturing capacity.

The technology has many readily identifiable applications as listed in Table 1. Cost effective applications usually occur where the cost of mains connection, supply by generating set, or from some other source is larger than the cost of a PV system. In some applications, the environmental benefits of silent, pollution free operation are enough to justify their use, even at higher cost.
Stand-alone Power Supplies (SPS or RAPS), Grid connected household arrays

Large arrays for power generation especially as an alternative to increasing transmission and distribution system capacity; also for premium priced “green” power

airport beacons, marine navigation lights, highway lighting, railway signalling systems, tall structure beacons

remote communications repeaters (telephone, TV, radio etc.), mobile communications stations, satellites

remote area water supply for stock, agriculture or for human consumption, water purification

highway traffic sensors, geological (seismic), environmental (pollution, solar radiation), meteorological (rainfall, wind speed, pressure, temperature), hydrological (water levels, flow rates)

cathodic protection, security systems, electric fencing, forest fire lookouts

solar powered calculators, watches, torches, toys etc.

holiday homes, mobile homes, golf carts, battery charging, boating equipment, caravan and campers, four wheel drives, mobile workshops or display stalls

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Typical Applications of PV Systems</th>
</tr>
</thead>
</table>

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2. PV cell technology

The basic photovoltaic unit is a PV cell (i.e. “solar cell”). In practice, a number of cells are connected together to form a module. There a number of chemical and electronic structures which exhibit the photovoltaic effect (the conversion of light directly to electricity). The following sections deal with the types of cells which are commercially available now. The characteristics of complete modules are dealt with in section 3, page 8.

2.1 Cell structure

The structure of a typical PV cell is shown in Figure 2. PV cells are electronic devices made from semiconductor material. The material most commonly used is ultra-pure silicon. The deliberate addition of very small amounts of impurity gives the silicon special electronic properties, creating material known as p-type or n-type material. P-type material is usually created by the addition of boron, while phosphorus will create n-type material.

At the junction of p- and n-type regions, an in-built voltage is formed. This is not a voltage that can be directly measured with a meter, but it does affect free electrons present in the cell. When light strikes the silicon, it will penetrate a short distance until it is absorbed. The energy of each photon of light either creates heat, and/or energizes an electron which is then released and able to flow as an electrical current. The in-built voltage pushes the electrons towards the top contact, where they are collected. Likewise the “holes” where the electrons came from are pushed towards the rear contact. An electric current can then flow if a circuit is made between the two contacts (i.e. a circulation of electrons from the top [negative] contact around to the bottom [positive] contact).

The p-n junction structure described above is actually a semiconductor diode. However, the design of the device, unlike ordinary diodes, is optimised to receive light and to generate current.

The dimensions marked on the diagram below give an appreciation of the scale of the cell structure. Typical cells for bulk power generation are around 10 cm × 10 cm. Note the thickness of the cell is only 0.25 to 0.3 mm (250 to 300 μm).
Figure 2  Structure and dimensions of a typical crystalline silicon PV cell.

2.2 Mono-crystalline cells

In the manufacture of **mono-crystalline** cells a single large cylindrical crystal is drawn from a molten bath of p-type silicon. This process is slow and must be extremely carefully controlled. The crystal ingot is then sliced into wafers (Figure 3). In modern modules the wafers are trimmed square to increase cell packing density and reduce module size.

The wafers are then chemically etched to remove saw damage and create a matt finish surface to reduce reflection. The front surface is then "doped" with phosphorus and fired in an oven at 900°C to form the n-type region and create the p-n junction. The rear conductor and then the front metallic grid are then deposited, usually by screen printing and baking a conductive paste on the surface. Wafers are typically 10 - 15 cm in diameter.

These mono-crystalline cells have the highest efficiency, particularly at low light levels. A modification of this process, developed at the University of New South Wales, uses very thin grid contact lines which are buried into laser cut grooves in the cell to produce the most efficient cells commercially available today.

Mono-crystalline cells have a uniform dark blue colour, and in a module, each of the cells are individually recognizable.
2.3 Poly-crystalline cells

Poly-crystalline cells are manufactured by casting silicon into a square ingot, from which the wafers are cut. This results in a collection of large irregular shaped crystallites rather than one single crystal. The appearance is similar to that of galvanizing on steel. Poly-crystalline cells have a speckled blue colour, and in a module, each of the cells are individually recognizable.

Wafers are then processed in a similar way to mono-crystalline cells.

The advantage of this method is the lower cost of production of the silicon ingot, and the fact that wafers are produced square and do not need to be trimmed. The efficiency is less than that of mono-crystalline cells because of the electronic defects which exist at the boundaries between crystallites. Like mono-crystalline cells, poly-crystalline technology is used for all of the larger scale applications requiring tens of watts up to megawatts of power.

2.4 Amorphous cells

Amorphous cells are formed by depositing very thin layers of silicon on a piece of glass or other materials such as plastic or stainless steel. The silicon atoms arrange themselves in a completely irregular (non-crystalline) fashion and this means that the electronic properties of the material are poor compared to crystalline silicon. Consequently, the efficiency is low.

A feature of amorphous cells is that they gradually lose efficiency in the first 3 - 12 months of operation, before stabilising. They are rated at the lower (stabilized) output level.

This type of technology can be flexible and is diverse in its application. Watches, calculators and battery chargers and other consumer goods are everyday applications of this type of cell. Novel applications of amorphous cell technology include semi-transparent sunroofs for cars and caravans, hatches for boats, clock faces...etc., all of which are employed to charge batteries.

The production process is highly automated and generally produces a complete module as the basic unit, rather than individual cells. Until recently their use is limited largely to applications requiring a fraction of a watt of power, up to several watts.
Some larger modules, with UV stabilised polymer lamination on a stainless steel backing, have recently become available for high power applications. These include triple junction cells, where each junction is optimised to operate at different wavelengths of the visible spectrum, producing a higher overall efficiency (though still lower than crystalline cells).

Amorphous modules have a uniform colour, and can look similar to tinted glass, with lines across the module dividing the surface into strips. Each of the strips is one cell.

2.5 Comparison of technologies

Due to the high manufacturing costs involved and the use of relatively large quantities of expensive ultra-pure silicon, prices of mono-crystalline and poly-crystalline cells using conventional methods, are projected to remain relatively high. Very low costs will only be achieved by production of thin film PV cells, which use little semiconductor material, are mass produced in large quantities in a highly automated production line. Thin film technologies include amorphous silicon, thin film poly-crystalline silicon and other semiconductor materials such as Cadmium Telluride and Copper Indium Diselenide.

In 1999 in Australia, research and development into three very different technologies promising lower costs, was under way. These are thin film poly-crystalline, developed at the University of NSW; epi-layer crystalline silicon, developed at the Australian National University; and titania solar cells which are being developed under license from a university in Switzerland. The latter are not silicon based, and operate on a principle similar to that of photosynthesis in plants.

Currently similar retail costs apply to mono-crystalline, poly-crystalline and triple junction amorphous modules (about $7 to $10 per peak watt). "Standard" amorphous modules are generally available only in small sizes, and their cost per watt is higher (e.g. $20/Wp or more). The cost of thin film technology may be very low in the future (down to about $1 per peak watt).

Typical efficiency figures are shown in Table 2.

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Production:</td>
<td></td>
</tr>
<tr>
<td>Mono-crystalline</td>
<td>12 - 16 %</td>
</tr>
<tr>
<td>Poly-crystalline</td>
<td>10 - 12 %</td>
</tr>
<tr>
<td>Amorphous</td>
<td>6 - 7 %</td>
</tr>
<tr>
<td>Triple Junction Amorphous</td>
<td>9%</td>
</tr>
<tr>
<td>Laboratory cells:</td>
<td></td>
</tr>
<tr>
<td>Mono-crystalline</td>
<td>&gt; 23%</td>
</tr>
<tr>
<td>Poly-crystalline</td>
<td>18%</td>
</tr>
<tr>
<td>Multi layer Amorphous</td>
<td>Up to 16%</td>
</tr>
</tbody>
</table>

Table 2: Typical PV cell efficiencies
Many high power PV modules available in Australia currently have a 20-year warranty on power output, others 10 or 15 years.

3. Cell characteristics

3.1 IV curves

The key to understanding the electrical behaviour of solar cells is understanding the IV curve. The IV curve is a graph of current ($I$) vs voltage ($V$) for a cell or module. It shows what electrical output the cell will produce in a given set of conditions.

To introduce the concept, first consider the behaviour of a battery, for example a car battery. A car battery produces a nominal output voltage of 12 V. Under no load (i.e. an open circuit) the output voltage will be say 12.5 V. When a load is connected, for example headlights, a current will flow, (say 10 A) and the battery voltage will drop a little, e.g. to 12.3 V. If a very heavy load is connected (e.g. the starter motor) a large current will be drawn (say 150 Amps) and the battery voltage will drop more e.g. to 10 V.

The voltage at the battery terminals will depend on the current being drawn. This can be represented by the graph shown in Figure 4. This graph is shown in two ways: first as a graph of voltage vs current; then with the two axes swapped, as a graph of current vs voltage i.e. an IV curve.

![Graph of IV curve for a battery](image)

Figure 4  The electrical behaviour of a battery, shown in two ways. The right hand graph, with Current on the y axis is called an IV curve.

For a battery, the voltage stays nearly constant, and the load current can cover a wide range. A battery is, ideally, a constant voltage source. If the battery is short circuited, the current flow can be enormous, and potentially dangerous.
A solar cell behaves very differently. It is essentially a constant current source, rather than a constant voltage source. This means that it is quite safe to short circuit it, and that over a range of load voltages, it will maintain a nearly constant current. This kind of behaviour is quite different to what most people are used to.

There is of course a limit to the voltage it can produce. The shape of a typical solar cell IV curve is shown in Figure 5. This figure also shows the test setup that would be used to measure the points on this curve.

Note that the information presented here applies to crystalline silicon cells and modules only. Amorphous modules have a similar shaped but much more sloping IV curve. The behaviour of amorphous modules with temperature is also much more complex.

![Test circuit and IV Curve for a PV cell](image)

**Figure 5**  Test circuit and IV Curve for a PV cell
Introduction to Renewable Energy Technologies

When the load is removed (i.e. infinite resistance), the current will be zero and the voltage at the cell terminals is called the open circuit voltage ($V_{oc}$).

When the cell is short circuited (i.e. zero load resistance) the resultant current is called the short circuit current ($I_{sc}$) - and the output voltage is zero. On the curve $V_{oc}$ is where the graph crosses the voltage axis and $I_{sc}$ is where the graph crosses the current axis.

At all times, the solar cell will be operating at some voltage and current which corresponds to a point on the IV curve. The operating point moves along that curve as the load varies. For example, if the PV cell was powering a lamp directly, the operating point would depend on the resistance of the lamp. If it was charging a battery, it would operate at the voltage of the battery under charge.

All PV cells of the same type (e.g. mono-crystalline) will produce similar open circuit voltages under similar conditions. However the current produced by a cell is proportional to its area, so higher output can only be achieved using larger cells unless the efficiency is improved.

### 3.2 Maximum power point

In dc circuits, power is simply the product of voltage times current.

$$ P = V \times I $$

Therefore when either $I$ or $V$ are zero, the output power of the cell is zero. This occurs at both $I_{sc}$ and $V_{oc}$. From the shape of the curve it can be seen that the power will reach a maximum value somewhere between these two points. If you were to plot a graph of power vs voltage, the result would be as shown in Figure 6. When this is overlaid onto the IV curve, the maximum power point (MPP) on the IV curve can be easily seen. It is interesting to see that the MPP occurs around the “knee” of the IV curve.

Note that the rated output of PV cells and their quoted efficiencies are taken at the maximum power point. At every other point on the curve the output and therefore the operating efficiency of the cell will be lower. It is therefore important to ensure that the PV cell is operated at or near this maximum power point. The voltage and current at which maximum power is obtained are called $V_{MP}$ and $I_{MP}$ respectively.
3.3 Irradiance response

The IV curves shown above will be valid for one particular value of irradiance only. The short circuit current ($I_{sc}$) generated by the cell is proportional to the irradiance, so a series of curves is used to show the cell's behaviour under different irradiance levels. This is shown in Figure 7.

The effects of irradiance on the short circuit current ($I_{sc}$) and the open circuit voltage ($V_{oc}$) are shown in Figure 8.
It can be seen that while $I_{SC}$ responds linearly to increasing irradiance, $V_{OC}$ is much less affected. As the irradiance increases, $V_{OC}$ will approach a limit of approximately 0.6 Volts. Only at low light levels does $V_{OC}$ drop off markedly. These characteristics produce the evenly spaced intercepts on the current axis and bunched up intercepts on the voltage axis seen in Figure 7.

3.4 Temperature effects

Figure 9a shows a series of IV curves which demonstrate the effect of cell temperature. These are all drawn at a constant irradiance. The most significant effect is that $V_{OC}$ reduces with increasing temperature. The short circuit current, $I_{SC}$, increases with temperature, but only very slightly. Figure 9b summarizes the effects on $I_{SC}$, $V_{OC}$ and $P_{MP}$.

The reduction in $V_{OC}$ for higher temperatures means that the knee of the curve and hence the maximum power point shifts to a lower voltage. In other words $V_{MP}$ reduces, $I_{MP}$ stays very nearly the same, and the combined effect is that $P_{MP}$ is reduced. This amounts to a reduction in power of around 0.4 to 0.5 % per degree.

For amorphous cells, an additional temperature effect occurs. Exposure to high temperatures partially reverses the degradation in power output that amorphous modules suffer when they are first used. This does not happen instantly, but produces a noticeable variation in the apparent power rating of a cell from summer to winter. In other words, an amorphous cell tested in summer will show a higher output under standard test conditions than one tested in winter. The overall effect of temperature on triple junction amorphous modules is such that their output power does not vary much at all with different operating temperatures. This gives them an advantage over crystalline silicon in extremely high ambient temperatures such as in central and northern Australia.

Prolonged operation above 70 °C will cause accelerated ageing of any type of photovoltaic cell.