Electricity – Innovative Technologies towards Sustainable Development

'Learning-by-Notes' Package for Senior School - Physics

Lesson 5: Solar & Wind

- How Do We Make Electricity from Solar Cells?

- How Do We Make Electricity from Wind Turbines?

Teaching Sustainability in High Schools: Subject Supplement

Developed by:

The Natural Edge Project
Griffith University

Funded by:

PORT of BRISBANE
Here for the future

As part of the:

Sustainable Living Challenge

Acknowledgements

The development of the '*Sustainability Education for High Schools: Year 10-12 Subject Supplements'* has been supported by a grant from the Port of Brisbane Corporation as part of the Sustainable Living Challenge. The Port of Brisbane Corporation is a Government Owned Corporation responsible for the operation and management of Australia's third busiest container port. Its vision is, 'To be Australia's leading port: here for the future'. Sustainability for the Port of Brisbane Corporation means making economic progress, protecting the environment and being socially responsible. In response to the recent drought, and the wider global debate on climate change, the Port is committed to working with the port community to showcase the Port of Brisbane as a sustainable business precinct. Initiatives aimed at reducing the Port of Brisbane's ecological footprint include energy efficiency, a green corporate fleet and constructing green buildings.

The development of this publication has been supported by the contribution of non-staff related on-costs and administrative support by the Centre for Environment and Systems Research (CESR) at Griffith University; and the Fenner School of Environment and Society at the Australian National University. The material has been researched and developed by the team from The Natural Edge Project. Versions of the material have been peer reviewed by Cameron Mackenzie, Queensland Department of Education, and Ben Roche, National Manager, Sustainable Living Challenge, University of New South Wales.

Project Leader: Mr Karlson 'Charlie' Hargroves, TNEP Director
Principle Researcher: Ms Cheryl Desha, TNEP Education Director
TNEP Researchers: Mr Michael Smith, Mr Peter Stasinopoulos
Copy-Editor: Mrs Stacey Hargroves, TNEP Editor

The Natural Edge Project

The Natural Edge Project (TNEP) is an independent non-profit Sustainability Think-Tank based in Australia. TNEP operates as a partnership for education, research and policy development on innovation for sustainable development. TNEP's mission is to contribute to, and succinctly communicate, leading research, case studies, tools, policies and strategies for achieving sustainable development across government, business and civil society. Driven by a team of early career Australians, the Project receives mentoring and support from a range of experts and leading organisations in Australia and internationally, through a generational exchange model. TNEP's initiatives are not-for-profit. Our main activities involve research, creating training and education material and producing publications. These projects are supported by grants, sponsorship (both in-kind and financial) and donations. Other activities involve delivering short courses, workshops, and working with our consulting associates as we seek to test and improve the material and to supplement the funds required to run the project. All support and revenue raised is invested directly into existing project work and the development of future initiatives.

Enquires should be directed to: Mr Karlson 'Charlie' Hargroves, Co-Founder and Director, The Natural Edge Project
charlie@naturaledgeproject.net www.naturaledgeproject.net

Lesson 5A: Solar Energy

How Do We Make Electricity from Solar Cells?

The Australian Solar Cities program is an innovative $75 million program which is designed to demonstrate how solar power, smart meters, energy conservation and new approaches to electricity pricing can combine to provide a sustainable energy future in urban locations.

***Australian Federal Department of Environment, Water, Heritage & the Arts, 2008*[1]**

Educational Aim

The aim of this lesson is to describe the key components of solar cells and the process used by solar cells to generate electricity from the sun's energy.

Key Words for Searching Online

Photovoltaic cells, photovoltaic modules, photovoltaic panels, photovoltaic arrays, semiconductors, n-type and p-type semiconductors, built-in electric field, photovoltaic effect.

Key Learning Points

1. A 'solar cell' is a device that converts sunlight into electricity. The device can also be referred to as a 'photovoltaic (PV) cell'. Individual solar cells are used for powering small devices such as electronic calculators. Each cell contains a very thin wafer of 'semiconductor' material, which captures the energy from sunlight hitting it.
2. Semiconductors are special non-metal materials that conduct electricity. They are produced by modifying or 'doping' an element with either extra electrons (n-type semiconductors, where the 'n' stands for negative) or 'extra holes' (p-type semiconductors, where the 'p' stands for positive) that are free to move from atom to atom. Pure crystalline silicon is the element used to make semiconductors for more than 90 percent of solar cells.
3. In a typical solar cell, an n-type and a p-type semiconductor are brought into contact. This situation creates a *voltage* (or a 'greater potential for current to flow') between the semiconductors and hence an electric field at the junction. The electric field prevents electrons from crossing the junction from the n-type to the p-type semiconductor, but still allows electrons to cross from the p-type to the n-type semiconductor.
4. Exposing a solar cell to sunlight can generate electricity via a process called the 'photovoltaic effect'. Packets of sunlight's energy, called photons, are absorbed by electrons in the p-type semiconductor. With this extra energy, these electrons have enough energy to escape from their atom's hold. Initially, the electrons are attracted to the positive n-type semiconductor but, once in the n-type semiconductor, are then attracted back to the holes in the p-type semiconductor. The electrons travel in this manner, on a path through an electric circuit. The combination of the voltage between the two semiconductors and electricity generated by the photovoltaic effect delivers the solar cell's power. Wire then conducts the electricity to wherever it is needed.

[1] See Federal Department of Environment, Water, Heritage and the Arts website - *Welcome to Australia's Solar Cities* at http://www.environment.gov.au/settlements/solarcities/. Accessed 3 March 2008.

5. Solar cells are often electrically connected and encapsulated as a ‘PV module’, with a sheet of glass on the front (sun-up) side. This allows light to pass through while protecting the semiconductor wafers from the weather. When solar cells are connected ‘in series’ (i.e. one after the other), this creates more *voltage*. Connecting cells in parallel gives a higher *current*. These modules are then interconnected, in series or parallel, or both, to create a ‘PV array’ with the desired voltage and current. PV arrays, themselves, can also be linked together to generate even more power. PV modules and PV arrays can be packaged with other components in ‘PV systems’.

6. PV arrays generate a form of renewable electricity that can either be used as part of an electricity grid, or independently for stand-alone applications such as remote housing, and satellites, using batteries to store the energy that is not needed immediately. For some appliances, electricity can be used directly from the batteries. This is called ‘direct current’ (DC) and it powers appliances such as car headlights, flashlights, portable radios, etc. However, to run most appliances found in the home, ‘alternating current’ (AC) is still needed - the type in ordinary wall sockets. Using an inverter, direct current from the batteries can be transformed into alternating current. The inverter's output can then power the circuit breaker box and the common outlets in the home.

7. Once we understand how solar cell technology works, we can begin to innovate improvements. There have been three ‘generations’ of solar cell technology so far, where the properties of the semiconductor wafer have been improved:

   a) First-generation solar cells (also known as silicon wafer-based solar cells) are based on n-type and p-type semiconductors, and are the most used technology on the market for land-based solar cell applications.

   b) Second-generation solar cells are still based on n-type and p-type semiconductors, but use an innovation called ‘thin-film technology’. An advantage of thin-film technology theoretically results in reduced mass so it allows fitting panels on light or flexible materials, even textiles. Second-generation solar cells are still most widely used in space-based applications.

   c) Third-generation solar cells are very different from the previous semiconductor devices as they do not rely on a traditional n type – p type junction. For terrestrial (land based) applications, these new devices include photo-electrochemical cells, polymer solar cells, nanocrystal solar cells and dye-sensitized solar cells and are still in the research phase.

8. A typical, modern solar cell still converts only about 10-20 percent of the sunlight that strikes its surface to electricity. A key reason for this relatively low conversion efficiency is that only about 30 percent of the sunlight is absorbed – the remainder is either reflected, passes through, or is stopped by the metal conductor on top of the cell which is in the shape of a grid and so shades a small area of the semiconductor. Reflected light can be reduced to less than 5 percent by placing an anti-reflective coating above the semiconductors. Power can also be maximised by using semiconductors that balance both electricity and voltage.

9. Solar cell technology has in the past been quite energy and materials intensive to produce, with quite toxic by-products. There are some exciting technology improvements also underway to produce non-toxic, low embodied energy solar cell technology.[2]

[2] More information on innovation in solar energy technology is available from the Australian National University website http://solar.anu.edu.au/. Accessed 17 July 2008.

Brief Background Information

Solar (Photovoltaic) Cells

The term photovoltaic comes from the Greek word 'phos' meaning light, and 'voltaic', after the name of the Italian physicist Volta (after whom the electrical measurement unit 'volt' was named). *Solar cells (or Photovoltaic (PV) cells*), are small devices that convert sunlight into electricity, and are made of six layers of materials, as shown below in Figure 5.1.

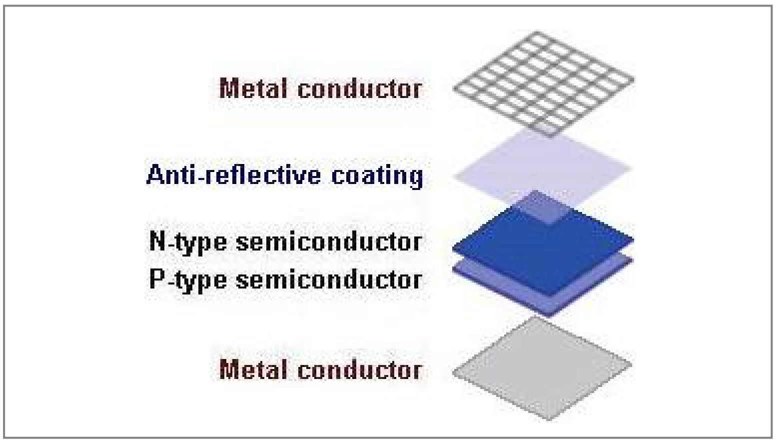


Figure 5.1. Exploded view of a photovoltaic cell

Source: Adapted from Massachusetts Technology Collaborative[3]

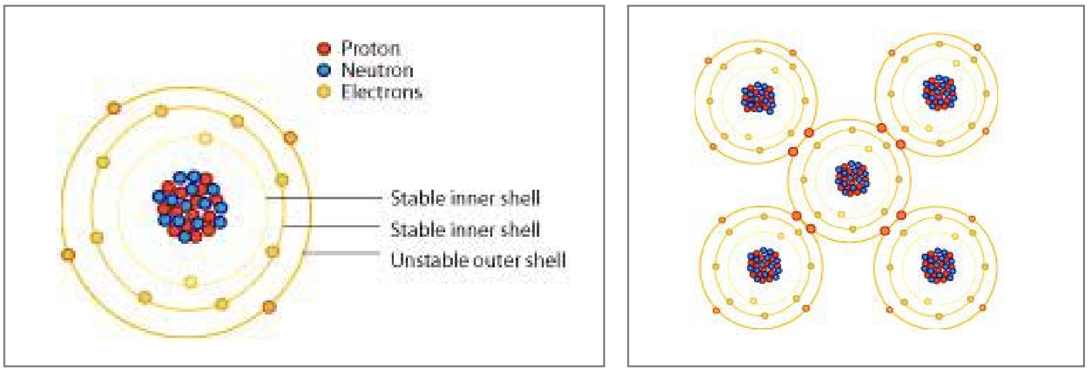
Semiconductors

Semiconductors are special materials that conduct electricity, though not as well as metals. Materials used as semiconductors in solar cells include silicon, gallium arsenide, copper indium diselenide, cadmium sulfide and cadmium telluride. Silicon is used in more than 90 percent of solar cells and is highly abundant, making up more than 25 percent of the Earth's crust. Silicon atoms can also be arranged in crystalline form, which makes them very suitable for use in solar cells.

A silicon atom has 14 electrons, arranged in three different *shells* as shown in Figure 5.2 (a). The two inner-most shells hold up to 2 and 8 electrons, respectively, so both shells are full (stable). While the outer shell can hold up to either 8 or 18 electrons, there are only 4 electrons remaining, so the outer shell has holes that desire to be filled (unstable). A silicon atom can become stable by filling either 4 or 14 holes in its outer shell. The atom can fill 4 holes by sharing electrons with other silicon atoms, as shown in Figure 5.2 (b). This arrangement is called a *crystalline form*. Pure, crystalline silicon is a poor electrical conductor because all electrons are strongly held in place by protons in the nucleus and the need for the atom to maintain a stable shell.

> ***Fundamentals***
>
> *Charges* are attracted to the opposite charge and are repelled by the same charge. Protons carry positive charge and electrons carry negative charge.

[3] See Massachusetts Technology Collaborative – *From Cells to Panels to Arrays* at http://www.mtpc.org/cleanenergy/solar_info/panel.htm. Accessed 18 November 2007.



(a) (b)

Figure 5.2. (a) A silicon atom, and (b) crystalline silicon

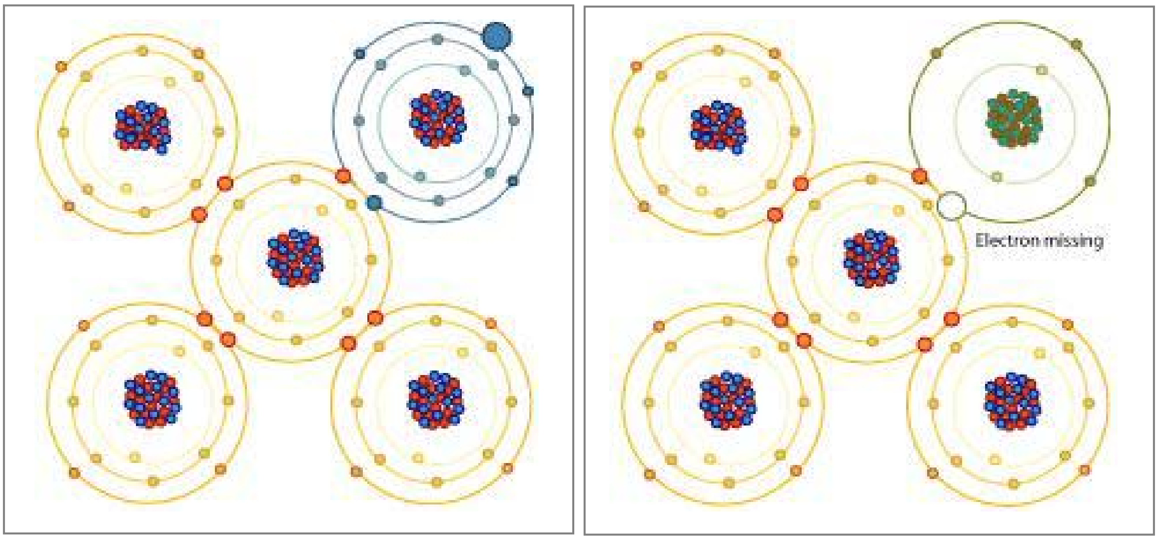
Source: Massachusetts Technology Collaborative[4]

Pure, crystalline silicon is made into a semiconductor via a process called 'doping', where different atoms, called *dopants* are added to add either extra electrons or extra holes that are free to move from atom to atom.[5] One dopant is added for approximately every 1 million silicon atoms. The extra electrons or holes allow the silicon to conduct electricity. Note that although semiconductors contain extra electrons or holes, they are still electrically neutral – that is, semiconductors have no net charge because they contain an equal number of electrons and protons.

Semiconductors with extra electrons are called 'n-type semiconductors', where the 'n' stands for negative. Adding electrons is achieved by adding dopants that have five outer shell electrons, such as phosphorous or arsenic atoms. Four outer shell electrons are shared with the four neighbouring silicon atoms, while the remaining electron is weakly held in place (bound) by the proton in the dopant's nucleus only, as shown in Figure 5.3 (a). The dopant wants to release the electron to acquire a stable shell.

Semiconductors with extra holes are called 'p-type semiconductors', where the 'p' stands for positive. Adding holes is achieved by adding dopants that have three outer shell electrons, such as boron, aluminium or gallium atoms. The three outer shell electrons are shared with three of the neighbouring silicon atoms, while the remaining silicon atom does not receive an electron, thus creating a hole, as shown in Figure 5.3 (b).

[4] See Massachusetts Technology Collaborative – *The Science Behind Photovoltaics* at http://www.mtpc.org/cleanenergy/solar_info/science.htm. Accessed 18 November 2007.
[5] A moving hole is the result of moving electrons. When an electron then fills a hole, another is created adjacent.



(a) (b)

Figure 5.3. (a) N-type silicon (phosphorous doped) and (b) P-type silicon (boron doped)

Source: Massachusetts Technology Collaborative[6]

Creating a Voltage: The Inbuilt Electric Field

In the typical solar cell, n-type and p-type semiconductors are brought into contact. This situation creates a *voltage* between the semiconductors and hence an *electric field* at the junction via the following process:

- When the semiconductors come into contact, some of the extra electrons in the n-type semiconductor are attracted to the holes in the p-type semiconductor. Those electrons cross the junction to fill those holes. However, these electrons are weakly bound in those holes by the dopant's desire to maintain a stable shell only – there is no proton in the dopant's nucleus holding the electron.
- Now the n-type semiconductor has lost some electrons, giving it a net positive charge (remember that before the two semiconductors were brought into contact, they were electrically neutral), and the p-type semiconductor has gained some electrons, giving it a net negative charge (see Figure 1.4).
- As more electrons fill more holes, the accumulating electric field makes it increasingly difficult for more electrons to cross the junction.

> ***Fundamentals***
>
> A difference in charge between two surfaces is called a *voltage difference*, or simply a *voltage*. A voltage creates an *electric field*, which dictates the behaviour of charges. Charges are attracted to the surface with the opposite charge and are repelled by the surface with the same charge.

- Eventually, a barrier is formed that prevents any more electrons from crossing the junction from the n-type to the p-type semiconductor, but that still allows electrons to cross from the p-type to the n-type semiconductor as shown in Figure 5.4.
- A typical, modern solar cell has a voltage of 0.5 Volts.

[6] See Massachusetts Technology Collaborative – *The Science Behind Photovoltaics* at http://www.mtpc.org/cleanenergy/solar_info/science.htm. Accessed 18 November 2007.

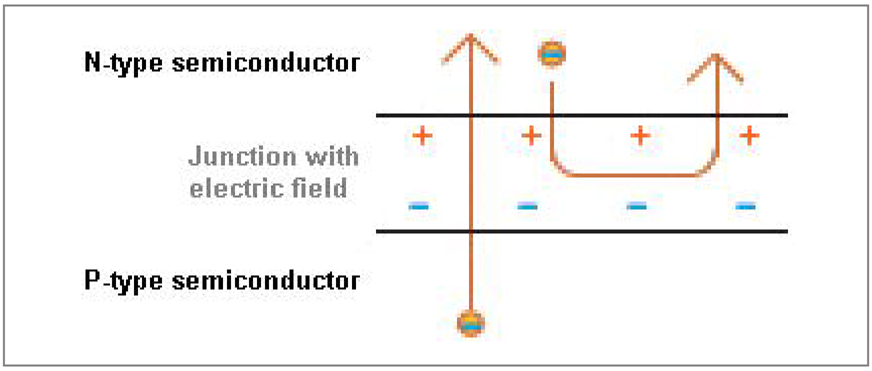


Figure 5.4. The electric field at the junction of n-type and p-type semiconductors, and its effect on electrons

Source: Adapted from Massachusetts Technology Collaborative[7]

Generating Electricity: The Photovoltaic Effect

Exposing the solar cell to sunlight can generate electricity, or *electric current*, via the following process, called the *photovoltaic effect*:

- *Photons* from sunlight pass through the n-type semiconductor and strike the atoms in the p-type semiconductor near the junction.
- Photons with energy equal to at least a specific amount, called the *band gap*, are absorbed by the weakly-bound electrons in the dopants. These electrons now have enough energy to escape the dopants' hold.

> ***Fundamentals***
>
> Sunlight carries light energy in the form of *photons*, which are small packets of energy. Sunlight is made up of photons of a wide spectrum of energies.

- Initially, the electrons are attracted to the positive n-type semiconductor but, once in the n-type semiconductor, the electrons encounter atoms that already have stable shells or extra electrons.
- The electrons are then attracted back to the holes in the p-type semiconductor but are unable to cross the junction due to the electric field's effect described above.
- Instead, the electrons take the following alternative path as shown in Figure 5.5: through the n-type semiconductor; through the metal conductor on the n-type semiconductor; through the load (any device that runs on electricity, such as a lamp, calculator or motor, or even a car or building); through the metal conductor on the p-type semiconductor and finally back into the p-type semiconductor.

> ***Fundamentals***
>
> *Electricity*, or *electric current*, is the flow of electrical charge. Electrons carry electrical charge. Thus, the flow of many electrons creates an electrical current.

[7] See Massachusetts Technology Collaborative – *The Science Behind Photovoltaics* at http://www.mtpc.org/cleanenergy/solar_info/science.htm. Accessed 18 November 2007.

- The flow of electrons is electricity that can be used by the load. A typical, modern solar cell generates direct current electricity of 2 to 4 Amperes (or 'Amps' - a unit expressing the rate of flow of electric current).

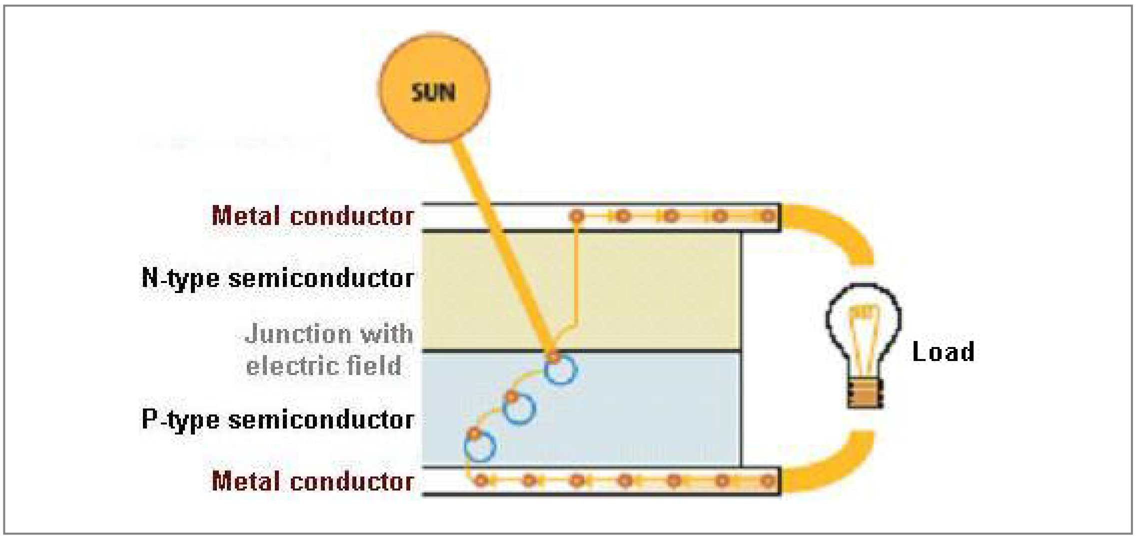


Figure 5.5. The flow of electrons caused the photovoltaic effect in a photovoltaic cell

Source: Adapted from Massachusetts Technology Collaborative[8]

Powering the Load

The combination of the voltage between the two semiconductors and electricity generated by the photovoltaic effect delivers the PV cell's *power* to the load. A typical, modern PV cell generates power of 1 to 2 'Watts' (electric measurement of power at one point in time, as capacity or demand).

> ***Fundamentals***
>
> Electrical Power = Voltage x Electrical Current

Photovoltaic Cell Conversion Efficiency

A typical, modern PV cell converts 10 to 20 percent of the sunlight that strikes its surface to electricity. There are several reasons for this relatively low conversion efficiency:

- Only about 30 percent of the total photon energy in sunlight that strikes a PV cell can be absorbed – the remainder is either reflected or passes through. Remember that only photons with energy at least equal to the band gap are absorbed by electrons. Photons with less energy pass through, photons with the exact energy are fully absorbed, and photons with more energy are partly absorbed, with the remaining energy passing through. In addition, some sunlight is reflected by the semiconductors, which have a very shiny surface. The amount of sunlight reflected is reduced to less than 5 percent by placing an *anti-reflective coating* above the semiconductors.
- Different semiconductors have different band gaps. Using a semiconductor with a lower band gap means that the electrons will absorb more photons and hence more electricity will

[8] See Massachusetts Technology Collaborative – *The Science Behind Photovoltaics* at http://www.mtpc.org/cleanenergy/solar_info/science.htm. Accessed 18 November 2007.

be generated. However, a lower band gap also means that a lower voltage will be generated. Conversely, a semiconductor with a higher band gap will generate less electricity but create a higher voltage. Therefore, power is maximised by using the semiconductor that balances both electricity and voltage.

- The flow of electrons passes through the metal conductors that surround the semiconductors. The bottom metal conductor completely covers the semiconductor, so the electrons are required to travel only a small distance to reach it. However, the top metal conductor cannot completely cover the semiconductor because it would totally block the sunlight. Instead, the top metal conductor is in the shape of a grid, which covers only a small area of the semiconductor while requiring the electrons to travel only a small distance to reach any part of it. Remember, semiconductors do not conduct electricity as well as metals, so minimising the distance required for the electron travel in the semiconductor will improve electron flow, but at the same time blocks some of the sunlight from reaching the semiconductor surface.

Photovoltaic Modules, Arrays and Systems

The 1 to 2 Watts of power generated by a single PV cell is too low to be of much use. PV cells can be linked together and encased in rigid packaging to form *PV modules*, also called *PV panels*, which generate a useful amount of power (see Figure 5.6). Typically, 36 PV cells are grouped together to form a module that provides 18 volts at peak power, and 12 volts at nominal (a type of average) power.

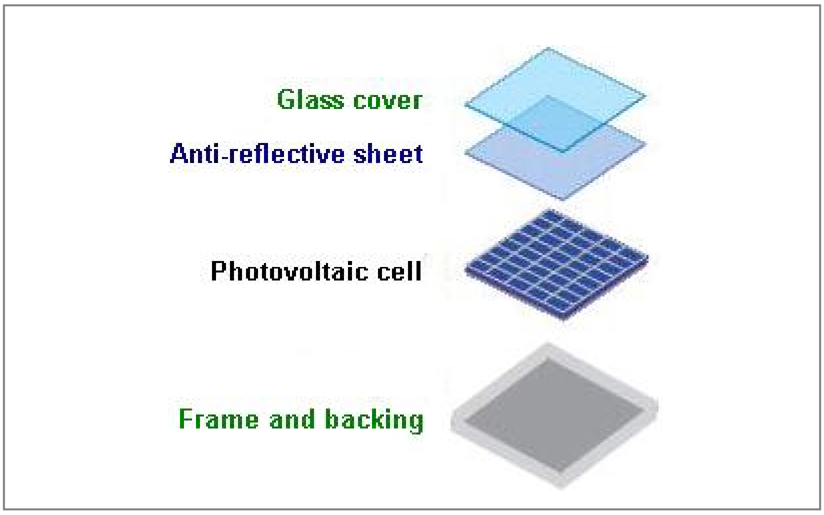


Figure 5.6. Exploded view of a photovoltaic module

Source: Adapted from Massachusetts Technology Collaborative[9]

PV modules can be linked together to form *PV arrays*, which generate more power as shown in Figure 5.7. Combining PV modules in series increases the total voltage, and combining PV modules in parallel increases the total electricity. PV arrays, themselves, can also be linked together to generate even more power.

[9] See Massachusetts Technology Collaborative – *From Cells to Panels to Arrays* at http://www.mtpc.org/cleanenergy/solar_info/panel.htm. Accessed 18 November 2007.

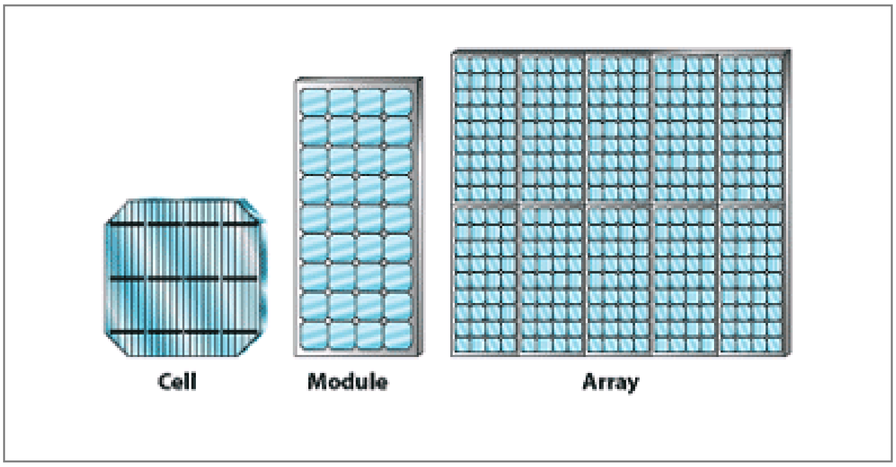


Figure 5.7. Photovoltaic cell, photovoltaic module and photovoltaic array

Source: US Department of Energy [10]

In practice, PV modules and PV arrays are mounted on structures that make them face the sun and are also integrated with other electrical components to convert the electricity generated into a useful form. This package is called a *PV system*. PV modules and PV arrays operate most effectively when their surfaces are kept clean and unshaded. Since PV cells are connected in series, shading any cell can substantially reduce the electricity generated.

Solar Cell Technology – Materials and Energy Considerations

When we consider the potential for solar cell technology to offset electricity from non-renewable fuels such as oil and coal, mainstream solar cell technology still uses a lot of energy to make ('embodied energy'), and can still have quite a large environmental footprint with a variety of possible toxic waste products during its production. However, innovations, such as the development of titanium oxide films for PV cells, and installation systems that avoid aluminium frames, are rapidly reducing the embodied energy and also the cost of producing the cells.

Thin film panels are an exciting future path for solar cell technology, because of their ability to be placed on walls, windows and other surfaces. However, the challenge has been in making a thin film that is as efficient and durable as silicon, and designing toxic processes out of the production of thin films. For example, some thin-film technology has involved cadmium, telluride and selenide, but there are environmental concerns about the manufacture and disposal of these heavy metals. Researchers around the planet are working to develop molecules out of organic compounds – like carbon and hydrogen. An exciting innovation by Australian scientists is the 'Sliver Solar Cell' technology which uses as little as one tenth the amount of hyper-pure silicon as in square solar PV technology.[11] Proprietary 'nano-particle silicon printing' processes are also being developed, which can be printed reel to reel on stainless steel or other high temperature substrates. Indeed, numerous companies, universities and research institutes are busily working in a solar technology race to develop the best solar technology possible for the world's future energy needs.

[10] See US Department of Energy – *The Photoelectric Effect* at http://www1.eere.energy.gov/solar/photoelectric_effect.html. Accessed 12 November 2007.
[11] Centre for Sustainable Energy Systems website http://solar.anu.edu.au/docs/Slivers.pdf. Accessed 17 July 2008.

Key References – Electricity *(Alphabetical Order)*

1. Aldous, S. (n.d) *How Solar Cells Work*, Howstuffworks. Available at http://science.howstuffworks.com/solar-cell.htm. Accessed 12 November 2007.
2. Brain, M. (n.d.) *How Semiconductors Work*, Howstuffworks. Available at http://computer.howstuffworks.com/diode.htm. Accessed 12 November 2007.
3. Eiffert, P. and Kiss, G.J. (2000) *Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures: A Sourcebook for Architects*, National Renewable Energy Laboratory. Available at http://www1.eere.energy.gov/femp/pdfs/25272.pdf. Accessed 12 November 2007.
4. Massachusetts Technology Collaborative website – *Introducing Solar Photovoltaics* at http://www.mtpc.org/cleanenergy/solar_info/intro.htm. Accessed 18 November 2007.
5. Research Institute for Sustainable Energy (2006) *Photovoltaics*, Murdoch University. Available at http://www.rise.org.au/info/Tech/pv/index.html. Accessed 14 November 2007.
6. US Department of Energy website – *Photovoltaics* at http://www1.eere.energy.gov/solar/photovoltaics.html. Accessed 12 November 2007.

General Reference:

7. Diesendorf, M. (2007) *Greenhouse Solutions with Sustainable Energy*, UNSW Press.
8. Solar Energy Research at the Australian National University: http://solar.anu.edu.au/.

Lesson 5B: Wind Turbines

How Do We Make Electricity from Wind Turbines?

With global warming a recognised environmental, social and economic concern, the development of science-based alternative forms of energy that are reliable, efficient and profitable is a national priority … Our Wind Energy Research Unit (WERU) has successfully identified significant areas of high wind-energy potential in Australia, and demonstrated the potential of wind as a renewable energy option for this country.

Commonwealth Scientific and Industrial Research Organisation[12]

Educational Aim

The aim of this lesson is to describe the key components of wind turbines and the process used by wind turbines to generate electricity using the sun's energy.

Key Words for Searching Online

Wind energy, wind turbine, blade, airfoil, aerofoil, air turning, air circulation, lift, Bernoulli's Equation, Newton's Third Law, gears, gear ratio.

Key Learning Points

1. Wind is caused by the Earth's rotation and the sun's heat energy, with wind energy consuming about 2 percent of the sun's heat energy that reaches the Earth.
2. The two main types of wind turbines available are:
   a) The *Horizontal-axis turbine*, which has a shape a lot like a pedestal fan. These are favoured due to a smaller physical footprint and optimum elevation to catch wind energy.
   b) The *Vertical-axis turbine*, which has a shape reminiscent of an egg beater. These are not favoured due to their relatively large physical footprint, and the fact that they are usually quite close to the ground, so don't capture as much wind energy.
3. A typical wind turbine can meet the energy needs of up to 1000 homes. At the end of 2006, there were 27 wind farms operating in Australia with an installed electricity generation capacity of 817 Megawatts.[13]
4. Making electricity from wind is generally a three step process (for an animated depiction of this process, see http://science.howstuffworks.com/wind-power.htm:
   1) The wind turbine is built in a location that is known to be in the path of steady and significant wind.
   2) The wind passing through the wind turbine is used to rotate a turbine shaft.
   3) The rotating turbine shaft powers an electric generator, generating electricity.

[12] See CSIRO website – *Overview of Research: Wind energy research unit* at: www.csiro.au/science/ps2k7.html. Accessed 4 April 2007.
[13] Hargroves, K., and Smith, M. (2007) 'Energy superpower or sustainable energy leader?' *CSIRO ECOS*, Oct-Nov 2007. Available at: http://www.publish.csiro.au/?act=view_file&file_id=EC139p20.pdf. Accessed 4 November 2007.

5. The amount of wind energy a wind turbine and electric generator can convert to electrical power depends on three main factors: wind speed, blade length and efficiency.[14] To increase the amount of power, one or more of the following need to be addressed:

   1) The wind speed needs to increase

   2) The blade length and shape needs to be improved

   3) The efficiency of the rotating turbine shaft and electric motor needs to be improved

6. Wind turbines convert wind energy to mechanical rotation, usually incorporating two or three blades. In addition to the turbine blades, other key components of the turbine include the gearbox and the electric generator.

7. A turbine blade's cross section has a tilted, airfoil shape. Air behaves differently as it flows around the blade – air travelling above the blade increases in velocity while wind travelling below the blade decreases in velocity. This behaviour is known as 'turning', or 'circulation'.

8. 'Turning' of the air ultimately applies a force on the blade that makes the blade move, but the way in which that force is applied is in debate. Although the maths is well understood, there are two sides to the debate on how 'turning' happens, which is based on the interesting features of the air and its flow around an airfoil:

   1) Based on Bernoulli's Equation, we can consider that air particles with various velocities are at various pressures. Each particle applies a force on the blade that pushes or pulls it in some direction. The overall sum of all the forces on the blade is in the upwards-downstream direction, and the vertical component of the resultant force is the lift force.[15]

   2) Based on Newton's Third Law, we can consider that the change in the velocity of the air particles means that a force was applied to the air particles by the blade. The overall force on all the air particles is in a downwards-downstream direction, as evidenced by the downwash being more pronounced than the upwash, resulting in a reaction force applied to the blade by the air in the upwards-downstream direction (perpendicular to the overall force). The vertical component of this reaction force is the lift force.[16]

9. The rotational velocity of the turbine shaft can be increased by gearing up with a gearbox and a second shaft. In the gearbox, a large gear (with many teeth) meshes with a small gear (with few teeth). For each rotation of the large gear, the small gear rotates several times. The small gear is attached to one end of the second shaft and the other end of the shaft powers the electric generator.

10. The mechanism of the electric generator is discussed in Lesson 6.

[14] Layton, J. (n.d) 'Modern Wind-Power Technology', *How Wind Power Works*. Available at http://science.howstuffworks.com/wind-power2.htm. Accessed 12 November 2007.

[15] Brain, M. and Adkins, B. (n.d.) 'How Airplanes Work', *Howstuffworks*. Available at http://travel.howstuffworks.com/airplane.htm. Accessed 10 January 2008; Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight,* av8n.com, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Bernoulli and Newton* at http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Lift from Pressure-Area* at http://www.grc.nasa.gov/WWW/K-12/airplane/right1.html. Accessed 10 January 2008; Nave, C.R. (2005) 'Bernoulli or Newton's Laws for Lift?', *HyperPhysics*. Available at http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/airfoil.html. Accessed 10 January 2008.

[16] Anderson, D. and Eberhardt, S. (2001) *Understanding Flight*, McGraw-Hill (see 'A Physical Description of Flight'). Available at http://home.comcast.net/~clipper-108/lift.htm. Accessed 14 January 2008; Craig, G.M. (2007) *Physical Principles of Winged Flight*, Regenerative Press, IN. Available at http://www.regenpress.com/. Accessed 14 January 2008; See National Aeronautics and Space Administration – *Bernoulli and Newton* at http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html. Accessed 10 January 2008; Nave, C.R. (2005) 'Bernoulli or Newton's Laws for Lift?', *HyperPhysics*. Available at http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/airfoil.html. Accessed 10 January 2008.

Brief Background Information

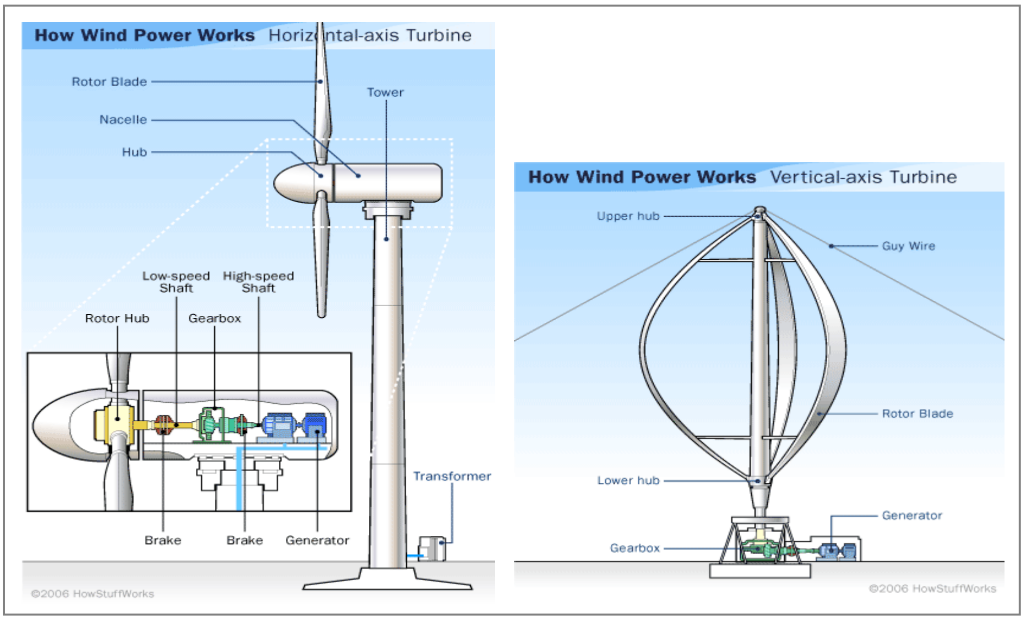
Background Context: Wind

Wind is caused by the Earth's rotation and the sun's heat energy. About 2 percent of the sun's heat energy is converted to wind[17] in the following process: Firstly, the sun's heat energy is absorbed by the land. Next, the land radiates that heat energy into the atmosphere where it is absorbed by nearby air. Finally, the hotter air rises while cooler air sinks. This air movement is wind. The wind's speed changes when it has to flow over and around undulations (bumps) on the Earth's surface.

> ***Fundamentals***
>
> The *volume* of a gas in an open space varies with *temperature* (the *pressure* remains the same):
>
> - volume $\propto$ temperature
>
> The heat energy is absorbed by the gas particles, which then become more active and thus can travel a larger *distance*.
>
> The larger distance between individual gas particles (with the same total amount of particles) makes the gas less *dense*. Less-dense objects float above more-dense objects.

Main Types of Wind Turbines

The two main types of wind turbines used to capture energy from the wind and convert it to electricity are the *vertical-axis* wind turbine and the *horizontal-axis* wind turbine. Both could be used at small or large scale and can use two or three blades as shown in Figure 5.8 below. Small-scale wind turbines used to power individual homes or telecommunications dishes provide less than 100 kilowatts of power while large- or utility-scale turbines provide between 100 kilowatts and several megawatts of power.[18] Several large-turbines can be grouped together to form a *wind farm*. The turbines are compared in Table 5.1.



(a) (b)

Figure 5.8. (a) Horizontal-Axis Turbine; and a (b) Vertical-Axis Turbine
Source: Layton, J. (n.d)[19]

[17] See HiEnergy Technology – *Wind Energy* at http://www.hi-energy.com.tw/selection-2-english.htm. Accessed 10 January 2008.
[18] See US Department of Energy – *How Wind Turbines Work* at http://www1.eere.energy.gov/windandhydro/wind_how.html. Accessed 12 November 2007.
[19] Layton, J. (n.d) 'How Wind Power Works', *Howstuffworks*. Available at http://science.howstuffworks.com/wind-power.htm. Accessed 12 November 2007.

Table 5.1: Comparison of horizontal-axis wind turbines and vertical-axis wind turbines

Horizontal-axis wind turbines	Vertical-axis wind turbines
Common, small-scale and large-scale	Rare, small-scale
Shaft is mounted horizontally, parallel to ground	Shaft is mounted vertically, perpendicular to ground
Constantly moving to align with the wind, by moving the rotor to capture the wind energy	Always aligned with the wind so no adjustment necessary when wind direction changes
Blades start spinning without assistance	Blades start spinning with assistance from an electrical starter motor
Tower support	Guy wires support
Optimum elevation and high wind speed: optimum efficiency	Low elevation and low wind speed: low efficiency
Components elevated: small footprint, difficult installation and servicing	Components at ground level: large footprint, easy installation and servicing

Source: Layton, J. (n.d)[20]

As the table shows, vertical-axis wind turbines have a number of features that make them less attractive for use. The horizontal wind turbines are usually mounted on a tower at a height of 30 metres or more above ground, where wind moves faster and straighter because it doesn't need to flow over and around bumps on the Earth's surface.

Optimising Wind Turbine Performance

The amount of wind energy a wind turbine and electric generator can convert to electrical power depends on three main factors:[21]

1. *Wind speed*: where Power is proportional to the cube of wind speed (i.e. wind speed^3). Wind speed is estimated to increase by about 12 percent with each time the turbine's height, or *elevation*, is doubled.
2. *Blade length*: where Power is proportional to the blade's *swept area*, and the blade's swept area is in turn proportional to the square of the blade length (i.e. blade length^2).
3. *Efficiency*: maximum theoretical efficiency is 59 percent. The most efficient wind turbines and electric generators have combined efficiencies of about 53 percent.

Inefficiencies in wind turbine operation arise mainly from the components' *inertia* and the components' internal *friction*. These inefficiencies prevent the blades from turning in wind slower than a certain speed, called the *cut*

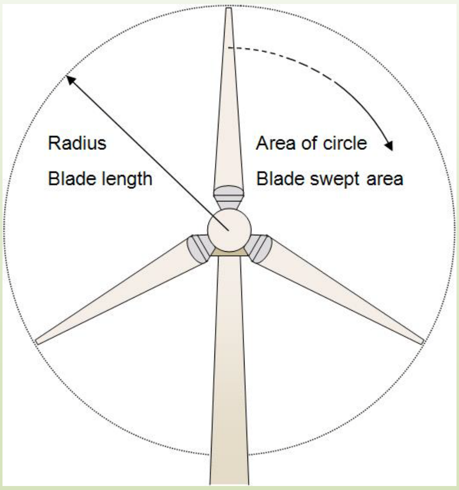
Fundamentals

The blade swept area is the total circular area covered by the turbine blades as they rotate:

Area of circle = Π x radius^2

∴ Swept area = Π x blade length^2

∴ Swept area $\propto$ blade length^2



[20] Layton, J. (n.d) *How Wind Power Works*, Howstuffworks. Available at http://science.howstuffworks.com/wind-power.htm. Accessed 12 November 2007.
[21] Layton, J. (n.d) 'How Wind Power Works', *Howstuffworks*. Available at http://science.howstuffworks.com/wind-power2.htm. Accessed 12 November 2007.

in speed, which is usually about 3-4 metres per second. In addition, the wind turbine's structural integrity prevents the blades from turning in wind faster than a certain speed, called the *cut out speed*.

> ***Fundamentals***
>
> An object's *inertia* causes it to resist a change in *velocity* (magnitude or direction). Depending on the type of motion, inertia is a measure of:
>
> - linear motion: *mass*
> - rotating objects: mass *distribution* around the *centre of rotation*

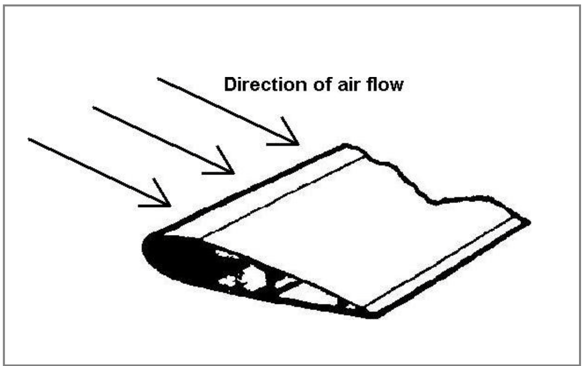
> ***Fundamentals***
>
> *Friction* is a force that resists motion by two objects in contact. Friction depends on surface *roughness*, *contact area* and the force with which the two objects are held together.

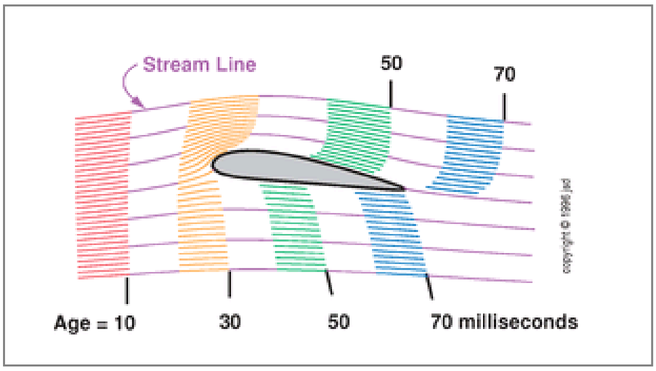
Main Components of Wind Turbines

The three main components of a wind turbine are the turbine blades, the gearbox, and the electric generator. We will now consider the first two components in more detail. Electric generators are discussed in the following lesson (Lesson 2).

1. Turbine Blades and Mechanical Rotation (How Wind Moves the Blades)

Wind turbines convert wind to mechanical rotation, so let us consider what mechanical rotation means. A turbine blade's cross section has a tilted, airfoil shape, which is the same shape used for aircraft wings and propellers as shown in Figure 5.9 (a). Air behaves differently as it flows around a blade with an airfoil shape – air travelling above the blade increases in velocity while air travelling below the blade decreases in velocity as shown in Figure 5.9 (b) – the very closely-spaced lines show that air particles that were originally aligned (red) become misaligned as they move around the blade (green, blue) due to the change in their velocities.[22]





(a) (b)

Figure 5.9. (a) Airfoil cross section of a blade[23]; (b) tilted airfoil in air flow with 'smoke' pulses

Source: (a) Adapted from US Department of the Army (1991)[24]; (b) Denker, J.S. (2005)[25]

[22] Craig, G.M. (2007) *Physical Principles of Winged Flight,* Regenerative Press, IN. Available at http://www.regenpress.com/. Accessed 14 January 2008; Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight,* AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Lift from Flow Turning* at http://www.grc.nasa.gov/WWW/K-12/airplane/right2.html. Accessed 10 January 2008.

[23] This image shows the cross section of a helicopter blade, which is similar to that of a wind turbine blade.

This behaviour is known as *turning*, or *circulation*, because the effect is similar to a turn being applied to the air, as shown in Figure 5.10. The process by which *turning* is generated is quite complicated – see Craig, G.M. (2007)[26] for a description.

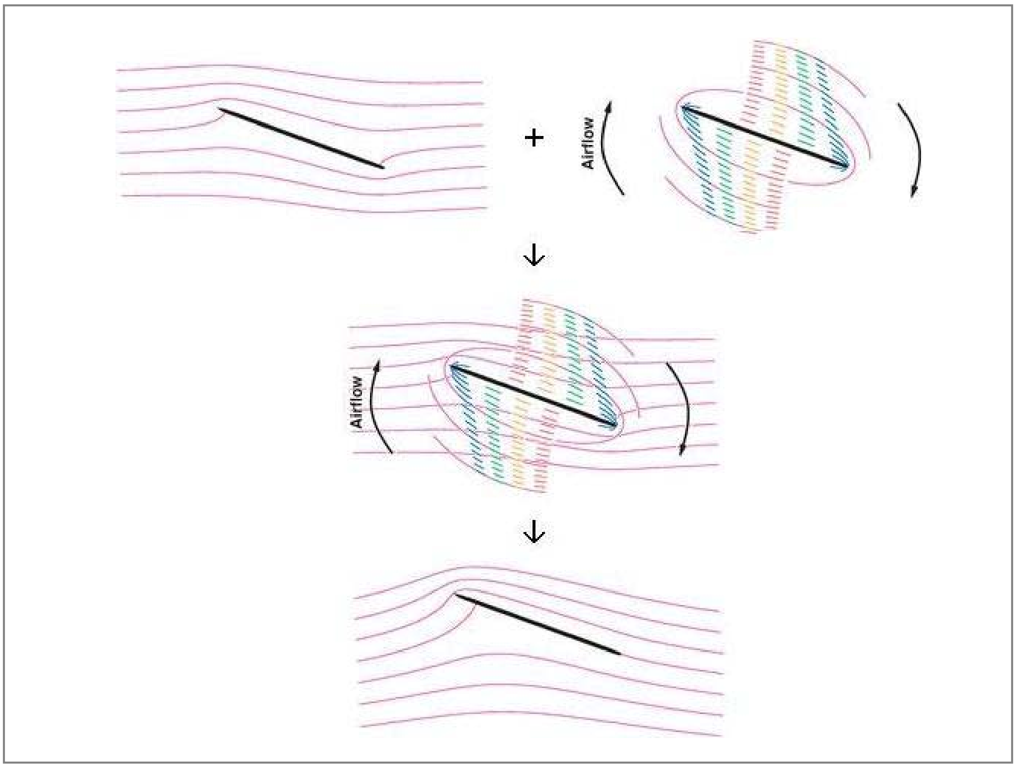


Figure 5.10. Turning of moving air around a blade

Source: Adapted from Denker, J.S. (2005)[27]

So, turning of the air ultimately applies a force on the blade. Although the maths is well understood, the way in which that force is applied is in debate. There are two sides to the debate, which are based on the interesting features of the air and its flow around an airfoil:

Fundamentals

If the air *velocity* is low (and no *energy* is added), *pressure* along a *streamline* varies with velocity:

- linear velocity $\propto$ 1/pressure

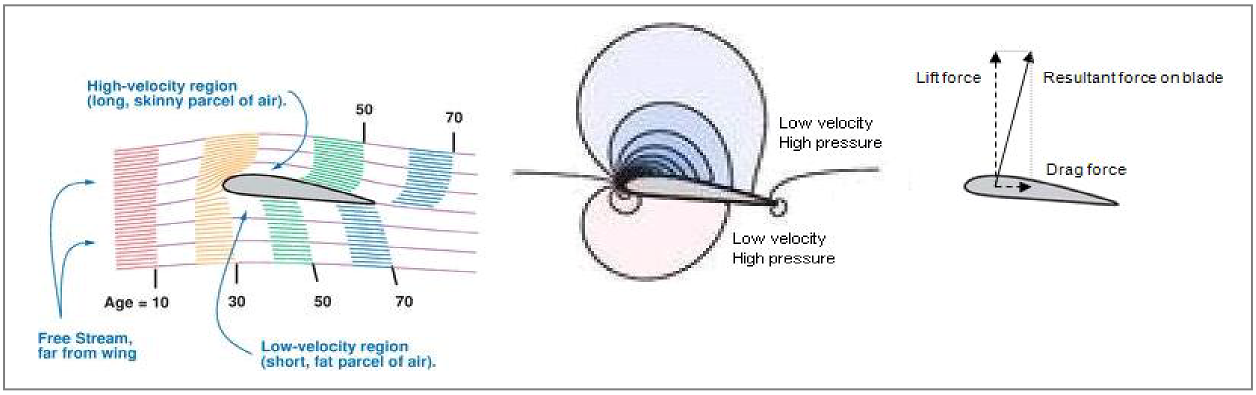
[24] US Department of the Army (1991) *FM 1-514: Fundamentals of Rotor and Power Train Maintenance – Techniques and Procedures,* Cavalry Pilot., Chapter 3: Rotor System Operation. Available at http://www.cavalrypilot.com/fm1-514/Ch3.htm. Accessed 14 January 2008.

[25] Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight,* AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008.

[26] Craig, G.M. (2007) *Physical Principles of Winged Flight*, Regenerative Press, IN. Available at http://www.regenpress.com/. Accessed 14 January 2008.

[27] Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight*, AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008.

Bernoulli's Equation: One side of the debate is based on *Bernoulli's Equation*[28] and argues that air particles with various velocities are at various pressures. The pressure of each particle applies a force on the blade that pushes or pulls it in some direction, as shown in Figure 5.11 (a) and Figure 5.11 (b), where the airflow on the underside pushes the blade up and the airflow on the top-side pull on the blade. The overall sum of all the forces on the blade (the *resultant force*) is in the upwards-downstream direction; and the vertical component of the resultant force is the *lift force*, as shown in Figure 5.11 (c).



(a) (b) (c)

Figure 5.11. Generating a lift force on an airfoil force based on Bernoulli's Equation

Source: Adapted from Denker, J.S. (2005)[29]

Note that there are also two popular but inaccurate theories based on Bernoulli's Equation:

- **Inaccurate theory #1:** *Longer Path* or *Equal Transit* Theory:[30] the air velocity increases above the airfoil so that it can re-merge with the air below the airfoil at the trailing edge. The difference in velocities above and below the airfoil creates a difference in pressures and hence a lift force. (See references for what is accurate and inaccurate about this theory.)
- **Inaccurate theory #2:** *Venturi* Theory:[31] the top of the airfoil acts like a *nozzle*, causing the air velocity to increase above the airfoil. The increased air velocity above the airfoil creates decreased pressure and hence a lift force. (See references for what is accurate and inaccurate about this theory.)

Newton's Third Law: The other side of the debate is based on *Newton's Third Law*[32] and argues that the change in the velocity of the air particles means that a force was applied to the air particles by the blade.

[28] Brain, M. and Adkins, B. (n.d.) 'How Airplanes Work', *Howstuffworks*. Available at http://travel.howstuffworks.com/airplane.htm. Accessed 10 January 2008; Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight*, AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Bernoulli and Newton* at http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Lift from Pressure-Area* at http://www.grc.nasa.gov/WWW/K-12/airplane/right1.html. Accessed 10 January 2008; Nave, C.R. (2005) 'Bernoulli or Newton's Laws for Lift?', *HyperPhysics*. Available at http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/airfoil.html. Accessed10 January 2008.

[29] Denker, J.S. (2005) 'Chapter 3: Airfoils and Airflows' in *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight*. Available at http://www.av8n.com/how/. Accessed 10 January 2008.

[30] Brain, M. and Adkins, B. (n.d.) *How Airplanes Work,* Howstuffworks. Available at http://travel.howstuffworks.com/airplane.htm. Accessed 10 January 2008; See National Aeronautics and Space Administration – 'Incorrect Theory #1' in *Into the Wind*. Available at http://www.grc.nasa.gov/WWW/K-12/airplane/wrong1.html. Accessed 10 January 2008.

[31] See National Aeronautics and Space Administration – 'Incorrect Theory #3' in *Into the Wind*. Available at http://www.grc.nasa.gov/WWW/K-12/airplane/wrong3.html. Accessed 10 January 2008.

[32] Anderson, D. and Eberhardt, S. (2001) 'A Physical Description of Flight' in *Understanding Flight*, McGraw-Hill. Available at http://home.comcast.net/~clipper-108/lift.htm. Accessed 14 January 2008; Craig, G.M. (2007) *Physical Principles of Winged Flight*.

Fundamentals

Force = mass x acceleration

$$= \text{mass} \times \frac{\text{change in velocity}}{\text{change in time}}$$

∴ Force ∝ change in velocity

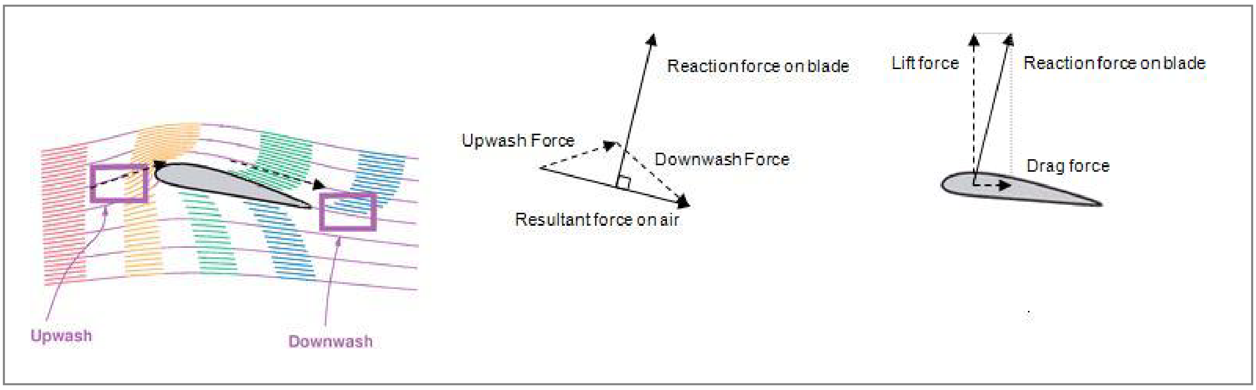
Fundamentals

When object A applies a *force* on object B, object B applies a *reaction force* on object A that is equal in magnitude and opposite in direction.

The overall force on all the air particles is in a downwards-downstream direction, as evidenced by the *downwash* being more pronounced than the *upwash,* shown in Figure 5.12 (a) and Figure 5.12 (b). Thus a *reaction force* will be applied to the blade by the air in the upwards-downstream direction (perpendicular to the overall force on all the air particles). The vertical component of this reaction force is the *lift force* as shown in Figure 5.12 (c).

Note that there is also a popular but inaccurate theory that is based on Newton's Third Law:

- **Inaccurate theory #1:** *Skipping Stone* or *Bullet* Theory:[33] the air particles strike the bottom of the airfoil, creating a *reaction force* that is the lift force. (See references for what is accurate and inaccurate about this theory.)



(a) (b) (c)

Figure 5.12. Generating a lift force on an airfoil force based on Newton's Third Law

Source: Adapted from Denker, J.S. (2005)[34]

As shown in Figure 5.12, turbine blades experience resistance in the form of a *drag force* in the same direction as the wind – the result of air resistance. Efficient turbine blades are designed to produce much higher lift force than drag force. Lift forces cause the blades to move in a straight line, perpendicular to their length. However, since the blades are attached to the turbine shaft, the blades cannot fly off and thus are restricted to a rotation movement.

Available at http://www.regenpress.com/. Accessed 14 January 2008; See National Aeronautics and Space Administration – 'Bernoulli and Newton' in *Into the Wind*. Available at http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html. Accessed 10 January 2008; Nave, C.R. (2005) *Bernoulli or Newton's Laws for Lift?*, HyperPhysics. Available at http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/airfoil.html. Accessed 10 January 2008.

[33] Brain, M. and Adkins, B. (n.d.) 'How Airplanes Work', *Howstuffworks*. Available at http://travel.howstuffworks.com/airplane.htm. Accessed 10 January 2008; See National Aeronautics and Space Administration – *Incorrect Theory #2* at http://www.grc.nasa.gov/WWW/K-12/airplane/wrong2.html. Accessed 10 January 2008.

[34] Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight,* AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008.

2. Gearing Up the Gearbox

The rotating blades cause the turbine shaft in the wind turbine to rotate with a rotational velocity of about 10-60 revolutions per minute, however, the electric generator requires a rotational velocity of about 1200-1800 revolutions per minute.[35] The rotational velocity is increased by *gearing up* with a *gearbox* and a second shaft in the following process:

- In the gearbox, a large *gear* (with many *teeth*) is attached to the end of the turbine shaft. This large gear meshes with a small gear (with few teeth) as shown in Figure 5.13.
- As the large gear rotates, the small gear is forced to rotate, but at a higher rotational velocity – for each rotation of the large gear, the small gear rotates several times.
- The small gear is attached to one end of the second shaft and the other end of the shaft powers the electric generator.

For a more detailed explanation of the wind turbine components, see US Department of Energy,[36] Layton, J. (n.d),[37] Research Institute for Sustainable Energy (2006),[38] and the US Department of Energy[39] (animation).

Figure 5.13. A large gear and a small gear meshing

Source: Nice, K.[40]

35 See US Department of Energy –*Wind Power Animation* at http://www.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=10501. Accessed 12 November 2007.
36 See US Department of Energy – *How Wind Turbines Work* at http://www1.eere.energy.gov/windandhydro/wind_how.html. Accessed 12 November 2007.
37 Layton, J. (n.d) 'How Wind Power Works', *Howstuffworks*. Available at http://science.howstuffworks.com/wind-power.htm. Accessed 12 November 2007.
38 Research Institute for Sustainable Energy (2006) *Wind Electric*, Murdoch University. Available at http://www.rise.org.au/info/Tech/wind/electric.html. Accessed 14 November 2007.
39 See US Department of Energy –*Wind Power Animation* at http://www.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=10501. Accessed 12 November 2007.
40 Nice, K. (n.d.) 'How Gears Work', *Howstuffworks*. Available at http://science.howstuffworks.com/gear2.htm. Accessed 10 January 2008.

Key References (Alphabetical Order)

1. US Department of Energy website – *How Wind Turbines Work* at http://www1.eere.energy.gov/windandhydro/wind_how.html. Accessed 12 November 2007.
2. Research Institute for Sustainable Energy (2006) *Wind Electric*, Murdoch University. Available at http://www.rise.org.au/info/Tech/wind/electric.html. Accessed 14 November 2007.
3. Layton, J. (n.d) 'How Wind Power Works', *Howstuffworks*. Available at http://science.howstuffworks.com/wind-power.htm. Accessed 12 November 2007.
4. National Aeronautics and Space Administration website – *Into the Wind* (Follow the 'Theories of Lift' trail). Available at http://www.grc.nasa.gov/WWW/K-12/airplane/guided.htm. Accessed 10 January 2008.
5. Nave, C.R. (2005) 'Bernoulli or Newton's Laws for Lift?', *HyperPhysics*. Available at http://hyperphysics.phy-astr.gsu.edu/hbase/fluids/airfoil.html. Accessed 10 January 2008.
6. Denker, J.S. (2005) *See How it Flies – A New Spin on the Perceptions, Procedures, and Principles of Flight,* AV8N, Chapter 3: Airfoils and Airflows. Available at http://www.av8n.com/how/. Accessed 10 January 2008.
7. Anderson, D. and Eberhardt, S. (2001) *Understanding Flight*, McGraw-Hill (see 'A Physical Description of Flight'). Available at http://home.comcast.net/~clipper-108/lift.htm. Accessed 14 January 2008.
8. Craig, G.M. (2007) *Physical Principles of Winged Flight,* Regenerative Press, IN. Available at http://www.regenpress.com/. Accessed 14 January 2008.
9. Brain, M. and Adkins, B. (n.d.) 'How Airplanes Work', *HowStuffWorks*. Available at http://travel.howstuffworks.com/airplane.htm. Accessed 10 January 2008.