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# Renewable Energies Laboratory



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## Renewable Energy Lab

### Experiment No. 1 Photovoltaic Characteristics

#### Background

The I-V curve (Figure 1) represents all of the possible operating points (current and voltage) of a PV module or string of modules at the existing conditions of sunlight (irradiance) and temperature. The curve starts at the short circuit current and ends at the open circuit voltage. The maximum power point, located at the knee of the I-V curve, is the operating point that delivers the highest output power. It is the job of the inverter to find and operate at that point on the I-V curve, and to adapt as the curve changes with irradiance and temperature. The P-V curve (power versus voltage) reads zero at the ends and a maximum at the knee of the I-V curve.

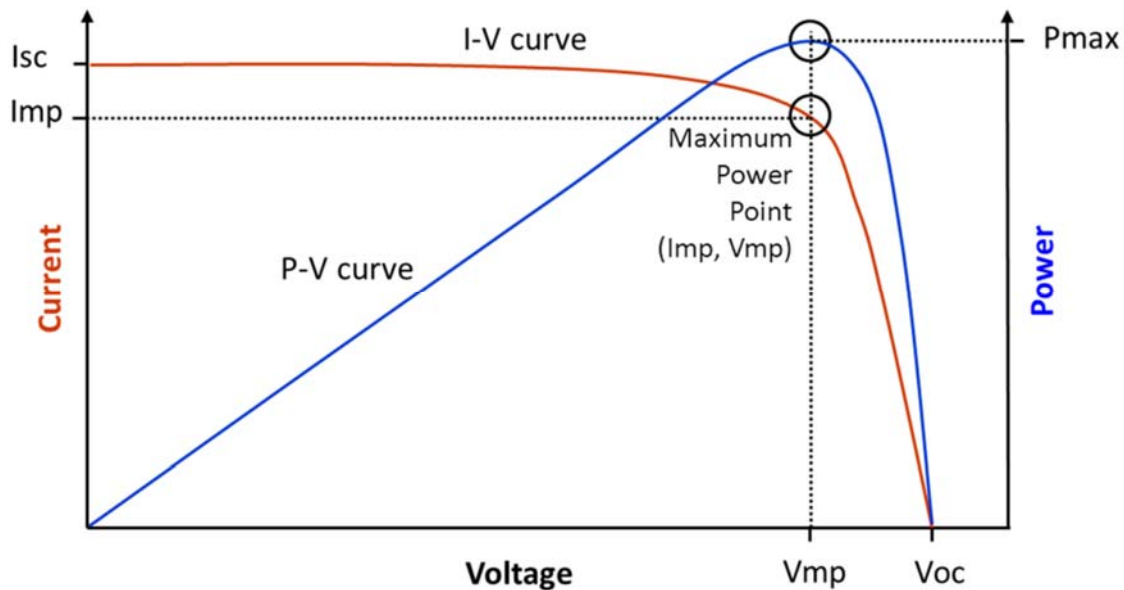


Figure 1 I-V and P-V curves for a PV module or string

## Experiment

Connect the terminals of the PV panel with a load, pure resistance load, and change the load from minimum to the maximum in steps. In each step record the voltage and the current.

## Report

1. Record time and date of the day of experiment.
2. Measure azimuth, altitude, and GPS coordinates of the site of PV panels.
3. From your recorded measurements of voltage and current, draw the I-V curve.
4. Repeat step 2 to draw the P-V curve.
5. Count the number of cells in the PV panel.
6. From step 3, find the no-load voltage for each cells and how they are connected to provide the total no-load voltage of the PV panel.
7. State your conclusion of the above steps and your experiment.

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## Renewable Energy Lab

### Experiment No. 2 Optimum Orientation of Solar Panel

#### Overview

This experiment requires clear skies for the time the experiment is conducted. Clouds that block the sun significantly change the incident solar radiation and this will affect the experiment result. The idea is to have the panel oriented towards the sun while it is tilted upwards, as shown in Figure 1, at degree, let say  $20^\circ$ , intervals while the current and voltage are monitored and recorded. The result should show that the optimum tilt is when the panel is nearest to perpendicular to the incident sunlight.

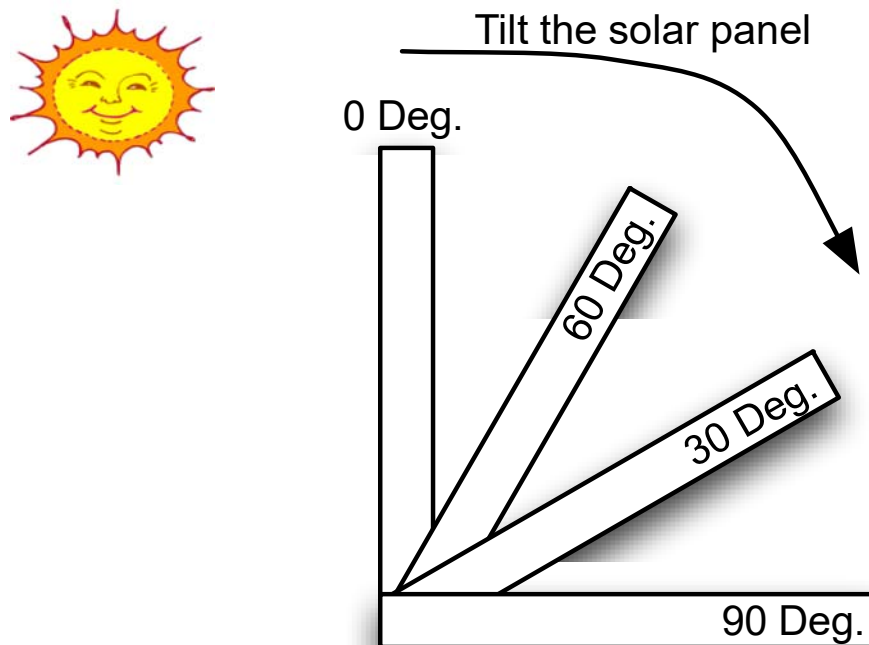


Figure 1 Tilt angles of solar (PV) panel

## Experiment

In this experiment you need to tilt the PV panel between 0 to 90 degrees. Note that this is a manual process and needs a bit of patience!

1. Connect the terminals of the PV panel with a load, pure resistance load
2. Make sure that the panel is well secured and it does not fall
3. Tilt the panel manually and change the load from minimum to the maximum in steps. In each step record the voltage and the current. **DONOT SHORT CIRCUIT OF THE PV TERMINALS!**
4. Repeat step 3 until you passed all degrees between 0 and 90 in steps of 20°.
5. Secure the panel at its original tilt before your test.

## Report

8. For each tilt degree, draw the I-V curve.
9. On the I-V curves, point the maximum power of the PV. What is the tilt degree that gives maximum solar power?
10. Briefly, explain what happens as you tilt the panel. Why PV panels installed on the roofs of buildings are slightly titled?
11. The angle at which sunlight strikes the Earth varies by location, time of day, and season due to the Earth's orbit around the sun and the Earth's rotation around its tilted axis. How does this impact the way we install PV panels?

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## Renewable Energy Lab

### Experiment No. 3

#### Effect of Cell(s) Shading on PV Panel Efficiency

##### Overview

In PV modules designed for grid-tie applications, the individual cells are typically all connected in series. The amount of current a PV cell can generate (or pass along from other cells) depends directly on the amount of light power (irradiance) hitting the cell. This means that shading of even just one PV cell can create an electrical bottleneck that hurts the performance of the entire chain. This situation can also lead to extreme heating of the shaded cell.

To protect individual cells from overheating under partially shaded conditions, and to keep the rest of the array producing energy, modules are equipped with bypass diodes, which are typically mounted inside the junction boxes on the back of the modules. Each bypass diode is connected across a different sub-string of PV cells within the module. In a typical 72 cell module, there are usually 3 bypass diode, as shown in Fig. 1. When shade falls on a PV cell, the bypass diode that spans that particular group of cells turns on, shunting current around the shaded cells.

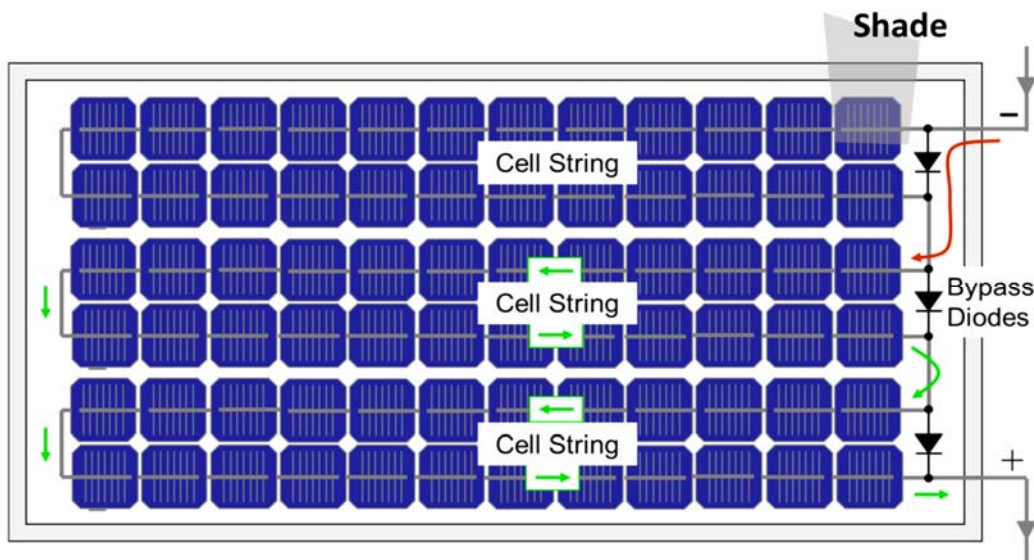


Fig. 1 The path of current in a 72-cell, 3 cell string, grid tie PV module

This reduces heating of the shaded cell and keeps the rest of the cells producing energy. Because shading of a single cell causes its cell string's bypass diode to switch off the entire group of cells, PV modules are very sensitive to shade, and the response to the shade is less predictable than in the case of solar thermal collectors (where the collector energy drops in direct proportion to the amount of surface that is shaded).

## Experiment

In this experiment you need to shade the PV panel manually using a piece of dark paper(s) that fit one and two cells.

6. Before starting this test, make sure that the sky, in the site of PV panel, is the same till finishing the test.
7. Connect the terminals of the PV panel with a load, pure resistance load.
8. Without shading any cell, let the PV panel full loaded by adjusting the load.
9. Record voltage and current in no shading condition. Shade one cell, first cell of the top-right-side of PV panel (Fig. 1).
10. Shade two adjacent cells, two cells of the top-right-side of PV panel (Fig. 1). Without changing the load, record PV panel voltage and current.
11. Shade two cells, two cells under each other of the first column of the top-left-side of PV panel (Fig. 1). Without changing the load, record PV panel voltage and current.

## Report

12. Compute generated power for steps 4, 5, and 6 respectively.
13. Compare the power losses between step 3 and steps 4, 5, and 6. Which case is the worse?
14. Write down your conclusion about the affection of the shaded cell(s) on the PV panel efficiency.
15. What is the difference between shaded cells and cloudy sky?

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## Renewable Energy Lab

### Experiment No. 4

#### Cut-In and Cut-Off Wind Speeds of the Wind Energy Conversion System

##### Overview

The main components of a WECS are the rotor, the transmission system and the power generator unit. Figure 4.1 outlines a horizontal-axis wind turbine. The rotor comprises the blades where the aerodynamic conversion takes place, the hub that links the blades to the transmission and the pitch servos, which are placed inside the hub, that rotate the blades around their longitudinal axes.

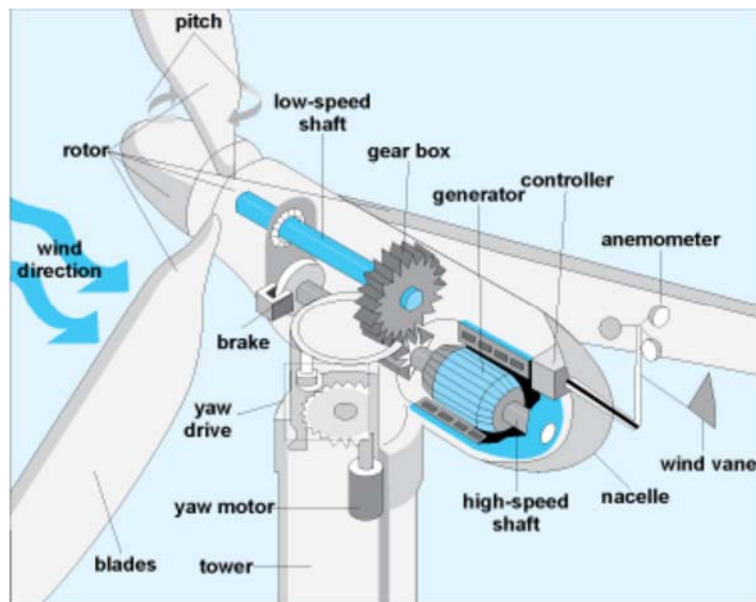


Figure 4.1 WECS with horizontal-axis wind turbine

The transmission system transmits the mechanical power captured by the rotor to the electric machine. It comprises the low- and high-speed shafts, the gearbox and the brakes. The gearbox increases the rotor speed to values more suitable for driving the generator, typically from 20-50 rpm to 1000-1500 rpm. The electric generator is the device that

converts mechanical power into electricity. Its electric terminals are connected to the utility network. In the case of variable speed WECS, an electronic converter is used as interface between the AC grid and the stator or rotor windings.

## Measuring Wind Direction and Wind Speed

The characteristics of the wind energy resource are important in different aspects regarding wind energy exploitation. The first step in every wind energy project is the identification of suitable sites and prediction of the economic viability of the wind project. The energy available in the wind varies as the cube of wind speed. Wind is highly variable, both in space and in time. The importance of this variability becomes critical since it is amplified by the cubic relation of the available energy.

The direction of wind, in degree, is measured using wind vanes aligning themselves, under wind pressure, to the prospective direction of the wind. The result can be transferred mechanically or electronically to a registration instrument. Instrument that measure the wind speed (anemometers), meter per second, are distinguished as either measuring the instantaneous or the mean value. It is generally accepted that measurements are based on readings at 10 meters above ground and the distance between the anemometer and any obstruction is at least ten times the height of the obstruction. Both wind vane and anemometer of the wind turbine are depicted in Figure 4.2



Figure 4.2 Wind vane and anemometer

## **WECS Operation Regions**

The uncertain, unstable, and uncontrollable nature of wind energy makes the fluctuations in the generated power of the wind power system. In general, according to the wind speed, the following regions can be classified for wind power systems:

1. **No power generation region**  
No power generation occurs when wind speed is either very low or very high. At very low wind speeds, usually less than 4 meter per second, there will be insufficient torque exerted by the wind on the turbine blades to make them rotate and therefore no power will be generated. As wind speed increases, the force on the turbine structure will continue to rise and, at some point, there is a risk of damage to the rotor and other mechanical parts of the wind power systems. As a result, a braking system is employed to bring the rotor to a standstill and no power will be generated. This is called a cut-off speed and usually occurs when wind speed is above 25 meter per second.
2. **Variable power generation region**  
The wind turbine starts to rotate and generate power at wind speed which of around 4 meter per second. This is known as a cut-in speed. The generated power continuously rises with the increase of wind speed until the wind speed reaches the rated wind speed which is around 12-14 meter per second where the turbine generates constant power.
3. **Constant power generation region**  
For the range of wind speed between rated wind speed and cut-off speed, the design of the wind turbine is arranged to limit the power to the maximum possibility of capturing wind energy, which is referred to as the rated power output, and there is no further increase in the output power. This is done by adjusting the blade pitch angles to keep the rotor wind speed generating a constant power regardless of wind speeds as long as they are between rated and cut-off wind speed.

The above regions are shown in Figure 4.3. However, the figure shows the large range for the wind speeds which provide the rated turbine power in comparison to the variable region, but in reality, the wind speed varied between all regions and especially between cut-in and rated wind speeds. Therefore, intermittences and fluctuations of the generated electrical power are related to the wind power systems. They become a behavior of these systems and cannot be avoided.

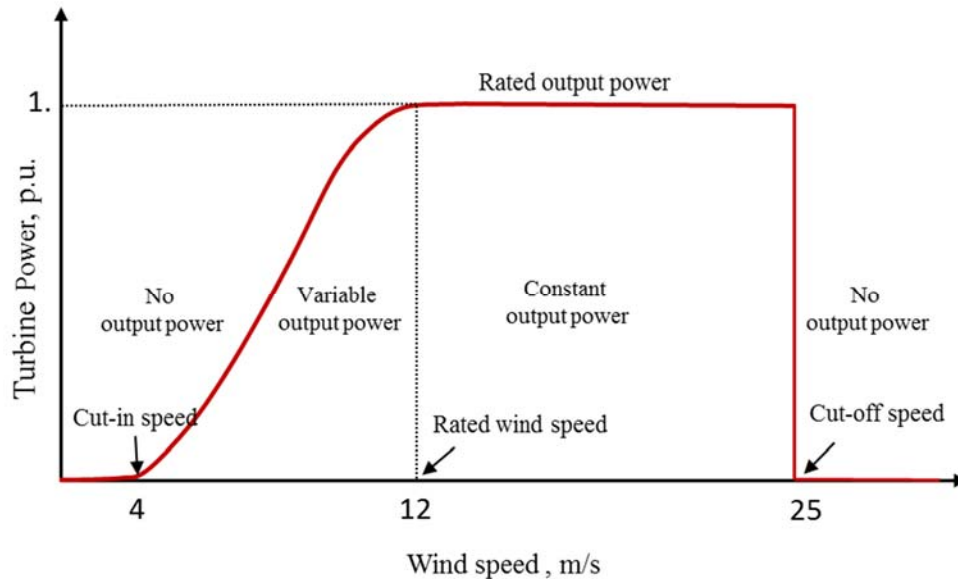


Figure 4.3 Typical wind turbine output power with wind speed

## Experiment

This is a simulation based experiment. No wiring, no hardware, no components, and no real measurement devices are used in this experiment. Matlab Simulink<sup>®</sup> is used. Matlab skill is required to perform this test. No coding and no designing are required. A complete WECS simulation package is already provided in the lab which can be loaded to Matlab environment as needed.

The objective of this test is to find the cut-in and cut-off speed of the WECS. Follow the Lab instructor advice and the following instruction to perform this test as follows:

12. With the help of the lab advisor, start computer and locate MATLAB and run it.
13. In MATLAB, locate and run the designated simulation file, startup\_Wind\_Turbine.m
14. Test the simulation, Wind\_Turbine.slx, before changing anything to make sure that the simulation works without problems.
15. On the main simulation page, locate block named Wind. Inside this block there are two blocks Wind Speed and Wind Direction.
16. Assume no direction changes, Set all Amplitude values to zero.
17. In Wind Speed block, insert a different set values for Amplitude which represents wind speed in m/s. Note, use only one decimal points as a wind speed, such as 1, 1.5, 2, 2.5, etc.
18. Run the simulation and observe at which time and win speed the wind turbine starts.
19. Repeat steps 6 and 7 if necessary until you find the exact starting wind speed, cut-in.

20. Repeat steps 6 and 7 for another set wind speed values that make the turbine to stop, cut-off.

## Report

16. Based on your record, fill-out the following table.

Cut-in m/s	Cur-off m/s

17. To your knowledge, wind speed is higher or lower as measured on higher altitude of a surface? Why?

18. To your knowledge, wind power is stronger or weaker as the temperature decreases?

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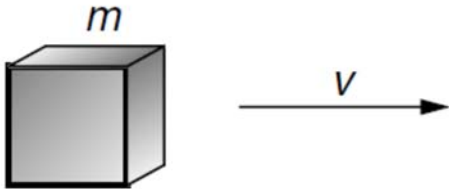
## Renewable Energy Lab

### Experiment No. 5

#### Power Generation of the Wind Energy Conversion System

##### Power in the Wind

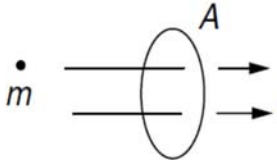
Consider a “packet” of air with mass  $m$  moving at a speed  $v$ . Its kinetic energy (K.E.) is given by the familiar relationship:



A 3D cube is shown with the letter  $m$  above it. To its right, a horizontal arrow points to the right with the letter  $v$  above it.

$$\text{K.E.} = \frac{1}{2}mv^2 \quad 1.1$$

Since power is energy per unit time, the power represented by a mass of air moving at velocity  $v$  through area  $A$  will be



A diagram shows two horizontal arrows pointing to the right. The left arrow is labeled  $\dot{m}$ . The right arrow is labeled  $v$ . A vertical oval is drawn between the two arrows, with the letter  $A$  above it.

$$\text{Power through area } A = \frac{\text{Energy}}{\text{Time}} = \frac{1}{2} \left( \frac{\text{Mass}}{\text{Time}} \right) v^2 \quad 1.2$$

The mass flow rate  $\dot{m}$ , through area  $A$ , is the product of air density  $\rho$ , speed  $v$ , and cross-sectional area  $A$ :

$$\left( \frac{\text{Mass passing through } A}{\text{Time}} \right) = \dot{m} = \rho Av \quad 1.3$$

Combining (1.3) with (1.2) gives us an important relationship:

$$P_w = \frac{1}{2} \rho A v^3$$

1.4

In S.I. units;  $P_w$  is the power in the wind (watts);  $\rho$  is the air density ( $\text{kg/m}^3$ ) (at  $15^\circ\text{C}$ ,  $\rho = 1.225 \text{ kg/m}^3$ );  $A$  is the cross-sectional area through which the wind passes ( $\text{m}^2$ ); and  $v$  = wind speed normal to  $A$  ( $\text{m/s}$ ) (a useful conversion:  $1 \text{ m/s} = 2.237 \text{ mph}$  or  $3.6 \text{ km/h}$ ). The relation of wind power and wind speed is shown in Figure 1.1. Notice that the power shown there is per square meter of cross section, a quantity that is called the *specific power* or *power density*.

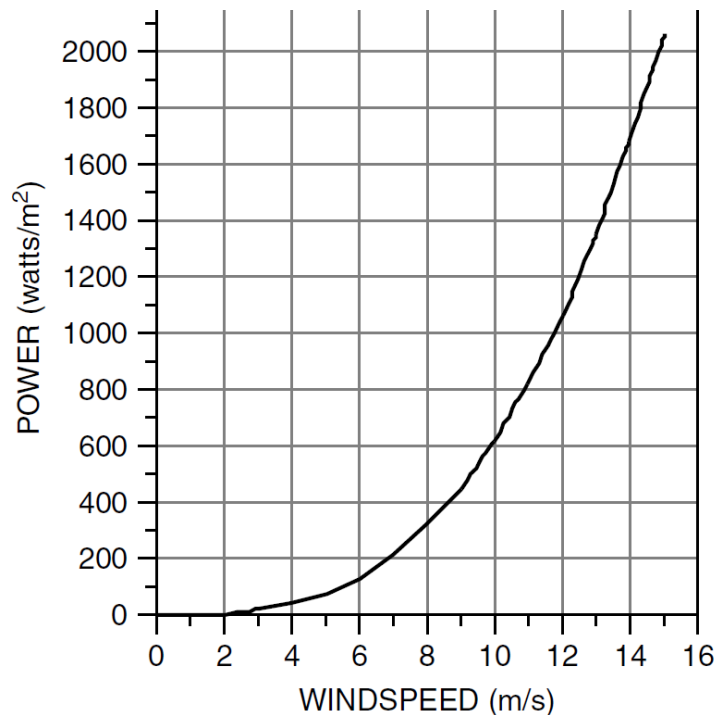


Figure 1.1 Power in the wind, per square meter of cross section, at  $15^\circ\text{C}$ .

Notice that the power in the wind increases as the *cube* of wind speed. This means, for example, that doubling the wind speed increases the power by eightfold. Another way to look at it is that the energy contained in 1 hour of  $32 \text{ km/h}$  winds is the same as that contained in 8 hours at  $16 \text{ km/h}$ , which is the same as that contained in 64 hours (more than  $2 \frac{1}{2}$  days) of  $8 \text{ km/h}$  wind.

Equation (1.4) also indicates that wind power is proportional to the swept area of the turbine rotor. For a conventional horizontal axis turbine, the area  $A$  is obviously just  $A = (\pi/4)D^2$ , so wind power is proportional to the square of the blade diameter. Doubling the diameter increases the power available by a factor of four. That simple observation helps explain the economies of scale that go with larger wind turbines. The cost of a turbine increases roughly in proportion to blade diameter, but power is proportional to diameter squared, so bigger machines have proven to be more cost effective.

## Maximum Wind Turbine Rotor Efficiency

Why can't the turbine extract all of the kinetic energy in the wind? If it did, the air would have to come to a complete stop behind the turbine, which, with nowhere to go, would prevent any more of the wind to pass through the rotor. The downwind velocity, therefore, cannot be zero. And, it makes no sense for the downwind velocity to be the same as the upwind speed since that would mean the turbine extracted no energy at all from the wind. That suggests that there must be some ideal slowing of the wind that will result in maximum power extracted by the turbine. Albert Betz, a German physicist, showed that an ideal wind turbine would slow the wind to one-third of its original speed. So the fundamental relationship for the power delivered by the rotor becomes

$$P_{turbine} = \frac{1}{2} \rho A v^3 C_p \quad 1.5$$

Theoretical maximum rotor efficiency  $C_p = 0.593$  or 59.3%, which is called Betz efficiency or Betz' Law.

## Experiment

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2. In MATLAB, locate and run the designated simulation file, startup\_Wind\_Turbine.m
3. Test the simulation, Wind\_Turbine.slx, before changing anything to make sure that the simulation works without problems.
4. On the main simulation page, locate block named Wind. Inside this block there are two blocks Wind Speed and Wind Direction.
5. Assume no direction changes, set all Amplitude values to zero.
6. In Wind Speed block, test the system for the following wind speeds: 5 m/s, 10 m/s, 15 m/s, and 20 m/s.
7. For each of wind speeds in step 6, record the generated output active power. To read generation data, locate Generator Scopes block, inside this block the scope Power is for presenting the generation active and reactive powers. (Note, wait for stable operation of the generator before recording your reads)



## Report

Assume the generator efficiency to be 90%, using equation 1.5, and from your data record, fill-out the following table:

Wind Speed m/s	Generator Output Active Power, MW	Turbine output Power, MW	Turbine Blade Length, m
5			
10			
15			
20			

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## Renewable Energy Lab

### Experiment No. 6

#### Relationship Between Power Coefficient, Blade Pitch Angle, and Tip Speed Ratio of the Wind Turbine

##### Introduction

The wind energy is in the form of kinetic energy. The perfect measurement of wind speed is important because of power dependence on the speed. The relation between the mechanical power  $P$  and the speed can be expressed as follows

$$P_m = \frac{1}{2} \rho A C_p(\lambda, \beta) v^3$$

where  $\rho$  is the air density,  $v$  is the wind speed,  $A$  is the swept area of the rotor,  $C_p$  is the performance coefficient of the turbine,  $\beta$  is the blade pitch angle, and  $\lambda$  is the tip speed ratio.

A wind energy converter is known for the characteristic tip speed ratio. The local speed ratio  $\lambda$  is the ratio of the rotor speed at radius  $R$  to the wind speed at  $v$ :

$$\lambda = \frac{\omega R}{v}$$

where  $\omega$  is the angular velocity of the rotor and  $R$  is the rotor radius.

The relationship between  $C_p$ ,  $\beta$ , and  $\lambda$  can be given by

$$C_p(\lambda, \beta) = c_1 \left[ \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right] e^{-c_5/\lambda_i} + c_6 \lambda$$

with

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

The coefficients  $c_1 - c_6$  are :  $c_1 = 0.5176$ ,  $c_2 = 116$ ,  $c_3 = 0.4$ ,  $c_4 = 5$ ,  $c_5 = 21$  and  $c_6 = 0.0068$ .

The  $C_p(\lambda, \beta)$  characteristics, for different values of the pitch angle  $\beta$ , are illustrated below. The maximum value of  $C_p$  ( $C_{pmax} = 0.48$ ) is achieved for  $\beta = 0$  degree and for  $\lambda = 8.1$ . This particular value of  $\lambda$  is defined as the nominal value of  $\lambda$ .

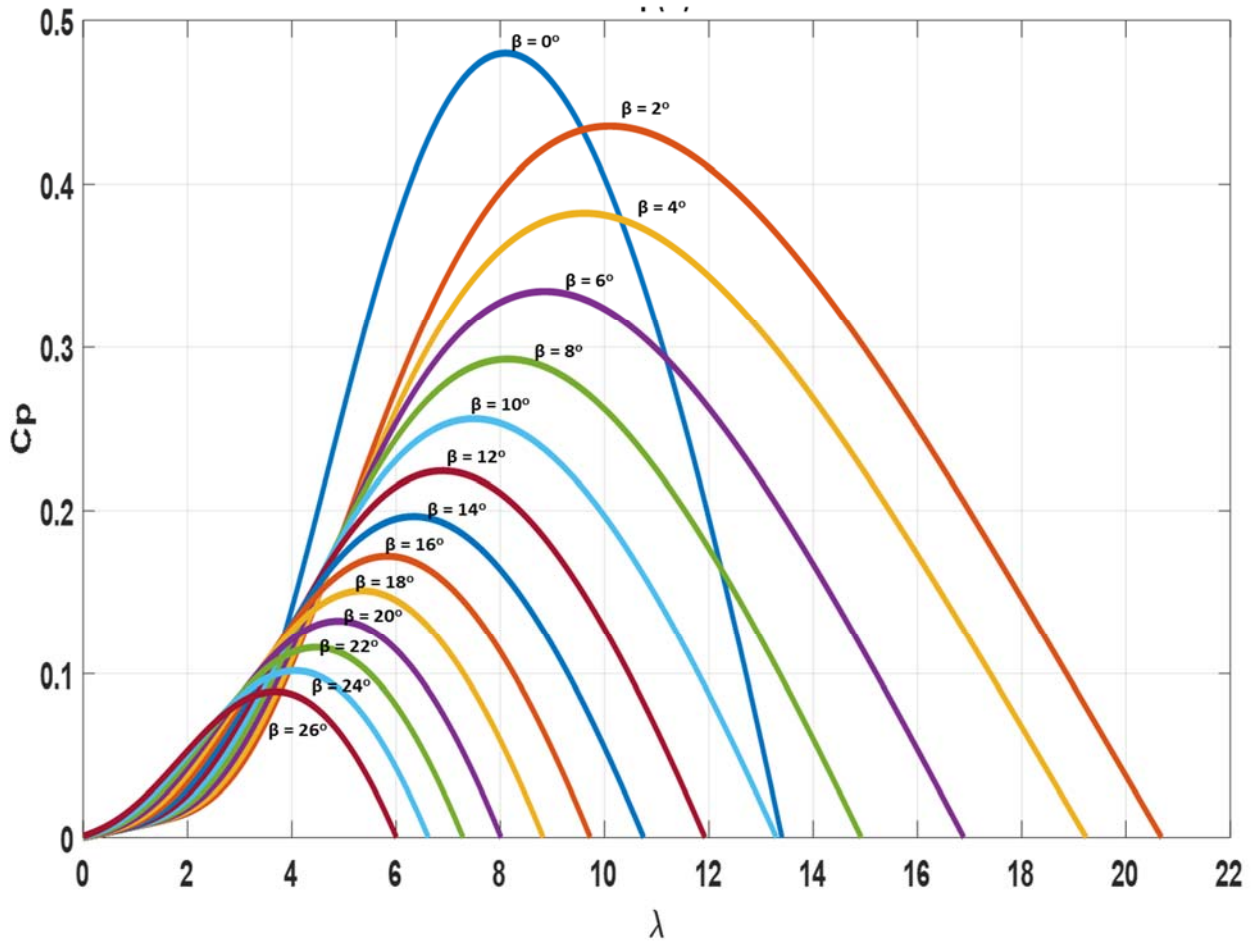


Fig.1 Cp vs. λ

### Objective

The objective is to determine the variation of power coefficient,  $C_p$ , with blade pitch angle,  $\beta$ , to any rotor speed.

### Experiment

This is a simulation-based experiment. No wiring, no hardware, no components, and no real measurement devices are used in this experiment. MATLAB Simulink ® is used. MATLAB skill is required to perform this test. No coding and no designing are required. A complete WECS simulation package is already provided in the lab which can be loaded to MATLAB environment as needed.

Follow the Lab instructor advice and the following instruction to perform this test as follows:

21. With the help of the lab advisor, start computer and locate MATLAB and run it.
22. In MATLAB, locate and run the designated simulation file, startup\_Wind\_Turbine.m

23. Test the simulation, Wind\_Turbine.slx, before changing anything to make sure that the simulation works without problems.
24. On the main simulation page, locate block named Wind. Inside this block there are two blocks Wind Speed and Wind Direction.
25. Assume no direction changes, set all Amplitude values to zero.
26. Run the simulation for multiple different wind speeds such as: 5, 7, 10, 15, 18, 20
27. For each of wind speeds in step 6, record the generated output power, rotor speed, and blade pitch angle from provided scopes, respectively. (Note, wait for stable operation of the generator before recording your reads)

## Report

1. Assume the generator efficiency to be 90%, blade radius of 40m, and with the help of Fig.1, fill out the following table:

Wind Speed m/s	Generator Output Active Power, MW	Rotor Speed, rpm	Blade Pitch Angle, $\beta$ , degree	$C_p$
5				
7				
10				
15				
18				
20				

2. Plot the relation between  $\beta$  and  $\lambda$
3. Plot the relation between  $\beta$  and  $C_p$
4. Discuss why the output power is constant at high wind speed.

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