WIND ENERGY

Problem 1

Determine the maximum mechanical power output for a 17-m-diameter, 20-m-high Sandia Vertical Axis Wind Turbine operating at 50 rpm in 40 km/hr steady winds. The mechanical efficiency of the running gear is 0.85.

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Problem 2

A wind turbine travels with the speed is 20 m/s and has a blade length of 30 m. Calculate the wind power.

Density of air is ρ = 1.23 kg/m^3

Answer: 13.91 MW

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Problem 3 (ME436s16h8)

During a typical day at a certain location, an anemometer near a wind turbine records the following data for a 1 hour period.

minute	mph	minute	mph	minute	mph	minute	mph
1	14.6	16	11.8	31	13	46	11.3
2	13.9	17	10.6	32	11.9	47	12
3	13.9	18	12.5	33	13.3	48	11.2
4	13.5	19	10.9	34	12.9	49	10.9
5	13.4	20	11.7	35	13.6	50	10.3
6	14.2	21	11.7	36	13.3	51	9.7
7	13.1	22	12.3	37	12	52	9.8
8	12.5	23	11	38	11.6	53	8.9
9	11.9	24	13.2	39	12.1	54	8.5

10	11.5	25	12.5	40	12.2	55	9.1
11	11.7	26	11.7	41	11.8	56	9.9
12	10.7	27	11.2	42	12.5	57	11.1
13	11.9	28	12.6	43	11.6	58	11
14	11.9	29	12.6	44	12.5	59	10.7
15	11.8	30	12.5	45	11.6	60	9.6

The following data is available:

The air density is 1.18 kg/m^3

The wind turbine has a diameter of 3.2 m

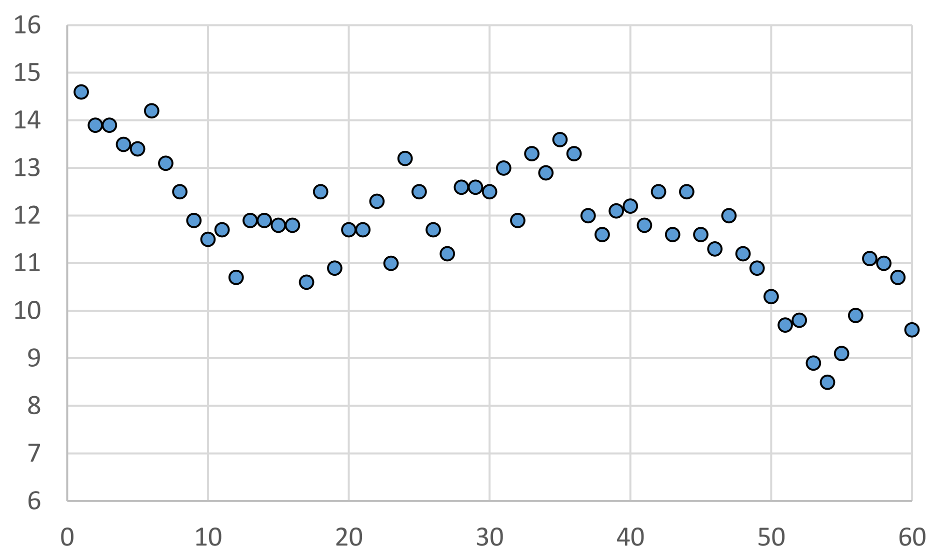
The turbine parameters are that the turbine collects a fraction $C_p = 0.335$ of the wind, the generator efficiency is $N_g = 0.80$, and the bearing efficiency is $N_b = 0.95$.

The instantaneous electrical power that is generated by the wind is given by the expression,

$$P = \frac{1}{2} \rho \, A \, C_P \, N_g \, N_b \, V^3$$

where A is the swept area of the wind turbine.

Plot of the given data:



a) Determine the instantaneous power for the wind turbine as a function of time.
b) Use the power data to estimate the cumulative electrical energy produced in kWh.

c) Assuming similar wind over the course of an entire day, estimate kWh for the day and then compare with the average energy consumption for a household in Turkey. Assume it is 10 kWh / day.
d) An electrolysis unit operates at 60% efficiency. If the theoretical amount of energy needed to convert 1 mol of liquid water into 1 mol of hydrogen and ½ mol of oxygen is 285 kJ, determine the mass of hydrogen produced in g for one day. Use your answer in kWh from part c.

Answer: (b) 0.181 kWh

(c) Fraction of daily use = 43.4 %

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Problem 4 (ME436f16q6 / ME436s17q6)

Based on average speed data only, estimate the annual energy production from a horizontal axis wind turbine with a 12 m diameter operating in a wind regime with an average wind speed of 8 m/s. Assume that the wind turbine is operating under standard atmospheric conditions (ρ = 1.225 kg/m3). Assume a turbine efficiency of 0.4.

Answer: 124 300 kWh

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Problem 5 (ME405f16m2-3)

A 40 m diameter, three-bladed wind turbine produces 700 kW at a wind speed (hub height) of 14 m/s. The air density is 1.225 kg/m^3. Find:

a) The rotational speed (rpm) of the rotor at a tip-speed ratio (TPR) of 5.0.

b) What is the tip-speed (m/s)?

c) If the generator turns at 1800 rpm, what gear ratio is needed to match the rotor speed to the generator speed.

(d) What is the power coefficient?

(e) What is the efficiency of the wind turbine system (including blades, transmission, shafts, and generator) under these conditions?

Hints:

- The tip-speed ratio (TPR) of wind turbines is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind,
- In order to convert tip speed to rpm (revolutions or rotations per minute) first find the distance covered or travelled by the tip in one revolution.
- Gear ratio is the rpm of the generator shaft to the rpm of the rotor.
- Actual power: $P = \frac{1}{2} \rho_a A_T V^3 C_P$ where C_P is the power coefficient.

Answer: (a) 33.42 rpm

(b) 70 m/s

(c) 53.85

(d) $C_P = 0.33$

(e) 56 %

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Problem 6 (ME436s17m2-3)

The following specifications for two HAWTs (Horizontal Axis Wind Turbines) are supplied by the manufacturers.

Item	**Turbine A**	**Turbine B**
Rotor diameter	25 m	28 m
Power coefficients	38	35
Gearbox efficiency	90	88
Generator efficiency	98	95
Capital cost	$99 000	$103 000
Maintenance cost per year	$4000	$4000

Assume the site wind availability to be 2000 hours per year, and average wind speed of 6 m/s, select the wind turbine which will be most economical. Assume life expectancy for each to be 20 years, and the unit cost of power to be $0.06 per kWh to remain constant.

$\rho_a = 1.2\ kg/m^3$

Maximum ideal power: $P_{max} = \frac{1}{2} \rho_a A_T V^3 \frac{16}{27}$

Answer: Turbine B

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Problem 7 (ME436s18q7 / ME405s18q7 / ME436s20f-4)

Find the size of a wind turbine rotor (diameter in meters) that will generate 100 kW of electrical power in a steady wind (hub height) of 7.5 m/s. Assume that the air density is $\rho = 1.225$ kg/m^3, power coefficient is $C_P = 16/27$, and generator efficiency is $\eta = 1$.

Answer: 28.8 m

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Problem 8 (ME436s18h6 / ME405s15h5)

The following specifications for two HAWTs are supplied by the manufacturers:

ITEM	TURBINE A	TURBINE B
Rotor diameter	25 m	28 m
Power coefficient	38	35
Gearbox efficiency	90	88
Generator efficiency	98	95
Capital cost, pounds	99 000	103 000
Maintenance cost, pounds/year	4 000	4 000

a) Draw up a table for the performance of each turbine for wind speeds 4-12 m/s in intervals of 2 m/s

b) Assume the site wind availability to be 2000 hours per year, and average wind speed of 6 m/s, select the wind turbine which will be most economical. Assume life expectancy for each to be 20 years, and the unit cost of power to be 0.06 pounds per kWh to remain constant.

ρ_{air} = 1.2 kg/m^3

Answer: Turbine B

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Problem 9 (ME436s19q10 / ME405s19q10 / ME436s20q10 / ME405f22q11)

A wind turbine rotor turning at 60 rpm is brought to a stop by a mechanical brake. The rotor inertia is 13 558 kg.m^2.

(a) What is the kinetic energy in the rotor before it is stopped? How much energy does the brake absorb during the stop?

(b) Suppose that all the energy is absorbed in a steel brake disc with a mass of 27 kg. Ignoring losses, how much does the temperature of the steel brake disc rise during the stop? Assume a specific heat for steel of 0.46 kJ/kg.K.

Answer: KE = 267.6 kJ; $\Delta T = 21.5\ ^\circ C$

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Problem 10 (ME436s19h8 / ME405s19h8 / ME436s20h9)

An isolated power system serving the community of Cantgettherefromhere uses a 100 kW diesel generator. The community plans to add 60 kW of wind power. The hourly average load and power from the wind turbine over a 24-hour period is detailed in the Table below.

Hour	Load, kW	Wind, kW
0	25	30
1	20	30
2	15	40
3	14	30
4	16	20
5	20	10
6	30	5
7	40	5
8	50	15
9	70	20
10	80	25
11	90	40

Hour	Load, kW	Wind, kW
12	85	45
13	95	45
14	95	50
15	90	55
16	80	60
17	72	60
18	60	48
19	74	50
20	76	55
21	60	60
22	46	60
23	35	55

The diesel generator has a no-load fuel usage of 3 liter per hour and an additional incremental fuel use of 1/4 liter per kilowatt-hour. For the day in question, using the hybrid system design rules, determine:

(a) The maximum renewable energy that can possibly be used in an ideal system.

(b) The maximum renewables contribution without storage, and the maximum with storage.

(c) The maximum fuel savings that can be achieved.

(d) The minimum diesel fuel use that can be achieved with intelligent use of storage and controls.

The hybrid system design rules are:

Rule 1: The maximum renewable energy that can be used is limited by the load.

Rule 2: The use of renewable energy will be further limited by temporal mismatch between the load and the renewables.

Rule 3: The maximum possible benefit with improved controls or operating strategies is a system approaching the fuel use of the ideal diesel generator - fuel use proportional to the diesel-served load.

Rule 4: The maximum fuel savings arising from the use of renewables in an optimized system is never greater than the fuel savings of an ideal generator supplying the proportional reduction in load resulting from use of renewables.

Answers:

(a) the maximum renewables contribution over the day would be 1338 kW

(b) The maximum renewables contribution without storage would be 819 kWh.

The maximum renewables contribution with storage is 913 kWh.

(c) Savings = 300.25 L/day

(d) 72 L/day

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Problem 11 (ME436s19m2-2 / ME405s19m2-2 / ME405f23f-5)

A small community has 2000 residents and each of them consumes an average of 100 liters of water per day. They have access to an aquifer 100 m below ground level and are considering acquiring a wind electric water pump to bring the water to the surface. What would be the rated power of wind turbine (kW) that would pump, on the average, an amount of water equal to what the community uses?

Assume that the capacity factor of the wind turbine is 0.25 and that the efficiency of the water pump is 80%.

Assume that one person consumes 0.1 m^3 water per day.

Density of water is about 1000 kg/m^3.

Acceleration of gravity is 9.81 m/s^2.

Capacity factor: The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period.

Answer: P_{water} = 2839 W   P = 11.35 kW

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Problem 12 (ME436s21q10 / ME405s21q11)

Suppose the wind turbine captures 1 MW of wind power when the wind speed is 12 m/s and the coefficient of performance (C_P) is 0.2. Find the length of the blades. Assume the density of air is 1 kg/m^3.

Answer: r = 43 m

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Problem 13 (ME436s21h10 / ME405s21h11)

For a wind turbine, its coefficient of performance depends on the radius of the blade, r, in the following form:

$$C_P = \frac{1}{1 + e^{0.0443\, r}}$$

Find the radius of the blade that extracts the most power

Answer: 50 m

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Problem 14 (ME436s21f-1 / ME405s21f-1)

HAWT (Horizontal Axis Wind Turbine) and VAWT (Vertical Axis Wind Turbine) designs have advantages and disadvantages over each other. For each of the reasons below mark if it is an advantage for a HAWT or an advantage for a VAWT.

Reason	HAWT Advantage	VAWT Advantage
Less strain on the axle, reduces maintenance		
Easy maintenance because rotor housing is near ground		
Wind direction does not matter		
Has a higher efficiency because the blades don't rotate into the wind (so don't drag)		
Can be installed in locations where taller structures are prohibited or are undesirable		
Higher installations increase the available wind energy		

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Problem 15 (ME436s22q11 / ME405s23q9)

A wind turbine with 100 m diameter rotor has a wind cut-in speed of 3 m/sec and a cut-out speed of 10 m/sec. It is placed in a region where the wind speed has a uniform probability, $f(V) = 0.1$ for wind speed $0 < V < 10$ m/s, and $f(V) = 0$ for $V > 10$ m/s.

(a) What is the average power that this turbine produces?

(b) What is the maximum power it can produce (sometimes referred to as the rated power)?

(c) What is the capacity factor for this turbine?

$$P = \frac{1}{2}\,\frac{\pi\, d^2}{4}\,\rho\, V^3 \qquad P_{av} = \frac{\int_3^{10} P(V)\, f(V)\, dV}{\int_0^{10} f(V)\, dV} \qquad P_{max} = \frac{16}{27}\,\frac{1}{2}\,\frac{\pi\, d^2}{4}\,\rho\, V_{max}^3$$

$$\text{Capacity Factor} = \frac{P_{av}}{P_{max}}$$

Answer: $P_{av} = 0.97$ MW $P_{max} = 2.33$ MW CF = 42 %

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Problem 16 (ME405f22h11)

The basic rating load for ball bearings, L_R, is that load for which a bearing should perform adequately for at least one million revolutions. A general equation relates the basic rating load for ball bearings [with balls up to 1 inch (0.083 m diameter)] to a few bearing parameters:

$$L_R = f_c \left[n_R \cos(\alpha)\right]^{0.7} Z^{2/3} D^{1.8}$$

where f_c = constant, between 3,500 and 4,500 (260,200 to 334,600 for ball diameter in m), depending on D cos(α) / d_m ; D = ball diameter, inches (m); α = angle of contact of the balls (often 0 deg); d_m = pitch diameter of ball races [= (bore + outside diameter)/2]; n_R = number of rows of balls; Z = number of balls per row.

If two bearings are to operate for a different number of hours, the rating loads must be adjusted according to the relation:

$$\frac{L_2}{L_1} = \left(\frac{N_1}{N_2}\right)^{1/3}$$

A bearing used on the output shaft of a wind turbine's gearbox has the following characteristics: OD = 4.9213 inches (0.125 m), ID (bore) = 2.7559 inches (0.07 m). The bearing has 13 balls, each 11/16 inches (0.01746 m) in diameter.

(a) Find the basic rating load of the bearing. Suppose that the gearbox is intended to run for 20 years, at 4000 hours/year.

(b) How does the bearing load rating change?

Assume that f_c = 4500. The angle of contact of the balls is equal to zero. The shaft is turning at 1800 rpm.

Answer: $L_R = 56\ 400$ N , $L_2 = 2750$ N

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Problem 17 (ME405f22f-4 / ME405f23f-4 / ME405f24h10)

A horizontal axis wind turbine has a 12-m diameter rotor. The wind regime at that location has a maximum speed of 12 m/s. The average wind speed is 8 m/s. Assume that the wind turbine is operating under standard atmospheric conditions (ρ = 1.225 kg/m^3). The power coefficient is 0.4. The Betz limit is about 53 %.

(a) What is the maximum power it can produce (sometimes referred to as the rated power)?

(b) What is the capacity factor?

(c) Based on average speed data only, estimate the annual energy production in kWh.

$$P = \frac{1}{2} \rho A C_P V^3$$

Answers: (a) P_{max} = 63 442 W (b) P_{av} = 14 187 W (c) Capacity Factor = 0.22

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Problem 18 (ME405s23h10)

You have been asked to do a conceptual design layout of a wind farm intended to produce a maximum of 1000 MW of power. The wind turbines are designed with a 100 m diameter rotor, and can operate in a maximum wind-speed of 10 m/sec (i.e. the turbine will "feather" the blades so that no power is produced if the wind speed exceeds this value). You can extract a maximum of 1 MW of power per km^2 of land area (due to turbine-turbine interactions as well as effects of the turbines slowing down the wind).

(a) How many turbines are required to meet the maximum design power?

(b) What is the total land area needed?

(c) what is the spacing between the turbines

(d) If the capacity factor of the site is 0.35, what will be the average power?

(e) Research the capital costs of wind turbines. What would this wind farm cost to install?

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Problem 19 (ME405s23f-4)

The coefficient of performance of a wind turbine depends on the radius of the blade, r, in the following form:

$$C_P = \frac{1}{1 + e^{0.0443\, r}}$$

Set up the equation to find the radius of the blade that extracts the most power. Do not solve the equation.

$$P = \frac{1}{2} \rho A V^3 C_P$$

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