Australian National University

Second Semester 2015

ENERGY RESOURCES AND RENEWABLE ENERGY TECHNOLOGIES

(ENGN4516 and ENGN6516)

Writing period : 2 hours duration
Study period : 10 Minutes duration
Permitted materials : One A4 page with handwritten notes on both sides
Calculator (non-programmable)
Dictionary (no approval required)

All questions to be completed in the script book provided.

100 marks total

Question 1

Is this a closed question? **(1 mark)**

Yes! (1 mark)
(Because it can be answered with a yes or a no)

Question 2

What is the definition of a capacity factor? **(2 marks)**

The capacity factor is the ratio of energy actually generated by a system (1 mark) to the energy that would be generated if the system were running continuously at its rated capacity (1 mark).

Question 3

What are the main factors that determine emissions of CO_2 due to energy? **(2 marks)**

Population, GDP, Energy intensity of GDP and CO2 intensity of energy (2 marks)

Question 4

What is the expected capacity factor of a solar PV plant located in Alice Springs (average insolation: 6 sunshine-hrs/day)? **(2 marks)**

Capacity factor = Energy generated/ Energy at continuous rated power

Energy generated = X (Kw) * 6hrs (0.5 marks)
Energy at rated power if operating continuously = X (kW)*24hrs (0.5 marks)
(ok if they just jump straight to the ratio of sun-hours)

∴ CF = 6/24
= 0.25 (1 mark)

Question 5

What is the capacity factor of a wind turbine rated at a windspeed of 12m/s, if it's installed somewhere the wind blows at an average windspeed of 8m/s? Assume a constant Cp.
(5 marks)

Capacity factor = Energy actually produced / Energy at continuous rated power
E produced = P (@v_{actual}) x t
E rated = P (@v_{rated}) x t

Now the equation of power for a wind turbine is: $P = C_p \frac{1}{2} \rho A v^3$ (1 marks)

Since we calculate over the same t, the Capacity factor will be the ratio of turbine powers

$$CF = C_p \tfrac{1}{2} \rho A v_{actual}^3 / (C_p \tfrac{1}{2} \rho A v_{rated}^3)$$

Assuming constant Cp, the capacity factor is the ratio of the velocities cubed. (3 marks)

$$CF = v_{actual}^3 / v_{rated}^3$$
$$= (8/12)^3$$
$$= 0.296$$ (1 mark)

Question 6

Lawrence the Luddite hasn't switched to Netflix yet, but instead loves to watch DVDs. Being energy conscious, he's worried about the standby electricity consumption of his DVD player. How many DVDs does Lawrence need to watch each year for the electricity-used-when-watching-DVDs to be greater than the standby-electricity? Info: DVD player standby power: 2W, DVD player running power: 120W
Justify your answer, noting any assumptions you've made. **(8 marks)**

Energy = Power x time

$E_{standby} = P_{standby} * t_{standby}$
$E_{DVDs} = P_{DVDs}$*number_of_DVDs*t per DVD (2 marks)

For $E_{DVDs} > E_{standby}$

∴ number_of_DVDs > $P_{standby} * t_{standby}$ /(P_{DVDs}*t per DVD) (2 marks)

Assuming a t per DVD of 2hrs: (1 mark – between 0.5 and 3)

number_of_DVDs > 2*24*365/(120*2) (2 marks)
= 73

Lawrence needs to watch more than 73 DVDs per year. (1 mark – answer between 49 and 292)

Question 7

Dr I. Lovetrees (PhD Harvard) wants to build a self-powered treehouse on the slopes of Black Mountain. She's exploring energy storage solutions and is concerned about energy density (Wh/kg). One option she's considering is a small pumped hydro system with a bathtub in her tree and another bathtub higher up on Black Mountain.

a) How much higher does the other bathtub need to be for the water in the system to have the same energy density as a lithium ion battery? How feasible is this? **(8 marks)**
Info: Li-ion energy density: 250Wh/kg, round-trip pumped hydro efficiency: 80%, density of water: $1000 kg/m^3$.

Useable Stored Energy of a pumped hydro system (J) = $\eta\ m\ g\ h$ (2 marks)

Energy density (J/kg) = $\eta\ g\ h$
For the energy density of water to equal that of a Li-ion battery:

$$\eta\ g\ h = ED_{battery}$$

$$\therefore\ h = ED/(\eta\ g) \quad \text{(3 marks)}$$

Now 250 Wh/kg = 250*3600 J/kg = 9×10^5 J/kg
(1 mark for converting to the right units)

$$\therefore\ h = 9 \times 10^5 /(0.8*9.81)$$
$$= 1.1 \times 10^5 m$$
$$= 114\ km \text{ (1 mark)}$$

(1 mark for any explanation of why this is crazily high. Higher than the highest mountain on Earth, g isn't really constant out to these heights, etc)

b) What's the maximum pumped-hydro energy density available from water using Black Mt's relief (h) of 256m, in Wh/kg? **(2 marks)**

Energy density (J/kg) = $\eta\ g\ h$ (1 mark)
= 0.8*9.81*256
= 2×10^6 J/kg
= 0.55 Wh/kg (1 mark, 0.5 if they only get the J/kg result)

c) If Dr Lovetrees wanted to power a 1kW power drill using the Black Mountain height difference, how long would it take for the bathtub to drain? **(10 marks)**
Info: bathtub dimensions: 1.5m x 40cm x 50cm,

$$\text{Energy} = \eta\ m\ g\ h$$
$$= \eta\ p\ V\ g\ h \text{ (2 marks)}$$

Power = Energy/time
$P = n\ p\ V\ g\ h\ /t$ (3 marks – ok if they express it in Q)

with a power of 1kW, and a volume of 1.5*0.4*0.5 m^3, we have the time to drain the bathtub:

$$t = n\ p\ V\ g\ h\ /P \text{ (3 marks)}$$
$$= 0.8*1000*1.5*0.4*0.5*9.81*256/1000$$
$$= 602 \text{ seconds (2 marks)}$$
$$\sim 10 \text{ minutes}$$

<u>Question 8</u>

Terence Moonseed looked at the wind turbines on Lake George and was concerned about their impact on orange-bellied parrots. Being a numerate fellow, and knowing that water is 1000 times more dense than air, he had an idea: Could the turbines be relocated under the sea at Jervis Bay to utilise the East Australia Current? He wants to know:

a) What Cp is required for the underwater turbine (operating in water) to produce the same power as the turbine above land (operating in wind)? Comment on how achievable this is.
(8 marks)

Info: Wind turbine $C_p = 0.4$, Water density: 1000kg/m^3, air density: 1 kg/m^3 turbine diameter: 60m. Avg wind velocity at Lake George: 8m/s
Avg ocean current velocity at Jervis Bay: 0.5m/s

Now the equation of power for a wind turbine is: $P_0 = C_p\ ½\ \rho\ A\ v^3$ (2 marks)

$$\therefore\ C_p = P_0 / (½\ \rho\ A\ v^3)$$

For the turbine to give the same P, with a new ρ' and v', then we need:

$$C_{p'} = P_0 / (½\ \rho'\ A\ v'^3)$$

$$= C_p\ ½\ \rho\ A\ v^3 / (½\ \rho'\ A\ v'^3)$$

$$= C_p * (\rho/\rho') * (v^3 / v'^3) \text{ (4 marks)}$$
$$= 4.10 * C_p$$
$$= 1.64 \text{ (1 marks)}$$

This is unphysical – because it is above the Betz limit of ~0.6 (the theoretical maximum for a turbine operating in continuous horizontal flow). (1 mark)

b) Terence finds a start-up company based out at Lord Howe Island where the East Australia Current flows at 3m/s. They guarantee installation of the underwater turbines at the same Cp as the wind turbine on land (Cp = 0.4). And they quote the system with an Annualised Life-Cycle Cost of Electricity 100 times higher than that for the wind turbine. Should Terence move the wind turbine?

Justify your answer, noting any assumptions that you've made. **(12 marks)**

Terence should move the turbine if the LCOE is lower underwater than with the wind.
Now, LCOE = ALCC/Electricity Generated per Year
We want to find P/P0. If this is higher than 100, ie. if the underwater turbine produces 100 times more electricity than it would in the wind, than Terence should move the turbine,

$$P = C_p \, ½ \, \rho \, A \, v^3$$ (1 mark)

$$\therefore \; P/P_0 = C_{p'} \, ½ \, \rho' \, A' \, v'^3 \; / \, (C_p \, ½ \, \rho \, A \, v^3)$$ (3 marks)

with Cp and A constant we have:

$$P/P_0 = (\rho'/\rho) * (v'^3/ v^3)$$ (3 marks)
$$= 53$$

That is, the underwater turbine will produce 53 times more electricity. (1 mark)

LCOE = ALCC/Electricity Generated per Year (2 marks)
With the $ALCC_{underwater}$ = 100 x $ALCC_{wind}$, and Electricity $Generated_{underwater}$ = 53 Electricity $Generated_{wind}$, the LCOE will be ~ 2x higher for the underwater turbine. (1 marks)
So Terence shouldn't move the turbine. (1 marks)

Question 9

The Hon Josh Frydenberg MP is keen to see the Galilee Basin Coal Mine start operation, but is also concerned about Australia's CO_2 emissions.

a) Estimate what fraction of the world's 2°C CO_2 budget will be used if all of the coal in the Galilee Basin is burnt for electricity (neglecting emissions from extraction). **(5 marks)**

Info: Global CO_2 budget to remain under 2°C: 565 G Tonnes of CO_2
Coal in Galilee Basin: 20×10^{12} kg_{coal}
Carbon content of coal: 70% ie. $0.7kg_{carbon}/kg_{coal}$
CO_2 emissions per kg of carbon burnt: $3.67kg_{CO2}/kg_{carbon}$

CO2 emissions from the Galilee Basin can be calculated:

$CO_{2Galilee}$ (kg_{CO2}) = $Coal_{Galilee}$ (kg_{coal}) * Carbon/Coal (kg_{carbon}/kg_{coal})
* CO2/Carbon (kg_{CO2}/kg_{carbon}) (3 mark)

$= 5.138 \times 10^{13}$ kg_{CO2}

As a fraction of the Global 2°C CO_2 budget, this is:

Fraction = $CO_{2\ Galilee}/\ CO_{2\ Planet}$ (1 mark)

= 20×10^{12} kg_{coal} * $0.7kg_{carbon}/kg_{coal}$ * $3.67kg_{CO2}/kg_{carbon}$ / $565 * 10^{12}$ kg_{CO2}
= 5.138×10^{12} kg_{CO2} / $565 * 10^{12}$ kg_{CO2}
= 0.091
= 9.1% (1 mark)

b) Assume the global 2°C CO_2 budget is allocated per capita across the world (that is X kg_{CO2} allowed to be emitted per person).
If all the Galilee coal were burnt in Australia, how much CO_2 would be emitted per Australian, and what fraction is this of the global per-capita 2°C CO_2 budget?

What fraction of the global per-capita 2°C CO_2 budget would it be for Indians if all the coal were exported and burnt in India?
Info: Australia's population: 23million, India: 1.25billion, World: 7.3billion.
(5 marks)

Global 2°C CO_2 budget per person = 565×10^{12} kg_{CO2} / World population
= 7.74×10^4 kg_{CO2}/person (1 mark)

If all Galilee coal was burnt in Australia, the CO_2 emissions per person are given:
Australian per capita emissions = 5.138×10^{13} kg_{CO2} / Australian population
= 2.25×10^6 kg_{CO2}/Australian

This is 29 x the world CO_2 budget per person (2 mark)

If all Galilee coal was burnt in India, the CO_2 emissions per person are given:
Indian per capita emissions = 5.138×10^{13} kg_{CO2} / Indian population
= 4.11×10^{4} kg_{CO2}/Indian

This is 0.53 x the world CO_2 budget per person. (2 mark)

c) What is the rate of change required of the world's CO_2-intensity-of-energy for it to account for an 80% reduction of the planet's 2015 emissions by the year 2040, given the following information? **(10 marks)**

Global population growth: 1% per year;
Global GDP growth: 3.5% per year.
Global energy intensity of GDP: decreasing 1.4% per year

The Kaya Identity is: CO2 emissions ~ Population* GDP* Energy/GDP * CO2/Energy
(1 mark)

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Possible to read the question as:
CO2_2040 = 0.8 * CO2_2015 **or** CO2_2040 = **0.2** * CO2_2015

If CO2 in 2040 is 80% of today's emissions then we have:

0.8 = Population Growth * GDP Growth * Energy Intensity Change * CO2/Energy change.
(3 marks. ok if 0.2 = Pop…)

Solving for CO2/Energy:

CO2/Energy change = 0.8 /(Population Growth * GDP Growth * Energy Intensity Change) (2 marks, similarly)

Now each change is given: $(1+r)^t$

CO2/Energy change = $0.8/ (1+r_{Pop})^t *((1+r_{GDP})^t *(1+r_{EnergyIntensity})^t)$
= 0.1988 (2 marks for the right equation)
= 0.0939 (if using 0.2)

Solving for $r_{CO2/E:}$

$(1+r_{Pop})^t$ = 0.1988 (1 mark for the right equation)
$\therefore$ r = -0.063
$\therefore$ r = -0.09 (if using 0.2)

The CO2 intensity of energy needs to decrease at 6.3% (9.0%2) per year. (1 mark)

Question 10 (Student question)

Bio-Pond Ltd, an innovative green-tech company, grows large quantities of ‘Botryocuccus braunii’ algae in large, open ponds. Once the algae has been harvested, they use a process called ‘thermochemical liquifaction’ to turn the algae into green crude oil, known as ‘bio-oil’.

(a) Thermochemical liquefaction requires processing at high temperature and pressure. Calculate the amount of energy, in MJ, required to produce 1 Litre of bio-oil from a fresh batch of algae cultures **(4 marks)**.
Information:

- Electrical energy required for cultivation, fertiliser application and harvesting is 8.85 MJ/kg of algae
- Heat energy required for thermochemical liquefaction is 4.28 MJ/kg of algae
- 1kg of algae produces 0.64kg of bio-oil
- 1L of bio-oil weighs 1.2kg

Solution (Student-generated (with some editing)):
Energy required per kg (MJ/kg algae) = energy required to grow algae (MJ/kg algae) + energy required for liquefaction (MJ/kg algae)
= 8.85 MJ/kg algae + 4.28 MJ/kg algae = 13.13 MJ/kg algae (2 marks)
Energy required per litre (MJ/L bio-oil) = energy required (MJ/kg algae) * weight ratio (kg algae/kg bio-oil) * bio-oil density (kg bio-oil/L bio-oil)
= 13.13 MJ/kg algae *1/0.64 kg algae/kg bio-oil * 1.2 kg bio-oil/L bio-oil
= 24.6 MJ/L bio-oil (2 marks)

Acceptable range = 24-25 MJ/L (allows for rounding error)

(b) The fossil fuel energy ratio is defined as the ratio:

Ratio = Energy output of the final bio-fuel product /
Fossil fuel energy required to produce the biofuel.

The energy density of the final bio-oil product is 45.9 MJ/kg. Assuming that Bio-Pond Ltd uses electricity from fossil fuels to power their entire algae production process, calculate the fossil fuel energy ratio **(4 marks)**.

Energy density of bio-oil (MJ/L) = energy density of bio-oil (MJ/kg) * density of bio-oil (kg/L)
= 45.9 MJ/kg * 1.2 kg/L
= 55.1 MJ/L (2 marks)
Fossil fuel energy ratio = energy density of bio-oil (MJ/L) / energy required in production (MJ/L)
= 55.1 MJ/L / 24.6 MJ/L
= 2.2 (2 marks)

Acceptable range = 2.1-2.3 (allows for rounding error through part (a) and (b))

Also acceptable to calculate using MJ/kg.
No deduction for error carried from (a)

(c) Bio-Pond Ltd wants to improve their fossil fuel energy ratio by using a concentrated solar thermal system to produce the heat required just for the thermochemical liquefaction stage.

Calculate the solar collector area required to accumulate enough heat to process the thermochemical liquefaction of a 1/2 hectare batch of algae in over the course of three days **(12 marks)**.

Information:

- 1 hectare produces 15 tonnes of algae
- The average efficiency of the solar thermal system (including optical and thermal losses throughout heat collection and heat storage) is 70%
- The location receives 5 peak solar hours (5 hours at 1000W/m^2) per day

Weight of algae produced (kg) = algae produced over area (kg/hectare) * area (hectares)
= 15,000 kg/hectare * 1/2 hectare
= 7,500 kg (1 mark)

Heat energy required to process thermochemical liquefaction of algae (MJ)
= heat energy required for thermochemical liquefaction per weight of algae (MJ/kg) * weight of algae produced (kg)
= 4.28 MJ/kg * 7,500 kg
= 32,100 MJ (2 marks)

Possible common error: Use of combined energy (electrical and heat) instead of just heat energy. (Award 1 mark out of 2)

<u>Equation set up</u>
Heat energy (J) = Solar power (W/m^2) *area (m^2) * time (seconds) * efficiency (4 marks)

<u>Rearrange</u>
Area required (m^2) =

$$\frac{\text{Heat energy required (J)}}{\text{Solar irradiance (W/m}^2\text{) * time (seconds/hr) * time(hrs/day) * time (days) * efficiency}}$$

(3 marks)

Possible common errors:

- Omission of time factors (seconds/hr, hrs/day, days). Award 2 marks out of 3.
- Omit efficiency. Award 2 marks out of 3.

Area required (m^2) =

$$\frac{32{,}100 * 10^6 \text{ J}}{1000 \text{ W/m}^2 * 3600 \text{ seconds/hr} * 5 \text{ hrs/day} * 3 \text{ days} * 0.7}$$

$$\frac{32{,}100 * 10^6 \text{ J}}{37.8 * 10^6 \text{ J/m}^2}$$

= 849 m^2 (2 marks)

Acceptable: 846-853 m^2