IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2011

EEE PART IV: MEng and ACGI

SUSTAINABLE ELECTRICAL SYSTEMS

Friday, 13 May 10:00 am

Time allowed: 3:00 hours

Corrected Copy

There are SIX questions on this paper.

Answer FOUR questions.

Q6 10.35

All questions carry equal marks.

Q5 12.15

Use a separate answer book for Sections A and B

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : G. Strbac, T.C. Green
Second Marker(s) : T.C. Green, G. Strbac

The Questions

Section A

1.

a)

i) Give an expression for the power flow of a wind stream passing through a cross-sectional area A. [1]

ii) Why is it not possible for a wind turbine to extract all of this energy? [3]

iii) Define the tip speed ratio (lambda) of a wind turbine and sketch the graph of wind power against lambda. [4]

b)

i) Explain the advantages and disadvantages of the different styles of generator that various manufacturers choose to use in wind turbine systems. [4]

ii) Discuss the advantages and disadvantages of using a gearbox in the drive train. [2]

c) A survey of a potential wind turbine site has yielded the wind speed data given in Table 1.1.Th swept area of the planned turbine is 4000m^2 and the turbine has a C_p value (at zero pitch) of 0.49, a cut-in speed of 3 m/s and a cut-out speed of 24 m/s. The air density is 1.2 kg/m^3.

i) It is thought desirable to have the turbine enter a constant power range for wind speeds above 12 m/s. Calculate the power rating that should be specified for the generator. [2]

ii) Calculate expected energy yield per annum in MWh for this wind turbine design. [4]

Wind Speed Range (m/s)	Centre of Range (m/s)	Duration per annum (h)
0 – 3	1.5	2,000
3 – 6	4.5	3,000
6 - 9	7.5	2,300
9 - 12	10.5	500
12 -24	18	900
> 24		100

Table 1.1 Annual distribution of wind speed at test site

2.

a)

i) Describe air mass number and explain what factors affect it. [3]

ii) What other factors might affect the amount of light energy that a solar panel is able to collect? [2]

iii) Explain why concentrating PV systems are expected to have higher efficiencies than a mono-crystalline cell without concentration. [2]

iv) Explain why are such cells less applicable in the UK than in countries considered to be sunnier. [1]

b)

i) Describe the structure and operating principle of a amorphous thin film silicon photovoltaic cell. [6]

ii) Describe and explain the structure of a multi-junction amorphous silicon cell. [4]

iii) Explain why a multi-junction cell has a higher efficiency than a mono-crystalline solar cell. [2]

3.

a)

i) Describe three different operating principles for Wave Energy Converters (WEC). [6]

ii) Discuss the advantages and disadvantages of wave energy converters as a sustainable energy resource. [4]

b)

i) Discuss how the output from tidal generation schemes varies and compare this to other renewable energy sources. [4]

ii) Explain how pumped storage can be used to enhance the operation of a tidal barrage or tidal lagoon electricity generation scheme. [2]

iii) Many tidal stream energy generating devices use similar principles to wind turbines; explain why a tidal stream turbine is very much smaller than a wind turbine of equivalent power output? [2]

iv) Describe the difference between a tidal stream and an ocean current and explain why tidal stream energy generators are not suitable for ocean currents. [2]

Section B

4.

a)

i) Explain why large-scale penetration of wind power would impose on an electricity supply system additional requirements for flexibility and explain why the requirements for "reserve" would increase. [3]

ii) Describe how the presence of wind influences reserve requirements across time scales from seconds to hours. [3]

iii) Differentiate between "spinning" and "standing" reserves by describing how they are provided and how they are used. State the factors that set the costs of these forms of reserve. [3]

iv) Discuss how the requirements for reserve provision may reduce the ability of a system to accommodate wind power. [3]

b) A system has 26 GW of wind capacity installed and 8.4 GW of must-run nuclear generation. Consider a "snap shot" of the operation of the system. The system operator expects that in four hours ahead of real time, the demand will be at 28 GW and wind output will be 10 GW. The system operator has decided to schedule 6.5 GW of reserve by de-loading a number of 550 MW CCGT units. These CCGT units have a minimum stable generation of 300 MW, a CO_2 emission level of 0.5 tonne/MWh in normal use and run 15% less efficiently when at minimum stable generation.

i) Determine whether it will be possible to accommodate all of the wind generation that is predicted. [5]

ii) Determine the additional hourly CO_2 emissions associated with providing the required reserve from the part-loaded CCGT. [3]

Table 5.2

5.

Government of Borduria is considering its response to the climate change challenge and proposes a change in generation mix (in terms of energy outputs). In Table 5.1 two generation mixes are presented, one corresponds to the present 2011 mix and other to the future 2030 mix. For each case, the table provides:

- the energy share of different sources for centralized production and the relevant CO_2 emission factors per unit of electrical output; and
- the estimated average efficiency of transmission and distribution η^{TD} for the overall system (that is, including T&D losses down to the consumption level).

a) Calculate the average electricity-related emission factor $\mu_{CO_2}^{ESP}$, referred to a unit of electricity delivered to an LV user, for the overall energy mix in the two cases. [4]

b) You have been commissioned by the Government of Borduria to estimate the potential of Combined Heat and Power (CHP) within the present (2011) and the future (2030) systems using a case study that is a micro-turbine (MT) for supply of the electrical and thermal demands of a large flat building is selected. The MT would be connected to the LV distribution network, and would exhibit the hourly rated performance reported in Table 5.2. Table 5.2 also contains:

- the estimated emission factor for natural gas used for the MT;
- the estimated average heat-output-related emission factor for separate heat production in the two mixes, assuming that heat in the building would be conventionally produced in boilers (this emission factor already takes into account heat distribution losses).

i) For generation mixes in 2011 and 2030, estimate the *CO2ER* (CO2 Emission Reduction) that the CHP system would achieve with respect to average separate production of electricity and heat. Express the result as a percentage of the total emissions from average separate production. [8]

ii) Estimate the *CO2ER* for the 2030 mix assuming that a mix of natural gas and bio-gas is used as fuel input to the MT, with a fuel-related emission factor $\mu_{CO_2}^{F}$ of 0.1 [kg_{CO2}/kWh_F]. [3]

iii) Discuss the role of CHP in 2011 and 2030 mixes on the basis of the results obtained in (i) and (ii). [5]

Source	*Share (%)*		*Electricity-related emission factor* μ_{CO_2} *[kg$_{CO2}$/kWh$_e$]*
	Mix 2011	*Mix 2030*	
Nuclear and Renewables	15	45	0
Oil	5	0	0.75
Coal	45	10	0.95
Gas	35	45	0.50
T&D efficiency η^{TD} *(%)*	*92*	*94*	

Table 5.1. Centralized (separate production) electrical generation characteristics

		Mix 2011	*Mix ~~2020~~* 2030
MT Electrical output *W*	[kWh$_e$]	70	
MT Thermal output *Q*	[kWh$_t$]	130	
MT Fuel input *F*	[kWh$_F$]	240	
MT Fuel-related emission factor $\mu^{F}_{CO_2}$	[kg$_{CO2}$/kWh$_F$]	0.200	
Heat-output-related emission factor for separate heat production $\mu^{TSP}_{CO_2}$	[kg$_{CO2}$/kWh$_t$]	0.270	0.150

Table 5.2. Rated characteristics of the MT CHP unit

Q6 CLARIFICATION 1pu = Capacity of all generators on the busbars

6.

a) Explain the notion of and reason for capacity margin in a modern power system. Describe how the optimal capacity margin may be determined. [3]

b) Discuss how the level of redundancy in electricity network design changes with the level of connected load. Explain why, in most cases, there is no network redundancy at the LV level. [4]

c) Discuss why it is important to consider the contribution that distributed generation can make to distribution network security. [3]

d) Consider the situation depicted in figure 6.1 in which 3 identical landfill-gas-based generators of 2.5 MW capacity are connected to a 33 kV distribution network. The availability of each generator is 85%. The winter demand profile of the load is shown in figure 6.2. Quantify the contribution to network security that is provided by the three generators. You may find it useful to complete Table 6.1 and calculate the Expected Energy Not Supplied (EENS). [10]

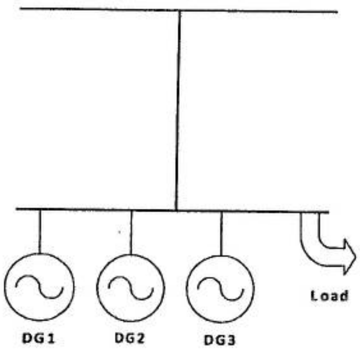


Figure 6.1. Example Network

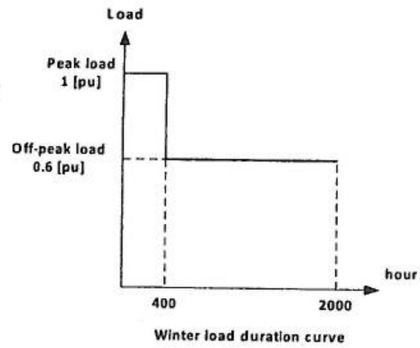


Figure 6.2. Load Duration Curve

Capacity In Service	Probability	Loss of load during peak period (MW)	Loss of load during off peak period (MW)	EENS (MWh)
7.5				
5				
2.5				
0				

Table 6.3. Loss of Load Table

EE4-50 2011 Answers

Section A

1.

(a)

(i) Give an expression for the power flow of a wind stream passing through a cross-sectional area A. [1]

$$P_w = \frac{d}{dt}E_k = \tfrac{1}{2}\rho V^2 \frac{d(Ax)}{dt} = \tfrac{1}{2}\rho A V^3$$

(ii) Why is it not possible for a wind turbine to extract all of this energy? [3]

To capture all the energy in the flow would require stopping the flow entirely and this would cause an accumulation of air in the wake and a build up of local pressure that prevented further inward flow. Some down-stream velocity must remain. The power extracted by a turbine will be given by the product of the force exerted on the flow and the velocity of the flow at that point. The velocity at the turbine is midway between the upstream and down-stream flow rates because the flow decelerates ahead of the turbine because of the pressure build up. The two terms in the product are thus linked and the product must be optimised. Betz showed that the optimum occurs when the flow velocity over the turbine is 2/3 of the up-stream velocity and the power yield is 16/27 of the power in the upstream airflow. A realistic turbine can approach but not exceed 59% power capture.

(iii) Define the tip speed ratio (lambda) of a wind turbine and sketch the graph of wind power against lambda. [4]

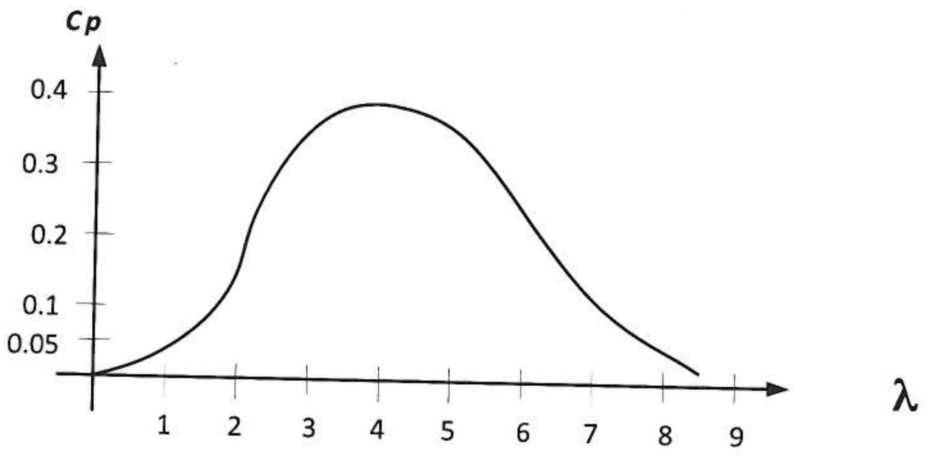
The tip speed ration is the ratio of the velocity of the blade tip to the velocity of the wind given by

$$\lambda = \frac{\omega_T R}{V_U}$$

This ratio can be used to characterise the performance of a wind turbine.

If *Cp* is plotted against the wind speed, *V*, there is a different curve for every value of the rotational speed of the blades, ω_T. Similarly, if *Cp* is plotted against ω_T, there is a different curve for every value of *V*. The number of curves involved makes it very difficult to visualise the characteristics of *Cp*. However, if the power coefficient is plotted against the tip-speed ratio, a single characteristic curve is obtained.

This single curve incorporates *V* and ω, and it provides an easier way to evaluate the performance of a particular wind turbine. This is the reason why the tip speed ratio is so widely used by manufacturers, developers and researchers. A typical *Cp* versus tip speed ratio characteristic is shown in the figure below.



Power coefficient, C_P versus tip-speed ratio, λ

The **Error! Reference source not found.** above indicates that for a particular wind speed, there is a tip-speed ratio that maximises the power extraction from the wind. The common three-bladed turbine has an optimal λ of about 4 but individual designs vary around this value.

(b)

(i) Explain the advantages and disadvantages of the different styles of generator that various manufacturers choose to use in wind turbine systems. [4]

[Bookwork - 4 of major points below require for full marks]

Fixed speed induction machine devices - cheap and cost effective but inflexible and the output is not optimised.

Variable speed designs are now more cost effective when compared to the total cost of the wind turbine. They allow the turbine to operate at peak efficiency whilst still generating at grid frequency.

Initial attempts to do variable speed designs involved using resistors in the rotor of an induction generator to vary its speed. Crude and wastes a lot of energy in the resistors.

The straight forward way of achieving variable speed is to allow the generator to produce AC at whatever frequency is dictated by its rotational speed and then perform a frequency conversion in order to connect to the grid. The frequency conversion would normally be rectification to DC followed by inversion to 50 or 60 Hz as shown. This is known as a full-converter design because all of the generated power is passed through power electronic power converter. The magnetic field on the rotor would be produced by a permanent magnet in low power designs and a wound field in high power designs. Such a system would normally be paired with a variable-pitch turbine and a control scheme that actively controls both the pitch angle and turbine speed to follow the maximum power or the power limit as appropriate. The full-converter design places no restriction on the range of rotational speeds that can be accommodated which means the optimal power point can be tracked across a wide range. These are sometimes known as wide speed-range wind turbines (WSR) or full-converter wind turbines. This design is favoured by Enercon.

It has been considered that the power electronics of a full-converter design is too costly. It is also noted that wide speed-range is not really necessary.

It has been considered that the power electronics of a full-converter design is too costly. It is also noted that wide speed-range is not really necessary as the incidence of the higher power wind speeds is such that there is little advantage in the extra cost. This opens up the possibility of a compromise in which we settle for a limited speed range in exchange for using lower rated power converters. This is achieved using a doubly-fed induction generator. The DFIG differs from the standard induction generator by having slip-rings which allows the rotor currents to be processed through an external circuit, in this case a power converter. Put simply the allowable slip range can be widened (in comparison to a standard induction machine) by exercising control over the rotor currents and indirectly the stator currents - a somewhat less crude system than the resistor system.

If a relatively small amount of power is extracted from the rotor, it allows the machine to generate at higher speeds and if a relatively small amount of power is injected into the rotor it allows generation down to lower speeds.

As with any induction machine, the frequency of currents and voltages in the rotor is given by the difference between the rotational speed of the magnetic field (the synchronous speed imposed by the stator frequency) and the rotational speed of the rotor. The rotor-side AC/DC converter must be synchronised to this frequency.

When operating below synchronous speed, the slip is positive and the rotor power is in the opposite sense to the stator power. When acting as a generator, power is introduced in mechanical form and exported from the stator. Below synchronous speed, power needs to be injected into the rotor. Above synchronous speed, power is exported from the rotor. The power exchange between the rotor and the rotor-side AC/DC converter is passed through the DC-link and grid-side AC/DC converter.

Vestas is one of the main proponents of this design and in their design it can be paired with either a pitch-controlled turbine or an active-stall turbine. The advantage is that the cost of the system is much reduced from the full converter design.

(ii) Discuss the advantages and disadvantages of using a gearbox in the drive train [2]

The gearbox introduces an efficiency loss into the drive train of the wind turbine (efficiency is between 70-95%). Also a gearbox at a power rating of several megawatt capable of handling sharply fluctuating torque is large, expensive and, in some cases, not sufficiently reliable.

Enercon does not provide a gearbox between the turbine and the generator. This means that the generator is a high-torque, low speed design. The disadvantage is that high torque generators are proportionately larger. Enercon uses a very large diameter generator which takes the form of an annulus to reduce weight.

(c) A survey of a potential wind turbine site has yielded the wind speed data given in Table Q1.1.Th swept area of the planned turbine is 4000m^2 and the turbine has a C_p value (at zero pitch) of 0.49, a cut-in speed of 3 m/s and a cut-out speed of 24 m/s. The air density is 1.2 kg/m^3.

(i) It is thought desirable to have the turbine enter a constant power range for wind speeds above 12 m/s. Calculate the power rating that should be specified for the generator. [2]

(ii) Calculate expected energy yield per annum in MWh for this wind turbine design. [4]

Wind Speed Range (m/s)	Centre of Range (m/s)	Duration per annum (h)
0 – 3	1.5	2,000
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6 - 9	7.5	2,300
9 - 12	10.5	500
12 -24	18	900
> 24		100

Table Q1.1 Annual distribution of wind speed at test site

[Manipulation of known formulae]

(i) The power yield of a turbine is

$$P_T = \tfrac{1}{2} C_P \rho A V^3$$

At 12 m/s, the power will be

$$P_T = \tfrac{1}{2} \times 0.49 \times 1.2 \times 4{,}000 \times 12^3 = 2.032\,MW$$

A 2MW generator could be chosen and power limited by pitching for all speeds above 12m/s. [2]

For each wind speed point, one can calculate the achieved power, capped this at the maximum turbine power as necessary, and multiply by the number of hours per annum to gain the energy yield per annum (in Wh initially and converting to MWh). Speeds below the cut-in and above the cut-out are ignored. It is sufficient to work with the centre speed of each set of duration data. [1]

For a 1.8 MW turbine

Wind Speed Range (m/s)	Centre of Range (m/s)	Duration per annum (h)	Capped Power (MW)	Energy (MWh)
0 – 3	1.5	2,000	0	0
3 – 6	4.5	3,000	0.107	321
6 - 9	7.5	2,300	0.496	1,140
9 - 12	10.5	500	1.360	681
12 -24	18	900	1.800	1,800
> 24		100	0	0

[2]

Total Energy is 3,940 MWh [1]

Excel spreadsheet for Calculating Results Above

Wind Speed Range (m/s)	Centre of Range (m/s)	Duration per annum (h)	Capped Power (MW)	Energy (MWh)	cut in		capped PowerW	Energy
0 – 3	1.5	2,000	0	0	0	0	0.00E+00	0.00E+00
3 – 6	4.5	3,000	0.107	321	1	107163	1.07E+05	3.21E+08
6-9	7.5	2,300	0.496	1,140	1	496125	4.96E+05	1.14E+09
9-12	10.5	500	1.36	681	1	1361367	1.36E+06	6.81E+08
12-24	18	900	2	1,800	1	6858432	2.00E+06	1.80E+09
> 24		100	0	0	0	0	0.00E+00	0.00E+00
								3.94E+09
total				3,940				
0.49								
1.2								
4000								
2.00E+06								

2.

(a)

(i) Describe air mass number and explain what factors affect it. [3]

[Bookwork – some elaboration of these basic points expected]

Atmospheric path affects the absorption at certain wavelengths of the light spectrum by gasses in the air. Path length depends on angle of light through the atmosphere which in turn depends on the time of day, season and location. Often summarised as an air mass number, AM1.5 indicating the spectrum after a path 1.5 times longer than a radial path.

(ii) What other factors might affect the amount of light energy that a solar panel is able to collect? [2]

Angle of incidence of the light on the panel will set the effective area presented to the light. Dependent on time of day and day of year on the one hand and the elevation and azimuth of the panel on the other. It is possible to make the panel track the sun's position in either one or two planes. It is also possible to find a single position for optimal light capture over a year (or optimal summer and winter positions etc).

Cloud cover will block direct light but some indirect light will reach the panel. Shadows from buildings may also block light at certain times of day in urban environments.

(iii) Explain why concentrating PV systems are expected to have higher efficiencies than a mono-crystalline cell without concentration. [2]

[Book work] Concentrating PV Systems - As the name suggests, these systems use mirrors or lenses to focus the light onto a small PV cell, usually an expensive high efficiency cell is used. They have the advantage that a large amount of energy can be converted by a small PV cell, although the aperture of the concentrator must be large enough the capture the same light as an equivalent flat plate array but at much reduced cost, especially with the use of low cost Fresnel lenses reduces the cost. However, it is usually only the direct component of sunlight that can be concentrated, so the system must track the sun to ensure that the cell is working as efficiently as possible. Also, it is important to ensure that the solar concentration does not raise the temperature of the cell to a point where the efficiency is adversely affect or the cell damaged.

(iv) Explain why are such cells less applicable in the UK than in countries considered to be sunnier. [1]

Only direct or beam radiation can be focussed efficiently and due to the atmospheric conditions in the UK, even on a "sunny day" only about half of the incident light energy is direct or beam radiation. More traditionally sunny countries get a much greater proportion of direct radiation.

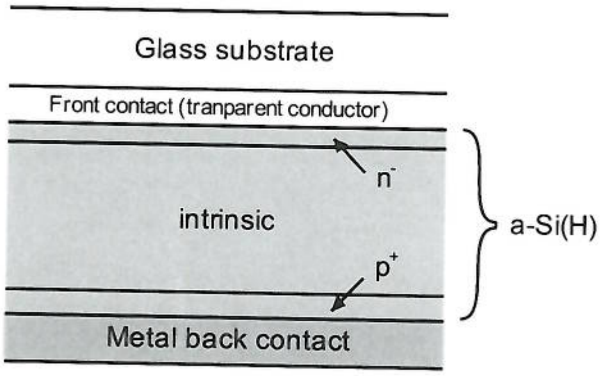
(b)

(i) Describe the structure and operating principle of a amorphous thin film silicon photovoltaic cell. [6]

From 2009 notes: Amorphous Silicon Thin Film Cells - Amorphous silicon is a very poor conductor (The structure of the silicon within these cells is very disordered and generally, they make poor semiconductors as they have a large number of dangling bonds that tend to sweep up any stray carriers), therefore the material used is actually alloyed with hydrogen to produce Si-H, which can in turn to doped to work as a semiconductor.

An amorphous silicon cell consists of a glass substrate that allows light into the cell.

A transparent front contact followed by a sandwich made up of a relatively thick layer of intrinsic (i.e. undoped) a-Si(H) sandwiched between a thin p layer and a thin n layer. Finally there is a metal back contact. The intrinsic layer is present because it has relatively good carrier mobility compared to the heavily doped layers.



. The structure of an amorphous silicon p-i-n cell

(Solar Electricity, Markvart, 2000)

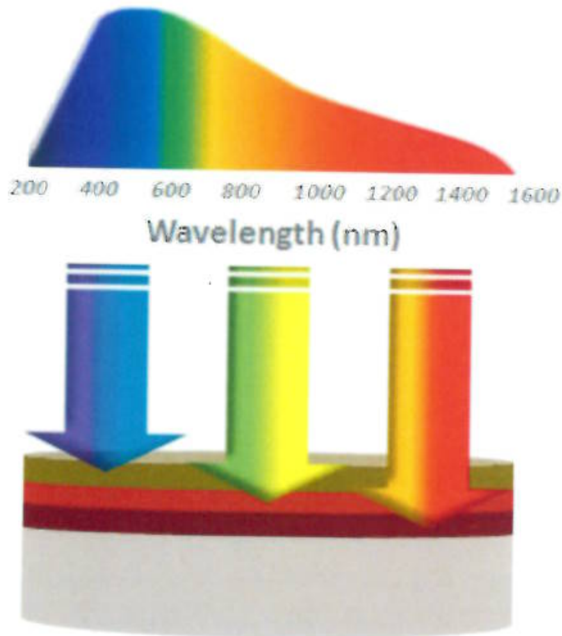
Light enters the cell through a thin layer of heavily doped p-type. The photon is generally absorbed in the intrinsic layer where an electron and hole are generated. The electric field of across the intrinsic layer causes the electrons to be swept across the cell towards the n type material into the external circuit where they can enter the external circuit.

The efficiency of such cells is not high.

This material is cheap to produce and has a high absorption coefficient, making it very attractive for PV cells. However, the semiconductor properties of the material are such that the cell structure is rather different from a standard crystalline silicon cell, as shown in 0.

(ii) Describe and explain the structure of a multi-junction amorphous silicon cell. [4]

Multi-Junction PV Cells - In this cell, also known as a 'tandem cell', different thin film cells are stacked so that the cell absorbs as much of the incident spectrum as possible. For example, in an amorphous silicon tandem cell, the a-Si is alloyed with different elements at each level to vary the band gap at each layer. The top layer (e.g. alloyed with carbon) absorbs the higher energy photons at the blue end of the spectrum, below this are other thin film cells alloyed with different elements to reduce the band gap so that light from the lower end of the spectrum is absorbed (e.g alloying with germanium reduces the band gap of intrinsic a-Si).



Since a PV cell will absorb any light that has a higher energy than its band gap, a the layer designed to absorb red light will also absorb blue light with the additional energy being expended as heat, therefore it is important to absorb the higher energy photons first; the lower energy photons will penetrate deeper into the cell before being absorbed.

(iii) Explain why a multi-junction cell has a higher efficiency than a mono-crystalline solar cell. [2]

A multi-junction cell absorbs a wider range of frequencies than a single junction cell, however, it also absorbs each wavelength of light in a material with a band gap designed specifically for it, hence more of the energy is absorbed from the higher energy wavelengths and less is wasted as heat.

3.

(a)

(i) Describe three different operating principles for Wave Energy Converters (WEC). [6]

[book work]:

The EMEC identifies 6 main types of Wave Energy Converter (WEC) (2 marks each):

Attenuators (floats or pitching devices)

Attenuators (or floats or pitching devices) generate electricity from the bobbing or pitching action of a floating object. The object can be moored to a floating raft or anchored to the ocean floor.

Point absorbers

These devices float on the surface of the sea and absorb energy in all directions.

Oscillating wave surge converters

These devices extract energy from the movement of water within wave surges.

Oscillating water columns

These devices generate electricity from the wave-driven rise and fall of water in a cylindrical shaft, as illustrated i. The rising and falling water column drives air into and out of the top of the shaft; the energy is harvested by a small wind turbine.

Overtopping devices (or focusing devices)

These shoreline devices, physically capture water from the waves as they rise above a wall around a raised reservoir. The water is returned to the sea via a standard low head turbine.

Submerged pressure differential devices

These devices are designed to be fully submerged near the shore and work by exploiting the pressure differential created by the varying mass of water above them as the waves pass overhead. The reciprocal motion is used to pump fluid through a system to generate electricity.

(ii) Discuss the advantages and disadvantages of wave energy converters as a sustainable energy resource. [4]

All of the wave energy is concentrated near the water surface with little wave action below 50 metres depth. This makes wave power a highly concentrated energy source with much smaller hourly and day-to-day variations than other renewable resources such as wind or solar.

Ocean waves can travel great distances without significant losses and so act as an efficient energy transport mechanism across thousands of kilometres. For example, waves generated by a storm in mid-Atlantic will travel all the way to the coast of Europe without significant loss of energy. This fact improves the predictability of this energy source.

Although few of these devices are yet commercialised, it is considered that from the point of view of the power system, connection to these devices will be relatively simple compared to other marine devices as current designs are in-shore devices so there are no long cable runs. Also they often use compressed air as a medium to get the energy onto land, hence the actual generator and converter station can be onshore.

In general, wave power devices have little environmental impact. They are also normally regarded as landscape friendly because they are low profile generators (compared to wind turbines, for example). Oscillating wave column and tapchan systems could also be used as a defence against shore erosion.

Waves are irregular in direction, duration and size; for these reasons it is difficult to build a fully "optimised" device.

Extreme weather conditions are challenging from the design point of view, and reliability (which is normally in conflict with cost) is a priority. Early experiments with wave devices (in the 1970s and 1980s) tended to be under-engineered and suffered damage in storms. Protecting devices against severe storms is a significant cost element.

With some type of wave-power device, navigation routes and activities such as fishing may be affected.

(b)

(i) Discuss how the output from tidal generation schemes varies and compare this to other renewable energy sources. [4]

Clearly, the most attractive advantages of tidal power is that the primary energy source is cost-free, it offers the opportunity to reduce our carbon emissions, and it helps to reduce dependency on imported fuel. Because of the periodicity of the positions of the earth, moon and sun; tidal power is very predictable (in time and magnitude) and this is also a very attractive characteristic of this generation scheme because it reduces the risks faced by generators in a liberalised market. Most other forms of renewable energy (wind, solar, wave) have significant uncertainty in their output on a day to day basis.

However, because tides actually occur roughly once every 12.4 hours, the actual timing of high/low tide varies throughout the year such that they are not synchronised to the demand for electricity (for instance the way solar power is) which makes it a little more difficult to integrate tidal power into the generation mix.

(ii) Explain how pumped storage can be used to enhance the operation of a tidal barrage or tidal lagoon electricity generation scheme. [2]

An enhancement to the tidal barrage arrangement is the introduction of pumped storage. Here, additional water would be pumped into the high level basin (ebb generation) or pumped out of the low level basin (flood generation) to increase the head when generation begins. In this way, the energy from the tides can be time-shifted that it is available at a time more in keeping with the demand for electricity.

Additional information: It should be noted that according to Bay of Fundy Tidal Power Reveiw Board and Management Committee, 1977, the benefits of pumping are limited to lower head installations as the need to design the turbines to have pumping capability reduces their effectiveness at high heads. Generally, turbines are most efficient when they are designed for a single mode of operation.

(iii) Many tidal stream energy generating devices use similar principles to wind turbines; explain why a tidal stream turbine is very much smaller than a wind turbine of equivalent power output?. [2]

The power equation for a wind turbine is

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

Where ρ is the density of the fluid.

Water is several hundred times more dense than air therefore, the power available from a turbine of equivalent size is much greater. However, tidal velocities are usually lower than wind speeds, hence the turbine is not hundreds of times smaller.

(iv) Describe the difference between a tidal stream and an ocean current and explain why tidal stream energy generators are not suitable for ocean currents. [2]

Tidal streams are the result of water flowing in and out of channels due to tidal movement of water; the direction of the current changes depending on whether the tide is a flood tide (incoming) or an ebb tide (outgoing). Ocean currents arise from the complex heat-exchange phenomena around the globe (such as the Gulf Stream) and flow continuously in predefined directions, usually circulating over very large areas.

Ocean currents are very predictable and constant but they have a very low flow rates and power density compared to tidal flows. Hence, the large turbine devices used for tidal flows are unsuitable for ocean currents, even where the ocean current is accelerated by narrow channels between islands and around headlands

Question 4

(a)
Increased variability requires flexibility. Increased requirements for reserve are driven by unpredictability of wind power.

(b) Uncertainty in wind forecast becomes a source of additional balancing requirements which can be fairly substantial in magnitude. Wind forecast time scales are important for determining reserve requirements. For time scales from several seconds to a few minutes, the fluctuation of the overall output of wind generation will be small given that there is considerable diversity in outputs of individual wind farms. In these very short (Response) time scales, the dominant variability factor is the potential loss of conventional plant, not fluctuations in wind power. However, given that it may take 30 minutes to re-establish response requirements, and that in this time scale wind may change, additional response requirements will be needed. Reserve requirements are concerned with the wind forecast uncertainty over longer time scales of minutes to hours.

(c)
In deciding the composition of system reserve, technical and economic considerations need to be made in selecting reserve options. Options include spinning and standing reserve. Combined cycle gas turbines (CCGT) or coal fired plant synchronized but running part loaded will provide spinning reserve. Generating plant that is not synchronized but it can start within the time scale required is classified as standing. Standing reserve is often provided by open cycle gas turbines (OCGT) or pump storage. Costs of holding spinning reserve include fixed fuel losses associated with start-up and no-load costs during running hours whilst utilisation costs are generally the same as system marginal costs. For storage the holding costs are negligible but utilisation costs are based on pumping costs which consist generally of marginal plant costs, plus losses incurred during the pumping/generation cycle. For gas turbines that provide standing reserve the holding costs are negligible but utilisation costs may be much higher. Synchronised reserve is used to accommodate relatively frequent but comparatively small imbalances between generation and demand while standing reserve will be used for absorbing less frequent but relatively large imbalances.

(d)
Reserve is allocated in order to meet imbalances between predicted and actual demand and it is beneficial to determine the optimal split between the allocation of spinning and standing reserve for achieving the lowest fuel costs. Fuel costs involve a trade off between the more expensive nature of standing reserve plant and the higher costs involved in running spinning reserve plant part loaded. Furthermore, in a generation system with wind, the allocation of reserve affects the ability of the system to absorb wind generation. A high allocation of spinning reserve requires a large number of generators to run part loaded, therefore delivery of energy accompanies provision of reserve. This "must run" generation leaves less room for utilisation of wind generation.

(e) 26 CCGT units will need to run deliver synchronised Reserve : 26x250 = 6,500 MW. These 26 units will also generate Power: 26x300 = 7,800 MW

Power output:
Must run 8,400 MW
CCGT: 7,800 MW
Wind: 12,000 MW
TOTAL: 28,200 MW

200MW of wind output will need to be curtailed.

7800 x 0.15 x 0.5 = 585 tonnes of additional CO2 is emitted due to the need to provide reserve.

Question 5

The average overall electricity-related emission factor referred to the *generated* unit of energy is obtained by averaging out the single emission factors using as weights the relevant penetration levels. The average emission factor $\mu_{CO_2}^{ESP}$ referred to the unit of electricity *delivered to the LV user* is then obtained by dividing the average emission factor calculated above by the network efficiency.
Hence, we have for mix 2011:

a) $\mu_{CO_2}^{ESP} = \dfrac{0.15\cdot 0 + 0.5\cdot 0.750 + 0.45\cdot 0.95 + 0.35\cdot 0.50}{0.92} = 0.696$ kg_{CO2}/kWh_e

and for *Mix 2030*

$\mu_{CO_2}^{ESP} = 0.340$ kg_{CO2}/kWh_e

(b)

(i)

The average *CO_2 Emission Reduction* from the CHP engine can be obtained from the formula

$$CO2ER\% = \left(1 - \frac{\mu_{CO_2}^{F}\cdot F}{\mu_{CO_2}^{ESP}\cdot W + \mu_{CO_2}^{TSP}\cdot Q}\right)\cdot 100$$

that is for 2011:

$$CO2ER\% = \left(1 - \frac{0.20\cdot 240}{0.696\cdot 70 + 0.270\cdot 130}\right)\cdot 100 = 42.7\%$$

2030:

$$CO2ER\% = -10.8\%$$

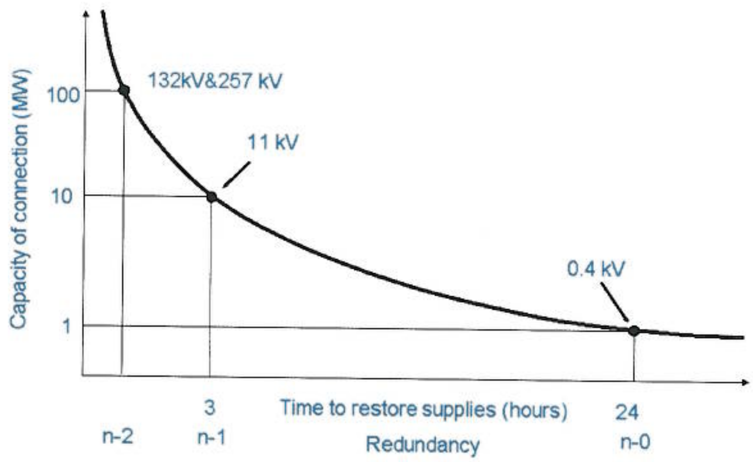
(ii) $CO2ER\% = 44.6\%$

(iii) Potential for cogeneration to decrease overall emission depending on the grid carbon intensity and reference emission factor for conventional thermal production (boilers).
In Mix 2011 there is very significant potential, but then the shifting towards a decarbonised grid in 2030 limits the role of natural gas fuelled CHP. The negative figure for *CO2ER* indicates cogeneration brings an *increase* in emissions relative to separate production. On the other hand, results from (ii) show that combined production could bring again significant benefits even in a more decarbonised environment provided that the input fuel is (even only partly) decarbonised too.

Question 6

The capacity margin represents the magnitude of installed electricity generating capacity above system peak demand. Power system should be planned with a certain capacity margin to ensure that the system's supply risk is kept at appropriately low levels. The level of capacity margin is determined by balancing the cost of investment in generation and benefits it brings in terms of reducing consequences of outages.

The level of security in distribution networks is graded and increases with increase in demand level. A simplified illustration of this network design philosophy is presented in Figure above. Small demand groups, less than 1MW peak, are provided with the lowest level of security, and have no redundancy (N-0 security). For demand groups between 1MW and 100 MW, network designs provide n-1 security. For demand groups larger than 100MW, the networks n-2 security. Providing redundancy at 0.4 kV level would significantly increase the cost of network service provision as more than 75% of the entire network cost is in the last mile, and it would not be justified given that amount of load lost would be small.



Where:
n-0 = no redundancy in security (must wait for repair of network); n-1 = one level of network redundancy; and n-2 = two levels of network redundancy.
Considering security contribution of DG is critical for their competitiveness. Electricity produced by centralised generation is sold in the wholesale market for around 4p/kWh; by the time this electricity reaches the end consumer it is being sold at a retail price of between 10-12p/kWh. This increase in value is driven by the added cost of transmission and distribution services to transport electricity from the point of production to consumption and supplier services. DG however, located close to demand, may be delivering electricity directly to consumers with limited requirement for the use of the network. This power may therefore have a higher value than that of conventional generation (e.g. an equivalent value of between 4-8 p/kWh) due to the potential of DG to reduce the demand for distribution and transmission network capacity and corresponding costs.

Contribution of DGs to security

Capacity In Service	Probability	Loss of load: peak load(MW)	Loss of load: off peak load(MW)	EENS (MWh)
7.5	0.6141	7.5-7.5 = 0	0	0
5	0.3251	7.5-5 = 2.5	0	0.3251 x (2.5 x 400) = 325
2.5	0.0574	7.5-2.5 = 5	0.6x7.5-2.5 = 2	0.0574 x (5 x 400 + 2 x 2000) = 344
0	0.0034	7.5-0 = 7.5	0.6x7.5 = 4.5	0.0034 x (7.5 x 400 + 4.5 x 2000) = 41

The EENS is 325 + 344 + 41 = 710 MWh

The capacity of the network (y) to achieve the same level of EENS:
$(7.5\text{-}y) \times 400 = 710$
$\Leftrightarrow 3000 - 400\,y = 710$
$\Leftrightarrow y = 5.7$ MW
Effective capacity value of DG1, DG2 and DG3 is 5.7 MW
The network capacity value (in term of % of installed capacity) is 5.7/7.5 = 76%

