IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2010

EEE PART IV: MEng and ACGI

SUSTAINABLE ELECTRICAL SYSTEMS

Thursday, 29 April 2:30 pm

Time allowed: 3:00 hours

Corrected Copy

G4

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

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) Describe the relevance of the Betz limit to a discussion of wind turbine design effectiveness. [3]

(ii) Describe why it is important for a wind turbine to be able to operate at a range of rotational speeds. [3]

(iii) Wind turbines often have two control regions: an optimal power region and a limited power region. Explain the reasoning in favour of having a limited power region. [3]

(b) A survey of a potential wind turbine site has yielded the wind speed data given in Table Q1.1. The choice has been made to use a turbine with a swept area of 5,000 m^2. A manufacturer offers two such turbines equipped with two different electrical generators: one with a maximum power of 1.5 MW and one with a maximum power of 2.0 MW. In each case, the turbine has a C_p value (at zero pitch) of 0.47, 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) Calculate expected energy yield per annum in MWh for each wind turbine design. [9]

(ii) Calculate the revenue per annum from the 1.5 MW turbine and the additional revenue for the 2.0 MW turbine if the selling price for wind energy (including any subsidy) is 60 £/MWh [2]

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 Q1.1 Annual distribution of wind speed at test site

2.

(a) In order to determine the potential of a solar installation, data about the energy available from the sun throughout the year is gathered at the proposed location. This data is often recorded in terms of *insolation* and *solar irradiation.*

(i) Explain the difference between the terms *insolation* and *solar irradiation.* [2]

(ii) Explain why it is beneficial for a PV panel to be adjusted to track the position of the sun throughout the day. [2]

(b) Figure Q2.2 shows the equivalent model of a photovoltaic cell. Explain the presence of each of the components in the model and the effect that each has on the operation of the cell and the output characteristic. [4]

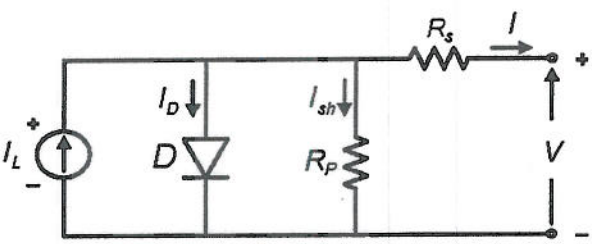

Figure Q2.2: Equivalent model of a PV cell

(c) Figure Q2.1 shows the output characteristic of a PV cell

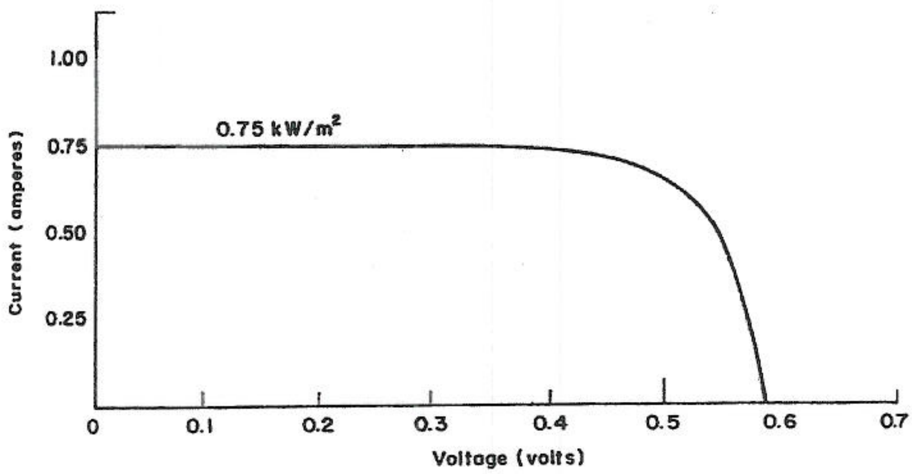

Figure Q2.1: Output characteristic of a PV Cell

(i) Define the open-circuit voltage of a cell and explain the creation of the open-circuit voltage in terms of the *photovoltaic effect*. [4]

(ii) State how the *short circuit current* and *open circuit voltage* would vary if the *irradiance* doubled to 1.5 kW/m^2. [1]

continued overleaf

(iii)	State how an increase in temperature would affect the output characteristic.	[1]
(iv)	For the cell characteristic shown in Figure Q2.1, identify the approximate coordinates (in terms of voltage and current) for the maximum power point of the cell and calculate the corresponding power.	[2]
(v)	Describe a simple "Perturb and Observe" Maximum Power Point Tracking algorithm including a discussion of any undesirable characteristics. Illustrate the operation of the algorithm assuming a starting point at the open-circuit voltage of the cell and constant irradiance.	[4]

3.

(a)

(i) Describe a simple *Ebb Generation* tidal barrage electricity generation system. [3]

(ii) Describe how can pumping be used to enhance the operation of an ebb generation tidal barrage. [2]

(iii) Explain why ebb generation schemes more effective than flood generation schemes. [2]

(b)

(i) Compare the benefits and disadvantages of tidal stream electricity generating devices and tidal barrage installations. [3]

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

(iii) 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]

(c) Existing off-shore wind farms around the UK coastline have been connected with conventional AC cables. Explain why HVDC links are being considered for connection of future offshore wind farms and explain why voltage-source rather than current-source HVDC might be preferred. [6]

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Section B

4. The emissions performance of a power system supplied by a range of generation technologies is given in Table Q4.1.

Source	Penetration (%)	Electricity-related emission factor [kg_{CO2}/kWh_e]
Nuclear and Renewables	10	0
Oil	15	0.750
Coal	40	0.950
Gas	35	0.500
Network losses (%)	7	

Table Q4.1. Emissions factors and network losses

(a) Calculate the average electricity-related emission factor $\mu_{CO_2}^{ESP}$ of the power system for the overall energy mix given in Table 4.1. ($\mu_{CO_2}^{ESP}$ should refer to the unit of electricity delivered to the end user taking into account the electrical network losses.) [5]

(b) An energy service company has decided to install a CHP (Combined Heat and Power) system to supply the electrical and thermal needs of a block of buildings. The CHP system consists of a natural-gas-fuelled internal combustion engine that is connected to the electrical distribution network. The rated characteristics (referred to an hour of operation) of the CHP engine are given in Table Q4.2.

Electrical output W [kWh_e]	80
Thermal output Q [kWh_t]	150
Fuel input F [kWh_F]	300
Fuel-related emission factor $\mu_{CO_2}^{F}$ [kg_{CO2}/kWh_F]	0.200

Table Q4.2. Characteristics of the cogeneration engine

Currently, the heat for the buildings is produced by boilers with an average heat output-related emission factor $\mu_{CO_2}^{TSP}$ (thermal separate production) estimated to be 0.260 kg_{CO2}/kWh_t (including heat distribution losses).

Continued overleaf

(i) Estimate the reduction in CO_2 emission that the CHP system could achieve with respect to separate production of electricity and heat when operating at the ratings given in Table Q4.2 (expressed as a percentage of the overall emissions from the separate production). [5]

(ii) Repeat the estimate of the reduction in CO_2 emission achieved by the CHP system against more modern separate production technologies. Electricity is produced by combined-cycle gas turbines, with an electricity output related emission factor of $\mu_{CO_2}^{ESP} = \cancel{400}$ 0.4 kg_{CO2}/kWh_e (this emission factor already takes into account electrical network losses). Heat is produced in a condensation boiler with a heat output-related emission factor $\mu_{CO_2}^{TSP} = \cancel{220}$ 0.22 kg_{CO2}/kWh_t (this emissions factor already takes into account heat distribution losses). [5]

(iii) Compare and discuss the results from cases (i) and (ii). [5]

5.

(a) Explain why the installed generation capacity should exceed peak demand in a power system and explain how the optimal level of capacity margin should be determined. [5]

(b) Consider a power system that has a peak demand of 600 MW and has 3 conventional generators each of 300 MW and each with an availability of 90%.

(i) Form a capacity outage probability table and calculate the probability that the generators will not be able to meet peak demand (i.e., the loss of load probability, LOLP). [5]

(ii) A wind farm of 600 MW is added to the system. Calculate the improvement in LOLP. The probability of various levels of power output from the wind farm during peak demand is given in the Table Q5.1. Determine whether it is possible to de-commission one of the conventional generators given the addition of the wind farm, if the maximum acceptable level of LOLP should not exceed 7%. [10]

Wind Power Output [MW]	Probability
600	0.2
300	0.5
0	0.3

Table Q5.1 Wind power output probabilities

6.

(a) An increased penetration of variable and unpredictable wind power will place an additional duty on the remaining generating plant with respect to balancing supply and demand. Discuss the provision of reserve generation in a system with increased wind generation. You should include the following topics: what will determine the amount of the various forms of reserve; what are the cost implications of the new reserve; what determines the magnitude of these costs and how might the reserve requirements limit the ability of the system to absorb wind. [8]

(b) It is proposed to connect 25 GW of wind generation to a power system in which demand varies between a minimum of 18 GW and a peak of 58 GW. The generation mix of the system is composed of inflexible nuclear plant of installed capacity of 5 GW and flexible Combined Cycle Gas Turbine (CCGT) plant with characteristics presented in Table Q6.1.

Rating of each unit [MW]	Minimum stable generation (MSG) [MW]	Marginal cost at full output [£/MWh]	CO_2 emissions at full power output [tonnes/MWh]	Loss in efficiency when run at MSG [%]
500	300	60	0.42	20

Table Q6.1 CCGT characteristics

Consider the balancing of this system during minimum and maximum loading conditions for a wind generation output of 12 GW. Assume that all 5 GW of the nuclear generation is running at all times. Further assume that in order to cover the uncertainty in wind power output, the system operator decides to schedule 3,600 MW of reserve to be provided by part-loading synchronised CCGTs.

(i) Determine the minimum number of flexible generators that need to run to provide the reserve required and state their power output. [4]

(ii) Determine the cost per hour of providing this reserve. [3]

(iii) Determine the additional CO_2 emitted per hour due to the need to provide reserve. [2]

(iv) Calculate the amount of wind power that may need to be curtailed in both the minimum and maximum system loading conditions. [3]

E4.50

Answers 2010

1.

(a)

(i) Describe the relevance of the Betz limit to the discussion of wind turbine design effectiveness. [3]

The Betz limit expresses what fraction of the kinetic energy of an air stream can be extracted by an ideal turbine (or similar device). That fraction is 16/27 (=59%). A limit exists because the power extracted depends on the product of velocity and force. These two factors are linked and increasing the force extracted by the turbine too far causes too much reduction in velocity. A practical turbine operated below the Betz limit because of imperfection of the blade aerodynamics, tower effects and the power losses in the drive train.

(ii) Describe why it is important for a wind turbine to be able to operate at a range of rotational speeds. [3]

The lift force created by a blade depends on the angle of attack. The flow over the blade of a turbine is composed of two perpendicular components: one due to the wind and one due to the rotation of the blade through the air. To ensure that the blade operates at the optimal angle of attack, the ratio of these two components needs to be preserved. Thus, if the wind speed increase, the turbine rotational speed should increase proportionally. This is normally expressed as maintaining a constant tip speed ratio. Students might draw Cp against tip speed curves or a family of Cp against rotational speed curves to illustrate.

(iii) Wind turbines often have two control regions: an optimal power region and a limited power region. Explain the reasoning in favour of having a limited power region. [3]

The main task of a wind turbine controller would seem to be to control the speed of the turbine to operate at the tip-speed ratio that gives the maximum power (maximum Cp). This is a process of optimising the power for the prevailing wind speed. This is not attempted at all wind speeds. Although high wind speeds give greater power (following a cubic law), wind speeds above about 12 m/s only occur for a relatively small fraction of the time and therefore do not large amounts of energy. To capture this energy requires all elements of the drive train to be rated for a high power. It is more economic to rate the drive train for a power that exists for wind around 12 m/s and above that pitch the turbine blades to take a limited amount of power that matches the drive train. This is a trade-off between additional energy revenue and capital cost.

(b) A survey of a potential wind turbine site has yielded the wind speed data given in Table Q1.1. The choice has been made to use a turbine with a swept area of 5,000 m^3. A manufacturer offers two such turbines equipped with two different electrical generators: one with a maximum power of 1.5 MW and one with a maximum power of 2.0 MW. In each case, the turbine has a C_p value (at zero pitch) of 0.47, 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) Calculate expected energy yield per annum in MWh for each wind turbine design. [9]

(ii) Calculate the revenue per annum from the 1.5 MW turbine and the additional revenue for the 2.0 MW turbine if the selling price for wind energy (including any subsidy) is 60 £/MWh [2]

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 Q1.1 Annual distribution of wind speed at test site

The power yield of a turbine is

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

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. [4]

For a 1.5 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	0.134	401
6 - 9	7.5	2,300	0.620	1,426
9 - 12	10.5	500	1.500	750
12 -24	18	900	1.500	1,350
> 24		100	0	0

Total Energy is 3,927 MWh [3]

For a 2.0 MW turbine only two cases need to be re-examined

Wind Speed Range (m/s)	Centre of Range (m/s)	Duration per annum (h)	Capped Power (MW)	Energy (MWh)
9 - 12	10.5	500	1.701	850
12 -24	18	900	2.000	1,800

Total Energy is 4,479 MWh [2]

The revenue for the 1.5 MW turbine is £235k per annum and the additional revenue for the ".0 MW turbine is £33k [2]

2.

(a) In order to determine the potential of a solar installation, data about the energy available from the sun throughout the year is gathered at the proposed location. This data is often recorded in terms of *insolation* and *solar irradiation.*

(i) Explain the difference between the terms *insolation* and *solar irradiation.* [2]

Insolation is an abbreviation of the term "Incident Solar radiation" and is a measure of the average energy flux on a unit area perpendicular to the beam, measured in W/m^2.

Solar irradiation is the energy delivered to a particular location over a particular time, measured in Joules (J/m^2 or Wh/m^2); it is essentially the integral of *insolation* over time.

(ii) Explain why it is beneficial for a PV panel to be adjusted to track the position of the sun throughout the day. [2]

Because the total energy collected by a solar panel is proportional to the area of that solar panel presented perpendicular to the beam, as the sun moves around the sky, the effective area of the solar panel presented to the beam changes. In order to achieve maximum power, the solar panel should be arranged so that the solar radiation arrives perpendicular to the surface of the panel at all times.

(b) Figure Q2.2 shows the equivalent model of a photovoltaic cell. Explain the presence of each of the components in the model and the effect that each has on the operation of the cell and the output characteristic. [4]

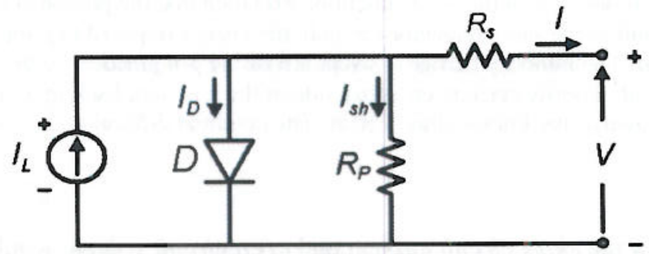


Figure Q2.2: Equivalent model of a PV cell

- I_L is the photo current generated in the cell by the absorption of photons of light; it is equal to the short circuit current on the cell characteristic.
- D is included because a PV cell is structurally similar to a reverse biased diode and hence a diode current will flow. As the output voltage increases, the diode current also increases, reducing the output current of the cell. Note that this is not an ideal diode as often used in electrical analysis; it must have the more detailed exponential characteristic.
- R_p is the shunt resistance due to imperfections in the crystal lattice creating parallel paths for the current. It is usually high, however, the effect is to reduce the output current.
- R_s is the series resistance of the cell due to such things as contact resistance, the resistance between the contacts and the silicon and also the resistance of the cell material itself. It is usually low, however, the effect is to reduce the output voltage.

(c) Figure Q2.1 shows the output characteristic of a PV cell.

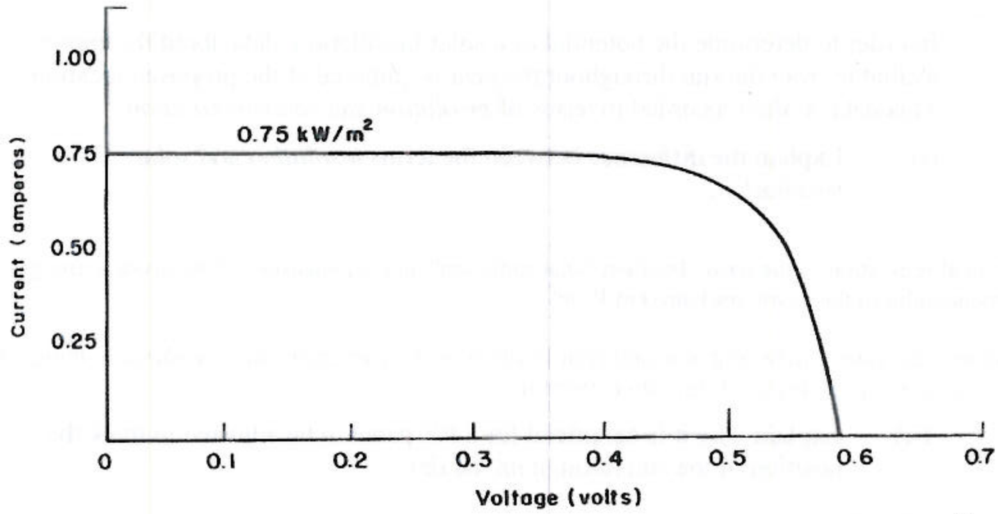


Figure Q2.1: Output characteristic of a PV cell at an irradiance of 0.75 kW/m^2

(i) Define the open-circuit voltage of a cell and explain the creation of the open-circuit voltage in terms of the *photovoltaic effect*. [4]

The open circuit voltage is the voltage measured across the cell terminals when no current flows; in this case it is equal to 0.6V.

When a photon of light is absorbed on one side of the a p-n junction. provided that the photon contains enough energy, an electron in the valence band of the semiconductor can gain the energy required to jump to the conduction band, producing an electron hole pair. The minority carrier is swept across the p-n junction by the action of the electric field, increasing the number of majority carriers on either side of the junction, leading to a potential difference across the cell. This is known as the Photovoltaic Effect. The potential difference across the cell can be used to do useful work.

(ii) State how the *short circuit current* and *open circuit voltage* would vary if the *irradiance* was doubled to 1.5kW/m^2? [1]

The short circuit current would also double to 1.5A, however, the open circuit voltage would decrease by a very small amount

(iii) State how an increase in temperature would affect the output characteristic. [1]

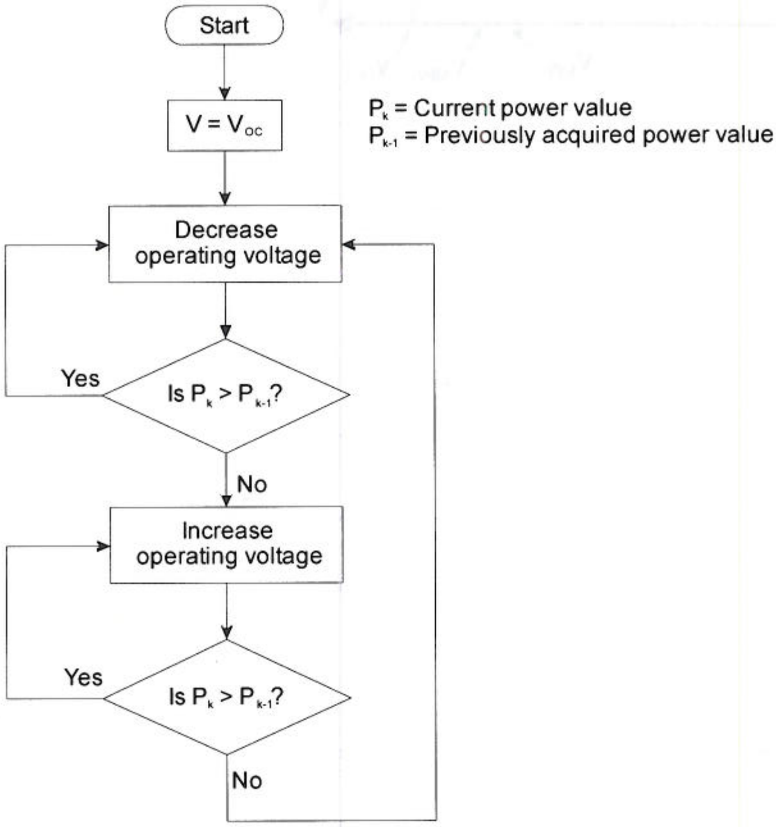
If the temperature were to increase, the short circuit current would be essentially unaffected, however the open circuit voltage would be reduced.

(iii) For the cell characteristic shown in Figure Q2.1, identify the approximate coordinates (in terms of voltage and current) for the maximum power point of the cell and calculate the corresponding power. [2]

From inspection of the graph, the voltage is approximately equal to 0.5 V and current is approximately equal to 0.7 A, hence the maximum power is 0.5x0.7 = 0.35W.

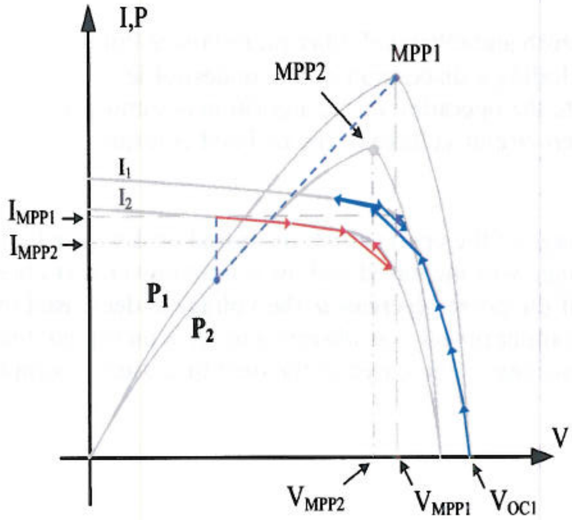
(iv) Describe a simple "Perturb and Observe" Maximum Power Point Tracking algorithm including a discussion of any undesirable characteristics. Illustrate the operation of the algorithm assuming a starting point at the open-circuit voltage of the cell and constant irradiance. [4]

At the start of each time step, the operating voltage of the cell is either increased or decreased and the output power of the cell is examined. If the voltage was increased and the output power was observed to have increased, the voltage is increased again; if the power decreased, the voltage is decreased in the next time step. If the voltage was decreased and the output power was observed to have increased, the voltage is decreased again; if the power decreased, the voltage is increased in the next time step. A simple flow chart is shown below:



Whilst this control strategy is very simple to understand and implement, the output power of the cell is not constant and oscillates slightly around the MPP.

An example of Perturb and Observe is given below. When the algorithm starts, the output voltage is set to V_{OC1}, the current is zero, therefore, the controller decreases the output voltage (blue arrows) until it reaches a point when the output power begins to fall. It then reverses direction in order to increase the voltage again. Eventually, the controller sets up a small oscillation around MPP1.


I,P
MPP1
MPP2
I1
I2
IMPP1
IMPP2
P1
P2
V
VMPP2
VMPP1
VOC1

3.

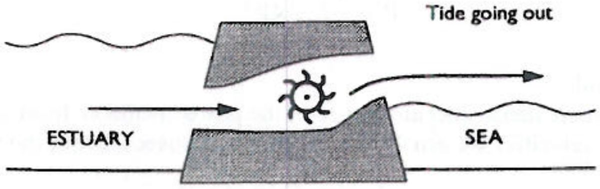
(a)

(i) Describe a simple *Ebb Generation* tidal barrage electricity generation system. [3]

Ebb Generation is where electricity is generated on the ebb tide; the ebb tide is where the ocean flows out after high tide. Ebb generation has the advantage that the turbines are most efficient when they are designed for a single mode of operation.

An *Ebb Generation* scheme consists of a tidal barrage that creates a tidal basin, usually using the natural shape of the shore. An alternative to the tidal barrage is to use tidal lagoons, which are totally artificial constructions set out in the sea to collect the tidal waters.

During the high tide, water is allowed into a barrage-limited reserve without attempting to generate electricity. At the highest level, the reservoir gates are closed and the water is stored in the barrage. The tide recedes and the water is let through water turbines to generate electricity, usually at a point where the water level has reached half the tidal range – see figure below. This is known as a single effect mode of operation.

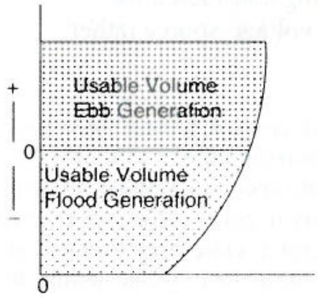


(ii) How can pumping be used to enhance the operation of an *Ebb Generation* tidal barrage. [2]

By pumping water into the tidal basin at high tide, the head available for generation is increased. In this way, the energy from the tides can be time shifted so that it is available at a time that is more in keeping with the demand for electricity.

(iii) Why are ebb generation schemes more effective than flood generation schemes? [2]

Natural tidal basins tend to taper towards the bottom, hence more water is available for generation in the upper half of the tidal basin (and hence tidal range) than in the lower half. On an ebb tide ,the best head applies to the upper volume and energy generation is high. For a flood tide, the best head applies to the lower volume and energy generation is lower.



(b)

(i) Compare the benefits and disadvantages of tidal stream electricity generating devices and tidal barrage installations. [3]

Tidal barrages are very expensive as they require vast civil works; they also require locks to allow the continued flow of river traffic. The changes in flooding of the tidal basin can adversely affect the local ecosystem.

Tidal stream devices require little or no civil works beyond their own foundations, as such, they are cheaper to install and have less effect on shipping. However, they are also of environmental concern as their effect on aquatic wild life has not been studied in great depth. They also require some form of marine power connection.

(ii) 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.

(iii) 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

(c) Existing off-shore windfarms around the UK coastline have been connected with conventional AC cables. Explain why HVDC links are being considered for connection of future offshore windfarms and explain why voltage-source rather than current-source HVDC might be preferred. [6]

- Cables have significant capacitance per unit length and as cable length is increased, greater current is drawn by the capacitance of the cable (if operated on AC) and less of the cable current rating is available for transfer of real power along the cable. This problem is also worsen as cable operating voltage is raised.
- Thus, as wind farms get larger and further from shore it becomes necessary to either compensate the cable reactive current or use DC and avoid current flow in the capacitance (except at switch on). Compensating a subsea cable would require offshore (platform) substations and STATCOMS at intermediate points. It is more convenient and cost effective to use AC.

- Current-source (line-commutated) AC/DC power converters require a stiff AC voltage to be present to achieve commutation. This is not present at an offshore site. Further, it will not be possible to "black-start" an offshore site via a CSC HVDC link. A VSC (self-commutated) HVDC link can black-start the windfarm and run with a weak AC voltage source.
- VSC HVDC at the onshore end of the link can provide additional reactive power service to AC network which CSC can not.
- VSC power converter are capable of independently controlling power injection/extraction in a multi-terminal DC network that might be required for redundancy in offshore connections

Model Answer to Question 4

(a) 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:

$$\mu_{CO_2}^{ESP} = \frac{0.10 \cdot 0 + 0.15 \cdot 0.750 + 0.40 \cdot 0.95 + 0.35 \cdot 0.50}{(1 - 0.07)} = 0.718 \ \text{kg}_{\text{CO2}}/\text{kWh}_\text{e}$$

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

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

(i) Hence, from the data provided for the CHP engine characteristics and the boiler emission factor, we have for *Case 1*

$$CO2ER\% = \left(1 - \frac{0.20 \cdot 300}{0.718 \cdot 80 + 0.260 \cdot 150}\right) \cdot 100 = 37.8\%$$

which is the emission reduction from the CHP system when operating under rated conditions.

(ii) For (*Case 2*), considering the improvements in terms of reference emission factors for the separate production of electricity and heat, the new emission reduction becomes

$$CO2ER\% = \left(1 - \frac{0.20 \cdot 300}{0.400 \cdot 80 + 0.220 \cdot 150}\right) \cdot 100 = 7.7\%$$

That is, the cogeneration benefit is now substantially less.

(iii) These answers highlight the main variables involved in the cogeneration assessment, and in particular how the separate production benchmark characteristics play a key role. In this regard, it can be appreciated how excellent environmental benefits brought by small scale CHP systems can arise when compared to a relatively highly carbon intense power system (*Case 1*); on the other hand, such benefits would decrease significantly if state of the art technologies are considered as separate production references (*Case 2*).

Model Answer to Question 5

(a)
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 capacity margin represents the magnitude of installed electricity generating capacity above system peak demand. The optimal 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. Often a number of proxies are used, such as risk measured through various reliability criteria such as loss of load probability index (LOLP). This index can be interpreted as the probability of annual peak demand exceeding the available generation (risk of supply deficits).

(b)

(i) The capacity outage probability table for the generation system composed of 3x300MW conventional generators is presented in Table 1. State probabilities can be determined by the application of the binomial distribution to each capacity in service state:

$$P_{Ci} = (C_x^n).p^x.(1-p)^{n-x}$$

Where:

P_{Ci}: is the probability of state i with capacity in service C
n: is the total number of conventional generating units
x: number of units in service of the state i with capacity in service C
p: is the availability of the conventional generating unit
(1-p): is the unavailability of the conventional generating unit

The state cumulative probabilities are determined by summing up the individual state probabilities starting from the 0MW capacity in service state up to 900MW capacity in service state.

Table 1. Capacity outage probability table (COPT) of 3x300MW conventional generator

State No.	Capacity In Service (MW)	Demand (MW)	State Margin (MW)	State Probability	State Cumulative Probability
1	900	600	300	0.729	1
2	600	600	0	0.243	0.271
3	300	600	-300	0.027	0.028
4	0	600	-600	0.001	0.001

Loss of load probability represents the probability of the annual peak demand exceeding the available generation. Therefore for a system with a peak demand of 600MW the loss of load probability is equal to 2.8%. This represents the cumulative probability of the first negative state margin.

(ii) The COPT for the generation system mix is shown in the table below.

Table of COPT for 3x300MW conventional generator plus 600MW wind farm

State No.	Capacity In Service (MW)	Demand (MW)	State Margin (MW)	State Probability	State Cumulative Probability
1	1500	600	900	0.1458	1
2	1200	600	600	0.4131	0.8542
3	900	600	300	0.3456	0.4411
4	600	600	0	0.0866	0.0955
5	300	600	-300	0.0086	0.0089
6	0	600	-600	0.0003	0.0003

With the addition of a 600MW wind farm the system loss of load probability decreases from 2.8% to 0.89% in order to supply the system with 600MW peak demand.

One conventional generating unit is retired from the system and the COPT recalculated.

Generation system: 2x300MW conventional generator

State No.	Capacity In Service (MW)	Demand (MW)	State Margin (MW)	State Probability	State Cumulative Probability
1	600	600	0	0.81	1
2	300	600	-300	0.18	0.19
3	0	600	-600	0.01	0.01

Generation system: 2x300MW conventional generator plus 600MW wind farm

State No.	Capacity In Service (MW)	Demand (MW)	State Margin (MW)	State Probability	State Cumulative Probability
1	1200	600	600	0.162	1
2	900	600	300	0.441	0.838
3	600	600	0	0.335	0.397
4	300	600	-300	0.059	0.062
5	0	600	-600	0.003	0.003

For a system with a peak demand of 600MW the loss of load probability is equal to 6.2% and therefore below the 7% limit. Hence, it is possible to decommission one of the conventional generators.

Model Answer to Question 6

(a)
Uncertainty in wind forecast becomes a source of additional balancing requirements which can be fairly substantial in magnitude. Wind forecast timescales 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") timescales, the dominant variability factor is the potential loss of conventional plant, not fluctuations in wind power. Reserve requirements are concerned with the wind forecast uncertainty over longer time scales of minutes to hours. Wind forecast techniques vary for different time scales. For longer horizons beyond several hours, forecasts based on meteorological information are preferred. For short-term forecasts, up to several hours ahead, meteorological methods are out-performed by various statistical techniques.

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. 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.

(b)

(i) 3,600 MW of reserve is required. Each CCGT unit operated at MSG provides 200 MW of reserve. Thus 18 units are required. These units produce 18x300 = 5,400 MW

(ii) Cost is determined from loss of efficiency when running CCGT at MSG, that is,
0.2x60x3,600 = 43,200 £/h

(iii) Additional CO_2 emissions also found from loss of efficiency
0.2x0.42x3600 = 302.4 t/h

(iv) Nuclear generation is 5 GW
CCGT for reserve given MSG is 5.4GW
Minimum conventional generation is 10.4 GW

Minimum Demand is 18 GW

Net demand to be served by wind at minimum demand is 7.6 GW
Wind power available is 12 GW
Wind power curtailed at minimum demand is 12 GW - 7.6 GW = 4.4 GW

Maximum Demand is 58 GW
Net demand to be served by wind at maximum demand is 47.6 GW
Wind power available is 12 GW
Net demand exceeds available wind so no curtailment necessary.