IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2009

EEE PART IV: MEng and ACGI

SUSTAINABLE ELECTRICAL SYSTEMS

Corrected Copy

Thursday, 30 April 2:30 pm

Time allowed: 3:00 hours

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

Section A

1.

(a) Explain why a wind turbine can not capture all of the kinetic energy in an air flow. Describe the Betz limit of a wind turbine and explain its importance. [4]

(b) The frequency (in hours per year) with which particular wind speeds occur at a site approximates a Wiebull distribution. Sketch graphs of approximate shape of frequency of occurrence against wind speed. Sketch also the available wind energy per year against wind speed. [4]

(c) Figure Q1 shows the power that a particular wind turbine can produce as a function of wind speed. Explain its shape. [4]

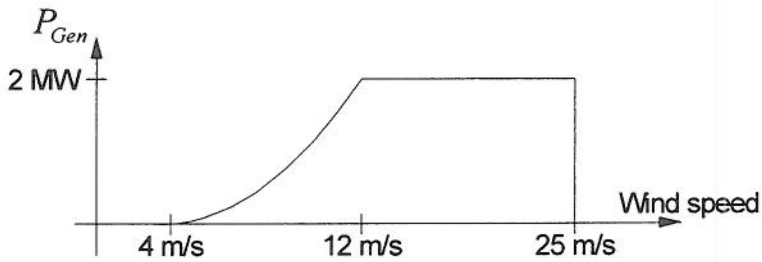


Figure Q1

(d) The blades of a turbine sweep an area of 3,800 m^2 and the turbine is connected to a generator rated at 1 MW. Choose a realistic value for the power coefficient of the turbine and estimate the wind speed at which the turbine reaches its power limit. Air density can be taken as 1.2 kg/m^3 [4]

(e) The "full-converter" and "doubly-fed induction generator" are two categories of variable speed wind turbine. Compare and contrast these designs. [4]

2.

(a) Describe the structure and operating principle of a photovoltaic, PV, cell. Explain why the cell is not perfectly efficient and give an approximate figure for cell efficiency. [8]

(b) Discuss the factors that affect how much light energy falls on a PV panel. [5]

(c) Describe the "maximum power point" of a photovoltaic panel and explain why this point needs to be tracked during operation. [5]

(d) PV panels are sometimes placed in series or parallel to provide higher voltages and currents. Explain what problem may arise from such series and parallel arrays. [2]

3.

(a) It is sometimes argued that distributed generation will reduce the need for transmission and distribution networks and that the future system will only need connections between local generators and loads. Discuss the extent to which this may be true. [5]

(b) Distributed generation raises a number of concerns for network operators that need to be addressed. For each of the following, explain the nature of the problem and the measures that may be agreed to overcome the network operators concerns.

(i) Voltage rise, [3]

(ii) Islanding, [3]

(iii) Congestion. [3]

(c) Consider a system with 25 GW of installed wind capacity, 9 GW of inflexible nuclear plant and 40 GW of flexible CCGT plant. The CCGT is composed of units rated at 500 MW with a minimum stable generation of 300 MW.

Operation of this system is to be considered under a particular condition which is with the output of the wind generation at 12 GW. In order to cover the uncertainty in wind power output, the system operator decides to schedule 3.6 GW of reserve by part-loading synchronised CCGT plant.

(i) Determine the minimum number of flexible generators that need to run to provide the reserve required. [2]

(ii) Determine the power output of the part-loaded plant. [2]

(iii) Calculate the maximum amount of wind power that the system can be absorb under a minimum summer loading of 22 GW and with 2 GW of nuclear generation being on annual maintenance outage. [2]

Section B

4.

(a) Explain the philosophy of the historical distribution network design by considering the relationship between the amount of peak demand that can be disconnected (lost) due to network outages and the allowed time to restore it. Sketch this relationship and indicate how the level of redundancy changes with the level of peak demand to be supplied. [5]

(b) Why is it important to consider the contribution that distributed generation can make to distribution network security? How might this contribution impact the competitiveness of distributed generation? [5]

(c) Busbar Balcombe will be a new supply hub for several villages in West Sussex. EDF Energy engineers plan to connect Balcombe to the main grid through a 5 km, 33 kV overhead distribution circuit. There are also 2 identical landfill gas based distributed generators of 5MW capacity each connected to Balcombe, as shown in the figure Q4.1. The winter profile of the load connected to Balcombe Busbar is shown in figure Q4.2.

(i) If the availability of individual generating units is 90%, show that the contribution of the generators to network capacity is 7.8MW and calculate the optimal network capacity to secure demand. (The contribution of generation to network security is defined as the equivalent capacity of a perfectly reliable circuit that would produce the same expected energy-not-supplied) [5]

(ii) If the marginal cost of the circuit is 300 £/MW.km.year, calculate distribution network use of system charges for demand and generation during on and off peak. What annual revenue will these charges generate? [5]

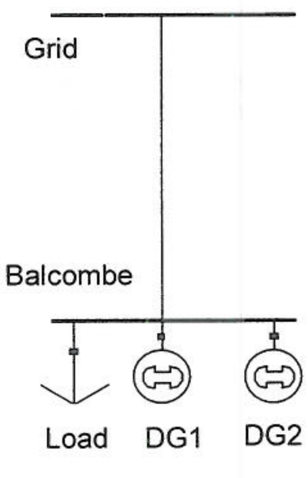


Figure Q4.1

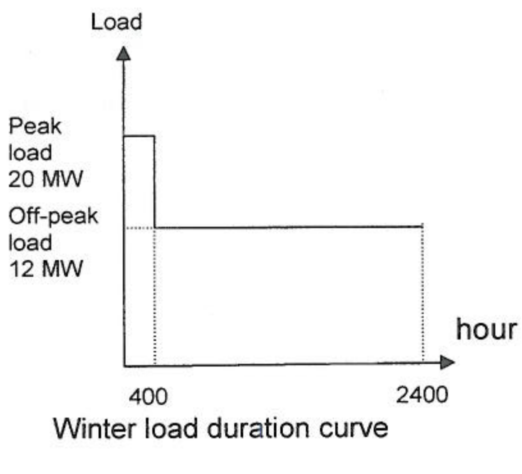


Figure Q4.2

5.

(a) What factors could limit the connection of Distributed Generators to urban and rural distribution networks respectively? [4]

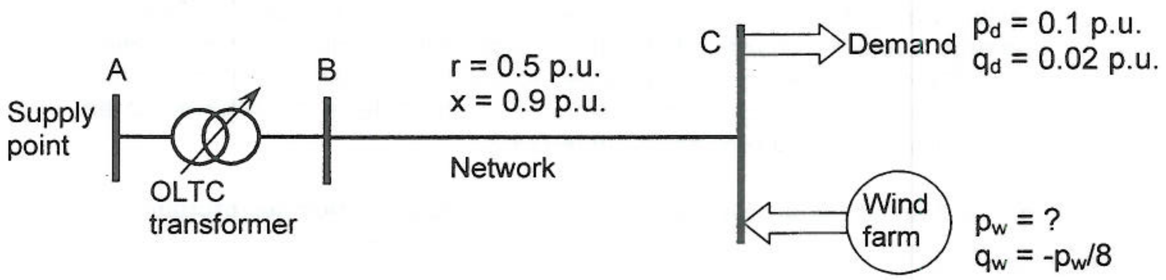
(b) What techniques can be applied to enhance the ability of the existing network to accommodate increased capacity of distributed generation? [5]

(c) Wind farm developer "West Sussex Wind" has applied for a connection of a wind farm to EDF Energy. In order to facilitate this connection, EDF Energy engineers need to investigate the voltage rise effect that might occur on the network presented in figure Q5. The On Load Tap Changing (OLTC) transformer is currently set to maintain the voltage at busbar B at 1.03 p.u. The minimum demand at the connection point (busbar C) is 10% of the maximum demand. As shown in Figure Q5, the wind farm will consume reactive power in proportion to the real power it generates.

(i) Estimate the amount of wind generation that "West Sussex Wind" could connect to the network if the allowable voltage variation in the network is +/- 6%. [6]

(ii) What would be the maximum amount of generation that "West Sussex Wind" could connect if a reactor of 0.01 p.u. is also connected to busbar C. [3]

(iii) In order to increase further the amount of generation that can connected to the network, EDF engineers are considering modifying the control set point of OLTC to 1.01 p.u. How much more generation capacity would it be possible to connect? [2]



(Base power is 100MVA)

Figure Q5

6.

(a) Explain how a distributed energy system may achieve higher energy efficiency than a centralised one. [5]

(b) Discuss the impact of diversity of demand on the size of the system and on the generation capacity needed to supply it. [5]

(c) A country wishes to reduce environmental impact of its generation mix. Table Q6.1 summarises the present (2009) and estimated future (2015) penetrations of different technologies and the relevant electricity-related CO_2 emission factors; the estimated average electrical transmission and distribution losses for the two cases are also presented. Calculate the average overall electricity-related emission factor $\mu_{CO_2}^{ESP}$ (referred to the unit of electricity delivered to the LV user) in the two scenarios. [5]

Table Q6.1 Centralized electrical generation characteristics for different scenarios

Source	*2009*	*2015*	*Electricity-related emission factor*
	Penetration (%)	*Penetration (%)*	*[kg_{CO2}/kWh_e]*
Nuclear and Renewables	35	40	0
Oil	5	0	0.700
Coal	25	15	0.950
Gas	30	30	0.450
Distributed Generation	5	15	0.500
Network losses (%)	*8*	*6*	

(d) A small factory in Balcombe has decided to install on its premises a distributed generator to satisfy its electricity and heat needs. The selected energy system consists of a natural gas-fuelled CHP (Combined Heat and Power) microturbine, connected to the LV busbar of the distribution transformer that supplies the factory. The characteristics (referred to an hour of operation) are given in Table Q6.2.

Table Q6.2 Rated characteristics of the considered cogeneration microturbine

Electrical output *W*	[kWh_e]	30
Thermal output *Q*	[kWh_t]	50
Fuel input *F*	[kWh_F]	100
Fuel-related emission factor $\mu_{CO_2}^{F}$	[kg_{CO2}/kWh_F]	0.200

It has been estimated that the average heat output-related emission factor $\mu_{CO_2}^{TSP}$ for separate heat generation is currently equal to $0.280 kg_{CO2}/kWh_t$ but it is expected to drop to $0.250\ kg_{CO2}/kWh_t$ by 2020. Assume that the average overall electricity-related emission factors at present and in 2020 are estimated to be at 0.47 kg_{CO2}/kWh_e and $0.37 kg_{CO2}/kWh_e$ respectively.

Use this information on heat generation in boilers and the information on average centralised electrical production (including network losses) given in Table Q6.1 to estimate the average emissions reduction (in % of the overall emissions from separate production) in the following two scenarios:

- the CHP system operating at full load in 2009;
- the CHP system operating at full load in 2020 taking into account that, due to aging, the fuel emission factor will have increased by 15% and the electrical output will have decreased by 5%.

Compare and comment on the CHP results from the two scenarios. [5]

SOLUTIONS 2009

E 4.50 Sustainable Energy Systems

Section A

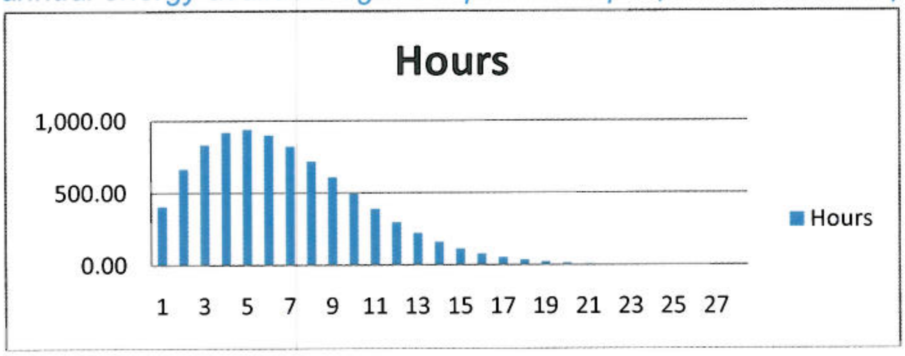
1.

(a) Explain why a wind turbine can not capture all of the kinetic energy in an air flow. Describe the Betz limit of a wind turbine and explain its importance. [4]

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.

(b) The frequency (in hours per year) with which particular wind speeds occur at a site approximates a Wiebull distribution. Sketch graphs of approximate shape of frequency of occurrence against wind speed. Sketch also the available wind energy per year against wind speed. [4]

[From notes] Graphs of expect duration (hours) against wind speed and expected annual energy available against speed. Shapes, not numbers expected here.



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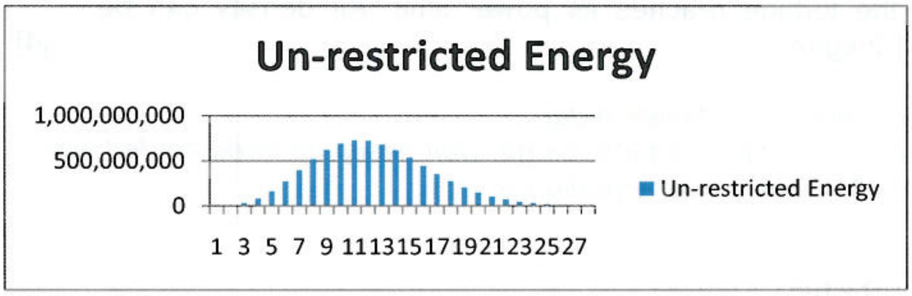


(c) Figure Q1 shows the power that a particular wind turbine can produce as a function of wind speed. Explain its shape. [4]

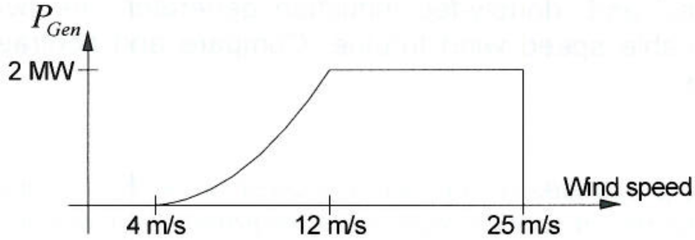


Figure Q1

[Interpretation of notes]

Between 4 m/s and 12 m/s the power is a cubic function of wind speed as expected from the power equation for a fluid flow. In this region, the turbine is run so as to maximise the capture of energy from the flow.

The turbine is seen to cut-in at 4 m/s. Below this wind speed there is little power available and after accounting for the losses in the system and the need to run the auxiliary systems, it is not possible to generate power below this point.

Above 12 m/s the turbine is seen to hold a constant power (probably by pitching the blades). This is because the drive train (gearbox, generator and power converters) have been rated for 2 MW. Above this point, more power could be generated but only at the expense of larger components. Because of the relatively small fraction of time spent operating here, it is not worthwhile rating a turbine for this condition. Above 25 m/s the turbine is cut-out (with the blades feathered and parked) because the limited strength of the structure. This applies for very few hours a year (<100h) and building a stronger structure is not worthwhile.

(d) The blades of a turbine sweep an area of 3,800 m^2 and the turbine is connected to a generator rated at 1 MW. Choose a realistic value for the power coefficient of the turbine and estimate the wind speed at which the turbine reaches its power limit. Air density can be taken as 1.2 kg/m^3 [4]

[Unseen calculation and a need to estimate data]
The Betz limit on wind energy capture is 59%. Large, well-designed three-bladed wind turbines should achieve 45%. The power equation is:

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

$$V^3 = \frac{2P}{C_P \rho A} = \frac{2 \times 10^6}{0.45 \times 1.2 \times 3800} = 975$$

$$V = 9.91 \quad m/s$$

(e) The "full-converter" and "doubly-fed induction generator" are two categories of variable speed wind turbine. Compare and contrast these approaches. [4]

[Interpretation of notes]
The full-converter electronically processes all the turbine power twice, first through a rectifier and then through an inverter in order to achieve a frequency conversion. This allows the generator to operate at any rotational speed and gives complete freedom to optimise the tip-speed ratio for best energy capture.

The DFIG generates a fraction of its power at line frequency and this fraction does not need to be processed through power converters. The other fraction of power is at rotor slip frequency and must under go an AC/DC/AC conversion. The fractional split depends on the slip (normalised speed difference). So, a compromise exists between the allowable speed range and the rating of the power converters. However, a wind turbine can work well on a relatively small speed range. The required range is the cut-in to nominal speed (with speed held constant to cut-out). This needs about a 3:1 range (12 m/s wind to 4 m/s wind). This range gives some saving in costs of power electronics and if the range is narrowed, further cost can be saved.

[4.50]

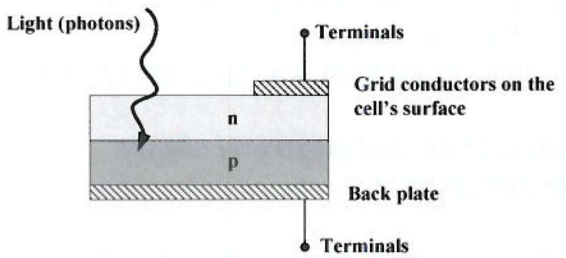
2.

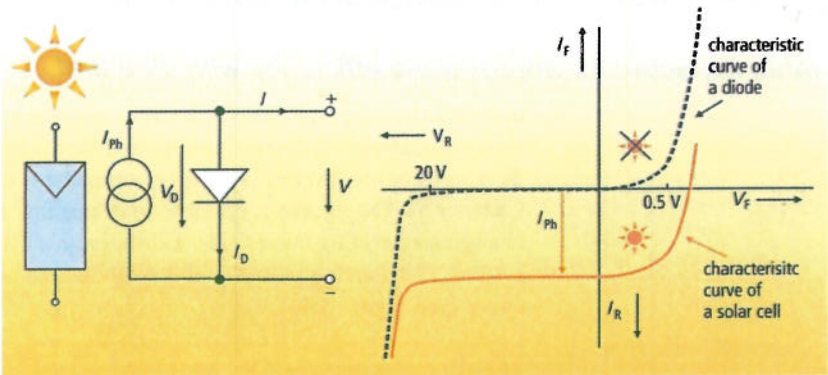
(a) Describe the structure and operating principle of a photovoltaic cell. Explain why the cell is not perfectly efficient and give an approximate figure for cell efficiency. [8]

[Bookwork]

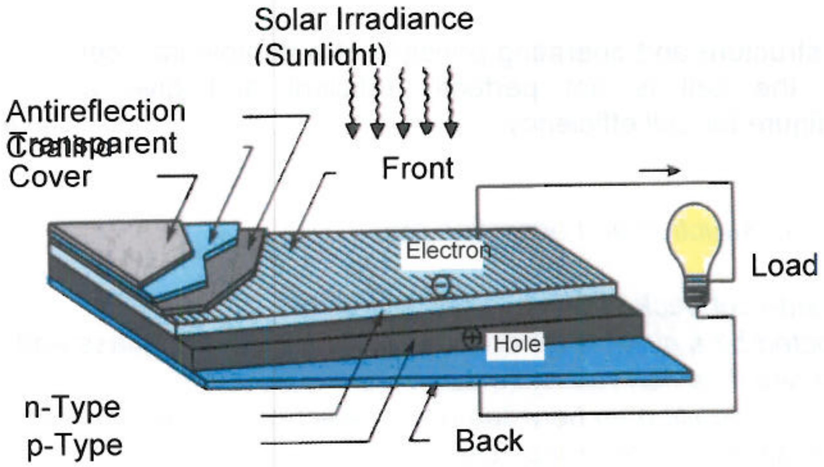
Basic points to be made on construction and operation are:

- *Cell is a pn junction*
- *Metalisation on one side cut back to allow passage of light*
- *The top side is protected by a glass layer and the interface between glass and silicon is treated to make it as non-reflective as possible*
- *Junction in zero bias has equilibrium between drift of electrons under junction potential and diffusion under concentration gradient.*
- *Photons in collision with the lattice are able to promote an electron into conduction band and create hole-electron pair.*
- *Electron swept by potential toward p-type material and hole toward n-type. This is an additional current flow to that of a normal junction and offsets the I/V curve.*
- *If the current is drawn out into a potential difference in an external circuit then work is done.*





[4.50]



The efficiency is affected by many factors some fundamental to the energy conversion and some arising from the construction. Basic points are:

- *Only photons with energy greater than the energy gap of semiconductor are captured, others are lost (to heat or reflection)*
- *Of the captured photons, only the energy equal to the band-gap gives rise to electrical energy, the remainder becomes thermal energy*
- *Multi-junction or quantum-well structures allow more than one band-gap to be provided*
- *Some light is reflected at interface of glass and air and glass and silicon.*
- *Some of the silicon is shaded by top-side metalisation*
- *Some photons pass through the cell*
- *Some electrical energy is lost to heat in the resistance of the semiconductor*

One or two figures from this table expected for approximate efficiency with idea that better cells more expensive.

[4.50]

Cell Type		Cell Efficiency (%)
Crystalline Silicon Cells	Mono-crystalline Cells	15-18
	Poly-crystalline Cells	13-16
	Poly-crystalline Cells (made of poly-crystalline wafers produced by ingot casting)	10
	Poly-crystalline Band Cells	
	i.edge-defined file-fed growth (EFG)	14
	ii.string ribbon	12
	iii.dendritic web	13
	Poly-crystalline Thin-Layer Cells (APex)	9.5
Thin Layer Cells	Amorphous Silicon Cells	5-8
	Copper-Indium Deselenide (CIS)	7.5-9.5
	Cadmium-Telluride Cells (CdTe)	6-9
	Dye Cells	12 (Laboratory test)
	Microcrystalline and Micromorphous Cells	8.5-12

(b) Discuss the factors that affect how much light energy falls on a PV panel. [5]

[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.

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).

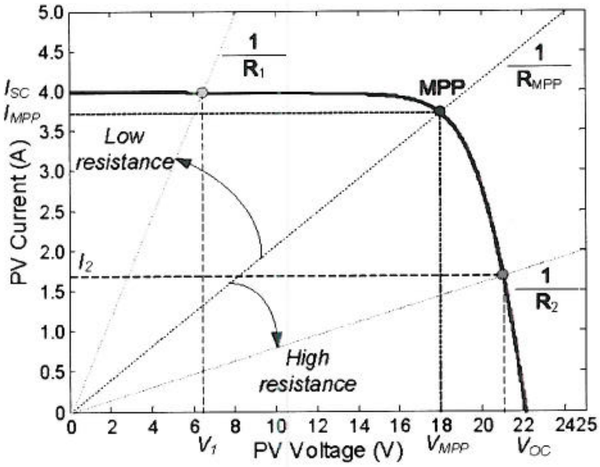
Cloud cover will block direct light but some indirect light will reach the panel. Shadows from buildings may also block light at certain times of day in urban environments.

(c) Describe the "maximum power point" of a photovoltaic panel and explain why this point needs to be tracked during operation. [5]

[Bookwork]

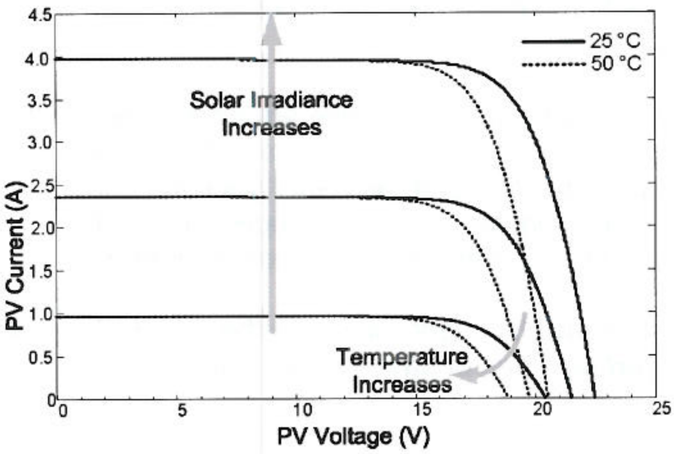
[4.50]

The shape of the I/V characteristic of a cell (or panel) is the exponential diode characteristic offset by a current proportional to the incident light power. The exponential term is temperature dependent.



If the panel operates into a load impedance circuit, then the voltage developed will be low and so too will be the power. If the circuit impedance is too high then as the voltage rises the current will fall steeply and the power will be low. Because V is a function of I in this way, the VI product exhibits a maximum value which is where the cell should be operated.

Because of the dependence of the I/V curve on the light intensity and temperature, the MPP changes during operation of the panel. Open loop prediction of the MPP operating point is impractical and so it is tracked in real-time by a hill climbing search algorithm (commonly a perturb and observe method).



[4.50]

(d) PV panels are sometimes placed in series or parallel to provide higher voltages and currents. Explain what problem may arise from such series and parallel arrays. [2]

[Bookwork]
A large area covered by an array of panels is likely to be affected by partial shading by either cloud fronts or shadows of adjacent buildings. . The shape of the I/V characteristic of a cell (or panel) is the exponential diode characteristic offset by a current proportional to the incident light power. The exponential term is temperature dependent.

Cells/panels in series are constrained to pass the same current which will be the current of the cell with the lowest incident light. This leads to loss of energy capture in the well-illuminated cells. Bypass diodes alleviate some of this problem. Cells/panels in parallel must operate at the same voltage which reduces and may even reverse the current in the less illuminated path. To prevent discharge into the low voltage strong blocking diodes are provided.

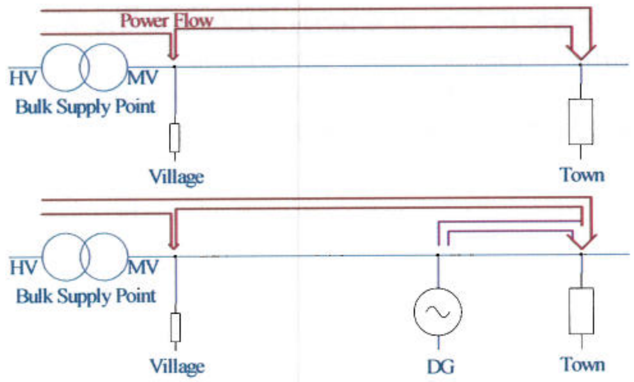
[4.50]

3.

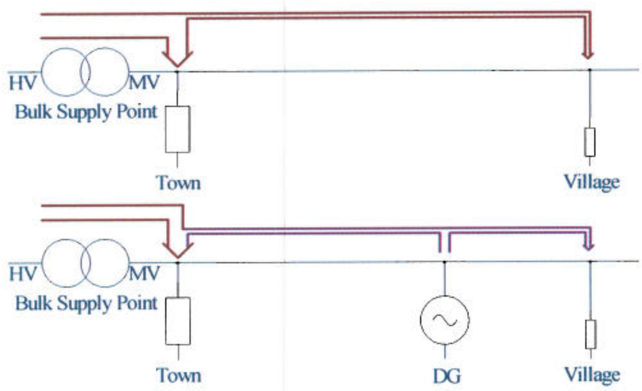
(a) It is sometimes argued that distributed generation will reduce the need for transmission and distribution networks and that the future system will only need connections between local generators and loads. Discuss the extent to which this may be true. [5]

[Bookwork with some fresh interpretation]

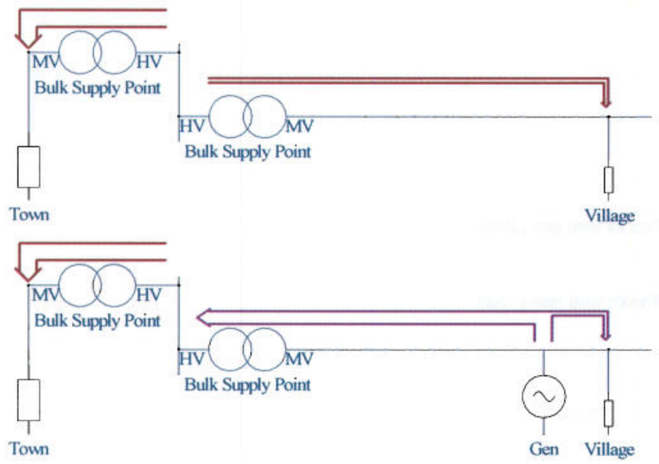
The proposition is illustrated in the first figure: DG close to a load centre reduces the flows through the distribution network (between bulk supply point and load) and reduces flows in transmission network from central generator to bulk supply point.



However, bulk supply points where placed at major load centres such as towns with the feeders running outward to smaller villages. DG such as biomass may be in rural settings which will require power flows back toward towns. Although this is a shorter physical distance than from a central generating plant, the flow is through a relatively low voltage system whereas the central plant will mainly use a more efficient higher voltage. Such a biomass plant will reduce the capacity requirement on transmission but may increase the burden on distribution.



The good sites for on-shore wind farms are upland sites in sparsely populated areas. The power generated will exceed local demand and the excess power *flows in reverse through the bulk supply point so it is exported via the transmission system to another part of the country. Here the DG has not reduced the need for network capacity.*



Micro-generation at household level may be expected to place no burden on the network if the household becomes self sufficient in electrical energy. However, this self-sufficiency is unlikely to be a self-sufficiency at each point in time but rather an average over a year. PV panels will only generate for a few hours around noon when the sun is strong buy demand is low in a household of working people. Export back through the network is needed. This will turn to import during the evening demand peak. The household makes use of the network for import and export services and for security of supply.

(b) Distributed generation raises a number of concerns for network operators that need to be addressed. For each of the following, explain the nature of the problem and the measures that may be agreed to overcome the network operators concerns.

- Voltage rise, [3]
- Islanding, [3]
- Congestion. [3]

Drop in voltage magnitude along a feed given by

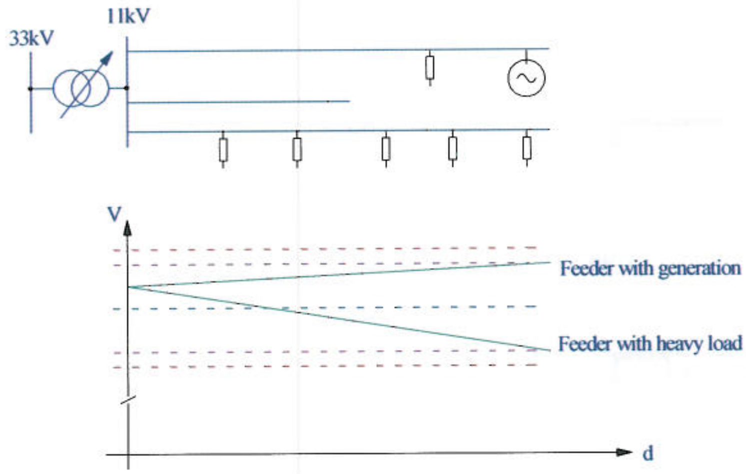
$$\Delta V = |V_1| - |V_2| \approx RI_{12P} - XI_{12Q}$$

$$\approx R\frac{P_2}{V_2} + X\frac{Q_2}{V_2}$$

The real power term is important in low voltage networks where R is similar to X. Reversal of P flow direction in the presence of DG leads to voltage rise rather than drop. If the DG is concentrated on one feeder with load concentrated on another then the voltage rise can not be corrected by tap-changer action and the DG will need to be limited. It may be possible to require the DG to import reactive

[4.50]

power to partially counteract the voltage rise. It may even be possible to require a degree of voltage control from the DG excitation system.



Islands may form when faults are cleared in radial systems. The opening of circuit breakers and isolators may leave some sections of feeder "off supply". With DG present, a voltage will remain. If the load and the generator are approximately matched, the generator may be able to support the load and keep the section "live" for several minutes. Closing a breaker onto this section to reconnect to the distribution system will cause an out-of-phase event and a large fault current. There is also a risk to repair crews from unexpectedly live conductors and a risk to consumer equipment from poorly controlled voltage. For these reasons network operators will insist on rather conservative anti-islanding measures (under/over voltage and current as well as loss-of-mains)

Line and transformer ratings clearly limit the generation that can be accepted without reinforcement work being undertaken. However, if a line or transformer is taken out of service because of a fault, it will become necessary to restrict the access of some DG so as not to overload the remaining network components. This is presently managed through inter-trips that link certain network events to certain generator constraints. However, as the number of DG rises, the number of relevant outages grows also and the combinations of events and responses needed becomes excessively complicated and difficult to design and maintain. A more sophisticated management of constraints in faulted networks is needed based on real time information about generation output, load and network loading. Without such a system in place, it may difficult to connect more DG.

(c) Consider a system with 25 GW of installed wind capacity, 9 GW of inflexible nuclear plant and 40 GW of flexible CCGT, with each unit rated at 500MW and minimum stable generation of 300MW. Operation of this system is to be considered under a particular condition which is with the output of the wind generation at 12 GW. In order to cover the uncertainty in wind power output, the system

[4.50]

operator decides to schedule 3.6GW of reserve by part loading synchronised CCGT plant.

(i) Determine the minimum number of flexible generators that need to run to provide the reserve required. [2]

Each CCGT generator can provide 500-300=200MW of reserve
To provide 3.6 GW of reserve we need 18 generators, 18 x 200 = 3,600MW

(ii) Determine the power output of the part loaded plant. [2]

These 18 generators, running at minimum stable generation will produce 18 x x300MW = 5,400MW

(iii) Calculate the maximum amount of wind power that the system can be absorb under a minimum summer loading of 22 GW and with 2 GW of nuclear generation being on annual maintenance outage. [2]

Generation production: 7 GW nuclear + 5.4GW of CCGT + 12GW of wind = 24.4GW.

Given the minimum demand condition of 22GW, amount of wind that this system can accommodate in this particular condition would be 9.6GW as 2.4GW of wind generation will need to be curtailed

[4.50]

Section B

4.

(a) Explain the philosophy of the historical distribution network design by considering the relationship between the amount of peak demand that can be disconnected (lost) due to network outages and the allowed time to restore it. Sketch this relationship and indicate how the level of redundancy changes with the level of peak demand to be supplied. [5]

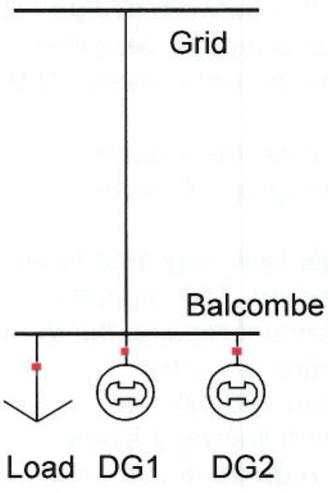
(b) Why is it important to consider the contribution that distributed generation can make to distribution network security? How might this contribution impact the competitiveness of distributed generation? [5]

(c) Busbar Balcombe will be a new supply hub for several villages in West Sussex. EDF Energy engineers plan to connect Balcombe to the main grid through a 5 km, 33 kV overhead distribution circuit. There are also 2 identical landfill gas based distributed generators of 5MW capacity connected to Balcombe, as shown in the figure Q4.1. The annual profile of the load connected to Balcombe Busbar is shown in figure Q4.2.

(i) If the availability of individual generating units is 90%, show that the contribution of the generators to network capacity is 7.8MW and calculate the optimal network capacity to secure demand. (The contribution of generation to network security is defined as the equivalent capacity of perfectly reliable circuit that would produce the same expected energy not supplied) [5]

(ii) If the marginal cost of the circuit is 300 £/MW.km.year, calculate distribution network use of system charges for demand and generation during on and off peak. What annual revenue these charges will generate? [5]

[4.50]



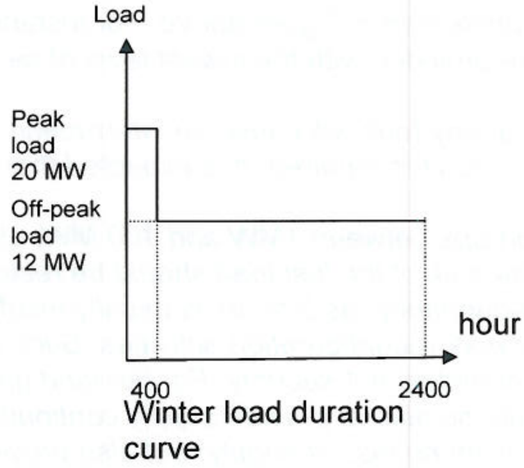
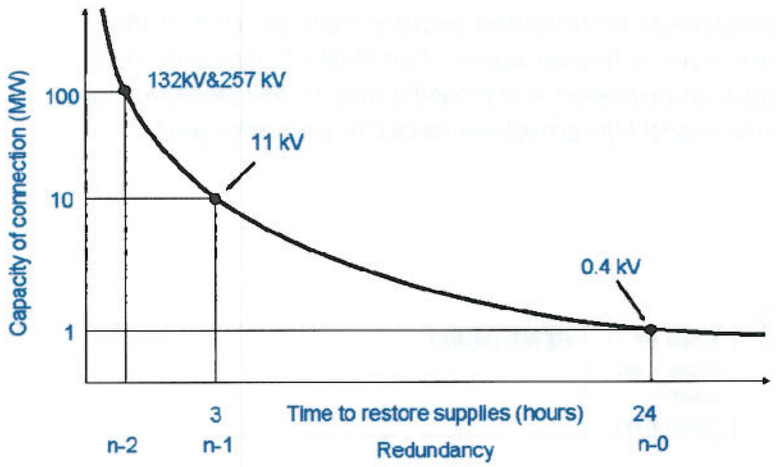


Figure Q4.1 **Figure Q4.2**

Solution

(a) For a full mark an appropriate discussion of this diagram is required.



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.

The level of security in distribution networks is defined in terms of the time taken to restore power supplies following a predefined set of outages. Consistent with this concept, security levels on distribution systems are graded according to the total

amount of peak power that can be lost. A simplified illustration of this network design philosophy is presented in Figure above. For instance small demand groups, less than 1MW peak, are provided with the lowest level of security, and have no redundancy (N-0 security).
This means that any fault will cause an interruption and the supply will be restored only after the faulty circuit is repaired. It is expected that this could take up to 24 hours.

For demand groups between 1MW and 100 MW, although a single fault may lead to an interruption, the bulk of the lost load should be restored within 3 hours. This requires presence of redundancy, as 3 hours is usually insufficient to implement repairs, but it does allow network reconfiguration activities. Such networks designs are often described as providing n-1 security. For demand groups larger than 100MW, the networks should be able to provide supply continuity to customers following a single circuit outage (with no loss of supply) but also provide significant redundancy to enable supply restoration following a fault on another circuit superimposed on the existing outage, i.e. n-2 security.

(b) For the full mark a discussion on the commercial integration of DG is required. Only when the impact of DG on network design is established, i.e. benefits and costs that DG brings / imposes, integration can be achieved. The importance of integration (location), at a high level, is illustrated by the value chain from power generation to consumption. 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 8-12p/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 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.

(c)
(i) Contribution of DGs to security

Outage (no of DG units)	**Probability**	**Loss of load – peak load(MW)**	**Loss of load – off peak load(MW)**	**EENS (MWh)**
0	0.9 x 0.9 = 0.81	0	0	0
1	2 x 0.9 x 0.1 = 0.18	10-5 = 5	6-5 = 1	0.18 x (5 x 400 + 1x 2000) = 720
2	0.1 x 0.1 = 0.01	10	6	0.01 x (10 x 400 + 6 x 2000) = 160

The EENS is 720 + 160 = 880 MWh
The capacity of the network (y) to achieve the same level of EENS:
(10-y) x 400 = 880

[4.50]

$\Leftrightarrow$ *4000– 400 y = 880*
$\Leftrightarrow$ *y = 7.8 MW*
Effective capacity value of DG1 and DG2 is 7.8 MW
The network capacity value (in term of % of installed capacity) is 7.8/10 = 78%
The optimal network capacity to secure demand is therefore 20 – 7.8 = 12.2 MW

(i) Network pricing calculation
Network requirement during maximum demand, effective contribution from DG is 20-7.8 = 12.2 MW
Network requirement during minimum demand amd maximum DG output is 12-10 = 2 MW
The network design of the 33 kV circuit is driven by peak load condition. Thus the charges and tariffs for demand and generation customers during off peak period is 0.
For peak period, demand customer will pay the network as if the capacity of the network is 20 MW.
Demand charges: 20 x 5 x 300 = 30,000 £/year
Tariff for demand customer is 30,000 / 20 = 1,500 £/MW.year = 1.5 £/kW.year
DG will get paid for reducing the need for network capacity by 7.8 MW
Payment to DG1 and DG2 (in total) = 7.8 x 5 x 300 = 11,700 £/year
Tariff for DG customers is -11700/10 = -1170 £/MW.year = -1.17 £/kW.year
Network revenue is 30,000 – 11,700 = 18,300 £/year
Network cost is 12.2 x 5 x 300 = 18,300 £/year

[4.50]

5.

(a) What factors could limit the connection of Distributed Generators to urban and rural distribution networks respectively? [4]

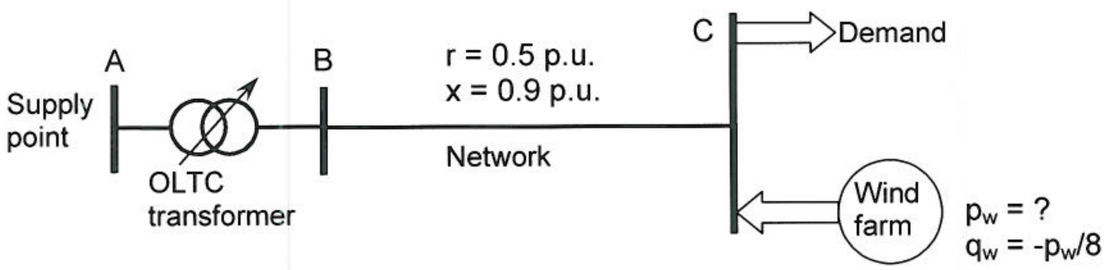
(b) What techniques can be applied to enhance the ability of the existing network to accommodate increased capacity of distributed generation? [5]

(c) Wind farm developer "West Sussex Wind" has applied for a connection of a wind farm to EDF Energy. In order to facilitate this connection, EDF Energy engineers need to investigate the voltage rise effect that might occur on the network presented in figure Q5. The On Load Tap Changing (OLTC) transformer is currently set to maintain the voltage at busbar B at 1.03 p.u. The minimum demand at the connection point (busbar C) is 10% of the maximum demand. As shown in Figure Q5, the wind farm will consume reactive power in proportion to the real power it generates.

(i) Estimate the amount of wind generation that "West Sussex Wind" could connect to the network if the allowable voltage variation in the network is +/- 6%. [6]

(ii) What would be the maximum amount of generation that "West Sussex Wind" could connect if a reactor of 0.01 p.u. is also connected to busbar C. [3]

(iii) In order to increase further the amount of generation that can connected to the network, EDF engineers are considering modifying the control set point of OLTC to 1.01 p.u. How much more generation would be possible to connect? [2]



(Base power is 100MVA)

Figure Q5

[4.50]

Solution

(a) Discussion of the following points is needed for full mark:

(a) urban distribution networks
   i. thermal limits, fault level
(b) rural distribution networks
   i. voltage rise effect i.e. voltage limits

(b) Discussion about the following active management options is required for full mark:

(c) generation curtailment
(d) local reactive power compensation
(e) area voltage control
(f) inline voltage regulator
(g) fault current limiters
(h) network reinforcement

(c)
(i) The critical condition which limits the amount of wind generation that can be connected is minimal demand condition.

$$v_C = v_B - \left[(p_d - p_w)r + \left(q_d + \frac{p_w}{8}\right)x\right] = 1.06$$

maximum demand condition

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{8}} = \frac{1.06 - 1.03 + 0.1 \times 0.5 + 0.02 \times 0.9}{0.5 - \frac{0.9}{8}} = 0.25\ p.u.$$

minimum demand condition

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{8}} = \frac{1.06 - 1.03 + 0.01 \times 0.5 + 0.002 \times 0.9}{0.5 - \frac{0.9}{8}} = 0.09\ p.u.$$

wind farm of 9MW can be connected.

(ii) The maximum amount of generation that could be connected if a reactor q_c = -0.01 p.u is also connected to busbar C is

$$v_C = v_B - \left[(p_d - p_w)r + \left(q_d + \frac{p_w}{8} - q_c\right)x\right] = 1.06$$

$$p_w = \frac{v_C - v_B + p_d r + (q_d - q_c)x}{r - \frac{x}{8}} =$$

$$= \frac{1.06 - 1.03 + 0.1 \times 0.5 + (0.002 - (-0.001)) \times 0.9}{0.5 - \frac{0.9}{8}} = 0.12\ p.u.$$

Wind farm of 12MW can be connected

[4.50]

(iii) If control set point of OLTC is set to 1.01 p.u. the maximum generation that can be connected is

$$p_w = \frac{v_C - v_B + p_d r + q_d x}{r - \frac{x}{8}} = \frac{1.06 - 1.01 + 0.01 \times 0.5 + 0.002 \times 0.9}{0.5 - \frac{0.9}{8}} = 0.15\ p.u.$$

therefore the increase in wind generation is 15MW – 9MW = 6 MW

[4.50]

6.

(a) Explain how a distributed energy system may achieve higher energy efficiency than a centralised one. [5]

(b) Discuss the impact of diversity of demand on the size of the system and on the generation capacity needed to supply it. [5]

(c) A country wishes to reduce environmental impact of its generation mix. Table Q6.1 summarises the present (2009) and estimated future (2015) penetrations of different technologies and the relevant electricity-related CO_2 emission factors; the estimated average electrical transmission and distribution losses for the two cases are also presented. Calculate the average overall electricity-related emission factor $\mu_{CO_2}^{ESP}$ (referred to the unit of electricity delivered to the LV user) in the two scenarios. [5]

Table Q6.1 Centralized electrical generation characteristics for different scenarios

Source	*2009*	*2015*	*Electricity-related emission factor [kg_{CO2}/kWh_e]*
	Penetration (%)	*Penetration (%)*	
Nuclear and Renewables	35	40	0
Oil	5	0	0.700
Coal	25	15	0.950
Gas	30	30	0.450
Distributed Generation	5	15	0.500
Network losses (%)	*8*	*6*	

(d) A small factory in Balcombe has decided to install on its premises a distributed generator to satisfy its electricity and heat needs. The selected energy system consists of a natural gas-fuelled CHP (Combined Heat and Power) microturbine, connected to the LV busbar of the distribution transformer that supplies the factory. The characteristics (referred to an hour of operation) are given in Table Q6.2.

Table Q6.2 Rated characteristics of the considered cogeneration microturbine

Electrical output *W*	[kWh_e]	30
Thermal output *Q*	[kWh_t]	50
Fuel input *F*	[kWh_F]	100
Fuel-related emission factor $\mu_{CO_2}^{F}$	[kg_{CO2}/kWh_F]	0.200

[4.50]

It has been estimated that the average heat output-related emission factor $\mu_{CO_2}^{TSP}$ for separate heat generation is currently equal to 0.280kg$_{CO2}$/kWh$_t$ but it is expected to drop to 0.250 kg$_{CO2}$/kWh$_t$ by 2020. Assume that the average overall electricity-related emission factors at present and in 2020 are estimated to be at 0.47 kg$_{CO2}$/kWh$_e$ and 0.37kg$_{CO2}$/kWh$_e$ respectively.

Use this information on heat generation in boilers and the information on average centralised electrical production (including network losses) given in Table Q6.1 to estimate the average emissions reduction (in % of the overall emissions from separate production) in the following two scenarios:

- the CHP system operating at full load in 2009;
- the CHP system operating at full load in 2020 taking into account that, due to aging, the fuel emission factor will have increased by 15% and the electrical output will have decreased by 5%.

Compare and comment on the CHP results from the two scenarios. [5]

[4.50]

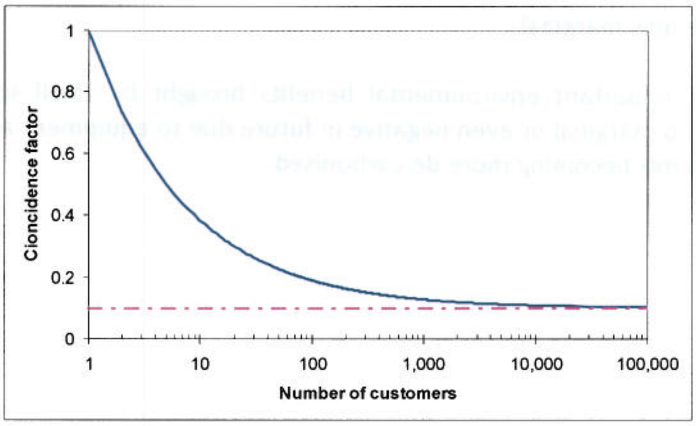
Solution

(a)

In the process of generating electricity, significant amount of heat energy is produced that is wasted. The overall thermal efficiency of modern type gas fired technologies (CCGT) is approaching 60%, while the coal based generation operates at less than 35%. An alternative policy (adopted by some European countries) has been to build smaller power stations nearer to load centres and use these to supply both electricity and heat to consumers (such as district heating) which allows greater use of the available heat and achieves overall efficiency for the supply of heat and electricity loads together of around 80% of the fuel burnt. However heat networks are required for this more distributed system

(b)

A key feature of demand is the diversity in usage of appliances. This is fully exploited both in system design and operation. The capacity of an electricity system supplying several thousand households would be only about 10% of the total capacity that would be required if each individual household were to be self sufficient (provide its own generation capacity). Distribution electricity networks are essential for achieving this significant benefit of load diversity. However, no material gains in the capacity of the electricity supply system would be made from increasing further the number of the households, as illustrated in Figure below



(c)

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:

- *Scenario 1*: $\mu_{CO_2}^{ESP} = \dfrac{0.35 \cdot 0 + 0.05 \cdot 0.70 + 0.25 \cdot 0.95 + 0.30 \cdot 0.45 + 0.05 \cdot 0.50}{(1 - 0.08)} = 0.470$ kg_{CO2}/kWh_e
- *Scenario 2* $\mu_{CO_2}^{ESP} = \dfrac{0.40 \cdot 0 + 0 \cdot 0.70 + 0.15 \cdot 0.95 + 0.30 \cdot 0.45 + 0.15 \cdot 0.50}{(1 - 0.06)} = 0.375$ kg_{CO2}/kWh_e

[4.50]

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

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

Hence, from the data provided for the CHP engine characteristics and the boiler emission factor, for *Scenario 1* we have

$$CO2ER\% = \left(1 - \frac{0.20 \cdot 100}{0.470 \cdot 30 + 0.280 \cdot 50}\right) \cdot 100 = 28.8\%$$

which is the emission reduction from the new CHP system when operating at full load.

For 2015, considering the worsening in emissions and electrical output performance of the CHP engine, as well as the expected improvements in terms of emission factors for the separate production of electricity and heat, we get

$$CO2ER\% = \left(1 - \frac{0.20 \cdot 1.15 \cdot 100}{0.375 \cdot 30 \cdot 0.95 + 0.250 \cdot 50}\right) \cdot 100 = 0.81\%$$

That is, the cogeneration benefits are now marginal.

This simple exercise highlights that important environmental benefits brought by small scale CHP systems installed today might turn into marginal or even negative in future due to equipment aging and to a centralized electricity generation mix becoming more de-carbonised.