E4.50

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2007

EEE PART IV: MEng and ACGI

Corrected Copy

SUSTAINABLE ELECTRICAL SYSTEMS

Wednesday, 25 April 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

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

Examiners responsible First Marker(s) : C.A. Hernandez-Aramburo, T.C. Green

Second Marker(s) : B.C. Pal, B.C. Pal

Question 1

a) State the definitions of tip-speed ratio (TSR) and power coefficient (Cp) of a wind turbine. [2]

b) Why does dynamically matching the rotational speed of a wind turbine to the speed of the wind improve the efficiency in capturing the energy in the wind? [4]

c) Sketch a Cp vs. TSR curve and give approximate values on the *x*- and *y-axes* for which the maximum Cp occurs for a large, 3-bladed horizontal-axis wind turbine. [6]

d) Show that, according to Betz's law, the power that can be extracted from the wind is less than 60% of the power available in the wind. [6]

e) List at least three assumptions that are made in deriving Betz's law. [2]

Question 2

a) Describe the two groups of specific energy crops and provide examples of the species of plants (or animals) associated with them.

[4]

b) Briefly explain what gasification is and the main differences between gasification and pyrolysis.

[4]

c) Explain the benefits that coal gasification may bring to the environment if used at a large scale in power plants.

[6]

d) Explain three disadvantages of using biomass to produce energy.

[6]

Question 3

For a crystalline silicon photovoltaic (PV) panel answer the following:

a) Explain how the photovoltaic effect occurs in one of the cells of a PV panel.
[4]

b) Describe the physical layers typically present in a commercial PV panel.
[4]

c) Explain the effects of temperature and irradiance on the terminal characteristics of a PV panel.
[4]

d) Explain how the "perturb and observe" maximum power point algorithm works. Illustrate your explanation with annotations on graphs of current *vs.* voltage and power *vs.* voltage. Show at least three operating points starting from the open-circuit condition. You may find useful to use the curves in figure 3.1 (provided here without any labels).
[8]

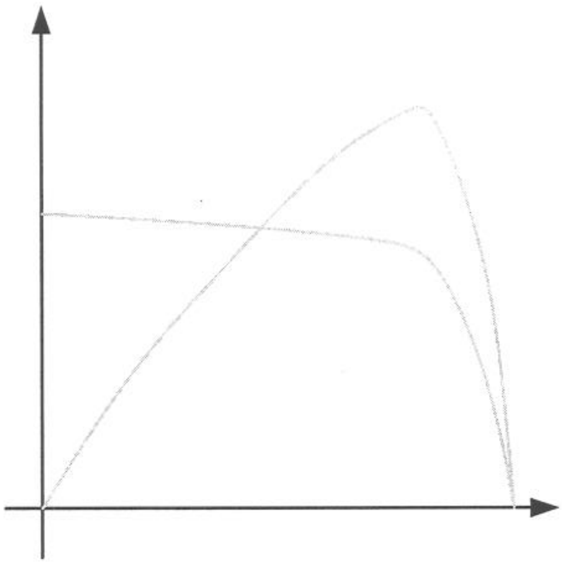


Figure 3.1

Question 4

Estimate the output power for each of the generation schemes below. In all cases the target is to export power to a 50 Hz grid. Take into consideration the efficiency of any intermediate power conversion stages that may be needed and sketch these stages in a block diagram. Use your engineering judgement to estimate any data not provided here.

a) A hydro scheme with a 10 m head and a 4 m^3/s discharge rate.

[5]

b) $100m^2$ of photovoltaic panels at standard test conditions.

[5]

c) A solid oxide fuel cell fed with hydrogen (approx. energy content=140 MJ/kg) at a rate of 0.2 g/s. For this case, estimate the thermal output power as well.

[5]

d) A wind turbine with a blade radius of 50m exposed to a wind speed of 10m/s. Assume a conversion scheme without any power electronic devices.

[5]

Question 5

a) Discuss the meaning of the terms Distributed Generation, Renewable Generation and Micro Generation.

[5]

b) Discuss the technical issues of concern to a network operator when a large amount of distributed generation connects to a distribution network. Include comments on the expected change in power flow in the network.

[15]

Question 6

a) Explain what is commonly meant by intermittent generation.

[3]

b) Explain why intermittent generation imposes additional costs on an electricity system as a whole.

[5]

c) Describe in outline which types of generation plant are expected to retire from the GB system by the year 2020 and which are expected to remain in service. Comment on the change in carbon intensity of the generation as a whole.

[5]

d) Describe the use of scenario analysis to explore the generation mix and network provision that Great Britain will need to make for the medium term (year 2020) and long term (year 2050).

[7]

Model answers for the 2007 exam on Sustainable Electrical Systems (EE4.50)

Question 1

a) **State the definition of tip-speed ratio (TSR) and power coefficient (Cp) of a wind turbine.**

[2]

Usually, the performance of a wind turbine for a particular operating condition (including all its losses) is characterised by a single coefficient, known as the power coefficient Cp, which is normalised to the swept area of the blades of the turbine.

Given that the efficiency of a wind turbine depends on both the wind speed and the angular speed of rotation, it is customary to introduce a new variable that incorporates both V_1 and ω. The tip-speed ratio (TSR) is defined as:

$$TSR = \frac{R\varpi}{V} \text{ [dimensionless]}$$

b) **Why does dynamically matching the speed of a wind turbine to the speed of the wind improve the efficiency in capturing the energy in the wind?**

[4]

A wind turbine's efficiency to extract power from the wind may decrease from an optimal value if:

1. The blades are so far apart, or rotating so slowly, that the air passes through the cross-section of the device (between the blades) without creating any useful work
2. The blades are so close together, or rotating so rapidly, that the turbulent air created by a blade interferes with the operation of the following blade.

For this reason, to obtain the maximum efficiency it is necessary to match the rotational frequency of the turbine to the particular speed of the incident wind.

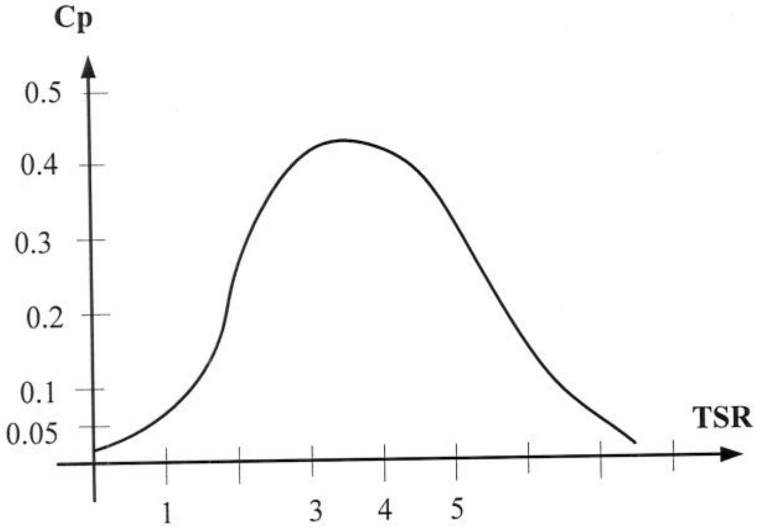
c) **Sketch a Cp vs. TSR curve and give approximate values on the *x*- and *y-axes* for which the maximum Cp occurs for a large, 3-bladed horizontal axis wind turbine**

[6]

$$TSR_{opt} = \frac{\varpi_{opt} R}{V_1} \approx \frac{2\pi}{nk}$$

For most wind turbines the optimal TSR usually lies between 3 and 6. For a commercial three bladed turbine n=3, k≈0.6 and therefore TSR_{opt}≈3.5.

A typical value for Cp in large turbine is 0.4 to 0.5 approximately



d) **Show that, according to Betz's law, the power that can be extracted from the wind is less than 60% of the power in the wind.**

[6]

$$E_{ex} = \frac{1}{2} m \left(V_1^2 - V_2^2 \right) \tag{3.1}$$

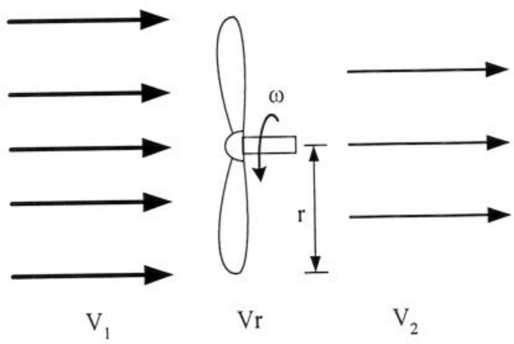


Figure 1. Energy extracted from the wind

Under these conditions the wind velocity through the rotor is simply the average between the upstream and downstream velocities:

$$V_r = \frac{\left(V_1 + V_2 \right)}{2} \tag{3.2}$$

The extracted power is then given by:

$$
\begin{aligned}
Pex &= \frac{d}{dt}E_{ex} = \frac{1}{2}\left(\frac{dm}{dt}\right)\left(V_1^2 - V_2^2\right) \\
&= \frac{1}{2}\left(\rho A V_r\right)\left(V_1^2 - V_2^2\right) \\
&= \frac{1}{2}\rho A\left[\frac{1}{2}\left(V_1 + V_2\right)\right]\left(V_1^2 - V_2^2\right) \\
&= \frac{1}{2}\rho A V_1^3\,\frac{1}{2}\left[1 + \frac{V_2}{V_1} - \left(\frac{V_2}{V_1}\right)^2 - \left(\frac{V_2}{V_1}\right)^3\right]
\end{aligned}
\tag{3.3}
$$

The value of the ratio $\frac{V_2}{V_1}$ that maximises the extracted power can be found by differentiating the previous equation with respect to this ratio and equating to zero.

The only feasible solution is:

$$
\frac{V_2}{V_1} = \frac{1}{3}
\tag{3.4}
$$

By substituting equation (3.4) into (3.3) we get:

$$
P_{ex}^{\max} = \frac{1}{2}\rho A V_1^3\left(\frac{1}{2}\right)\left[1 + \frac{1}{3} - \frac{1}{9} - \frac{1}{27}\right] = \frac{16}{27}\left(\frac{1}{2}\rho A V_1^3\right) = 0.593\left(\frac{1}{2}\rho A V_1^3\right)
$$

e) List at least three assumptions that are made in deriving Betz's law **[2]**

Some assumptions include:

- No turbulences or swirls
- No wake
- No friction on the blades
- No frame shading

Question 2

a) Describe two groups of specific energy crops and provide examples of the species of plants (or animals) associated with them

[4]

Woody crops

Traditional forestry may be modified to plant and harvest woody crops entirely to be used for energy production purposes. The process commonly followed is "short rotation forestry" (or "short rotation coppice"). "Rotation" refers to the periodic cutting of the wood every few years. Examples include fast growing species like willow and poplar that can be coppiced every 3 or 4 years.

Agricultural crops

Certain purpose-grown crops (such as maize and sugar cane) provide fuels with a high-density of energy. Some other crops not used for human or animal consumption and they can be entirely used for energy production; an example of this is miscanthus (a grassy plant) with a high yield of dry matter. Another type of energy crop is that of oily plants (such as rapeseed, sunflowers, soya beans) which is aimed at producing liquid fuels.

Water-based biomass

Algae, seaweed and other aquatic plants can be intensively grown in certain areas of the sea, in man-made flooded areas or in lakes.

b) Briefly explain what gasification is and the main differences between gasification and pyrolysis

[4]

Gasification is the process that seeks converting organic material into a combustible gas (called producer gas or syngas). The process itself involves the partial combustion of the biomass in restricted airflow conditions and elevated temperature (such as in pyrolysis, but with higher oxygen content). The emphasis of the gasification process is in recovering the producer gas; in pyrolysis, some liquid fuels are also recovered.

c) Explain the benefits that coal gasification may bring to the environment if used at a large scale in power plants

[6]

Gasification can also be applied to coal and burn the resulting syngas in a power plant with the idea of reducing its environmental impact. In an Integrated Gasification Power Plant (IGPP) low SOx and NOx emissions can be achieved because Sulphur emerges in a form that can be captured by processes currently present in the chemical industry and the syngas produced is virtually free of fuel-bound nitrogen. IGPP can also offer a further advantage with respect to CO_2 emissions because a more efficient electricity generation technology can be used. In a typical coal combustion plant, heat from burning coal is used to boil water to drive a steam turbine and generator. The typical efficiency of this arrangement is about 40%. An IGPP, the syngas is combusted in a gas turbine to generate electricity, which is altogether a more efficient technology. The total efficiency to obtain electricity from coal can be further improved if the plant is arranged in a "combined cycle".

d) Explain three disadvantages of using biomass to produce energy

[6]

For full-marks, the answer should elaborate on the following bullet points:

- Some biomass conversion technologies are not mature enough to be deployed at large scale
- If the fuel resource is locally available in large quantities (think of the sugar cane production in Brazil), biomass-based generation is definitively an option to consider. However, if the resource must be specifically grown then the best-use-of-land question comes into the question
- Local construction approvals are often difficult to get
- The major hurdles for bioenergy are transport and handling costs. It needs of a complex and robust supply chain. The lack of this chain increases the risks for investment.

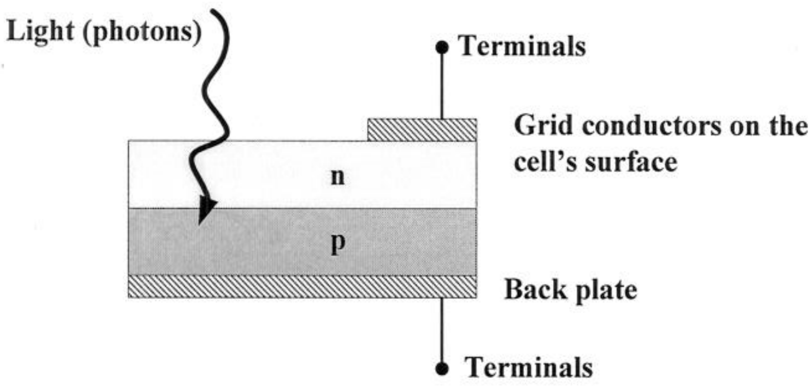
Question 3

For a crystalline silicon photovoltaic, PV, panel answer the following.

a) Explain how the photovoltaic effect occurs in one of the cells of a PV panel

[4]

A crystalline silicon cell resembles a diode in that it is made of two semiconductor lattices, one of a p-type material and the other of an n-type material; as shown in the figure below. It is important to note that the conductors on the surface facing the sun are shortened so the light can penetrate into the p-n junction.



Light with a particular wavelength (i.e., light of a particular colour) has a specific value of energy. When this light falls on a PV cell it disturbs the equilibrium conditions in the p-n junction. Incoming photons, with at least as much energy as the energy-gap in the semiconductor, knock electrons loose (i.e. promote electrons to the conduction band and create holes in the valence band); allowing electrons and holes to migrate across the junction.

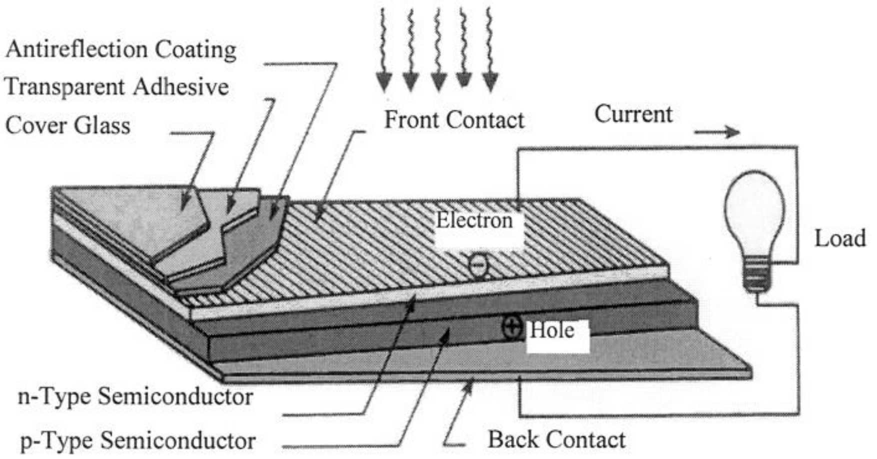
If the silicon cell is electrically isolated (in an open circuit), a measurable DC voltage appears across its terminals. If the cell has an external electrical circuit connected to its terminals then the forward biasing will produce an electric current through the device. The availability of current and voltage produces usable power.

b) Describe the layers typically present in a commercial PV panel

[4]

The figure below illustrates some construction features of a PV cell. This figure shows a transparent "glass" that protects the (expensive) inner layers without compromising too much on the incident radiation. Silicon layers have a very smooth surface and they reflect a large portion of the light they receive. To reduce this reflection, two approaches are normally followed. Geometric structures (*e.g.* "pyramids") are grown on the silicon surface, so any amount of light reflected by one structure is received and (hopefully) absorbed by another structure. The second approach is to use an anti-reflective layer over the silicon layers to trap the most of the light that reaches the cell (*i.e.*, the layer has a unidirectional light flow). This anti-reflective layer is also shown in the figure below

Solar Irradiance (Sunlight)



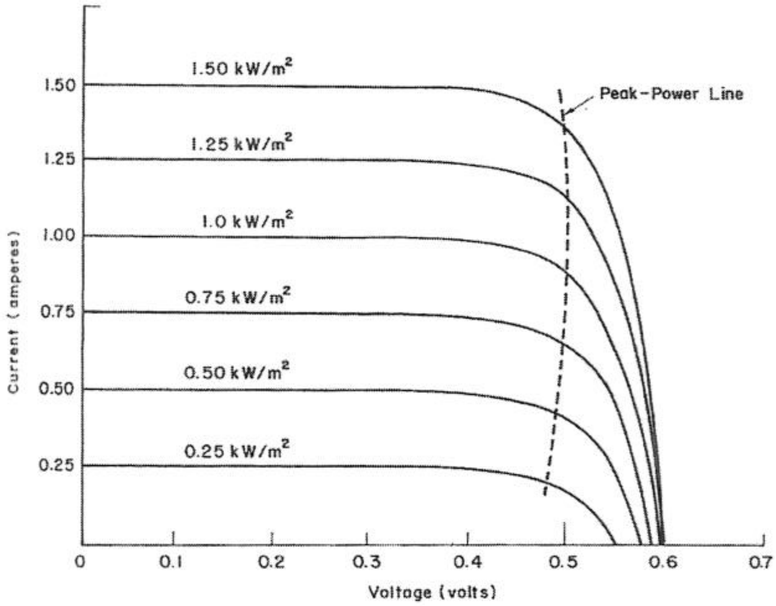
Layers of a PV cell

The electrical contacts of a PV cell are essential elements because they provide the connection point to external electrical load. The contact on the back a cell is relatively simple, it usually consists of a layer of aluminium or molybdenum metal; however, the front contact (on the side facing the sun) requires further explanation. When a PV cell is excited by light, a current of electrons is induced all over its surface. If the contacts are attached only at the edges of the cell, the current will not reach these contacts because of the large electrical resistance of the top semiconductor layer. Only a small number of electrons would make it to the contact. To collect the most current, a number of contacts are put across the entire surface of a PV cell, at the cost of reducing the area exposed to the solar radiation. This is normally done with a grid of metal strips.

c) Explain the effects of temperature and irradiance on the terminal characteristics of a PV panel

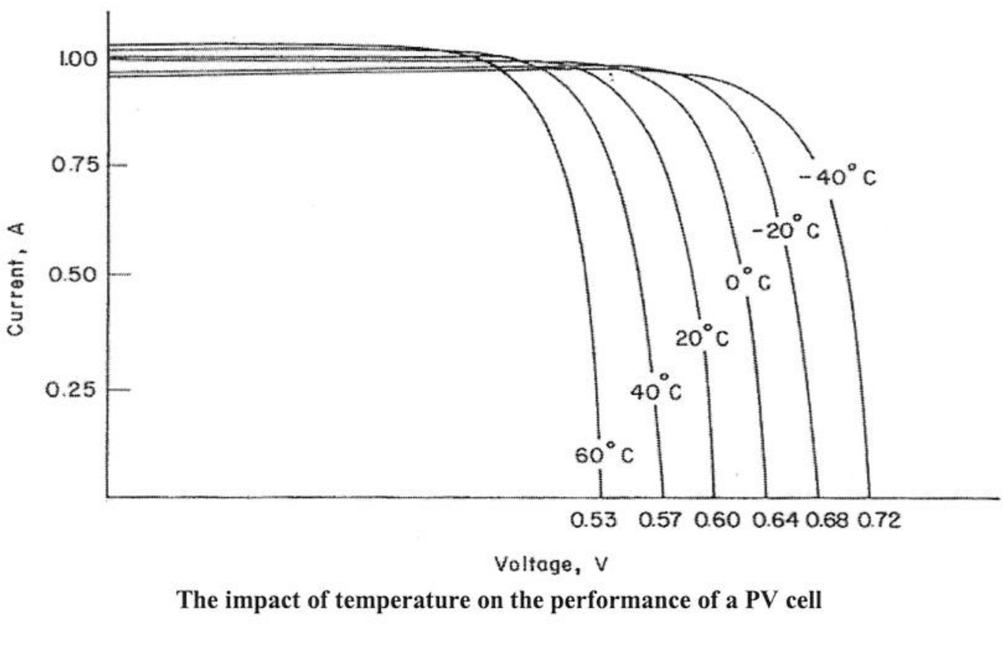
[4]

The current-voltage characteristic is influenced by the irradiance level as shown in the figure below. From this figure it can be seen that the current increases linearly according to the irradiance. The terminal voltage also increases, but not linearly. The combined effect of the increment in current and voltage causes the power to increase according to the irradiance as shown in the same figure.



The effect of irradiance on the performance of a PV cell

Temperature has an important effect on the performance of a PV cell, as illustrated in the figure below. This time the "almost linear" increase is on the terminal voltage against the change in temperature. The short circuit current decreases only marginally with an increase of temperature. Regarding the available power: the colder the cell, the more power it can deliver.



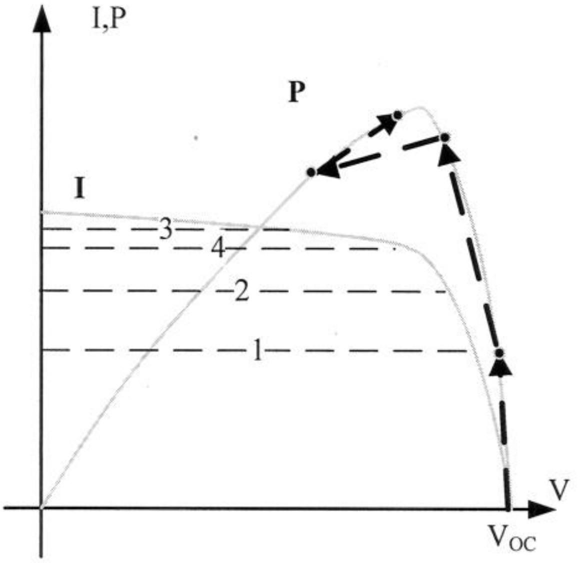
The impact of temperature on the performance of a PV cell

d) Explain how the "perturb and observe" maximum power point algorithm works. Illustrate your explanation with annotations on graphs of current *vs.*

voltage and power *vs.* voltage. Show at least three operating points starting from the open-circuit condition. You may find useful to use the curves in figure 3.1 (provided here without any labels).

[8]

The "perturb and observe" method works by constantly changing the set point for the output current. If the output power increases with the new set point, the algorithm continues changing the set point for current in the same direction. If the output power decreases with the new set point, the algorithm changes the set point for current in the opposite direction.



Question 4

Estimate the output power for each of the generation schemes below. In all cases the target is to export power to a 50 Hz grid. Take into consideration the efficiency of any intermediate power conversion stages that may be needed and sketch these stages in a block diagram. Use your engineering judgement to estimate any data not provided here.

a) **A hydro scheme with a 10 m head and a 4 m^3/s discharge rate.**

(a)

$P_{hy} \rightarrow$ Turbine $\rightarrow$ Generator $\rightarrow$ Transformer $\rightarrow P_{Grid}$

$$P_{hy} = \frac{dE}{dt} = \frac{d}{dt}(mgh) = gh\frac{d}{dt}m = gh\frac{d}{dt}\rho V = gh\rho Q$$

$$= \left[9.81\,\frac{m}{s^2}\right]\left[10\,m\right]\left[1000\,\frac{kg}{m^3}\right]\left[4\,\frac{m^3}{s}\right] = 392.4\,\frac{kg\cdot m^2}{s^3} = 392.4\ kW$$

Estimated by student

$$P_{Grid} = P_{hy}\cdot\eta_{Turbine}\cdot\eta_{Gen}\cdot\eta_{Transf.}$$

$$= \left[392.4\ kW\right]\left[0.87\right]\left[0.95\right]\left[0.99\right] = 321.075\ kW.$$

Estimated by student

[5 marks]

b) **100m^2 of photovoltaic panels at standard test conditions.**

(b)

$P_{dens} \rightarrow$ PV array $\rightarrow$ DC/AC $\rightarrow P_{grid}$

$$P_{grid} = \left[P_{density}\right]\left[Area\right]\left[\eta_{PV}\right]\left[\eta_{DC/AC}\right]$$

$$= \left[1000\,\frac{W}{m^2}\right]\left[100\,m^2\right]\left[0.16\right]\left[0.95\right] = 15.2\ kW_p$$

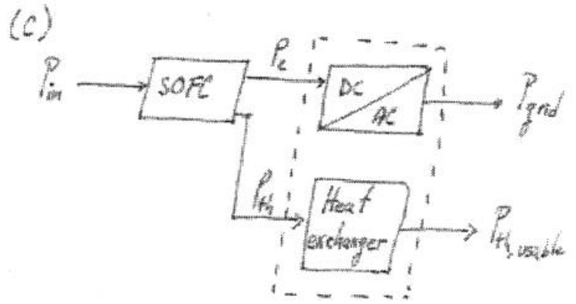
Not provided in the question

Estimated by student

[5 marks]

c) **A solid oxide fuel cell fed with hydrogen (approx. energy content=140 MJ/kg) at a rate of 0.2 g/s. For this case, estimate the thermal output power as well.**

(c)



These power converters were not explicitly covered for SOFCs this year, but the student should be able to incorporate them based on the knowledge of other power sources, such as PV panels and CHP reciprocating engines

H = Energy content
Q = Flow rate

$$P_{in} = \frac{d E_{in}}{dt} = \frac{d}{dt}\left[HQt\right] = HQ = \left[140\ \frac{MJ}{kg}\right]\left[0.2\ \frac{g}{s}\right] = 28\, k\frac{J}{s} = 28\ kW$$

Assume that the total efficiency of the SOFC is 85%, made from the electrical and thermal efficiencies in equal parts. (Power-to-heat ratio = 0.5)

$$P_e = P_{in}\,\eta_e = (28kW)\left(\frac{0.85}{2}\right) = 11.9\ kW_e$$

$$P_{grid} = P_e\,\eta_{DC/AC} = (11.9 kW_e)(0.95) = 11.305\ kW_e$$

Estimated by the student

$$P_{th} = P_{in}\,\eta_{th} = (28kW)\left(\frac{0.85}{2}\right) = 11.9\, kW_{th}$$

Estimated by the student

$$P_{th,usable} = P_{th}\,\eta_{HE} = (11.9\ kW_{th})(0.90) = 10.71\ kW_{th}\ \text{(usable)}$$

[5 marks]

d) **A wind turbine with a blade radius of 50m exposed to a wind speed of 10m/s. Assume a conversion scheme without any power electronic devices.**

(d)

$$P_{wind} \rightarrow \boxed{\text{Wind turbine}} \xrightarrow{P_{captured}} \boxed{\text{Gearbox}} \rightarrow \boxed{\text{Asynchronous generator}} \rightarrow \boxed{\text{Transformer}} \rightarrow P_{grid}$$

$$P_{wind} = \frac{1}{2}\rho A V^3 = \frac{1}{2}\left[1.29\ \frac{kg}{m^3}\right]\left[\pi\cdot(50m)^2\right]\left[10\frac{m}{s}\right]^3 = 5.065\ MW$$

Data not provided

Estimated by the student

$$P_{captured} = [P_{wind}][C_p] = (5.065\ MW)(0.4) = 2.026\ MW$$

$$P_{grid} = (P_{captured})[\eta_{gearbox}][\eta_{A.G.}][\eta_{trans.}]$$

$$= [2.026\ MW][0.9][0.95][0.99] = 1.715\ MW$$

Estimated by the student

[5 marks]

Question 5

a) Discuss the meaning of the terms **Distributed Generation**, **Renewable Generation** and **Micro Generation**. [5]

Discussion of the following including conflict between commercial and technical definitions

- Conventional Generation
  - Connected to EHV transmission network
  - Connection agreement struck with NG ETL etc
  - Part of the Balancing Mechanism but with bilateral trades
- Distributed Generation
  - Connected to HV/MV distribution network
  - Connection agreement struck with DNO
  - Not part of BM; bilateral trades or demand offset
- Micro Generation
  - Connected to LV system at point of load
  - Notification process rather than connection agreement
  - Mostly for demand offset but with sale of excess generation
  - Feed-in tariff used in some countries
- Renewable generation is about the nature of the prime energy source and could be conventional (e.g. off shore wind), distributed (e.g. on shore wind) or micro (e.g. roof top wind)

b) Discuss the technical issues of concern to a network operator when large amounts of distributed generation connects to a distribution network. Include comments on the expected change in power flow in the network. [15]

Discussion of

1. Disturbance of voltage profiles with possible over voltage conditions due to RP+XQ
2. Formation of unintentional power islands after fault and CB opening and possible safety implications of this
3. Congestion management in high penetration areas including provisions security of supply after credible contingency
4. Use of network for reverse power flow and the consequence for power losses and efficiency

Diagrams to explain effects mentioned would be expected.

Question 6

a) Explain what is commonly meant by intermittent generation. [3]

Intermittent is used to indicate generation in which the real power output is a function of some uncontrollable variable. The most common example is wind generation being dictated by wind speed although PV and tidal flow are also included. Unplanned maintenance of fossil-fuelled generation is not normally included.

b) Explain why intermittent generation imposes additional costs on an electricity system as a whole. [5]

There are two main elements to the additional cost.

Additional balancing: Short term variations of power generation and prediction errors in generation add to the supply-demand imbalance that must be corrected by the system operator. This requires additional responsive plant to be contracted for this duty (hydro plant or open cycle gas turbines or part load coal plant). For low penetration the increase is very small because balancing provision is dominated by load variation.

System Security Cost: Intermittent sources may or may not be able to generate at the time of peak demand (cold winter evening in UK). They are less likely to be available than conventional plant but not entirely unlikely. Since providing for meeting peak demand is an assessment of the statistics of load variation and plant availability, this complicates the calculation slightly by having some generation of quite different statistical profile but does not change the nature of the calculation. It is found that wind generation, for instance, makes less contribution to satisfying peak demand than it does to the general provision of energy across the year. Thus, when wind plant are introduced there is a difference between the amount of plant that can be retired when considering only energy supply and when considering the meeting of peak demand. The plant retained to meet peak demand are an additional cost. (Possible additional material on the difficulty of quantifying this in a market system with no specific market or responsibility for this item).

c) Describe in outline which types of generation plant are expected to retire from the GB system by the year 2020 and which are expected to remain in service. Comment on the change in carbon intensity of the generation as a whole. [5]

CCGT gas plant are relatively young (built 1990s) and are expected to stay in use beyond 2020.
Hydro plant are expected to have refurbishment of generators at existing sites and will be present in 2020
Coal plant are relatively old (built 1960s) and will be decommissioned by 2020
Nuclear plant of 1st and 2nd generation are all scheduled for decommissioning by 2020 (with only PWR at Sizewell B remaining)

Slightly more coal plant (relatively high CO_2 per MWh) than nuclear (zero-carbon) will retire but the remaining fleet is mostly fossil fuel with on 4% (on 2007 base) renewables in place. Remaining fleet is carbon intense. The key issue is what new plant is built.

d) Describe the use of scenario analysis to explore the generation mix and network provision that Great Britain will need to make for the medium term (year 2020) and long term (year 2050). [7]

Scenarios are plausible example futures that must be internally consistent. They should reflect a possible combination of the important factors such as economic growth, technological growth, environmental concerns, public attitudes and political/governmental stance. The very large combination of the possible situation under each factor can normally be captured with a few well chosen examples. For each example, a combination of analysis of source data and consensus judgement on the development will lead to a view of the generation mix, annual energy demand and peak demand that will apply. For 2050 about 7 scenarios capture the range and for 202 about 5. For each the implications for the network needed can be found from the generation mix. Answer should include some illustrative examples such as "Strong optimism" in which economic growth requires more energy but technology growth and environmental concerns bring forward renewable energy on all scales. The network must then support new large scale wind and marine energy in remote areas using new transmission infrastructure; must use active distribution systems to bring in generation at this level and perhaps microgrids for building level renewable energy. The group of scenarios indicate how diverse or correlated are the networks that are indicated. The scenarios do not predict which will be required but they do indicate key technologies and some common ground for all plausible scenarios.