Solutions - Sustainable Electrical System

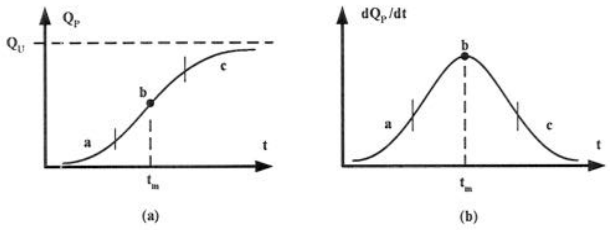
07/08 E4.50

1. Answer the following questions.

[This question is a textbook exercise]

a) Explain how the "logistics curve method" is used to estimate the availability of energy resources. Include in your explanation the following concepts: cumulative production curve (and explain its main segments), cumulative discovery curve and proven reserves curve.

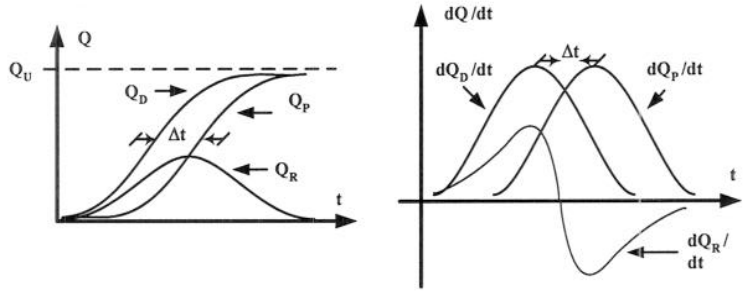
A widely use large-scale resource estimation technique is the "logistics curve method". It simply takes the historic pattern of exploration and extraction over time. These data are then extended to fit typical curves, appropriate for any finite resource. The figure below shows some of these curves. On the left, a cumulative production S-shaped curved is shown. On the right, the derivative of the cumulative production over time (rate curve) produces a bell-shaped curve.



The curves are usually divided into 3 major segments for their analysis:

- **Early segment. This segment corresponds to the period when the resource is just beginning to be exploited. The cumulative and the rate curves exhibit an exponential behaviour in time. Subject to demand, the exponential growth continues until the finite element of the resource reached.**
- **The mid-range segment is the earliest indication of the finiteness of the resource. The cumulative production has reached its maximum slope against time (at time t_m). The peak in the rate of cumulative production is a significant signal; it indicates that the resource will become increasingly scarce.**
- **In the late-time segment period the cumulative curve becomes asymptotic to the ultimate cumulative production value (Q_U, also called the "ultimate recoverable resource"). The cumulative production rate falls to zero (zero production).** ***NB*****: The total are under the rate curve must be equal to the ultimate cumulative production value Q_U)**

Two more curves complete the picture of a finite-resource typical exploitation: the cumulative discoveries curve (Q_D) the proved reserves curve (Q_R). These curves are plotted in the figure below.



(a) (b)

The cumulative discoveries curve is simply assumed to precede the cumulative production curve with the same relative shape against time (*i.e.* lagging by Δt). The cumulative proved reserves are equal to the cumulative discoveries minus the cumulative production: $Q_R(t)= Q_D(t)-Q_P(t)$.

[8]

b) What is the meaning of the reserve/production ratio?

The reserve/production ratio, also derived from the logistic curve method, is an extensively used parameter to obtain an insight into the remaining life of a particular resource. The reserve/production ratio $\frac{R}{P}$ is defined as: $\frac{R}{P} = \frac{Q_R}{\frac{dQ_P}{dt}}$ **[years]**

The interpretation of this ratio is the following: at the present production rate $\left(\frac{dQp}{dt}\right)$, the proved reserves (Q_R) would be depleted in $\frac{R}{P}$ years.

[2]

c) Explain (in about 250 words) what the energy security challenges for the UK are, what risks they carry, and how these risks are being addressed in the UK according to the white papers issued since 2003.

[The following text has about 500 words; the students have been asked to answer the question in 250 words, this will give them some allowance to make their answers shorter]

Challenges:
There are two main security-of-supply challenges for the UK:

1. **Managing increased dependence on oil and gas imports; and**
2. **Ensuring that the market delivers substantial and timely investment in electricity generating capacity and networks**

Risks:

- **The largest global reserves of oil and gas are concentrated in Russia, Central Asia, the Middle East, and African countries. We shall become increasingly reliant on supplies from these regions.**
- **Global energy demand is forecasted to grow strongly. This will mean greater competition for supplies.**
- **There is a risk that supplier countries may not make sufficient or timely investments to increase output.**
- **The global oil market has tightened, with a decline in spare production and refining capacity.**
- **Unlike oil, gas is not currently traded in a global market. While increasing shipments of Liquefied Natural Gas may make the market more flexible, gas is now largely supplied into regional markets and constrained by access to pipelines which may cross many countries.**
- **Overall, these trends could put upward pressure on prices and encourage increased political intervention in international energy transactions.**

In response to these risks, the energy white papers propose the following:

- **Building stronger political relationships with energy producers to ensure UK suppliers to have fair access to energy supplies.**
- **Backing the European Commission in securing an effective implementation of a competitive, liberal energy market.**
- **Improving the quality of information and analysis about the outlook for gas and electricity supplies.**

Securing electricity supplies

- **By setting out in the Review the Government's position on renewables, nuclear power, and carbon pricing, energy companies and investors obtain greater clarity about the future. This should create trust for fresh investments in generation and transmission and distribution networks.**

Securing gas supplies

- **There are three aspects for securing UK's gas supplies:**
- **Maximise the exploitation of UK's gas and oil reserves. This could be addressed by attracting investors to try and maximise the ultimate recovery levels.**
- **Limiting UK gas dependence. By implementing the energy saving measures and replacing the nuclear build our gas demand could be significantly reduced.**
- **Managing gas import risks. These risks could be mitigated by facilitating the timely construction of sufficient storage and import infrastructure.**
- **Competitive prices through effective markets. Two recent reports from the European Commission on the functioning of EU electricity and gas markets identified serious problems: the high degree of market concentration; vertical integration being used as a barrier to new entrants; the lack of market integration; the lack of transparency; and the lack of well functioning and transparent market mechanisms for setting prices. These problems have led to significant extra costs for UK consumers. The Energy Review proposes to continue the drive for EU energy markets liberalisation and integration.**
- **Protecting vulnerable consumers. This review continues its support towards tackling fuel poverty. Fuel-poor households are those who spend 10% or more of their income in heating. There are around 2 million fuel-poor homes in the UK (3 million fewer than in 1996) but this figure is expected to rise.**

[10]

2. A tidal generation system based on a barrage is proposed for the Severn estuary. The mean tidal range in this place is 10m and its area is approximately 70 sq. km.

[This question is mainly a numerical example from the theory explained in the lectures. The problem is relatively simple, but it is the first time the students come across with a numerical example in this topic. The question also covers some issues surrounding tidal generation that the students need to explain.]

a) Estimate the amount of potential energy available for tidal exploitation and the corresponding mean power.

$E = mgh = (\rho V)(g)(R/2) = (\rho AR)(g)(R/2)$

$= \rho g A R^2/2 = 343 \times 10^{11}$ [J]

$P = \Delta E / \Delta t = (343 \times 10^{11}) / (12.4\text{h} \times 3600\text{s/h}) = 768$ [MW]

[5]

b) Estimate the efficiency of the whole system, from the energy that can be recovered from moving water to electricity delivery.

Pout = P x (efficiency turbine) x (efficiency generator) x (efficiency transformer)
Pout = 650 MW

Assumptions:
There may be several assumptions (e.g. the tidal cycle occurs twice a day as opposed to 12.4 h) but the main one is that the water can be fully displaced in and out from the reservoir between tides. This factor is especially important because, according to the aspect ratio of the basin, it can reduce the available energy by a considerable amount.

[6]

c) If only Pelton, Francis, Kaplan and Crossflow turbine-families are under consideration, what is the most likely family to be chosen? Explain the reasoning behind your answer.

The discharge rate is bound to be very high for this application and the head is relatively low; therefore, Kaplan is the most likely family to be chosen. Francis-type turbines could also a feasible (but unlikely) solution if the number of turbines deployed is relatively high (w.r.t. a Kaplan-based solution) to reduce the discharge rate per turbine. Crossflow and Pelton are not suitable for this application.

[4]

d) Briefly explain the ebb and flood strategies for tidal generation.

- **Ebb generation. 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 just as it is reaching its lowest level, the water is left through water turbines to generate electricity.**

- **Flood generation. In this scheme, the reservoir gates remain closed as the tide is rising. Just as the tide is reaching its highest level, the gates are opened and water is let through the water turbines to generate electricity.**

[2]

e) What are the advantages of tidal lagoons with respect to a barrage system?

One disadvantage of barrages is that electricity is produced in "bursts"; large amounts in relatively short times. Schemes based on tidal "lagoons" have been proposed to overcome this disadvantage. In these schemes, the idea is to divide the tidal area into multiple reservoirs, and shift in time their individual production of electricity. This creates a smoother production profile.

[3]

3. Answer the following questions.

[The following questions are a textbook exercise]

a) Why are power electronic converters needed for the connection of some types of generators to a particular load or to the grid?

Many of the "new", renewable and/or energy-efficient generation technologies produce electricity at a frequency unsuitable for a direct connection to the grid (or to most of end-user applications, to that effect). Some examples of these generation technologies include: photovoltaic panels, wind turbines and High speed micro-turbines. A feasible solution is to use a power electronic converter between the energy source and the grid to process the "raw" power from the source and deliver a regulated power in voltage and frequency at its output terminals.

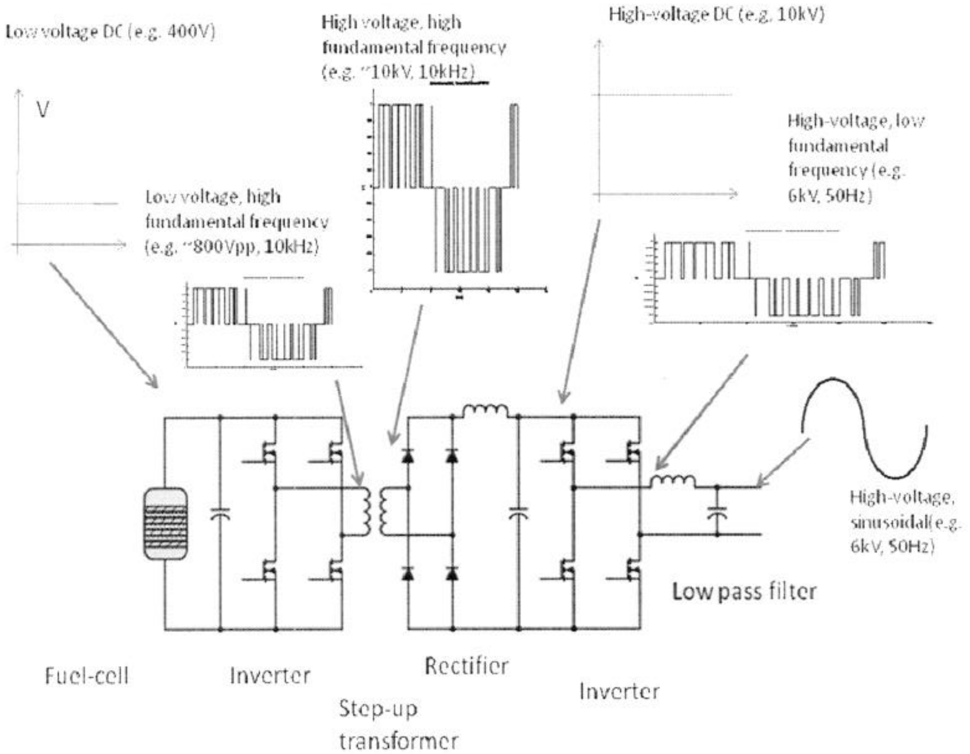
[2]

b) What are the main characteristics sought in such a power converter?

1. **Deliver regulated power within specifications**
2. **Able to cope with perturbations in the input and transients in the output**
3. **Able to protect itself against faults and, whenever possible, protect the rest of the equipment**
4. **Able to establish suitable operating conditions for the generator (MPPT for PV panels and adequate V&I output for SOFCs)**
5. **Efficient**
6. **Reliable**
7. **Cheap (this clashes with reliability; expected volume of sales vs. volume of returns)**
8. **Light in weight (high W/kg) and small in size (high W/m^3)**
9. **Modest requirements of ancillary circuitry (control systems, filters, ...)**
10. **Low maintenance requirements (rotating elements such as fans are not desirable but may be hard to avoid)**

[3]

c) Sketch the voltage waveforms likely to be seen at every stage of the power converter shown in figure Q3 during normal operation.



[6]

e) For a photovoltaic system, answer the following:

i) Explain why the maximum power point changes.

ii) Cite the theoretical and practical efficiencies of a crystalline silicon PV cell. Cite also the typical efficiencies for the PV cells currently found in the market.

ii) What are the components most likely to fail in a PV system?

i) The maximum power delivered by a PV system changes according to the incident radiation, temperature and PV-cell aging.

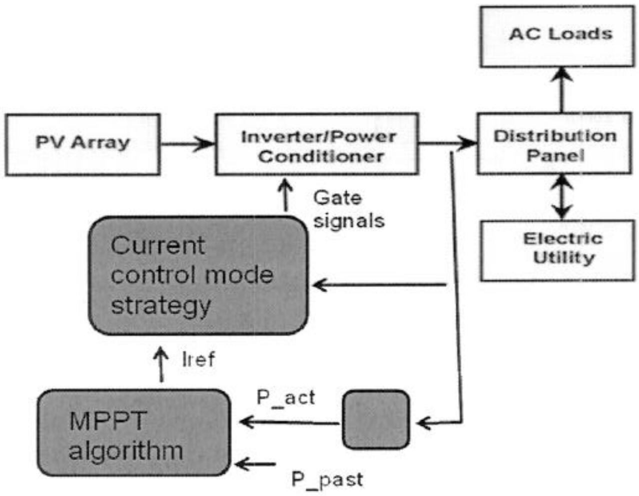
ii) The theoretical efficiency is around 36%, practical efficiencies are just below 30% and the typical efficiency for a cell in the market is below 20%

iii) In descending order: batteries, power converters and finally the PV array.

[3]

d) Draw a block diagram of a grid-connected photovoltaic system with an MMPT strategy incorporated in it. Briefly explain the aim of each block.

[6]



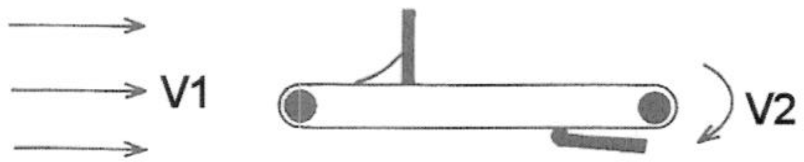
1. **The PV Array produces electrical energy from incident radiation.**
2. **The inverter processes the "raw" power from the PV array and delivers it to the grid.**
3. **The current controller ensures that the inverter delivers the power to the grid in an adequate form. To achieve this it performs several functions such as controlling the output current, keeping synchronisation with the grid, protection, etc.**
4. **The MPPT algorithm establishes the set point for the current controller to ensure that the maximum power is extracted from the PV array.**

4. Answer the following questions.

[The following questions are a combination of textbook and numerical exercises of the theory seen in lectures]

a) Show, from first principles, that the maximum power that a drag-only wind turbine can extract from the power available in the wind is less than 15%.

The following figure illustrates an ideal drag machine. The wind blows with a speed V_1 on to the upper blade of the turbine, which is moving with a speed V_2.



The power extracted from the wind depends on the force exerted on to the blade as:

$$P_{ex} = F \times V_2$$

Where:

P_{ex} **= Power extracted from the wind [W]**
F **= Force exerted on the moving blade [N]**
V_2 **= Speed of the moving blade [m/s]**

The force can be calculated from the following equation (fluid mechanics):

$$F = \frac{1}{2}\rho A V_{rel}^2$$

Where:

A = Blade area [m^2]
ρ = Air density [Kg/m^3]
V_{rel} **= Relative speed between the incident wind and the moving blade [m/s]**
= V_1-V_2

Therefore the extracted power becomes:

$$P_{ex} = \frac{1}{2}\rho A V_{rel}^2 V_2 = \frac{1}{2}\rho A (V_1 - V_2)^2 V_2$$

Deriving equation this equation with respect to V_2 and equating to zero, we find that the maximum power extraction occurs at:

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

Substituting this result into the preceding equation, the maximum power extraction may be expressed as:

$$P_{ex}^{max} = \frac{1}{2}\rho A\left(V_1 - \frac{1}{3}V_1\right)^2 \frac{1}{3}V_1 = \frac{4}{27}\left(\frac{1}{2}\rho A V_1^3\right)$$

This result means that an ideal drag machine can only extract $\frac{4}{27}\times 100\% = 14.81\%$ **of the maximum power available in the wind.**

[8]

b) Estimate the CO_2 savings (in tonnes) likely to be made over one year by a 4MW-rated, horizontal-axis wind turbine installed in the UK. State any assumptions you make.

Assumption: the fact a fairly large wind turbine suggests that it will be installed in a location with good wind resources. These locations have had a historic annual load factor between 25 and 30%. Therefore the annual average power delivered by this turbine is likely to be between 1 and 1.2MW.

Assumption: the CO2 savings are achieved in substitution of gas-based generation plant; which produce 0.5kg of CO2 per kWh (1kg/kWh for a coal-based power station)

For a 1MW prediction and gas-plant displacement:

E_{annual}=P*1 year =1MW*8760h=8760MWh=8.760x10^6 kWh

CO_2 savings = Eannual [kWh] x 0.5kg/kWh

=4.380x10^6 kg=4.380x10^3 tonnes

For a 1.2MW prediction and coal-plant displacement:

E_{annual}=P*1 year =1.2MW*8760h=MWh=10.512x10^6 kWh

CO_2 savings = Eannual [kWh] x 1.0 kg/kWh

CO_2 savings = 10.512x10^6 kg=10.512x10^3 tonnes

[4]

c) How can the market regulator in the electricity supply industry contribute to make electricity networks sustainable?

Electricity networks need to be sustainable not only from the "green energy" point of view; they need to offer long-term business opportunities and provide an adequate quality of service and supply as well. The regulator can contribute to achieve this by fulfilling its obligations which normally includes:

- **Protecting the interests of consumers of electricity in respect of prices charged and other terms of supply, continuity of supply, quality of services provided**
- **Promoting efficiency and economy**
- **Promoting research, development and use of new techniques to improve the network's performance**
- **Protecting the public from dangers**
- **Promoting the health and safety of persons employed in the electricity supply industry**

[4]

d) List the main parameters to assess quality of supply in the electricity supply industry.

1. **Frequency limits**
2. **Voltage limits**
3. **Harmonics**
4. **Voltage fluctuation**
5. **Voltage unbalanced**
6. **Voltage dips**

[2]

e) List the main parameters to assess quality of service in the electricity supply industry.

Quality of supply is normally assessed by the companies' ability to deal adequately with the following issues:

1. **New connections**
2. **Metering and billing**
3. **Restoration of supply**
4. **Customer complaints, enquiries and requests**

[2]

5. Answer the following questions.

[This is a numerical example of the theory covered in lectures]

a) Explain how a Ringbom Stirling engine works. Include in your answer schematic diagrams of the position two pistons and a brief explanation of the thermo-dynamical phenomena occurring during each state transition.

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State 0 → State 1: Isothermal compression

- The cold piston moves to its intermediate position and compresses the gas in the chamber (the Stirling engine receives mechanical input power at this stage).
- The pressure increases in the cold piston because the volume has decreased.
- Any heat created during this compression cycle is removed by the cold sink.

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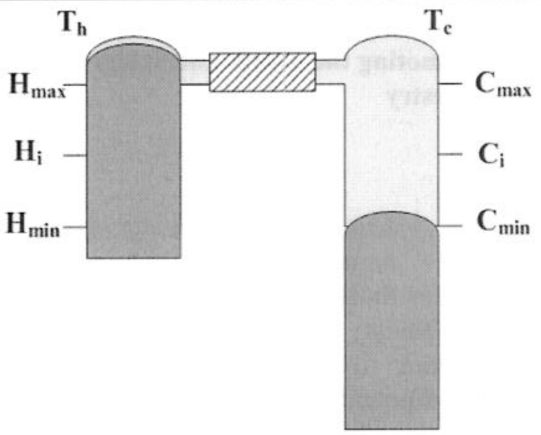

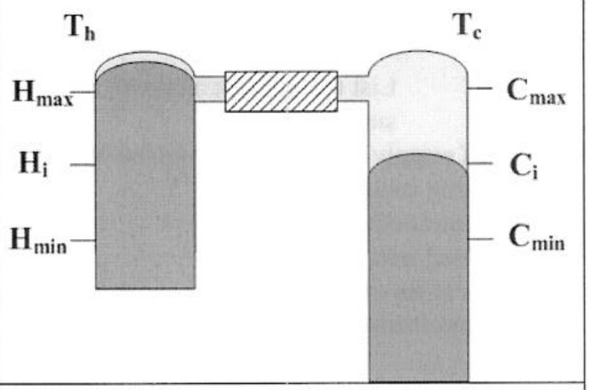

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State 1 → State 2: Isometric gas transfer and heat addition

- The cold piston pushes the cold gas into the hot piston. The volume remains constant.
- The working has gains temperature as it passes through the regenerator and enters the hot piston.
- The pressure in the hot piston increases because its temperature increases.

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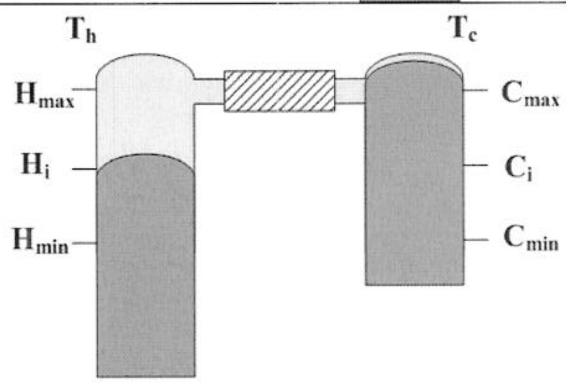

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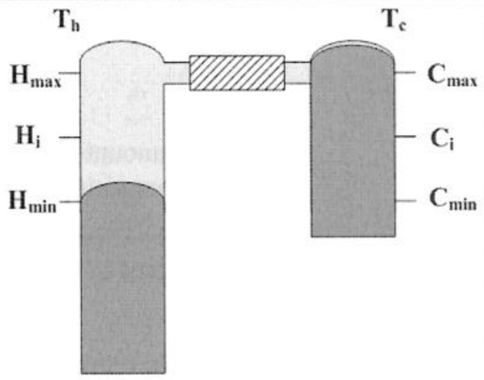
State 2 → State 3: Isothermal expansion

- The working gas displaces the piston (because of its increased pressure) **delivering mechanical power**.
- The pressure decreases because volume increases
- The temperature remains constant (the hot environment makes-up for any temperature drop caused by the drop in pressure).



[10]

b) Assume that the Ringbom Stirling engine has the following characteristics and operating conditions:

- Temperature of the hot and cold pistons: 700K and 300K, respectively.
- Compression ratio at the cold piston: 10 to 1
- Expansion ratio at the hot piston: 1 to 10
- $\mu = 40 \times 10^{-6}$ [kmoles]
- R = Gas constant = 8.3×10^3 [J/(K kmole)]
- C_V = Specific heat at constant volume = 20.8×10^3 [J/(K kmole)]
- There are no losses in the regenerator.
- The losses by friction and turbulence are negligible.

Calculate the following:

i) the amount of work that the engine receives at the cold piston by compression

$$W = \int_{V_i}^{Vf} pdV = \int_{Vi}^{V_f} \mu R \frac{T}{V} dV = \mu RT \int_{V_i}^{V_f} \frac{1}{V} dV = \mu RT \ln(\frac{V_f}{V_i})$$

At the cold piston: Vf/Vi =0.1 and T=300K

W= $(40 \times 10^{-6})(8.3 \times 10^3)(300)\ln(0.1)$=-229.69 [J]

[2]

ii) the amount of work done by the engine during the expansion of the hot piston

$$W = \int_{V_i}^{Vf} pdV = \int_{Vi}^{V_f} \mu R \frac{T}{V} dV = \mu RT \int_{V_i}^{V_f} \frac{1}{V} dV = \mu RT \ln(\frac{V_f}{V_i})$$

At the hot piston: Vf/Vi =10 and T=700K

W= $(40 \times 10^{-6})(8.3 \times 10^3)(700)\ln(10)$= 535.93 [J]

14

[2]

iii) the amount of heat added to the gas during its expansion in the hot piston

The amount of heat added during the expansion of the hot piston is equal to the work done by the piston; therefore:

Qadded= 535.93 [J]

[2]

iv) the amount of heat retained and released by regenerator

[2]

$\Delta Q = \mu c_v \Delta T$ **=(40x10^{-6})(20.8x10^{3})(700-300)=332.80 [J]**

v) the efficiency of the engine

[2]

$$\eta = \frac{E_{out}}{E_{in}} = \frac{E_{mech}}{E_{thermal}} = \frac{W_{\text{expansion at transtion 2 to 3}} - W_{\text{compression at transition 0 to 1}}}{\mathrm{Q}_{\text{added during expansion (transition 2 to 3)}}}$$

$$\eta = \frac{E}{E_{in}} = \frac{535.93 - 229.69}{535.93} = 0.5714$$

Note that the negative sign for the work done by compression should not be accounted for twice.

6. Answer the following questions

a) What is the "Renewable Obligation Order"?

The renewable obligation order establishes that licensed electricity suppliers are obliged to source a specific, and annually increasing, percentage of the electricity they supply from renewable sources.

[2]

b) What are the targets of the Renewable Obligation order 2007/2008 and for 2015/2016?

The target is 7.9% for 2007-2008. It is set to climb up until suppliers are obliged to generate 15.4% by 2015/16

[2]

c) What are "Renewable Obligation Certificates" and how are they issued?

A ROC is basically an incentive or subsidy mechanism for the UK's renewable energy sector. For each megawatt hour of renewable energy generated, a tradable certificate is issued.

[2]

d) What is the Climate Change Levy and what energy and fuel is exempt from it?

It is a tax on the use of energy to encourage industry to use less energy. The levy does NOT apply to:

- **energy used by registered charities for non-business uses**
- **energy used by very small firms, i.e. those using a "domestic amount" of energy**
- **fuels used by the domestic or transport sector**
- **fuels used for the production of other forms of energy (e.g. electricity generation) or for non-energy purposes (coal, for example can be used to produce carbon brushes)**
- **electricity generated from new renewable energy**
- **fuel used by "good quality" CHP**

[4]

e) What is usually meant by integrating (as opposed to "connecting") distributed generation into the networks?

In addition to the physical connection of a DG, the concept of integrating DG involves the following:

- **Establishing visibility of energy resources at all levels of the network**
- **Recognition of impact on the networks**
- **Enabling interaction with market participants and system operator**

- **Recognising the importance of location and time of output into the system**
- **Identification and quantification of value (or cost) from DG**
- **Development of commercial frameworks to reward (or charge) DG**

[4]

f) Explain what the concept of a "Virtual Power Plant" is, and its functions.

A VPP is an aggregation of distributed generators and controllable loads into a single portfolio of services presented to the market. It is aimed at enhancing the value of DG. Some of its functions are as follows:

- **Makes contracts in the wholesale market**
  - **Commercial aggregation services, market representation**
- **Offers services to the system operator.**
  - **Technical aggregation of DG & demand in a specific distribution network area**

[4]

g) Explain what "capacity value" is, and describe some scenarios where distributed generators may have low and high capacity values.

Capacity Value (CV) is the ability of new generation to displace energy and generation of conventional plant.

A photovoltaic system will have zero capacity value at night. A CHP plant has high capacity value during a winter night.

[2]