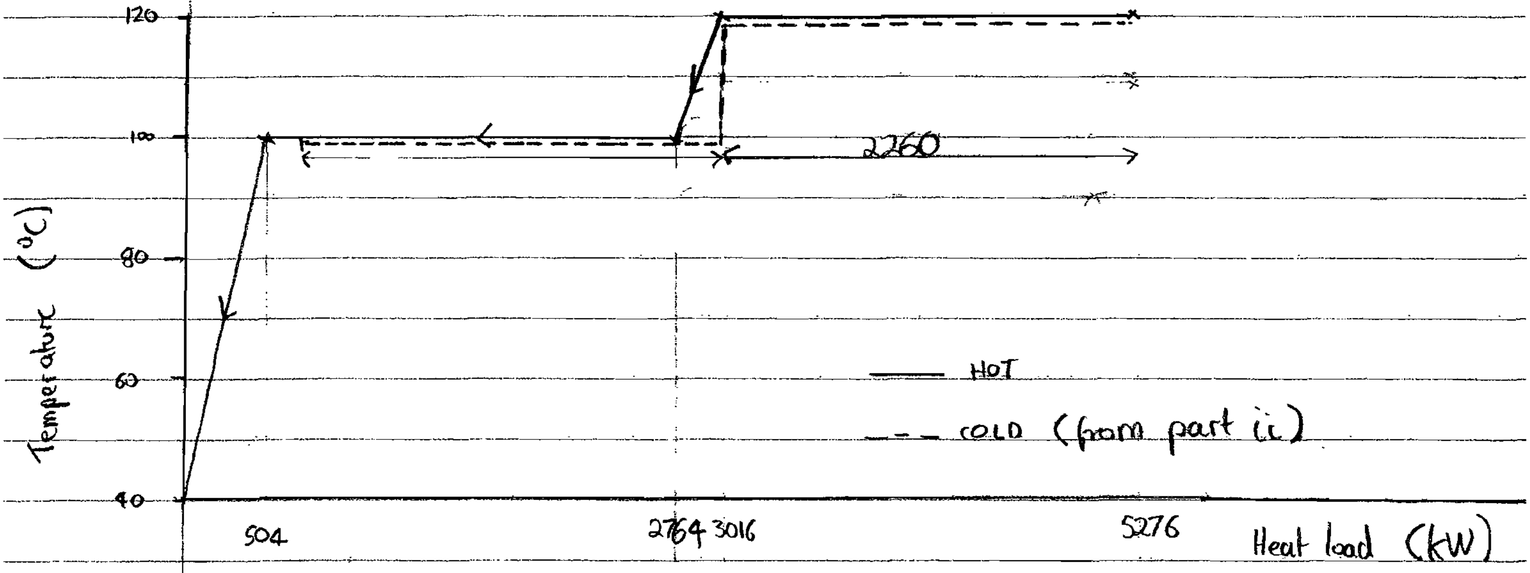
2008 IIB 4M15 SUSTAINABLE ENERGY DR S A SCOTT

1 a) i) Need to perform an interval analysis

Stream 1: Condense at 120°C then cool to 40°C.
Stream 2: cool from 120°C to 100°C
Stream 3: Condense at 100°C then cool to 40°C

Interval	Total heat capacity flow (kW/°C)	Heat load (kW)
120 – 120°C	N/A – condensing	2260 × 1 = 2260
120 – 100°C	1 × 4·2 + 2 × 4·2 = 12·6	12·6 × 20 = 252
100 – 100°C	N/A – condensation	2260 × 1 = 2260
100 – 40°C	1 × 4·2 + 1 × 4·2 = 8·4	8·4 × 60 = 504



Each evaporator boils 1 kg/s of water and so requires 2260 kW (ie $\Delta H^{vap} \times \dot{m}_{evaporated}$)

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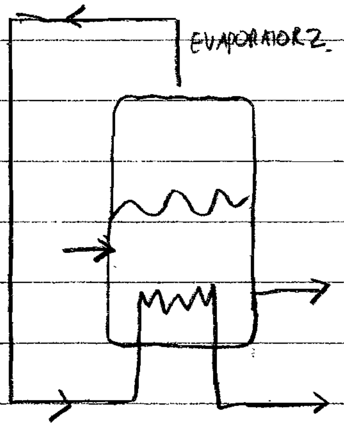
ii)

Interval	Hot Stream Heat Sources	Cold Streams Heat sinks	NET LOAD	CUMULATIVE NET LOAD
120 - 120°C	2260	- 2260	0	0
120 - 100°C	252	0	252	252
100 - 100°C	2260	- 2260	0	0
100 - 40°C	504		504	756

Therefore, in theory no heat is needed, since all the temperature intervals have are able to export heat to those below. The pinches are at 100 and 120°C. The cold composite which corresponds to 100% recovery is shown on previous graph. This is physically unreasonable because by operating under pinched conditions would require an infinite heat transfer area.

Also from the Q-T plot this would require that steam produced by evaporator 1 is condensed and the heat used to raise steam in evaporator 1



When running steadily this would imply that the evaporator could be run without an input of energy!

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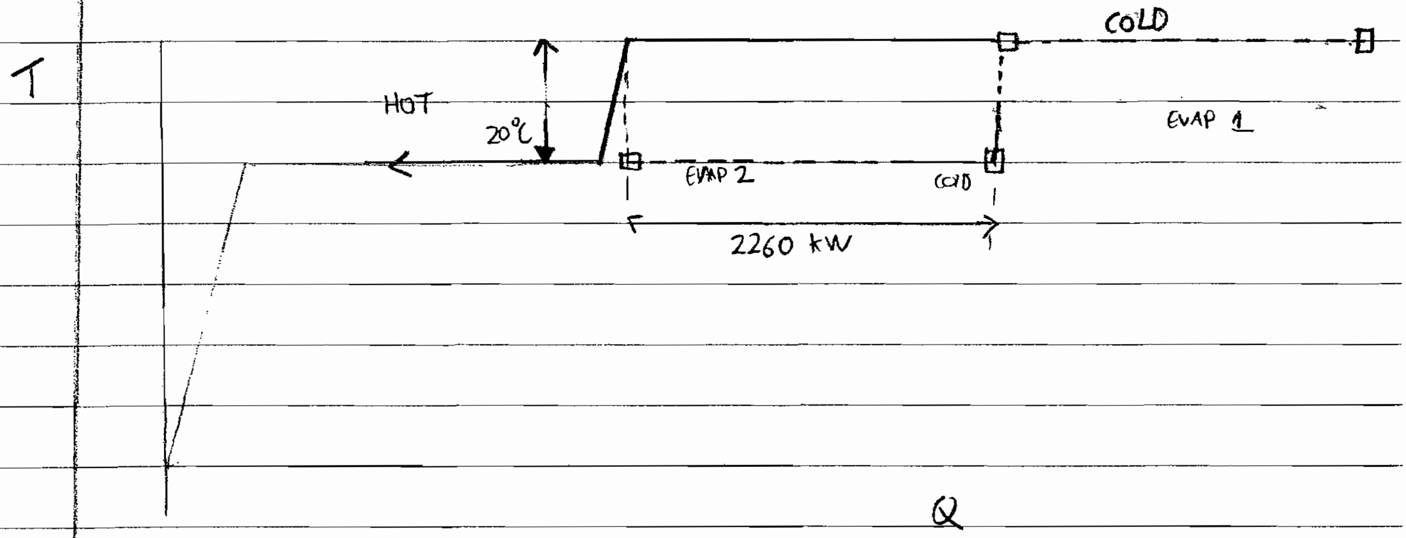
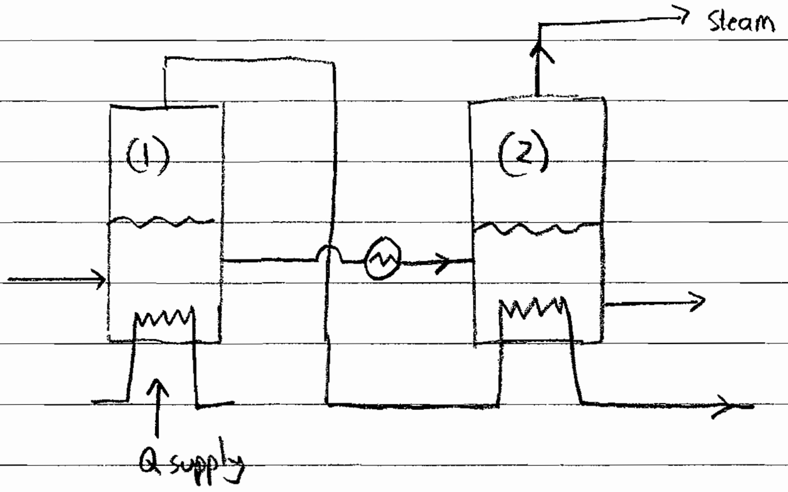
ii) Graphically, we can see that by sliding the cold composite curve to the right until ΔT min = 20°C that we can use all of the steam produced by evaporator (1) to raise steam in evaporator 2



∴ The heat load required is 2260 kW. The plant would require little modification to be run in this way i.e



i.e the heat required to raise 1 kg s^{-1} of steam can actually be used to raise 2 kg s^{-1}. Note, however, that the pressures have to be different in each evaporator

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b) If the ChP ran as a Carnot cycle with $\eta = 1 - \frac{T_C}{T_H}$

We would require 2260 kW of heat at 120°C (absolute limiting case).

$$W = Q_H \eta$$

$$W = (W + Q_C)\eta$$

$$W = \frac{Q_C \eta}{1-\eta}$$

$$\eta = 1 - \left(\frac{1200}{120+273}\right)^{-1} = 67.3\%$$

$$W = 2260 \times \frac{0.673}{1+0.673} = \underline{4638\text{ kW}}$$

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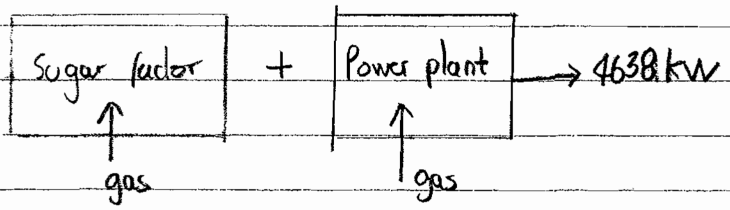
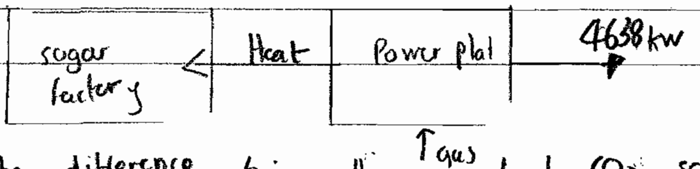
c) The environmental burden associated with producing the heat could be allocated via the relative market prices of the heat and power produced by the power station.

Another way of attributing the burden would be to compare the emmisions from



with



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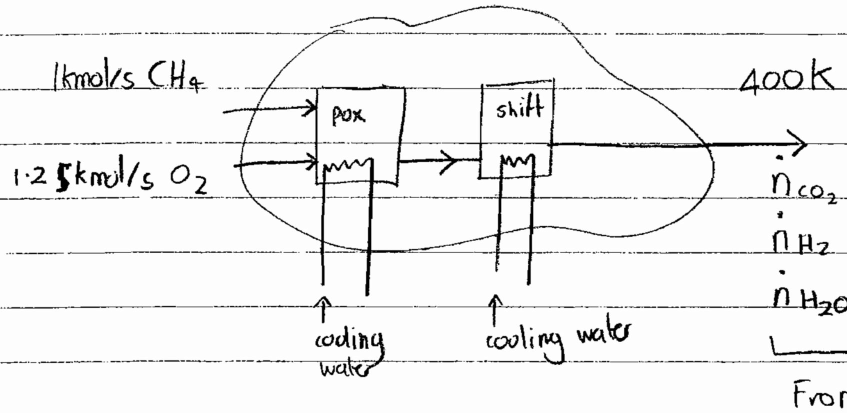
with the difference being the amount of CO_2 saved by the sugar factory

4i) Using a control volume around both the Pox and shift reactor:



$\dot{n}_{CO_2} = 1$ kmol/s $y_{CO_2} = 1/3$

$\dot{n}_{H_2} = 1.5$ kmol/s $y_{H_2} = 1/2$

$\dot{n}_{H_2O} = 0.5$ kmol/s $y_{H_2O} = 1/6$

From element balances.

For the shift reactor outlet

$$\sum \dot{n}_i \underline{H}_i(400k) = 1 \times -389506 + 1.5\times 2959.8 + 0.5\times -238374$$
$$= -504253 \text{ KJ/s}$$

The heat released in both reactors is

$$Q = \underbrace{\dot{n}_{CH_4}\underline{H}_{CH_4}(298.15) + \dot{n}_{O_2}\underline{H}_{O_2}(298.15)}_{\text{inflow}} - \underbrace{\sum \dot{n}_i \underline{H}_i(400k)}_{\text{outflow}}$$

$$= 1\times -74600 + 1.25\times 0 - (-542533)$$
$$= 429653 \text{ kJ/s}$$

This heat release is absorbed by boiling water at 2 bar. From steam tables, $h_{fg} = 2202$ KJ/Kg $\Rightarrow$ $\underline{\dot{m} = 429653 / 2202 = 195 \text{ kg/s}}$

[20%]

a)

ii) loss in exergy = Availability loss going from $CH_4 + O_2$ to product stream

− availability gained by cooling water

$$-\Delta E_{loss} = \Delta B_{realor} + \Delta B_{cooling\ watr}.$$

The entropy flow of the shift reactor exit is

$$\Sigma \dot{n} \bar{S} = \dot{n}_{CO_2}(\underline{s}_{CO_2} - R \ln y_{CO_2}) + \dot{n}_{H_2}(\underline{s}_{H_2} - R \ln y_{H_2}) + \dot{n}_{H_2O}(\underline{s}_{H_2O} - R \ln y_{H_2O})$$

$$= 1 \times (225.3 - 8.314 \ln \tfrac{1}{3}) + 1.5\,(139.2 - 8.314 \ln(\tfrac{1}{2})) + 0.5\,(198.8 - 8.314 \ln \tfrac{1}{6})$$

$$= 558.7.$$

$$\Rightarrow \text{Availability flow} = H - T_0 S = -504253 - 298.15 \times 558.7$$

$$= -670829 \text{ kJ/s}$$

Availability of methane = $1 \times (-74600 - 298.15 \times 186.4) = -130175$ kJ/s

Availability of O_2 = $1.25 \times (0 - 298.15 \times 205.1) = -76438$ kJ/S.

The change in availability over the reactor is

$$\Delta B_{reactor} = -670829 - (-130175 + 76438)$$

$$= -464216 \text{ kJ/s}.$$

For the cooling water

$$\Delta B = \dot{m}\,(h_{fg} - T_0 s_{fg}) = 195 \times (2202 - 298.15 \times 5.597)$$

$$= 103985. \text{ kJ/s}.$$

∴ Overall exergy loss is $\underline{360.3 \text{ MJ/s}}$.

[30%]

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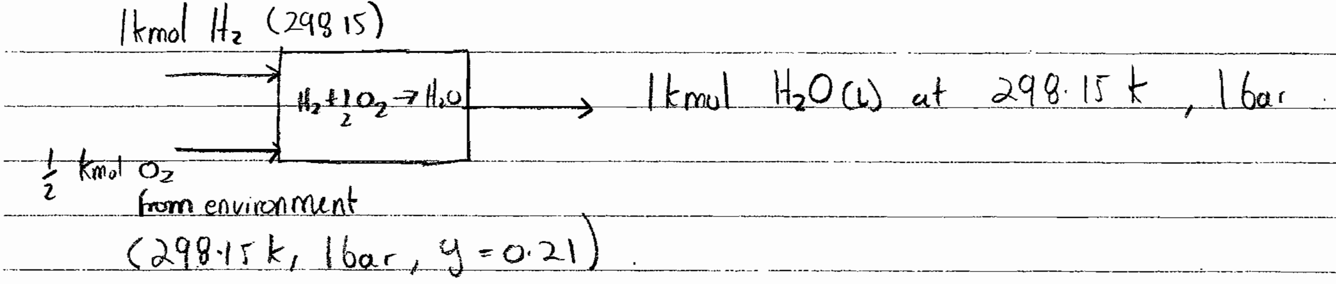
a iii) Exergetic efficiency $= \dfrac{\text{Exergy in } H_2 \text{ product} + \text{Exergy of heat exported as steam}}{\text{Exergy input with } CH_4}$

The exergy of H_2 can be calculated by bringing it to equilibrium with the environment.

For the H_2:



$$\text{Exergy} = \text{work output} = +\underline{b}_{H_2} + 0.5\,\underline{b}_{O_2}^{ENV} - \underline{b}_{H_2O(l)}^{env}$$

$$= \left(\underline{h}_{H_2} - T_0\underline{s}_{H_2}\right) + 0.5\left(\underline{h}_{O_2} - T_0\left[\underline{s}_{O_2} - 8.314\ln 0.21\right]\right) - \left(\underline{h}_{H_2O} - T_0\left[\underline{s}_{H_2O}\right]\right)$$

$$= -298.15 \times 130.7$$
$$+ -298.15 \times (205.1 - 8.314\ln 0.21) \times 0.5$$
$$- (-285830 - 298.15(70))$$
$$= 235\,193 \text{ kJ/kmol}$$

Previously the increase in availability for the cooling water/ steam was calculated to be 103 985 kJ/s.

$$\therefore \eta_{\text{exergetic}} = \frac{1.5 \times 235.193 + 103.985}{829.8}$$

$$= \underline{55\%}$$

[25%]

b) The work needed to compress the H_2 is

$$W = \int_{1bar}^{300bar} v \, dP$$

$$= RT \int \frac{dP}{P}$$

$$= RT \ln(300/1) = 14138 \text{ kJ/kmol}$$

The exergy of the fuel supplied to the cell is 235.2 MJ/kmol, since the hydrogen is throttled down to 298K and 1 bar before entering the fuel cell.

To drive 1km we need $\frac{2}{235.2 \times 0.5} = 0.017$ kmol of H_2

The CO_2 fot print due to compression is

$$14.138 \text{ MJ/kmol} \times 0.017 \text{ kmol} \times 0.166 \text{ kg}_{CO_2}/\text{MJ} = 0.0398 \text{ kg}$$

To produe 1kmol of H_2 in (a) releaed 1/1.5 kmol of CO_2. So the production of 0.017 kmol of H_2 required

$$0.017 \times \frac{1}{1.5} \times 44 = 0.499 \text{ kg of } CO_2$$

∴ Total carbon foot print is $\underline{0.539 \text{ kg/km}}$ [20%]

This value is much worse than a typical car ~ 0.25 kg/km running on petrol. This is partly due to all the environmental burden being placed on the H_2 produced in (a), and not distributing it between the heat and H_2. For H_2 as a fuel to make sene it must come from a non-carbon source or the CO_2 must be captured and stored.

[5%]

3) **Key points to be covered by the student include:**

Biofuels:

Liquid fuels can be produced from agricultural crops in a number of ways. One common method is to take sugars or starches and ferment them to alcohol, which must then be purified by distillation. Alternatively, biodiesel can be made by taking the fatty acids from plant seeds (e.g. soya) and esterifying with methanol.

Biofuels can be used in current vehicles with little or no modification to the vehicle. The liquid fuel can be blended with existing liquid fuels (e.g. 5% biodiesel in regular diesel). This also means that the existing infrastructure for distributing liquid transport fuels can be used.

The reductions in CO_2 emissions arise from the fact that biofuels absorb CO_2 as they grow, effectively storing solar energy in carbon based molecules in the plant, this CO_2 is released when the fuel is combusted. In theory at least, this means that there is no net release of CO_2 into the atmosphere.

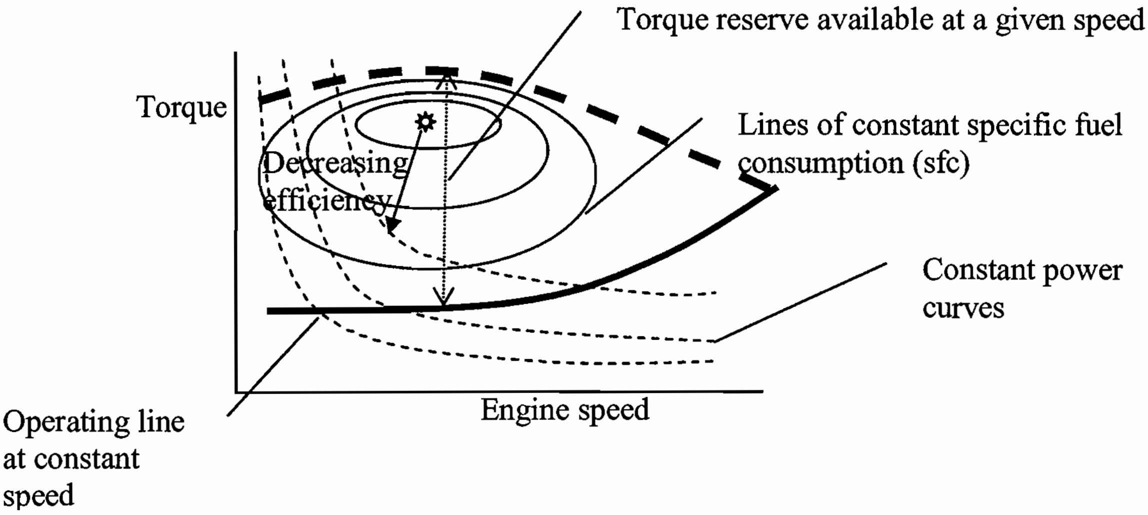
However, modern intensive agriculture requires inputs of fertiliser, pesticides, machinery and manpower. Thus, the CO_2 emissions over the entire lifecycle of the fuel must be considered. The net energy benefit (the energy contained in the biofuel, compared with the fossil fuel energy required to produce the fuel over its lifecycle) is typically close to unity. Thus, the benefit from biofuels can be marginal in terms of CO_2 saving and the net energy balance.

Most of the environmental burden for the bio fuels is associated with the agriculture, and for the case of bio-ethanol the energy required to remove the water from the alcohol. Part of the problem with current biofuels, is that only a small part of the plant grown is used to make the fuel (e.g. the sugars or the fatty acids in the seeds).

Aside from the lifecycle CO_2 footprint and embodied energy of the fuel, a major problem which exists with the biofuels is the huge land area required to grow enough crop. In particular, many developed countries are now importing energy crops from developing countries, where energy crops compete with food crops.

High efficiency, petrol/diesel driven vehicles:

Current internal combustion engined vehicles are currently not designed to operate at the highest fuel efficiency. Consider the typical operating characteristics of a engine,



In the above sketch, the specific fuel consumption (sfc) increases away from the optimum as follows:

1) The engine power being used to overcome friction increase with engine speed, as the friction torque does not decrease with rpm (in fact it increases). Thus the sfc increases with engine rpm (more strictly we should say with increasing rpm along constant power curves – see below).

2) When the engine load is varied at constant rpm, this has to be achieved by throttling the air intake. In this way the mass of charge (fuel + air) is reduced, while maintaining a constant (near stoichiometric) air/fuel ratio, necessary to ensure reliable combustion. Throttling represents a lost opportunity to do work, so necessarily increases sfc.

Other effects are a) the tendency to richen up the mixture to obtain maximum torque, which has the effect of increasing sfc near the maximum torque line, and b) the effect of large quantities of residual gas at throttled +low rpm conditions (where back flow from the exhaust into the inlet manifold occurs) on combustion duration, which leads to increased sfc at the lowest rpm's

An engine is sized and geared so that at a given speed (e.g. 70 mph) when cruising, the engine is running at a relatively low efficiency. The rational for this is that a torque reserved is needed should the car need to accelerate (also important for the driving experience.

One way to radically improve the efficiency is to allow the engine to operate close to the optimum fuel efficiency, and provide the torque reserve from an additional power source. Thus, a hybrid drive system will use a battery to provide extra energy to the drive system. The engine is made smaller and is allowed to operate at a more constant load, close to the most efficient operating point, with the engine used to charge the battery.

Several configurations are possible. (i) Series: an engine charges a battery; the battery is then used to drive a motor connected to the wheels. (ii) Parallel: both the engine and the electric motor are connected to the wheels via a power splitter, and the engine is used to charge the battery when it is producing more power than required to drive the vehicle.

The disadvantages of a hybrid vehicle are the cost and mass associated with carrying two power systems. Maintenance is more difficult and there is inevitably more to go wrong. Also, it is possible that performance and fuel efficiency can be poor if the car is driven for long periods with very high loads on the engine (e.g. motorway driving above the designed cruising speed) , since in this case the battery can only provide the extra torque required for a limited period before the car has to rely solely on the (now undersized) engine.

Conclusions

The key issue with biofuels is the lifecycle energy requirements and the land area required. Given this it is unlikely, that with current biofuel technology, the target can be met with biofuels. However, there is a large amount of work on second generation biofuels, where the entire crop (rather than e.g. just the seeds) is used. These will have a much more favourable energy benefit and mean that biofuels could contribute to the target in a meaningful way. Increasing the fuel efficiency of cars via hybrid power trains makes a lot of sense and the technology is now relatively established. Hybrid power systems could make a significant contribution to meeting the target. The only disadvantage is that it requires the entire fleet of vehicles to be replaced, and so will not happen quickly. Thus both options offer hope for the future, in the mean time, the target could probably be met by removing the largest and most fuel inefficient vehicles from the roads.

Mark scheme
5% for structuring in the form of an essay
80% for presenting the main arguments (of which 20% are for sketch of the engine characteristics).
15% for drawing some sort of sensible conclusion which brings together the arguments.