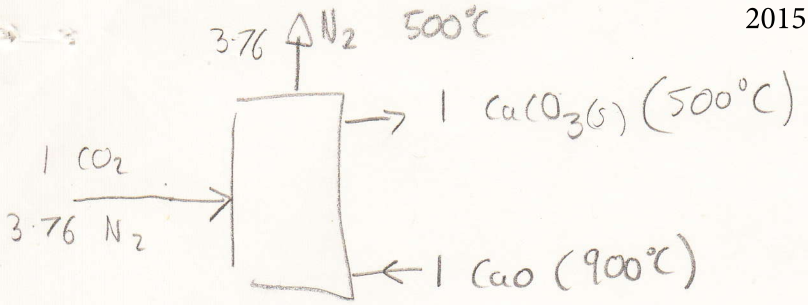
1 a i)



Flow rate obvious from carbon balance

Flow rate obvious from Calcium balance.

$$Q = \underbrace{\sum n_i \underline{h}_i}_{IN} - \underbrace{\sum n_i \underline{h}_i}_{out}$$

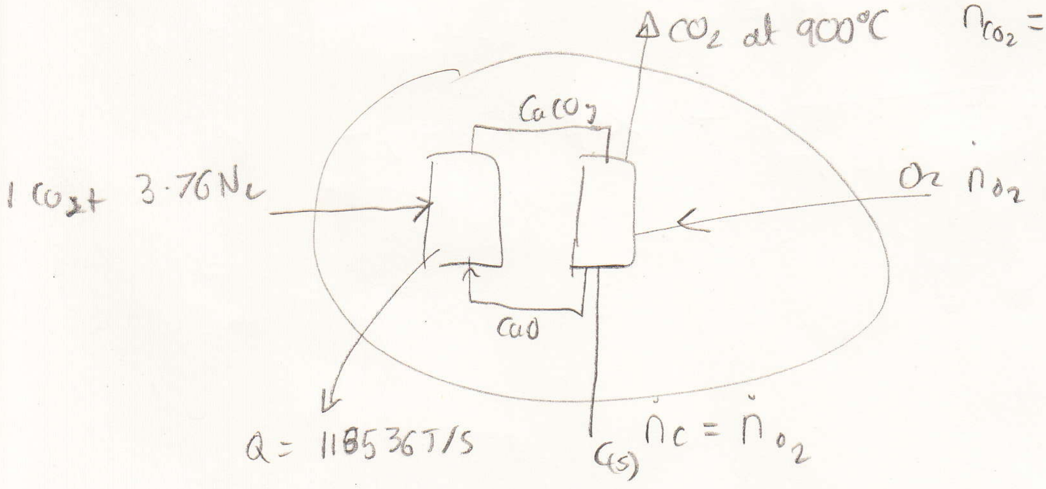
$$= \overset{CO_2\ IN}{1 \times (-393510)} + \overset{N_2\ IN}{3.76(0)} + \overset{CaO\ in}{1 \times (-591383)}$$

$$- \overset{N_2\ out}{3.76(14204)} - \overset{CaCO_3\ out}{1 \times (-1156837)}$$

$$= \underline{118536}\ kJ/s$$

ii) Calciner is adiabatic. Either use a control volume around the calciner or whole system.

$\dot{n}_{CO_2} = 1 + \dot{n}_{O_2}$
(since $C + O_2 \rightarrow CO_2$)



First law:

$$0 = \overset{Q_{out}}{-118536} + 3.76(0 - 14204) + \dot{n}_{O_2}(0)$$

$$+ \dot{n}_{carbon}(0) - (1 + \dot{n}_{O_2})(-350542)$$

$$+ 1(-393510)$$

$350542 \dot{n}_{O_2} = 214911$

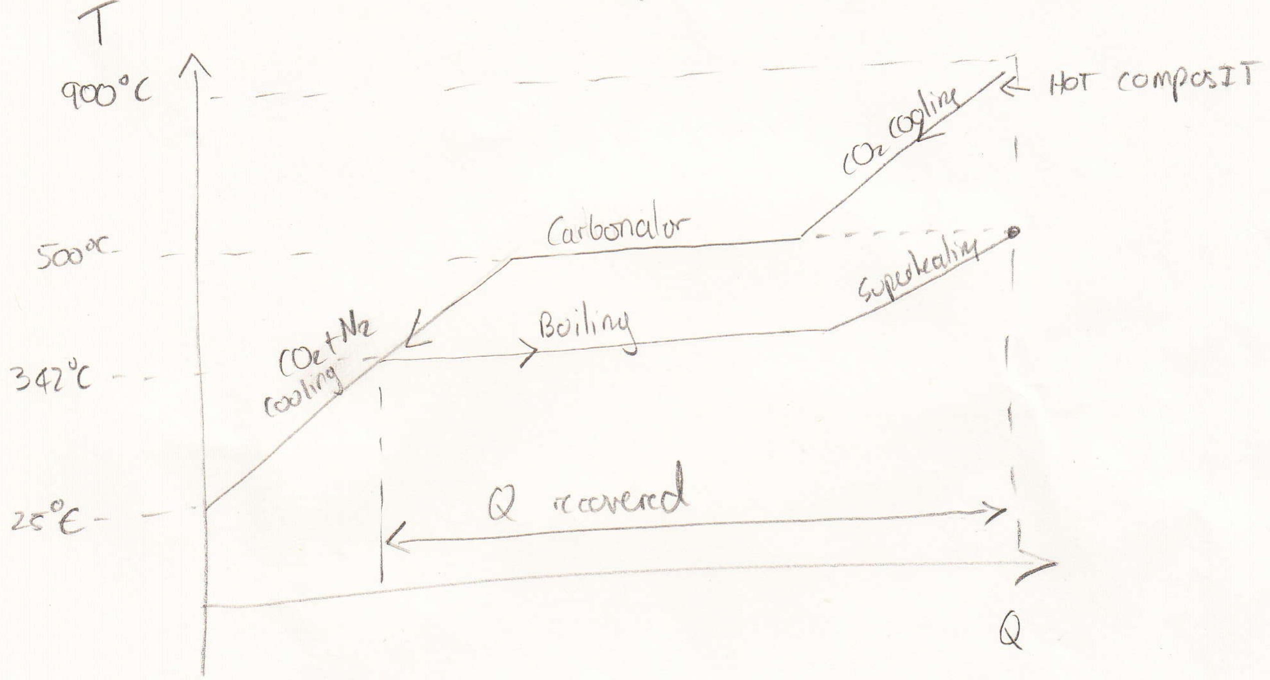
$\Rightarrow \dot{n}_{O_2} = 0.613$ kmol/s

ie $\frac{0.613}{1+0.63} = \underline{0.38}$ kmol O_2 per kmol CO_2 captured.

b)

Stream	T_{in}	T_{final}	Q
N_2	500	25	
CO_2	900	25	
Boiling water	342.16	342.16	$\dot{m}_s(1000.5)$
superheating water	342.16	500	$\dot{m}_s(3310.8 - 2610.8)$

From steam tables. saturated water at 150 bar and superheated water at 150 bar and 500°C



PINCH IS OBVIOUS. Could use average cp's etc... but from sketch it is easy to write down the heat loads (we have been given the enthalpies)

$$Q \text{ recovered} = \dot{m}_s(1000.5 + 3310.8 - 2160.8)$$

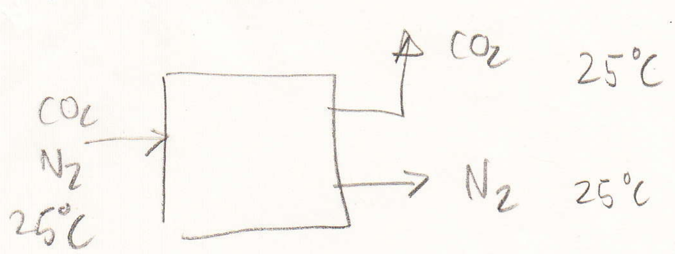
$$= 3.76(14204 - 9356) + 1.613(-350542 - -379874) + 118536$$

$$17005\,\dot{m}_s = 184079$$

$$\dot{m}_s = \underline{108.25 \text{ Kg/s}}$$

6ii)

Removed From Question to shorten



Note that since $T_{in} = T_{out}$ Everything cancels except the mixing term.

$$W_{min} = \Delta \text{ Availability}$$

$$= \dot{n}_{CO_2}(b_{CO_2 out} - b_{CO_2 in}) + \dot{n}_{N_2}(b_{N_2 in} - b_{N_2 out})$$

$$= \dot{n}_{CO_2}\left(-T_0 R \ln\left(\frac{y_{out}}{y_{in}}\right)\right) + \dot{n}_{N_2}\left(-T_0 R \ln \frac{y_{N_2 out}}{y_{N_2 in}}\right)$$

$$= 1 \times 298.15 \times 8.314 \left[-\ln\left(\frac{1}{0.21}\right) - 3.76 \ln\left(\frac{1}{0.79}\right)\right]$$

$$= \underline{\underline{6065 \text{ kJ/s}}}$$

iii) If all the fuel was combusted in the original plant then work output is

$$(\underbrace{1}_{\substack{CO_2 \text{ released by burning}\\ \text{original fuel}}} + \underbrace{0.613}_{\substack{\text{extra fuel to}\\ \text{run separator}}}) \times 120 \leftarrow 120 \text{ MJ/kmol of } CO_2 = 193 \text{ MJ/s}.$$

with the carbon capture system the work output is

$$1 \times 120 + \frac{108.3 \times 1000}{1000} = 228.3 \text{ MJ/s}.$$

Should also account for the work needed to produce the O_2 – which in the limiting case is the exergy flow

$$\varepsilon_{O_2} = -0.613 [RT_0 \ln 0.21) = 2.4 \text{ MJ/s}$$

∴ Energy penalty $= 193 - [228 - 2.4)$

$= -32.6$ MJ/s

c)i

This seems to defy expectation since carbon capture should give a positive energy penalty. Installing carbon capture has improved the efficiency.

- The old power station was inefficient so upgrading the steam system to maintain the same efficiency, despite the diversion of steam actually increased the efficiency at which heat is converted to work. The returned water would need to be brought back up to feed heater temp and pressure which at best would result in the same efficiency. Saying that upgrades mean this isn't required implies improvements to cycle efficiency.
- A large amount from the carbon capture system can be recovered back into the power cycle – it operates well above cycle temperature.
- Burning coal then using very high T heat to heat steam gives a massive loss of work which is usually lost to irreversibility. Using the carbon capture system as a topping cycle makes use of the change in exergy that would otherwise have been lost

Amine scrubbing — low temperature system – difficult to recover the heat rejected so larger energy penalty

Oxyfuel – use 1 kmol O_2 per kmol CO_2 captured – more than in this scheme. Our estimate of penalty massively underestimated the work need to actually produce O_2.

Q1 Thermodynamics of a carbon capture plant 16 attempts, Average mark 12.25/20, Maximum 16, Minimum 7.

Part (a) answered almost entirely correctly. Part (b1) was mixed with those students who understood composite curves getting almost 100%. Of those that understood part bi) the most common error was not including the reactor heat load in the integration, or not realising the pinch was at 342 °C (from the sketch. bii) most students wrote something but very few noted that some work would be needed to produce the oxygen required by the calciner, and that a lower bound estimate of this work input would be the exergy of the oxygen. In part (c) most students could give a partial answer but very few addressed all the issues or arguments correctly.

Question 2

2ai) The embodied energy is the amount of primary fossil fuel required to produce 1kg of the substance + any primary energy (i.e. fossil energy) the substance itself contains. The CO2 footprint is the amount of CO2 (or Co2 equivalent) released per kg by the manufacture of the substance on all previous stages of the lifecycle.

ii) A background system is a homogenous system which provides goods or services to the product system of interest. Although within the product system, the LCA is conducted by using database values for the average LCA inventory of the goods or services provided by the background system. As a consequence, it is only valid when the average value is appropriate - e.g. if electricity only used at the peak time, then it will have a higher carbon foot print than average. A system can only be assumed to be in the background if there is no feedback from the foreground system being analysed.

b) CO2 footprint (only include the fossil CO_2) - per tonne of bioethanol produced.

Stream	Contribution to inventory		
Wood	4×0.2	=	0.8
Other raw material	$0.1 \times .4$	=	0.04
Electricity	5×0.15	=	0.75
Heat (from gas	$\frac{1}{48}(\frac{44}{16} + 0.3)$ note that 44/16 accounts for the CO2 released when combusting the methane	=	0.0635
Waste	The waste will displace coal in the power station, on a calorific value basis 12/33 te of coal are no longer burned. So the CO2 footprint should fall by $\frac{12}{30} * (44/12.5 + 0.3)$	=	-1.528
Total			0.1255

Embodied energy (only the non- fossil energy) - per tonne of bioethanol produced.

Stream	Contribution to inventory		
Wood	4×0.5	=	2
Other raw material	$0.1 * 50$	=	5
Electricity	5×2.3	=	11.5
Heat (from gas	$\frac{1}{48}(50)$	=	1.042
Waste	The waste will displace coal in the power station, on a calorific value basis 12/30 t of coal are no longer burned. So the embodied energy should fall	=	-13.2

	$\frac{12}{30} \times 33$		
Total			6.34 GJ/t Bioethanol

The potential GHG saving must account for the saving incurred by displacing the petrol

Saving = $\frac{28}{43} \times \left(\frac{8*44}{12*8+18*1} + 0.4\right) - 0.1255 = 2.158$ t CO2 per te of bioethanol.

Thus, it looks like the bioethanol is very sustainable. However, most of the sustainability comes from the credit given by burning the waste which displaces coal.

c) Under these scenarios, the allocation of the environmental burdens becomes more complicated for several reasons

- The credit for the waste was previously calculated by assuming it displaces coal. However it isn't clear what it is now displacing.
- The bioethanol plant now causes the power station to change, so it cannot be analysed as a background system.
- The waste effectivity displaces electricity and since electricity cannot be stored, using average values can sometimes be misleading.

Scenario A: It isn't clear how the credit for the waste should be allocated. There are a number of possible answer and it depends on how the powerstation operates in the market.

If the power station has a fixed power output - i.e. it is base load, then the waste will displace the input fuel to the powerstation. So does the waste displace the wood, or the coal? It would in reality depend on the economics of using either wood or coal. The rational power producer would scale back on the least economic fuel. This does not mean the cheapest fuel (gate prices) as there are incentives for using biomass in terms of subsidies. If the waste displace the coal, then the answer would be the same as (b). If the waste displaces wood, the credit for the waste would reduce to $\frac{12}{13} * 0.5\ kg\ of\ CO2$

If powerstation does not operate at base load. There are several views of what the credit for the biomass should be. The waste is effectively free so will be used to generate energy regardless of the energy price. One (valid view point) is that the electricity from waste therefore displaces average electricity from the grid, in which case the credit would be $1 * 12 * 0.4\ GJ\ of\ grid\ electricity$. Even this is somewhat flawed since we have been given the overall average, and if the plant does not run continuously instantaneous average values would be needed. You could also take the view that the electricity generated from the waste would displace electricity form the powerstation at the margin, i.e. the plant following the load on the grid -this could be a coal station (so no change from b) or a wind turbine, in which case the credit would be almost zero.

In scenario b, the power station and the ethanol plant must be considered together as one product system that produced both electricity and ethanol. Wood used in the bioethanol plant can no longer be used in power station. For base load, this would force the power station to burn more coal. Therefore each unit of wood used by the bioethanol plant would cause one extra unit of coal to be combusted. Overall this means that the bio-ethanol is effectively being made from coal, not wood. 1 t of bioethanol requires 4 t of wood, so from the point of view of the power station

$4 * \frac{13}{30}$ tonnes of extra coal required with an embodied energy and CO2 footprint of 33 GJ and $\frac{44}{12+0.5} + 0.3$ kg CO2 per tonne to replace the wood.

No longer burning 4 t of wood with an embodied energy and CO2 footprint of 0.5 GJ and 0.2 kg Co2 per tonne

The waste can be assumed to displace coal given that the powerstation would try to burn as much biomass as possible (implying they would rather not burn coal), preventing the combustion of

Change in CO2 footprint from base case = $\left(+4 * \frac{13}{30} - 1 * \frac{12}{30}\right) * \left(\frac{44}{12+0.5} + 0.3\right) - 4 * 0.2 = 4.29$

Change in embodied energy from base case = $\left(+4 * \frac{13}{30}\right) * (33) - 4 * 0.5 = 55.2$

Below is a summary of the different outcomes. Given that the Embodied energy and GHG saving for the base case without the credit for the waste would be 19.5 GJ and 1.65 teCo2 per tonne, it can be seen that credit for the waste and penalty in scenario B are very significant. IF there is a finite amount of biomass available the environmental burden must account for alternative uses which have been displaced. A large PowerStation in the UK burning wood, would use so much wood that supply of biomass could be a problem. In this case, scenario B is a very real possibility, i.e. from the point of view of GHG saving, it would be much better to burn the wood in the PowerStation - all of it. Making bio-ethanol would not make much sense. Even in the other cases, the credit for burning the waste is very large which suggests burning biomass is better than converting it to bioethanol.

Table: Lifecycle credit for waste minus change increase in burden caused by forcing the power station to brun more coal.

		Embodied energy (GJ/t)	Change in CO2 saving (tCO2/t)
Base case	Coal displaced by the waste	13.2	1.528
Scenario A	Base load - Wood displaced by the waste	$\frac{12}{13} * 0.5 = 4.62$	$\frac{12}{13} * 0.2 = 0.42$
Scenario A	Base load - Coal displaced	13.2	1.528
Scenario A	Load following displace average grid electricity	$4.8 * 2.3$=11.04	$4.8 * .15 = 0.72$
Scenario A	Load following and displacing marginal electricity	Anything from the base case scenario (coal at the margin) to e.g. zero for wind	Anything from the base case scenario (coal at the margin) to e.g. zero for wind
Scenario B		13.2 - 55.2 = -42	1.528-4.29 =-2.76

Other points to note. There is a finite amount of land available, and the world needs food. Woody biomass could have come from forestry and not from land used to produce food. This is better than using food crops. Using biomass for fuel rather than co firing would make sense when all the coal burning plants have been replaced by renewables.

Q2 **Lifecycle analysis** 15 attempts, Average mark 10.4/20, Maximum 15 attempts, Maximum 15, Minimum 6.

Most students were able to define the embodied energy and CO2 footprint. A few got confused between background and reference systems in aii. Most students had a reasonable attempt at working out the embodied energy and GHG savings in b. However very few managed to correctly account for all the credits from the co products or the savings from displacing petrol. Quite a few students did not distinguish between the carbon from the combustion of biomass, which does no contribute to GHG, compared to that from fossil fuels. A few students ignored the combustion contribution. Part c was very open ended, with most students presenting some arguments which made sense. Some students correctly noted that key issue is how the waste products are allocated and some had a go a supporting their calculations correctly. No-one gave both a perfect explanation and a perfect calculation, though there were examples of students doing one or the other.

Question 3

A good answer would cover the following points

- The power available from wind turbines is proportional to the wind speed cubed, so high wind speeds are preferable. As important, is the consistency of the wind resource. Typically, wind speed will follow a Weibull distribution. Wind turbines are not designed to withstand peak loadings which might only happen for a few days a year, and either turn their blades from the winds or stall to prevent excessive loading. Overall capacity is therefore determined by the consistency of the wind resource.
- Offshore in the uk there are high and consistent wind speeds available. Capacity factors on some offshore might reach as high as 60%. From the point of view of resource, it does therefore make sense to move off shore.
- Offshore wind is more publically acceptable since no-one can see it. However this might partly be due to the split of benefits seen by communities that have to put up with wind turbines. Most of the community in line of sight of wind turbines receives no direct benefit, so are much happier getting their electricity for a coal fired power station built next to someone else. One way around this is to engage the community more with schemes in which the community see a direct financial benefit from the presence of the turbines - e.g. co-operatives or improvements to local facilities funding.
- However, off shore wind is logistically more difficult. Firstly the turbines themselves must be supported. In the shallow north sea this is done by using concrete monopile to the sea bed to which the wind turbine can be affixed.
- The additional support structure required offshore changes the energy payback ratio dramatically, from around 40 to 15. There is a very large embodied energy in the foundations. This implies that offshore is more costly, however the tower represents a large fraction of the energy but a lower fraction of the cost. Working offshore is also more costly.
- Currently offshore windfarms are small (might look big but in terms of power generation they are not a massive contribution to the UK power grid - maybe 1GW). Furthermore, they have been placed close to shore and near grid connections. If wind is massively scaled up, moving further offshore will be more challenging. Change to high voltage DC will require sub stations near the turbines and large amounts of subsea cabling to land. This not only increases the cost massively compared to onshore turbines, but means that for every 500 or so wind turbines you also need to manufacture and operate an offshore substation. The UK is aiming for the order of 10GW offshore.
- Cheap wind power relies on economy of scale. The wind turbines have to be standardised, the electricity distribution grid etc.. This has not happened in the past with e.g. different voltages used for transmission and each wind farm using different turbines. Once set up, the massive expense of the wind turbine factory is only recovered by building more of the same turbines. To produced a better turbine, e.g with larger blades, it is only worth doing if the manufacturers can see a very large market.
- Wind power systems, although large, are actually very small compared to power stations. Thus, economies of scale come from mass production, with the capital cost of the factory producing the turbines being very significant. To meet the EU targets for offshore wind, for example, 6 wind turbines per day would have to be installed.
- There is only a limited factory capacity in the world for wind turbines, and these tend to operate at capacity. With turbines already optimised for the onshore market, there isn't much incentive to switch capacity to new and untested off-shore turbines.
- Uk north sea is not a large enough market by itself to be attractive to most wind turbine suppliers. In the rest of the world, even the EU, onshore is looking more attractive. Rules about siting of wind turbines have been relaxed (e.g. ion Germany) and this has meant more incentive to produce wind turbines which can efficiently extract energy form the more moderate wind speeds on shore. These wind turbines are becoming workhorses - mass produce. Future development seems to favour the

produced of larger bladed variants of the onshore turbines, optimised for low wind speed. GE has already pulled out of off-shore wind. Building close to the consumer also eliminates the infrastructure costs associated with long distance transmission of electricity. There is therefore limited appetite for offshore wind-despite the government targets.

- The UK is a small country - it cannot dictate what the wind industry does.

Q3 Wind power 13 attempts, Average mark 14.1/20, Maximum 17, Minimum 8.

This question was mostly well answered by all those who attempted it. Of the issues covered most were described correctly. However, many students only discussed a subset of the important issues. The highest marks were awarded to answers which covered both the technical and economic issues.