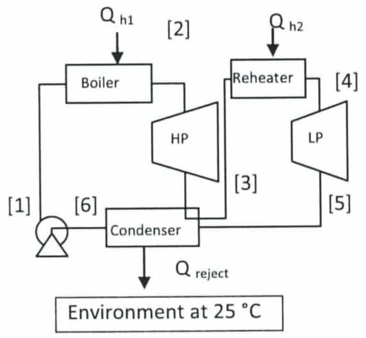
PART IIB 2010 4M15: SUSTAINABLE ENERGY

DR S. A SCOTT

1. (a) Describe what is meant by "availability". How does the exergy of a material stream differ from its availability?

The decrease in availability is defined as the **maximum** amount of **work** which could be extracted in changing between two thermodynamic states. This is realised using **reversible processes**, and only **exchanging heat with the environment, at the temperature of the environment**. The exergy is an absolute value of the availability, found by measuring the availability **relative to environment**. The exergy is the maximum work which could be extracted by bringing the material or stream **to equilibrium with the environment**.



	1	2	3	4	5	6
Temperature (C)	25.2	500	422	721	25	25
Pressure (bar absolute)	100	100	20	20	0.0317	0.0317
State	Liquid	Vapour	vapour	vapour	Sat Vapour	Sat Liquid
h	114.8	3375.1	3296.8	3966.5	2546.5	104.8
s	0.367	6.599	7.200	8.000	8.557	0.367

The mass flow of steam through the boiler is 1kg/s.

(b) A flow diagram for a power station utilising a steam cycle is shown in fig. 1. After leaving the boiler, the steam passes through a high pressure turbine (HP), is then reheated and finally goes through a low pressure turbine (LP), before entering the condenser. The mass flow of steam through the boiler is 1 kg s^{-1}. Table 1 gives the properties of the steam at each point in the cycle.

i) What is the thermal efficiency of the power station shown in fig. 1? **[10%]**

The total heat added is

$$(Q_{h1} + Q_{h2}) = (3375.1 - 114.8) + (3966.5 - 3296.8) = 3930 \text{ kJ/kg}$$

The total work extracted is

$$W_{lp} + W_{hp} = (3375.1 - 3296.8) + (3966.5 - 2546.5) = 1498.3 \text{ kJ/kg}$$

Work input (pump) is

$$W_{pump} = 114.8 - 104.8 = 10 \text{ kJ/kg} \text{ (which could be neglected)}$$

Therefore the thermal efficiency is:

$$\eta = \frac{W_{lp} + W_{hp} - W_{pump}}{Q_{h1} + Q_{h2}} = \frac{1498.3 - 10}{3930} = 0.38$$

ii) Calculate the increase in exergy of the steam as it passes through the boiler, and then the reheater, [10%]

Increase in availability due to Qh1 = $\Delta B_1 = \Delta H - T_o \Delta S$ =

$$(3375.1 - 114.8) - 298.15 \times (6.599 - 0.367) = 1402.2 \text{ kJ/kg}$$

Increase in availability due to Qh2 = $\Delta B_2 = \Delta H - T_o \Delta S$ =

$$(3966.5 - 3296.8) - 298.15 \times (8.000 - 7.200) = 431.18 \text{ kJ/kg}$$

ii) What is the exergetic efficiency of the whole system (i.e. steam cycle + heat source) if it is assumed that the heat supplied to the power station is supplied reversibly? [5%]

The exergy supplied to the power station is then equal to increase in availability of the steam. So, taking a basis of 1kg/s of steam flowing around the steam cycle (i.e. $\dot{m}$ = 1),

Therefore the exergetic (aka second law efficiency) is

$$\eta_{ex} = \frac{W_{lp} + W_{hp} - W_{pump}}{\Delta B_1 + \Delta B_2}$$

$$\eta_{ex} = \frac{1498.3 - 10}{1402.2 + 431.2} = 0.81$$

(c) The power station is to be altered so that 20% of the steam leaving the reheater (i.e. [4] in fig. 1) is now diverted through an isenthalpic throttle valve, into a heat exchanger. The pressure downstream of the throttle is 1 bar, and the water leaves the heat exchanger as a saturated liquid, and rejoins the main cycle before the boiler. The heat exchanger, provides heat to an amine based carbon capture system, in which the CO_2 is scrubbed from the flue gas (21 mol.% CO_2 in N_2), to produce pure CO_2 for sequestration. The carbon capture system processes 0.01 kmol of flue gas, per kg of steam through the boiler. The flow diagram for the modified power station is shown in fig. 2.

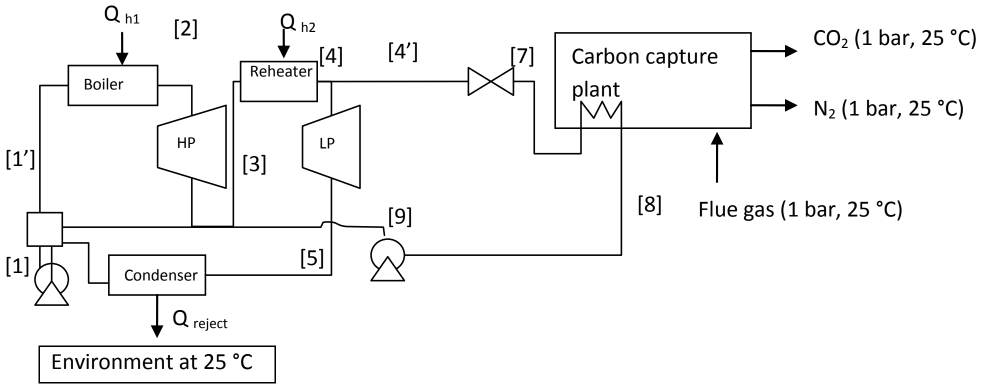


Fig. 2

Table 1. Temperature (T), Pressure (P), enthalpy (h) and entropy (s) at each point in the steam cycle

	[1]	[2]	[3]	[4]	[5]	[6]	[4']	[7]	[8]	[9]	[1']
T (°C)	25.2	500	422	721	25	25	721	716.3	100	100.4	40.3
P (bar)	100	100	20	20	0.0317	0.0317	20	1	1	100	100
h ($\mathrm{kJ\,kg^{-1}}$)	114.8	3375.1	3296.8	3966.5	2546.5	104.8	3966.5	3966.5	417.5	429.9	177.8
s ($\mathrm{kJ\,kg^{-1}}$)	0.367	6.599	7.200	8.000	8.557	0.367	8.000	9.380	1.303	1.303	0.573
State	l	v	v	v	v (sat)	l (sat)	v	v	l (sat)	l	L

i) What is the minimum amount work required to separate the CO_2 from the flue gases? [15%]

Availability balance gives

$$W_{min} = 0.0021\{h_{co_2} - T_o(s_{co_2})\} + 0.0079\{h_{N_2} - T_o(s_{N_2})\}$$

$$- \ 0.0021\{h_{co_2} - T_o(s_{co_2} - R\ln 0.21)\} - \ 0.0079\{h_{N_2} - T_o(s_{N_2} - R\ \ln 0.79)\}$$

$$= -\ 0.0021\{-T_o(-R\ln 0.21)\} - \ 0.0079\{-T_o(-R\ \ln 0.79)\}$$

$$= -0.01 \times 298.15 \times 8.314 \times (0.21 \times \ln(0.21) + 0.79 \times \ln(0.79))$$

= 12.74 kJ/kg of steam through the boiler.

Comment [s1]: Old Crib incorrectly had this as 54 kJ/kg

ii) By performing an exergy balance over the entire carbon capture plant, determine how much exergy is lost to irreversibilities in the carbon capture plant. **[10%]**

Loss work = loss in availability of the steam – increase in availability of separated gases

= loss in availability of the steam – minimum work required to separate the gases

= $0.2 \times (b_7 - b_8) - 12.74$

=$0.2 \times (3966.5 - 417.5 - 298.15 \times \{9.380 - 1.303\}) - 12.74$

= 215.4 kJ/kg of steam through the boiler.

Comment [s2]: Previously this was 54

Comment [s3]: Previously this was 54

Comment [s4]: Old crib had wrong answer here

n.b. the heat supplied to the carbon capture plant is

=$0.2 \times (3966.5 - 417.5)$ = 709.8 kJ/kg of steam through the boiler.

The HP turbine and the carbon capture plant are the largest sources of irreversibility in this plant.

iii) identify and quantify all other sources of lost potential for work in the modified power station. You may assume that heat is transferred to the boiler and reheater reversibly. Where are the largest sources of lost potential for work? [40%]

For adiabatic processes $T_o \Delta S_{irrev} = T_o \Delta S$ (since $\Delta S_{irrev} = \Delta S$ when there is no heat flow.

HP turbine: Adiabatic. Lost work = $T_o \Delta S$ = $298.15 \times (7.2 - 6.599)$ = 179.19 kJ/kg

LP turbine: Adiabatic. Lost work = $T_o \Delta S$ = $298.15 \times (8.557 - 8) \times 0.8 = 132.86$ kJ/kg

Mixer : also adiabatic. $T_o \Delta S$ = $298.15 \times (1 \times 0.573 - 0.8 \times 0.367 - 0.2 \times 1.303)$ = 5.605 kJ/kg

Throttle: Isenthalpic = adiabatic, Lost work = $T_o \Delta S$ = $298.15 \times (9.38 - 8) \times 0.2$=82.29 kJ/kg

Condenser: Rejects heat at environmental temperature – no lost work.

Pumps: both are adiabatic and isentropic. – no lost work.

iv) What is the new thermal efficiency of the power station with carbon capture added? Comment on your answer. [10%]

New heat input into boiler and reheater is

$$(Q_{h1} + Q_{h2}) = (3375.1 - 177.8) + (3966.5 - 3296.8) = 3867 \text{ kJ/kg}$$

The work output is now

$$W_{lp} + W_{hp} = (3375.1 - 3296.8) + 0.8 \times (3966.5 - 2546.5) = 1214.3 \text{ kJ/kg}$$

Neglecting the work for the pumps (which we saw previously was very small)

$$\begin{aligned}\eta &= \frac{W_{lp} + W_{hp}}{Q_{h1} + Q_{h2}} \\ &= \frac{1214.3}{3867} = 0.314\end{aligned}$$

The efficiency of the power station is dramatically reduced with the addition of an amine scrubber to separate CO_2 from the exhaust. The minimum work needed to separate the CO2 is actually quite small , however the actual amount of energy used is quite large. Separations, which make use of heat (such as boiling) are very inefficient. The exergetic efficiency of the carbon capture plant is for example $12.7/(215+12.7)$ = 0.06 (quite low for a second law efficiency). For current carbon capture technologies, there is a large energy penalty.

2. A company is proposing to place solar thermal systems in an isolated African country. The system will consist of parabolic troughs, each with a project area of 1 m^2 focussing sunlight onto an absorber tube containing a heat transfer fluid.

(a) In the context of life cycle analysis:

i) What is meant by a background system? What assumptions have to be made when using background systems in a life cycle analysis? [10%]

Back ground systems provide services to the processes chain being analysed. In order to extend the system boundary so that it encompasses these back ground systems, several assumptions can be made. For example, this may mean allocating electricity (say) a certain GWP, which represents all the GWP in the lifecycle of electricity production. To be useful, the service has to have come from a **homogenous market. The service needs to be freely tradable, so that there is no geographical dependence on its environmental burden**. Electricity is a good example of this, because (in the UK) the grid means that customers cannot really tell what kind of electricity they are buying, it doesn't matter where the electricity was produced, and the average GWP of one unit of electricity has some meaning.

ii) Discuss the problems encountered when allocating environmental burdens. Also, describe the method of allocating by price, or substitution, and their relative merits and limitations. [30%]

Allocation become an issue when the system being analysed produces more than one product (i.e. there are **co-products**). Allocation is then the **apportionment of the lifecycle environmental burden to the different products**. If allocation is required, using some kind of physical knowledge is preferred, for example if it is known, that producing on extra unit of product B causes some extra amount of burden. Unfortunately this is rarely possible, because there isn't usually the freedom to vary the amounts of each different product produced. Allocation by price is one method which is often preferred, since highest burden is associated with the highest value product. In a free market it could be argued that the price reflects the relative reason for producing one good over another.

Allocation by substitution is really a way of avoiding allocation. A "credit" (negative environmental burden) is applied for the co-product, equal to the amount of burden associated with the production of each unit of the co-product, if it would have other had to have been produced by another means. This approach only works well when the co-product is readily available from other processes in the market place, and also that these processes produce the good as a primary good, and not a co-product (So that it is possible to unambiguously assign an environmental burden to it). The answer from an LCA can change, depending on what he co-product is assumed to displace in the market place, so great care must to taken to define the allocation procedure.

(b) Each parabolic trough is mounted on motors, which allow it to track the position of the sun, and so maximise the amount of heat collected. The trough has a reflectance of 1. The absorber tube consists of an outer sheath of glass (transmissivity = 0.9), an air gap and an inner tube which approximates a black body. The total heat loss from the absorber is $Q_{loss} = 0.5\Delta T + 0.0011\,\Delta T^2$, where ΔT is the temperature difference between the absorber and the surroundings

(assumed to be at 25 °C). Neglecting any loss in energy as sunlight passes through the atmosphere, how much heat can be collected by a single trough when the heat transfer fluid is kept at half the maximum possible temperature? [20%]

$$Q_{captured} = \Phi\, \tau_{glass}\alpha_{absober} - Q_{loss}$$

$$= \Phi\, \tau_{glass}\alpha_{absober} - Q_{loss}$$

The total loss of (net inc radiation etc..) is $Q_{loss} = 0.5\Delta T + 0.00113094\, \Delta T^2$

The total irradiation focussed on the tube is 1387 W (since the surface stays perpendicular to the sun), therefore at the maximum temperature

$$Q_{captured} = 0 = 1387 \times 0.9 \times 1 - 0.5\Delta T - 0.0011\, (\Delta \mathrm{T})^2$$

Solving gives $\Delta T = 862$ C. So the tube temperature is 887 C. At half this temperature $\Delta T = \frac{887}{2} - 25$ = 418.5 C. The heat absorbed is then,

$$Q_{captured} = 1387 \times 0.9 \times 1 - 0.5 \times 418.5 - 0.0011\, (418.5)^2 = 846\, W$$

(c) The heat captured is used to drive a steam cycle in a power station which produces electricity (at a thermal efficiency of 30%), and heat. The heat is used is to be used in local industries, which would otherwise burn wood, grown sustainably. The electricity in the country comes predominantly from coal. Using the data given below:

i) What is saving in the global warming potential overall per dish in a year? [10%]

ii) What is the CO2 footprint of the electricity produced by the dish, if the heat is treated as a co-product, and the method of allocation by substitution is used. [10%]

Consider 1 year of operation:

1 m2 of solar collector	$Electricity$: .3 × 846 = 253.8 W Heat: . 7 × 846=592.2 W Over the year $Electricity: 0.2538 \times 365 \times 10$ = 926.37 kWh $Heat: 0.5922 \times 365 \times 10$ = 2161.53 kWh	Total GWP = $50/10 + 10$ 15 kg CO2
Base case: coal +wood	926.37 kWh Electricity + 2161.53 kWh of heat	$926.37 \times .6 + 2161.53 \times 0.01$ 577.4373 Kg CO2 eq

Therefore the overall saving in global warming potential is $577 - 15 = 562$ Kg CO_2 eq per dish per year.

The total burden for .3 kwh electricity and .7 kwh heat is $\frac{\frac{\frac{15}{0.846}}{365}}{10} = 0.00486$ kg CO2 equivalent.

If the heat displaces biomass burning, there is a credit of $.01 \times .7 = 0.007$ kg CO2, meaning that the burden associated with .3kwh of electricity is $0.004857 - 0.007 = -0.002143$ kg CO2 or $-0.002143/.3 = -0.00714$ kg CO2 equivalent per kwH.

(d) How your answers to part (c) would change if the country was not isolated, but was instead connected to the British electricity grid via an ultra efficient DC link, and if the biomass used to provide heat was not sourced sustainably. What does this suggest about the validity of result from life cycle analysis? [20%]

The connect to be british grid changes the assumption that the electricity displaced is generated solely from coal. The british grid is roughly equal amounts of gas and coal, some nuclear and a bit of renewables, so the GWP of a unit of electricity will be lower than that given in the question. This in-turn will mean that the GWP saving calculated will be somewhat lower.

Since it was assumed that heat produced displaced wood grown sustainably, the credit associated with heat was quite small (though still enough to make the burden associated with the electricity negative). If the wood is not grown sustainably, then a standing stock of carbon is be depleted (just like with fossil fuels), so the burden associated with the heat should increase to at least the amount of CO2 you get when burning the wood. Therefore, the credit applied to the electricity burden would be much higher. You would also increase the GWP saving calculated in (c)

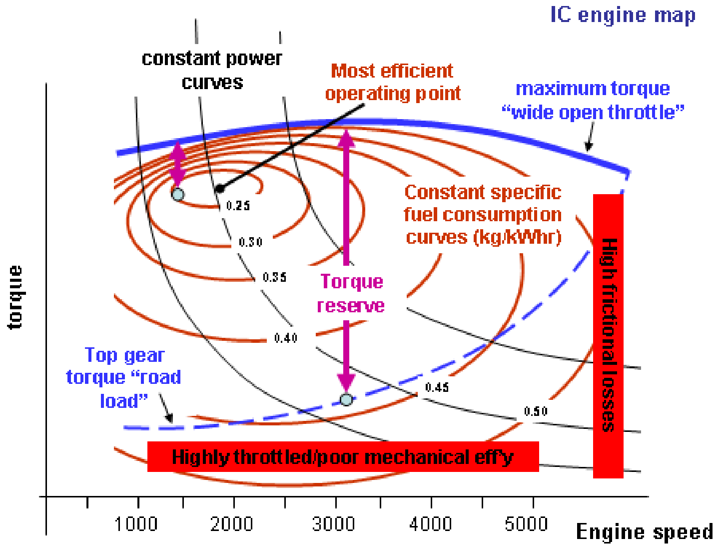
The lesson here is that life cycle results can be somewhat arbitrary and meaningless, unless the analysis is accompanied with a full description of what allocation methods were used, and also the assumptions made in the allocation. Otherwise, there many different answers are possible, and it is impossible to intelligently evaluate the results.

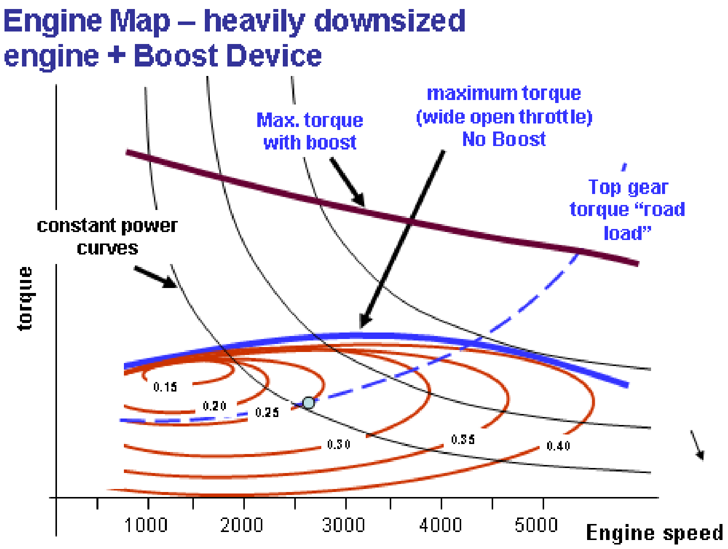
(a) Downsizing vehicle engines is perhaps the most attractive way of achieving fuel economy (and hence CO2) benefits, as it uses conventional technology. The reasons for wishing to down size are highlighted in the performance map in the first sketch. The most efficient operating point is far from the actual operating point for a typical cruise condition. The latter is at a point where the engine is highly throttled, with poor mechanical efficiency, and at a significant engine rpm (which leads to higher friction losses. The "advantage" of operating at this point is that there is a high "torque reserve", which makes the car attractive to drive.

The second figure shows an equivalent map for a heavily downsized engine, which has the advantage of operating, at a typical cruise condition, at a much better sfc. The problem is that there is very little torque reserve.

The fitting of "boost" devices can address this problem, by supplying short term power boost when required for acceleration, hill climbing etc. The compressed air system described in the question is one way of achieving this objective.

Another advantage of such a system is that it can be used for "inching" in traffic with out the need to start the engine, which can save a lot of fuel, since at idle and very low load conditions the base engine efficiency is dreadful – all, or nearly all the fuel is being burnt to drive the engine, rather than the vehicle.





(b) Electricity generated from solar power cannot be used directly in current vehicles. Two basic vehicle types can be imagined that could use such electricity:-

i) Direct electricity use e.g. battery or plug-in hybrid vehicles

ii) Indirect electricity use, via electrolytic generation of hydrogen fuel, and its use on the vehicle either via fuel cells, or direct combustion in an IC engine

A life-cycle analysis needs to be considered in both cases.

For i) – what is the energy input to make the PV's, store the energy (sunlight is intermittent); on the vehicle, what is the manufacturing energy cost (and re-cyclability) of the battery? Clearly the efficiency of energy transfer along the process is also very important. Also lifetime of the components (especially the battery)

For ii) – what is the energy efficiency of PV's, electrolysis (both ways), and the engine? What is the energy cost of creating the hydrogen fuel infrastructure? What is the energy cost of hydrogen storage (compression/cryo etc)?