Energy Efficiency for Sustainability 2

SOLUTIONS

Q1

a) The most widely used sources of energy are the fossil fuels: oil, natural gas and coal.

b) Thermal NO_x due to oxidation of nitrogen in combustion air.
Prompt NO_x due to oxidation of nitrogen in air in presence of free radicals from combustion of hydrocarbons.
Fuel NO_x due to oxidation of nitrogen in fuel.

c) Tidal energy may be extracted by a tidal barrage or by tidal flow turbines or similar devices.

d) Natural gas produces much less CO_2 per unit of useful energy produced than coal and it may also be burned in gas fired power stations that have much higher efficiency than coal fired power stations. So overall emission of CO_2 from gas fired power stations is less than half that of coal fired power stations. Coal fired power stations also produce higher levels of pollution such as SO_x, NO_x and particulates.

e) In a heat exchanger the thermal resistance between the two fluids is 1/UA. It may be reduced by increasing the surface area in contact with the fluids, by the use of a larger heat exchanger or by using fins.
Or the heat transfer coefficients may be increase in one or both fluids by using high velocities (but this will increase the pressure losses) or by encouraging more mixing/turbulence in the fluid, which may be achieved by using inserts in the heat exchanger tubes to promote turbulence.

f) Loss in dry products of combustion, Loss in water vapour in products of combustion, heat loss from structure. Could also include heat loss in hot ash and heat loss in boiler blow down in steam boilers.

Unburnt fuel is not acceptable as a loss as the question stated that there was complete combustion.

g) Maximum Coefficient of Performance for a heat pump is $COP = \frac{1}{\left(1-\frac{T_c}{T_h}\right)}$

$COP = \frac{1}{\left(1-\frac{279}{313}\right)}$ = 9.206. So minimum electrical power input = 15/9.206 kW = 1.63 kW

In the COP and exergy equations temperature must be in Kelvin.

h) Exergy is the maximum work potential of a system in its surroundings.

i) Thermal exergy $\dot{E}^Q = \dot{Q}\left(\frac{T_1-T_0}{T_1}\right) = -9\left(\frac{(-10+273)-(25+273)}{(-10+273)}\right) = 1.2$ kW. A heat flow from the room when it is below the environment temperature is a positive exergy flow into the room.

j) As the temperature rise of the hot stream is approximately half that in the cold stream, then the capacity of the hot stream must be about twice that of the cold stream, so the capacity ratio is approximately 0.5.

Some students estimated the effectiveness not the capacity ratio.

Q2

a) An energy audit is a survey of energy usage to identify what energy is consumed and where it is used. It results in a detailed breakdown of energy consumption.

Many students only considered measuring temperatures and not flow rates, oil consumption or flue gas composition……

b) Measurements taken:

- Oil consumption for the oil burner
- Electricity consumption for the fan and pump
- Flow rates of water and combustion air
- Temperature of water: cold, preheated, hot and temperature of flue gases before and after heat exchanger.
- Volumetric concentration of combustion products in flue gas.
- Estimate heat losses from boiler structure by taking surface temperature measurements.
- Calorific value of fuel.

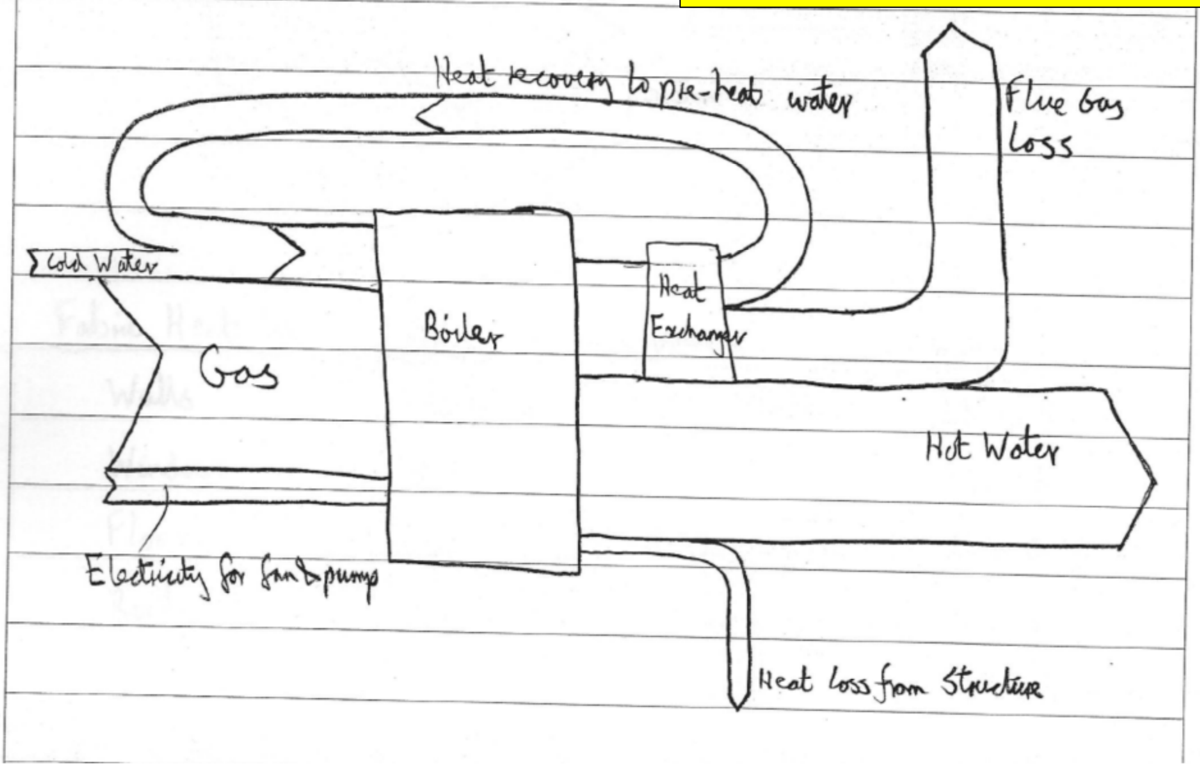
Give details of the calculations, rather than just stating what had to be calculated.

c) Calculations

- Fuel energy input from oil = oil flow rate × calorific value.
- Electricity input to fan and pump.
- Energy in flue gases before and after heat exchanger from enthalpy based on flue gas composition and temperature.
- Energy in water flows = mass flow rate × c_p × temperature change
- Heat losses from boiler based on surface temperature, surface areas and estimated heat transfer coefficients.
- Hence boiler efficiency

In the Sankey diagram try to estimate the relative magnitudes of the energy flows. Eg in a high efficiency boiler the energy in the hot water would be much higher than the losses.

Sankey Diagram



Q3 Products

	Moles	$\tilde{m}$ kg/kmol	kg/kmol of fuel	m_i kg/kg of fuel
CO_2	1	44	44	2.75
H_2O	2	18	36	2.25
O_2	0.8	32	25.6	1.6
N_2	10.53	28	294.84	18.43
	14.33			

Dry Loss

Use c_p values given:

c_p CO_2 0.871 kJ/kgK

c_p O_2 0.923 kJ/kgK

c_p N_2 1.040 kJ/kgK

So dry loss $= \Sigma m_i c_{pi}(T_{products} - T_{inlet})$

$= (2.75\times0.871 + 1.60\times0.923 + 18.43\times1.040)(100-20)$

$=$ 1843 kJ/kg of fuel

Wet Loss

Wet loss $= m_{H2O}(h_{product} - h_{water\ in})$

h_{prod} at 100°C is 2689 kJ/kg from superheat tables at zero pressure

$h_{water\ in}$ at 20°C is 83.9 kJ/kg

wet loss = $2.25\times(2689-83.9)$ = 5861 kJ/kg of fuel

Gross calorific value of fuel is 53400 kJ/kg

Losses:

Dry loss	1843	3.45%
Wet loss	5861	10.98%
Total	**7704 kJ/kg**	14.43%

a) So **boiler efficiency is** (100-14.4) = **85.6%**

From products analysis it can be seen that the mole fraction of water vapour in the products is 2/14.33 = 14%. As furnace operates at atmospheric temperature, the partial pressure of water vapour in the flue gases is = 0.14 bar. So water vapour will start to condense when flue gases cool to 52.6°C.

At 40°C, the saturation pressure of water vapour is 0.07375 bar.
In products, before condensation there are 12.33 moles of dry gases for every 2 moles of water vapour. After cooling to 40°C, the mole fraction of water vapour will be 0.07375. So number of moles of water vapour remaining *(x)* can be calculated from:

$$0.07375 = \frac{x}{(x+12.33)}$$

x = 0.9818 moles of water vapour per mole of fuel.

So 0.9818/2 = 49.09% of the water remains as a vapour in the flue gas and 50.91% will have condensed to liquid water.

So at 40°C, the products of combustion will contain 1.105 kg of water vapour and 1.145 kg of liquid water

Dry loss now becomes:

So dry loss $= \Sigma m_i c_{pi}(T_{products} - T_{inlet})$

$= (2.75\times0.871 + 1.60\times0.923 + 18.43\times1.040)(40-20)$

$=$ 460.8 kJ/kg of fuel

Calculate the wet loss accounting for both liquid water and water vapour in products:

Wet loss $= m_{H2O\ liquid}(h_{product\ liquid} - h_{water\ in}) + m_{H2O\ vapour}(h_{product\ vapour} - h_{water\ in})$

$h_{prod\ vapour}$ at 40°C is 2573.7 kJ/kg as water vapour in products is saturated at 40°C

$h_{prod\ liquid}$ at 40°C is 167.5 kJ/kg

$h_{water\ in}$ at 20°C is 83.9 kJ/kg

wet loss $= 1.145\times(167.5 - 83.9) + 1.105\times(2573.7 - 83.9)$

= 2847 kJ/kg of fuel

Losses:

Dry loss	461	0.86%
Wet loss	2847	5.3%
Total	**3308 kJ/kg**	6.2%

b) So **boiler efficiency is** (100-6.2) = **93.8%**

Some students were confused between the heat recovered in the heat exchanger and the loss in the flue gas leaving the heat exchanger. Note that the loss in the flue gas is the difference in enthalpy between the flue gas leaving the heat exchanger at 40 degC and the inlet temperature of 20 degC.

Some students also mistakenly assumed that the dry loss did not change even though the flue gas leaves the heat exchanger at the lower temperature of 40 degC

An alternative way of calculating the loss when the heat exchanger was included was to calculate the heat recovered in the heat exchanger and subtract it from the flue gas losses calculated in part a).

Q4 Environment temperature is the outside temperature of 7°C.

Find mass flow rate of refrigerant. Heat dissipation from condenser is 11 kW. So in condenser:

$11 = \text{mass flow} \times (h_2 - h_3)$

Mass flow = 11/(441.32 – 256.38) = 0.0595 kg/s

Quite a few students did not understand that this question is about a heat pump where the heat output from the condenser is 11kW. They assumed that 11kW was the heat input at the evaporator.

Work input needed to compressor

= mass flow ($h_2 - h_1$) = 0.0595×(441.32 – 398.43)

= 2.552 kW.

Electric motor efficiency is 90%, so electrical input power = 2.552/0.90

= 2.83 kW

Exergy output from heat pump is exergy of heat transfer into room which is determined from $\dot{E}^Q = \dot{Q}_1\left(\frac{(T_1 - T_0)}{T_1}\right)$ where T_1 is room temperature (19°C, 292K) and T_0 = environment temperature (7°C, 280K).

Exergy output = 11 (292 – 280)/292 = 0.45 kW.

a) So COP is = 11/2.83 = 3.88.

Rational efficiency = 0.45/2.83 = 15.9 %

The COP reqired here is the actual COP for this heat pump. Some students calculated the maximum theoretical COP for a perfect heat pump.

Evaluate flow exergy at each point in cycle from

$$\dot{E} = \dot{m}\left[(h_1 - h_0) - T_0(s_1 - s_0)\right]$$

	Pressure Bar	Temp °C	Enthalpy kJ/kg	Entropy kJ/kgK	Flow Exergy kW
1.	2.928	0.0	398.43	1.7264	1.33
2.	10.163	60.0	441.32	1.7788	3.01
3.	10.163	40.0	256.38	1.1903	1.81
4.	2.928	0.0	256.38	1.2063	1.55
Environment		7.0	409.2	1.845	

Undertake exergy balance on each component:

Irreversibility = exergy in - exergy out

b)

Irreversibility in evaporator is: 1.55 – 1.33 = 0.22 kW

Irreversibility in compressor is: 2.552 – (3.01 – 1.33) = 0.87 kW

Irreversibility in motor is: 2.83 – 2.552 = 0.28 kW

Combined irreversibility in motor and compressor is: 1.16 kW

Irreversibility in condenser is: (3.01 – 1.81) – 0.45 = 0.75kW

Irreversibility in throttle is: 1.81 - 1.55 = 0.27 kW.

Note that sum of all irreversibilities (2.39 kW) plus exergy output to building (0.45 kW) = exergy input to motor (2.83 kW)

c) The heat pump may be improved as follows:

The largest irreversibility is in the compressor. So a compressor with a better isentropic efficiency would improve the system.

A motor with a higher efficiency would also make an improvement.

The condenser also has a large irreversibility and this is due to the temperature difference between the working fluid and the room. Operating at a lower outlet pressure from the compressor help, but this would require a larger heat exchanger as the temperature difference would be lower.

Similarly a smaller temperature difference in the evaporator would reduce the irreversibility and improve the performance of the system.

There is a loss in the throttle valve, but in a small system it is unlikely to be worthwhile to use a mechanical expander to produce some work.

Q5. a) The rate of heat recovery from the exhaust gas heat exchanger is

$$= \dot{m}\, c_p \Delta T \quad = 0.68 \times 1.07\ (450 - 97) \ = 257\ \text{kW}$$

Some students did not calculate this heat recovery from the exhaust gas correctly.

There are four different periods of the year to consider when the electricity and gas prices are different (day/night and weekdays/weekends).
There are 48 working weeks at the site and so there are 48×5 weekdays = 240 and 48×2 = 96 weekend days.

Fuel input to CHP plant is 350/0.354 = 989 kW (based on gross CV)
Note that 1 kW for one hour = 0.0036 GJ.

<u>Weekdays during the day</u>

Saving in electricity = 350×0.0036×25	= £31.50/hour
Saving in gas in boiler = (257 + 245)×0.0036×5/0.85	= £10.63/hour
Maintenance cost = 350×0.02	= £ 7.00/hour
CHP fuel cost = 989×0.0036×5	= £17.80/hour
Total saving is £17.33/hour	

<u>Weekdays during the night</u>

Saving in electricity = 350×0.0036×12	= £15.12/hour
Saving in gas in boiler = (257 + 245)×0.0036×5/0.85	= £10.63/hour
Maintenance cost = 350×0.02	= £ 7.00/hour
CHP fuel cost = 989×0.0036×5	= £17.80/hour
Total saving is £0.95/hour	

At weekends the heat demand reduces to 265kW which is less than the total heat output from the CHP plant and so if it ran, some heat would have to be dissipated.

<u>Weekends during the day</u>

Saving in electricity = 350×0.0036×25	= £31.50/hour
Saving in gas in boiler = 265×0.0036×5/0.85	= £ 5.61/hour
Maintenance cost = 350×0.02	= £ 7.00/hour
CHP fuel cost = 989×0.0036×5	= £17.80/hour
Total saving is £12.31/hour	

<u>Weekends during the night</u>

Saving in electricity = 350×0.0036×12	= £15.12/hour
Saving in gas in boiler = 265×0.0036×5/0.85	= £ 5.61/hour
Maintenance cost = 350×0.02	= £ 7.00/hour
CHP fuel cost = 989×0.0036×5	= £17.80/hour
Total saving is -£4.07/hour	

It is only cost effective to operate the CHP during weekdays and the daytime at weekends. At night at weekends it is more cost effective to switch it off.

Saving during weekday days is $17.33 \times 240 \times 17$ = £70706/year.
Saving during weekday nights is $0.95 \times 240 \times 7$ = £1596/year.
Saving during weekend days is $12.31 \times 96 \times 17$ = £20090/year.
So total annual saving is £92392.

Some students did not correctly calculate the length of time the CHP plant would operate.

b) At weekends when the heat demand of the site is less than the heat output of the CHP plant then heat has to be dumped as the CHP plant can only operate at full output. A plant that could be modulated to operate at a lower output would be better as this could operate in "heat matching" mode at the weekend and this would improve the overall cost effectiveness. This could also be achieved by installing two smaller CHP units rather than one large one. One of the units could then be turned off at weekends, but the other could be used to meet the heat demand.

During the night period when electricity is much cheaper, the cost savings from the CHP plant are marginal and it may be better not to run at night in any case.