Sustainable Energy Systems Coursework

By Kush Kotecha, Lola Strout, William Pitt

Task 1

1.1 Overview

The available technologies for task 1's district energy centre are solar heaters, ground source heat pumps, EWF incineration, and EWF anaerobic digestors with a heat demand of 262.8 GWh and a power demand of 74.1 GWh. The models represent a full year of operation.

Using the given excel software, this system, the case without thermal storage optimised to use 12 units of EWF anaerobic digestion (9 replacements during the DES system lifetime) accounting for 96.1% of the heat required and all of the energy requirements. There are also 2 ground source heat pumps which produces 3.9% of the heat required (the return a hot water stream). When thermal storage is considered, the optimised system uses only the anaerobic digestion with the same 12 units requiring 9 replacements.

1.2 DE Centre Efficiency

The efficiency is defined as the ratio of the useful energy to the total fuel consumed.

Table 1: Values for the Overall Efficiency of the DE Centres

	DE Centre without Thermal Storage	**DE Centre with Thermal Storage**
Total Heat Production GWh	262.8	271.9
Total Energy Production GWh	232.1	253.9
Total Fuel Consumption GWh	930.6	1000.2
Efficiency	**53.2%**	**52.6%**

Table 1 shows that the efficiency of the two systems is very similar, within 0.6% of each other, the system without thermal storage being slightly more efficient. Since these values are so similar, the choice of which is the better system cannot be decided by efficiency alone.

1.3 CO_2 Emissions

Table 2: CO_2 Emissions of Task 1

	DE Centre without Thermal Storage	**DE Centre with Thermal Storage**
Fuel CO_2 Emissions, t/yr	1,499	1,596
CO_2 Emissions Credit, t/yr	78,168	92,039
CO_2 Emissions Debit, t/yr	557	4,119
Global CO_2 Emissions, t/yr	-76,112	-86,324
Percentage with respect to Baseline Emissions, %	-142	-161
CO_2 Emissions per unit of heat delivered, t/MWh	-0.332	-0.376

Fuel CO_2 emissions are those from burning the fuel to satisfy the energy demand, CO_2 emissions debit are those corresponding to imported electricity from the grid and finally CO_2 emissions credit are avoided emissions corresponding to electricity sold to the grid.

As shown, the DE centre without thermal storage produces less carbon dioxide as the overall fuel consumption is lower, imports less electricity from the grid and sells less back to the grid resulting in global CO_2 emissions of -76,112 t yr^{-1} with 0.332 tonnes of CO_2 being avoided per MWh of heat delivered from the system. When thermal storage is implemented, more fuel is burnt, more electricity is taken from the grid as well as sold back to the grid, however the percentage of emissions with respect to baseline is lower at -161% as the global overall emissions are lower at -86.324 t yr^{-1}. And 0.376 tonnes of CO_2 being saved per unit of heat delivered.

1.4 Fuel Consumption

As shown previously in table 1, the total fuel consumption for the centre without thermal storage is lower at 930.6 GWh, whilst the centre with thermal storage uses 1000.2 GWh to reach the same energy targets. Therefore, when considering only fuel consumption, option 1, without thermal storage, since some of the equipment can be slightly smaller and less transport is required. The centre is paid to use wet waste as a feed so feed cost is not a concern.

1.5 Economic Indicators

Table 3: Economic Indicators of Task 1

	Without Thermal Storage	With Thermal Storage
Total Annual Costs, £/yr	-9,505,123	-13,057,175
TAC per unit of heat delivered, £/ kWh	-0.015	-0.031

Since the fuel used is wet waste for both systems which is a revenue stream as the DE centre is paid to take this waste, and a large portion of the electricity is sold to the grid, the total annual costs of both systems are negative. When thermal storage is implemented, the system uses more fuel and sells more electricity to the grid, so this set up is more profitable, and the price needed to break even on the fuel is lower. However, less fuel requires smaller units and therefore reduces the capital cost.

1.6 Comparison of Results

Table 4: Comparison of Results of Task 1

	Without Thermal Storage	With Thermal Storage
Number of Units		Best
DE Centre Efficiency	Best	
CO_2 Emissions		Best
Fuel Consumption	Best	
Economic Indicators	Very Good	Best

Table 4 summarised the conclusions of each sub-section of task 1 giving an overall solution to which DE centre is the better option. As a group, we have decided that the DE centre with thermal storage is the best option as it requires fewer units with only one type of energy source, has a slightly higher profit, is more environmentally friendly, and although the efficiency is slightly lower the difference is negligible.

Task 4

4.1 Overview

Centre	**Available Technologies**	**Optimised Technologies**	**Number of Units Required over lifetime**
1 – W/O	NG Turbines	NG Turbines	3
1 – With	NG Turbines	NG Turbines	3
2 – W/O	NG Turbines + Biomass gasifiers	NG Turbines	3
2 – With	NG Turbines + Biomass gasifiers	NG Turbines	3
3 – W/O	Biomass gasifiers + GSHP	GSHP	21
3 – With	Biomass gasifiers + GSHP	GSHP	19
4 – W/O	GSHP + EWF anaerobic digestors	GSHP + EWF AD	GSHP: 2 EWF AD:22
4 – With	GSHP + EWF anaerobic digestors	EWF AD	19

Table 4.1: Technology Overview over the 4 Centres with and without Thermal Storage

Table 4.1 lists the optimized cases of each centre (with and without thermal storage (TS) separately). More units may seem worse considering high capital costs and environmental impacts of materials for construction, but these are one-off whereas operational impacts outweigh the initial (capital) over an extended period of time. Efficiency dictates the contribution of operation to the overall cost and environmental impact which is dependent on technology and sizing. Having more units also has the bonus of improved availability of the DE centre (less impact on the process/output if one-unit breaks). Fewer technologies (centre 1,2,3 and 4 only with TS) may be favourable because it reduces the complexity of the system, making operation, maintenance, and design easier, however having some variation in technology (centre 4 without TS) means that common mode failures are less impactful on overall operation i.e. lack of feedstock for the anaerobic digesters does not prevent operation of the GSHPs.

4.2 DE Centre Efficiency

	Centre 1		Centre 2		Centre 3		Centre 4	
	Without	With	Without	With	Without	With	Without	With
Total Heat Production GWh	262.8	257.4	262.8	257.4	262.8	255.5	262.8	279.1
Total Energy Production GWh	218.0	218.9	218.0	218.9	0	0	238.3	253.9
Total Fuel Consumption GWh	702.5	675.9	702.5	674.4	90.7	88.1	947.7	1000.2
Efficiency %	68.4	70.5	68.4	70.5	116	116	52.9	53.3

Table 4.2: Centre efficiency values for Task 4

Centres 1,2 and 4 can supply both the heat and power output while centre 3 is unable to produce any power and must be imported to the site (imported electricity assumed to have efficiency of 40%). All centres are able to supply the heat demand, however with optimization it appears that the heat demand reduces as there are fewer district heating losses (for centre 1,2 and 3 – where centre 4 output improves with optimization and removal of GSHP). Using TS increases the amount of electricity produced or reduces the amount of electricity required (centre 3). Only centre 3 must import electricity because the technology (model: AECOM Large GSHP) provides heat at a maximum of 99°C.

Electricity generation has not been considered within these cases but here is a brief discussion of how it could be done: One way of producing power from geothermal energy is to produce steam from the hot water, however at 99°C the steam produced will be very low pressure (at saturated conditions so ~1bar maximum) and there is only a low amount of energy available for extraction. The amount of steam generated depends on the pressure of water into the flash vessel (not seen more than ~40% recovery in problem questions). A condensing turbine produces more power than a back-pressure turbine so it is more likely to be economically feasible. The condensate can also be passed through the GSHP to increase the amount of hot water extracted (and in turn steam generated). Electricity generation in this instance will have poor economic desirability when considering the amount of steam produced and the cost of steam turbines and flash vessels. A more favourable option is to use an organic Rankine cycle - exploits the low boiling points of compounds such as propane or isobutane. Instead of a flash vessel, a heat exchanger is used to evaporate the working fluid (refrigerant). Vapour can be produced at higher pressures than that of steam and therefore more energy can be generated. This is preferable to a Kalina cycle which involves the use of ammonia with water – this technology has corrosion issues which incurs large costs through specialised construction materials for units and piping.

The gasifiers can produce both heat and electricity although the optimizer has deemed these non-optimal; the biomass gasifiers (model: Gasification -258) have a much higher carbon footprint, gasifier CAPEX is much higher, and the maximum temperature of thermal output is lower. Thermal storage improves the overall efficiency of centre 1,2 and 4 while making a negligible difference to the efficiency of centre 3.

The import of centre 3 is higher than the 74.1 GWh target due to operational requirements of the heat pumps, although this absolves the need for fuel and therefore there are no direct CO_2 emissions produced from operation of centre 3. Centre 1 and 2 use natural gas turbines which is a relatively efficient technology due to its extensive use and research in many fields including aeronautics (aeroderivative design), and industrial use including electricity generation for the national grid (industrial design) [4A].

Centre 4 has low efficiency since it uses anaerobic digesters which is a relatively new/under-developed technology compared to NG turbines, and wet fuel (wet waste) has a lower net calorific value than its dry counterpart when compared by mass. However, it is self-sufficient in that the heat for drying and pyrolysis is provided from the heat obtained from gasification; it can also be supplied from very low/waste grade heat because the bacteria are mesophiles. Centre 3 efficiency doesn't change with the addition of thermal storage because power is imported on demand, however costs of implementing TS will increase.

Improved efficiency reduces waste and resources required to treat it, reduces emissions and resources to treat them, and reduces operational costs through less feedstock consumption and less waste and emissions management costs. One way to improve efficiency is by utilizing waste streams as feedstock or by-product; while the efficiency of wet waste is quite low, it is converting an undesirable product into a long-term sustainable solution for energy production.

4.3 CO_2 Emissions

	Centre 1		**Centre 2**		**Centre 3**		**Centre 4**	
	Without	With	Without	With	Without	With	Without	With
Fuel Emissions, t/yr	131162	121483	131162	121257	0	0	1499	1596
Emissions Credit, t/yr	70242	77031	70242	76173	0	0	81203	92039
Emissions Debit, t/yr	557	7471	557	6838	80463	79240	557	4119
Global CO_2 Emissions, t/yr	61477	51923	61477	51922	80463	79240	-79147	-86324
Percentage concerning Baseline Emissions, %	115	97	115	97	150	148	-148	-161
CO_2 Emissions per unit of heat delivered, t/MWh	0.268	0.226	0.268	0.226	0.351	0.345	-0.345	-0.376
Manufacturing emissions, t/CO_2	692	698	692	698	1570	1424	267842	272065

Table 4.3: CO_2 Emissions for the four Centres Concerned in Task 4

People are becoming increasingly aware of the importance of environmental emissions which are responsible for climate change and the pollution of our environment. Carbon dioxide has been linked to climate change and global warming which can have devastating impacts if ignored. Ways to capture carbon dioxide include (physical absorption (NMP, DEPG), chemical absorption (MEA, DEA), and cryogenic distillation. Centres 1,2 and 3 have low manufacturing emissions but they have high annual fuel emissions whereas centre 4 has high manufacturing emissions but consumes large amounts of CO_2 during operation and after 4 years it will have fully offset these initial emissions. Other environmental impacts arise from things like mining which includes resource depletion and water pollution from leachate.

4.4 Fuel Consumption

	Centre 1		Centre 2		Centre 3		Centre 4	
	Without	With	Without	With	Without	With	Without	With
Fuel Type	NG	NG	NG	NG	Electricity	Electricity	Wet Waste	Wet Waste
Total Fuel Consumption GWh	702.5	675.9	702.5	674.7	90.7	88.1	948	1000

Table 4.4: Fuel Consumption and Types of Fuel for each Centre

NG is considered a non-renewable source as it takes hundreds of millions of years to form[4B]. Along with high carbon emissions upon combustion, it is not a desirable nor longevous fuel source. There are also issues with certain methods for obtaining natural gas such as fracking which can cause structural damage to the ground making it unstable[4C]. Electricity can be generated from many different sources such as renewables with low carbon emissions and costs: wind and solar, or from non-renewables ranging from coal to nuclear (which have high and low carbon emissions respectively, and different efficiencies). Center 3 has low risk of problems caused by fuel because electricity is made from so many technologies, compared to natural gas for turbines or wet waste in anaerobic digesters. Typically waste streams are problematic in that they need disposing (possibly storage) and often require treatment. This incurs costs and is a part of the system that cannot be ignored. Using waste as a feedstock is often economical although it may change the treatment required (pre-treatment).

4.5 Economic Indicators

	Centre 1		Centre 2		Centre 3		Centre 4	
	Without	With	Without	With	Without	With	Without	With
Total Annual Costs, £10^6/yr	23.39	20.15	23.39	20.23	24.80	24.21	-9.54	-13.83
TAC per unit of heat delivered, £/ kWh	0.128	0.114	0.128	0.114	0.134	0.131	-0.016	-0.034
CAPEX, B£	31.8	32.3	31.8	32.3	43.8	48.3	224	213

Table 4.5: CO_2 Economic indicators for Task 4

Many stakeholders view economics as the most (or only) important factor; the centre must be economically viable so that the project can actually happen, but it must also be reasonably priced for consumers so that it is accessible to as many people as possible. For renewables there may be financial incentives from the government in attempt to reduce their national environmental impacts. The cheapest (most favourable) centre design is centre 4 because it uses wet waste as a feedstock. The TAC per unit of heat is negative, which is due to the operational costs far outweighing the capital cost. This negative operational cost may represent the saving on waste management costs or could represent the DE centre being paid to utilize waste. Although it has a very high capital cost, it will have a similar payback time to centres 1,2 and 3 because of the huge difference in TAC (if heat and electricity is sold at the same price from the centre); after this payback period the DE centre will be making bank.

4.6 Comparison of Results

	Centre 1		Centre 2		Centre 3		Centre 4	
	Without	With	Without	With	Without	With	Without	With
Number of Units	Best	Best	Best	Best	-		-	
DE Centre Efficiency	-		-		Best	Best	-	
CO_2 Emissions	-		-		-		-	Best
Fuel Consumption	-		-		-		-	Best
Economic Indicators	-		-			-	-	Best

Task 4.6: Comparison of centre performances

Thermal storage can be used to provide both heat and power during periods of no generation from the primary source. Thermal fluids such as molten salts can be used to store heat at high temperatures (~565°C[4D]) which can be used to produce steam at very high pressures. In turn, this can be expanded to generate power and then directly used to extract latent heat or indirectly used for district heating (i.e. heat a secondary thermal fluid). Where cogeneration is not required, either steam can be passed through a condensing turbine; or steam should be avoided and a thermal fluid for district heating should be heated directly. Thermal storage increases the complexity of the system along with capital and operational costs. Construction materials will have carbon footprints but if thermal fluids can be recycled there won't be any additional operational emissions. Reference 4D conducts multiple feasibility studies for different molten salts (2 Gigagrams to supply 6 hours of thermal storage (ranging from 108-186 GWh) and a storage life of 112 hours); disposing of such large quantities of salt will be a challenge if the chemical or thermal capacity degraded. A disadvantage of thermal storage is the amount stored decreases with time, insulation is important but heat losses cannot be avoided completely – especially at higher temperatures.

Table 4.6 shows a comparison between centres for major factors impacting design, which have different weightings dependent on who the stakeholders are. Centre 4 has the best performance for economics, fuel consumption, and environmental emissions; the highest number of factors and the most important – covering the 3 sustainability pillars. Thermal storage generally improves the performance (lower performance with/without TS for each category is indicated by "-"). <u>Therefore centre 4 with thermal storage is the advised DE centre design.</u>

Other factors affecting feasibility include availability of feedstock, the future of technology, public opinion. As discussed in section 4.4, wet waste is quite readily available, however there is a logistical challenge; wet waste is produced in varying quantities from farm manure to household sewage to dog litter, which all has to be collected into one place (the DE centre). This logistical challenge makes thermal storage more desirable. Technology is improving constantly so it is useful to design a centre that can readily accommodate future improvements; it will ideally use technology of interest that has current and future research plans. Public opinion is also an aspect to consider – large quantities of sewage will bring pungent, unpleasant smells along with 'gross' and unsanitary connotations leading to a bad reputation as a 'poop factory'. However, it is a project that all local residents will be contributing towards, or in other words, a project they can all get 'behind'.

References

4A - *Combustion Engine vs. Aeroderivative gas turbine - introduction - wärtsilä energy* (no date) *Wartsila.com*. Available at: https://www.wartsila.com/energy/learn-more/technology-comparison-engines-vs-aeros/introduction#:~:text=Heavy%20frame%20turbines%20are%20designed,adapted%20from%20aircraft%20jet%20engines (Accessed: 22 April 2024).

4B – *Natural gas – what is it, where is it, and how do we capture it?* (no date) *Enbridge Inc.* Available at: https://www.enbridge.com/Energy-Matters/Energy-School/NatGas-101#:~:text=Natural%20gas%20is%20created%20naturally,Earth%20and%20pressure%20from%20rocks (Accessed: 22 April 2024).

4C - *Fracking* (2024) *Encyclopædia Britannica*. Available at: https://www.britannica.com/technology/fracking (Accessed: 22 April 2024).

4D - Kearney, D. *et al.* (2004) 'Engineering aspects of a molten salt heat transfer fluid in a trough solar field', *Energy*, 29(5–6), pp. 861–870. doi:10.1016/s0360-5442(03)00191-9.

Task 5

5.1 Hot Water Generation

Firstly, we will analyse the system with a dew point temperature of 110°C. As the stack temperature of the combustion gases is above that of the hot water value the delta T min value does not need to be applied.

To work out the available energy that can be transferred from the combustion gases to the water, equation 1 was used.

$$Q = m * C_P * \Delta T \tag{1}$$

$$Q = 120 * 1.11 * (450 - 110) = 45288\ kW$$

This value of 45288 kW is the energy of the hot water, however 15% of this is lost in the piping, making the value of the energy of the hot water at delivery 38495 kW. These values assume that the heat exchanger is 100% efficient - all the heat from the combustion gases is transferred to the supply water.

Next to find the approximate cost of hot water delivery we begin by selecting 1 year as the basis and considering capital cost first. Using equation 2, we found the area of the heat exchanger required to be 74.64 m^2, making the capital cost of the heat exchanger £52,245.

$$Q = U * A * T_{LMTD} \tag{2}$$

$$45288 = 3 * A * \frac{(450 - 80) - (110 - 15)}{\ln\left(\frac{450 - 80}{110 - 15}\right)}, \qquad A = 74.64 m^2$$

The question stated 20km of piping was required at £2000 per km. This gives an overall piping cost at £40,000. The total capital cost of these two parts were £92,245 with an annual payment of £18,384 using the given annualization factor. We assumed a counter-current heat exchanger in both scenarios as it minimises the area required.

The operating cost of the system is the cost of the water where we assume that the plant recycles BFW (replacing annually) and has 2 hours worth of water to account for any losses, and any waiting times to receive the now cold water. It is assumed that the water is obtained from a utility supplier rather than sourced independently (i.e. borehole, seawater). Therefore, we get an operating cost of £3,672 (£1,836 per hour).

Therefore, if the combustion gases' dew temperature is 110^{o}C, the annual cost of water delivery is £22,056.

Now we will consider the system to have a dew point temperature of 160^{o}C.

Using equation 1 again gives the generated energy of the hot water at 38628 kW, and therefore the energy at delivery is 32834 kW. The approximate cost of the hot water delivery begins again with the capital cost of the heat exchanger, The required area of the exchanger is 53.61 m^2, giving a capital cost of £37,526. The cost of the piping remains the same, but the cost of the water will decrease. The cost of the water is now £3,132 (£1,566 per hour).

Overall, if the combustion gases' dew temperature is 160^{o}C, the annual cost of water delivery is £16,075 after accounting for the pipe costs and the annualization factor for the overall capital costs.

5.2 Steam Turbine Inclusion

The steam produced, steam turbine power and hot water production will be calculated for both the case of 110°C and 160°C. Working will be provided for 160°C, with values only provided for 110°C as the same logic is followed.

BFW is supplied at 100 ^{o}C to be used for the production of superheated steam to 400 ^{o}C at 40 bar that will be used for steam supply to the steam turbine. The steam turbine efficiency is reported as 90%.

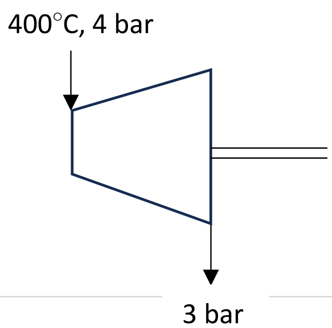

Figure 1 Schematic of steam turbine

Initially the value for heat provided by the exhaust gases needs to be calculated.

$$Q = m \times C_p \times \Delta T$$

Where m = 120 kg s^{-1} and C_p = 1.11 kJ kg^{-1} K^{-1}

$$\therefore Q = 120 \times 1.11 \times (450 - 160) = 38628\ kW$$

Next the mass flowrate of steam into the steam turbine can be calculated using the Q value calculated and the enthalpy change. Steam is produced on-site to avoid significant heat losses.

$$\Delta h = h_{fg,BFW} + \left(h_{SH\ steam} - h_{l,BFW}\right) = 2258 + (3214 - 2675) = 2797\ kJ\ kg^{-1}$$

$$\therefore m = \frac{Q}{\Delta h} = \frac{38628}{2797} = 13.81\ kg\ s^{-1}$$

However, the enthalpy-temperature graph shows that this is a completely unrealistic value because it violates the ΔT_{min} and both lines intersect. Therefore, the mass flowrate needs to be reduced so that ΔT_{min} is not breached. This is because ΔT_{min} drives heat transfer and is set at an optimised value to achieve target heat transfer rates.

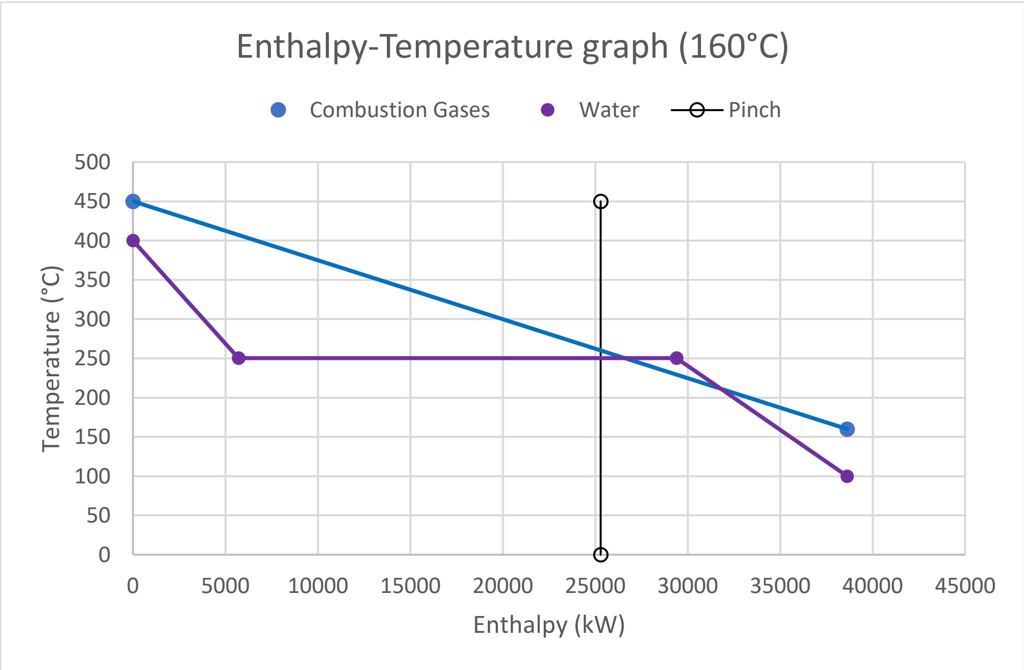

Figure 2 Enthalpy Temperature Graph for 160 ℃

The mass flowrate is limited by the pinch temperature which is at ($\Delta T_{min} + T_{sat,water}$) at 260.3°C. This means that a maximum of 25923 kW can be used for the vaporisation and superheat of steam at 40 bar (above pinch).

$$\therefore m = \frac{Q}{h_{SH\ steam} - h_{sat,40bar}} = \frac{25923}{(3214 - 1087)} = 12.19\ kg\ s^{-1}$$

This flowrate satisfies the ΔT_{min} constraint as seen in the graph below (the range on the y-axis is much larger than ΔT_{min} so it looks like the lines are touching).

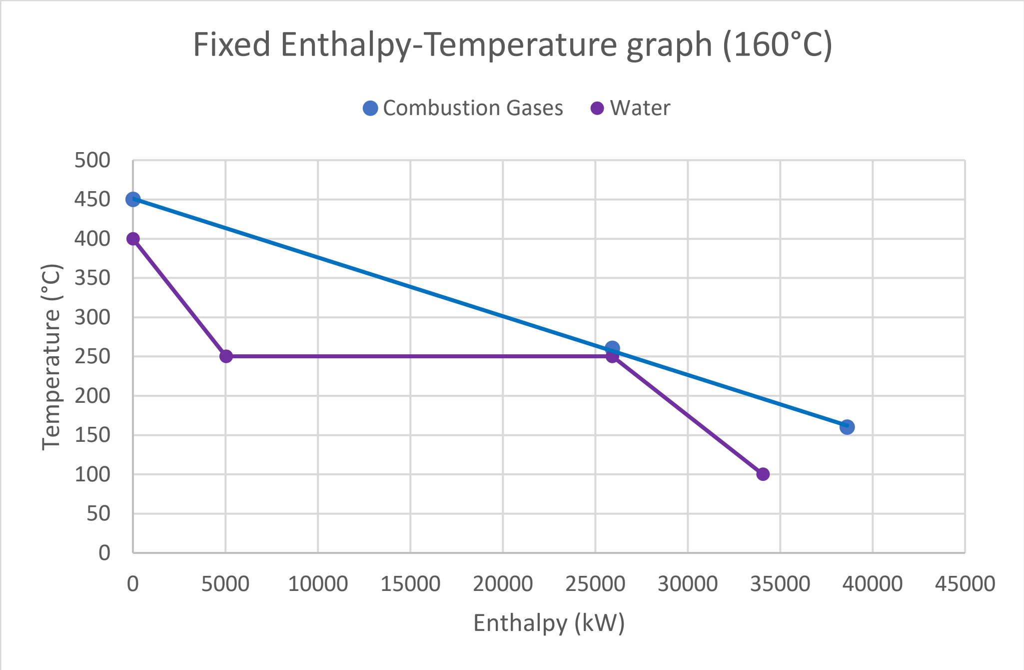

Figure 3 Corrected Enthalpy Temperature graph for 160℃

Steam exits the turbine at 3 bar.

Where $S_{in} = S_{out} = 6.769$, $S_g = 6.993$, $S_f = 1.672$

$6.769 = 6.993X + 1.672(1 - X)$

$$\therefore X = \frac{5.097}{5.321} = 0.9579 = 0.96$$

$$\therefore \Delta H_{steam} = (3214 - 419.1) = 2794.9\ kJ$$

h_2 = 561 kJ kg^{-1}, h_g = 2725 kJ kg^{-1}, h_{IS} = 2633.90 kJ kg^{-1}.

Δh = 3214 – 2633.9 = 580.1 kJ kg^{-1}

The efficiency of the steam turbine, 90%, should be taken into account at this point.

$$\therefore 580.1\ kJ\ kg^{-1} \times \frac{90}{100} = 522.09\ kJ\ kg^{-1}$$

Power produced by the Steam Turbine is calculated through the use of mass flowrate and enthalpy change.

$$\therefore Power = m \times \Delta h = 12.19 \times 522.09 = 6364.28\ kW$$

From this the quantity of hot water produced is found using the remaining superheat and latent heat of the steam.

$$h = (h_{SH\ steam} - \Delta h) = 3214 - 522.09 = 2691.91\ kJ\ kg^{-1}$$

$$Q = m \times \Delta h = 12.19 \times (2691 - 419.9) = 27684.71\ kJ\ s^{-1}$$

$$\therefore m = \frac{P}{h_{80°C} - h_{15°C}} = \frac{27684.71}{334.9 - 62.9} = 101.78\ kg\ s^{-1}$$

The final results for 160°C: m_{steam} = 12.19 kg s^{-1} , $Power_{ST}$ = 6364.3 kW, m_{hw} = 101.78 kg s^{-1}.

The same method is followed to obtain results for 110°C and it is found that both cases have the same pinch point therefore the same amount of steam, power and hot water can be produced. This is because both combustion gas lines have the same gradient, and both steam lines have the same Δh and T_{sat} values as shown by the graph below.

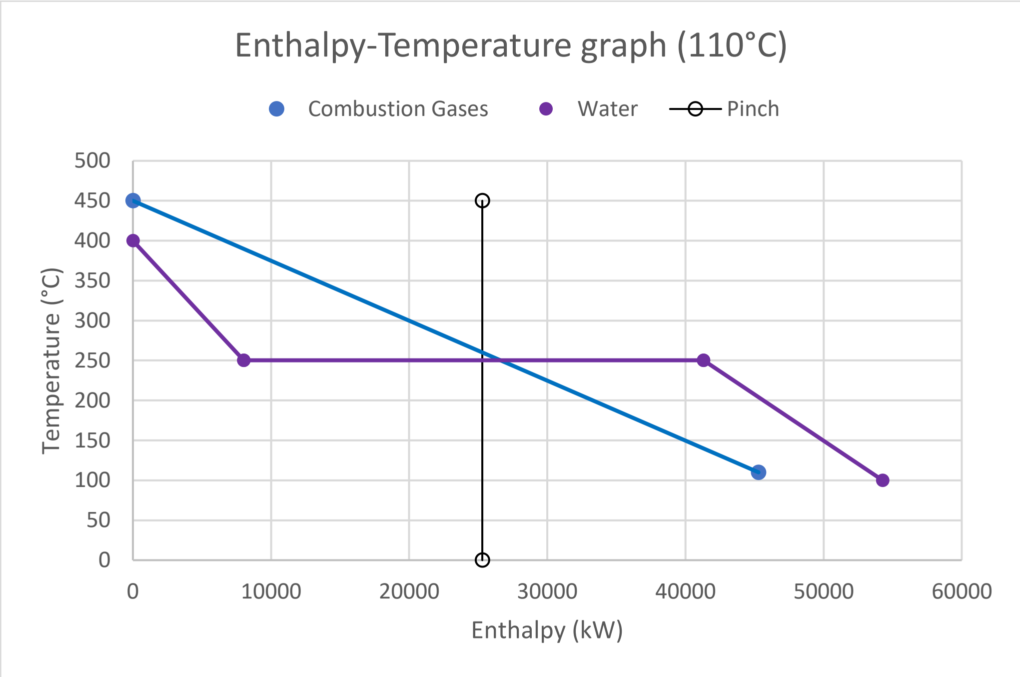

Figure 4 Temperature Enthalpy Graph for 110℃