**Sustainable Energy Systems Coursework**

# Task 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.

Using the given excel software, this system, without thermal storage, optimised to use ground source heat pumps, 2 units accounting for 3.9% of the heat required, and none of the energy required. This optimised system also uses EWF anaerobic digestion with 12 units, 9 replacements during the DE system lifetime accounting for 96.1% of the heat required and all of the energy requirements. This is as the ADs are combined heat and power producers, whereas ground source heat pumps are heat only suppliers.

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, this values for both with and without thermal storage are given in table 1.

Table : 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, with 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 CO2 Emissions

Table 2 shows the various carbon dioxide emissions, and prevented emissions, from this district energy centre, both with and without thermal storage.

Table : CO2 Emissions of Task 1

|  |  |  |
| --- | --- | --- |
|  | DE Centre without Thermal Storage | DE Centre with Thermal Storage |
| Fuel CO2 Emissions, t/yr | 1,499 | 1,596 |
| CO2 Emissions Credit, t/yr | 78,168 | 92,039 |
| CO2 Emissions Debit, t/yr | 557 | 4,119 |
| Global CO2 Emissions, t/yr | -76,112 | -86,324 |
| Percentage with respect to Baseline Emissions, % | -142 | -161 |
| CO2 Emissions per unit of heat delivered, t/MWh | -0.332 | -0.376 |

Fuel CO2 emissions are those from burning the fuel to satisfy the energy demand, CO­2 emissions debit are those corresponding to imported electricity from the grid and finally CO2 emissions credit are avoided emissions corresponding to electricity sold to the grid.

As shown, the DE centre without thermal storage produces less carbon dioxide from burning the fuel as the overall fuel consumption is lower, imports less electricity from the grid and sells less back to the grid resulting in global CO2 emissions of -76,112 t yr-1 with -0.332 tonnes of CO2 being produced 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. This results in a lower carbon dioxide emission per unit of heat delivered at -0.376 tonnes per MWh.

## 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, is better. The fuel used in both systems is wet waste, which the centre is given money to take rather than buy.

## 1.5 Economic Indicators

Table : 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, and as previously mentioned this 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, since both systems are in negative costs both are extremely good and profitable.

## 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 |  |
| CO2 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 2 – William Pitt

## 2.1 Overview

Table 2.1 Table showing overview of centre with optimisation details and number of units

|  |  |  |  |
| --- | --- | --- | --- |
| Centre | Available Technologies | Optimised Technologies | Number of Units Required over Project Lifetime |
| 1 – W/O | Natural Gas Boiler | Boilers | 3 |
| 1 – With | Natural Gas Boiler | Boilers | 3 |
| 2 – W/O | Natural Gas Boiler + Biomass Boiler | Boilers + Biomass Boilers | 20 (Boilers=3, Biomass Boilers=17) |
| 2 – With | Natural Gas Boiler + Biomass Boiler | Boilers + Biomass Boilers | 18 (Boilers=1, Biomass Boilers=17) |
| 3 – W/O | Biomass Boiler + Ground Source Heat Pump | Ground Source Heat Pumps + Biomass Boilers | 20 (Ground Source Heat Pumps=3, Biomass Boilers=17) |
| 3 – With | Biomass Boiler + Ground Source Heat Pump | Ground Source Heat Pumps + Biomass Boilers | 22 (Ground Source Heat Pumps=6, Biomass Boilers=16) |
| 4 – W/O | Ground Source Heat Pump + Solar Heater | Ground Source Heat Pumps | 23 |
| 4 – With | Ground Source Heat Pump + Solar Heater | Ground Source Heat Pumps | 22 |

The above table, Table 2.1, shows an overview of the available centre combinations that are to be compared. It can be seen that the transition of centres moves from a full carbon-based energy supplied centre in centre 1 to a non-carbon energy supplied centre in centre 4. The heat and power demand of 262.8 GWh and 74.2 GWh respectively is consistent for all centres.

The first column shows whether the centre is with or without (W/O) thermal storage. The 2nd column shows the technologies that will be used in each centre, whilst the third column shows which of these technologies is optimised for the system. The final column lists the number of each and the type of each unit that the centre will require over the lifetime of the project. It can be seen that as the centre design becomes less reliant on carbon-based energy sources the number of units required over the project lifetime increases. This is because a high number of biomass boilers are required as they have a lower heat production than conventional natural gas boilers and require a larger bulk of fuel to run. In terms of maintenance costs and reduced down time of the project for unit changeover it is advantageous to have a low number of units, such as in centre 1 that only has 3. There are however advantages to having different technologies supplying heat. For example, in the case of centre 3 ground source heat pumps provide a consistent heat supply year-round due to stable ground temperatures and do not rely on a fuel source input. Therefore, should there be supply issues with the biomass feed there would still be a base level of heat supply. It is also advantageous to have a fuel fed energy source, as should the heat demand increase or decrease the fuel supply can be adjusted within the design parameters to meet the new demand.

The DE Centre Efficiency, CO2 emissions, fuel consumption, economic indicators and thermal storage will be compared to identify the best system.

## 2.2 DE Centre Efficiency

Table 2.2 Table showing comparison of centre efficiency

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Total Heat Production GWh | 262.8 | 253.0 | 262.8 | 262.1 | 262.8 | 261.9 | 262.8 | 255.5 |
| Total Energy Production GWh | 0.0 | 0.0 | 0.0 | 0.0 | -11.3 | -22.6 | -90.7 | -88.1 |
| Total Fuel Consumption GWh | 310.4 | 298.8 | 333.3 | 331.4 | 295.4 | 252.1 | 0.0 | 0.0 |
| Efficiency | **84.7%** | **84.7%** | **78.8%** | **79.1%** | **84.7%** | **92.2%** | **155.9%(40%)** | **156.0% (40%)** |

Efficiency of each of the centre’s was worked out using the total heat and energy production in relation to the total fuel consumption. In centre 3 and 4 it can be seen that the energy production is reported as a minus value. This represents the fact the energy was imported from an off-site central power plant. The efficiency of this site is reported as 40% in the coursework information. Centre 4 therefore has two efficiency values reported. The 40% value is just that of the imported energy and the higher value represents the values for both imported and produced energy and heat. The centre 4 efficiency values for without and with thermal storage are 155.9% and 156% respectively. In the context of ground source heat pumps these are feasible values. It is reported in literature that ground source heat pumps can have a coefficient of performance of up to 4.5 [2A]. This means that for each unit of electricity input 4.5 units of heat are output. This value could also be reported as an efficiency of 450%. It is appropriate to report these values as it demonstrates that this centre does not require raw fuel input apart from the small amount of electricity imported. Centre 4 with thermal storage offers the best efficiency, marginally higher than the system without thermal storage. Centre 3 with thermal storage offers greater efficiency as it utilizes fewer biomass boilers and more ground source heating. Centre 1 has the same efficiency for with and without thermal storage, as the same number of natural gas boilers are used. Centre 2 has the poorest efficiency as it utilizes a large number of biomass boilers. In this centre the system with thermal storage has 0.3% improvement on its efficiency than without thermal storage. Therefore centre 4 with thermal storage is the best choice in terms of efficiency.

## 2.3 CO2 Emissions

Table 2.3 Table showing comparison of centre emissions

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Fuel Emissions, t/yr | 57,951 | 55,875 | 19,023 | 20,232 | 10,449 | 9,031 | 0 | 0 |
| Emissions Credit, t/yr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emissions Debit, t/yr | 36,491 | 36,491 | 36,491 | 36,491 | 41,973 | 47,451 | 80,463 | 79,240 |
| Global CO2 Emissions, t/yr | 94,442 | 92,366 | 55,514 | 56,723 | 52,422 | 56,482 | 80,463 | 79,240 |
| Percentage concerning Baseline Emissions, % | 177 | 173 | 104 | 106 | 98 | 106 | 150 | 148 |
| CO2 Emissions per unit of heat delivered, t/MWh | 0.411 | 0.402 | 0.242 | 0.247 | 0.228 | 0.246 | 0.351 | 0.345 |

Centre 1 shows better performance in terms of CO2 emissions with thermal storage, seen from the CO2 emissions per unit of heat delivered being 2.2% lower. In all the emissions performance is quite similar with the same emissions debit. The global emissions in centre 1 with thermal storage is 2076 t/yr lower due to the lower fuel emissions. Although centre 1 with thermal storage has lower annual emissions than without, the emissions associated with the construction of this thermal storage should also be considered.

Centre 2 shows very similar emissions results, the only difference between the two is due to the slightly higher fuel emissions from the centre with thermal storage. Therefore, also factoring in additional costs and emissions from the maintenance and construction of thermal storage the centre without thermal storage is the best option for centre 2. The emissions from biomass boilers are lower than those of the other centres. These emissions could be even lower than reported if the carbon lifecycle is taken into account as well. This is due to carbon capture that occurs in the process of new biomass sources being produced [2B].

Centre 3 has better emissions results for the centre without thermal storage, as the centre with thermal storage has 7.9% higher CO2 emissions per unit heat. This comes from the lower values of emissions debt and global emissions. The unit without thermal storage does have a higher fuel emission but this is offset by the other factors discussed.

Centre 4, despite having no conventional fuel input, actually has emissions that are higher than all but the natural gas fueled boiler. This can mainly be attributed to the high emissions debit due to centre 4 importing greater amounts of electricity form the grid. This could be explained by the only heat source being the ground source heating units and no solar heaters being included in the optimised design. The high initial cost of building and the emissions associated with this may be why it is better to import electricity than use solar heaters as a source. The centre with thermal storage is marginally better in terms of emissions.

Overall, Centre 1 without thermal storage had the worst emissions with CO2 emissions per unit of heat delivered being 0.411 t/MWh – this is the centre that only uses natural gas as a fuel. In contrast the lowest emitter is Centre 3 without thermal storage with CO2 emissions per unit of heat delivered being 0.228 t/MWh.

## 2.4 Fuel Consumption

Table 2.4 Table showing comparison of centre fuel type and consumption

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | | With | | Without | With | Without | With |
| Fuel Type | NG | NG | NG | Woodchip | NG | Woodchip | Wood chip | Woodchip | - | - |
| Total Fuel Consumption GWh | 310.4 | 298.8 | 44.8 | 288.6 | 55.9 | 275.5 | 295.4 | 252.1 | - | - |

Table 2.4 shows the breakdown of the fuel consumption of each of the centres. Centre 1 utilises Natural Gas at overall quantities that are second only to centre 2. Centre 1 without thermal storage has a fuel consumption 11.6 GWh higher than with thermal storage. Centre 2 uses a combination of Natural Gas and Woodchips. Centre 2 with thermal storage has a lower fuel consumption than without, all be it only by 2 GWh. Although centre 2 with thermal storage has a lower overall fuel consumption it has a higher natural gas consumption. The use of woodchips as a fuel source could be considered less impactful environmentally than Natural Gas per unit as woodchips could be sourced as a by-product of other processes and is a renewable resource. Centre 3 uses only woodchips with the centre with thermal storage having a lower fuel consumption than without. Centre 4 displays no fuel consumption. This is because heat is generated from ground source heating, therefore requiring no fuel input. It should however be noted that centres 3 and 4 also import energy from a central power plant. This is reported as being as carbon-free as possible. It is therefore not clear what fuel source is used and as such its fuel consumption has not been included in this section. Overall, Centre 4 has the lowest fuel consumption as heat is produced using ground source heating which does not require a fuel input.

## 2.5 Economic Indicators

Table 2.5 Table showing comparison between Economic Indicators for centres

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Total Annual Costs, £106/yr | 22.8 | 22.6 | 22.2 | 22.2 | 22.9 | 22.8 | 25.0 | 24.5 |
| TAC per unit of heat delivered, £/ kWh | 0.126 | 0.124 | 0.123 | 0.123 | 0.126 | 0.125 | 0.135 | 0.133 |

The economic results are best considered in terms of the total annualised cost per unit of heat delivered. It can be seen that the cost is lowest in centre 2, this is due to the low cost per unit of woodchips as a fuel source. Both centre 2 with and without thermal storage deliver the same cost per unit. Interestingly centre 4 has the top two highest costs out of all the centres. This can likely be attributed the high capital costs associated with the instillation of ground source heating. These costs come from civils, such as ground excavation that are required to install ground source heating infrastructure. Centre 4 without thermal storage has a marginally higher cost per unit, due to the slightly higher import of electricity that is required. Centre 1 has a slightly lower cost with thermal storage due to the lower fuel consumption of natural gas. Centre 3 has very similar cost per unit in both with and without thermal storage, however, the centre with thermal storage has a slightly lower cost per unit. Overall centres display very similar costs per unit between the two thermal storage options however centre 2 offers the lowest overall cost.

## 2.6 Comparison of Results

Table 2.6 Table Showing overall comparison of all centres

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Number of Units | Best  ^ | Best  ^ |  | Best | Best |  |  | Best |
| DE Centre Efficiency | Best | Best |  | Best |  | Best |  | Best  ^ |
| CO2 Emissions |  | Best | Best |  | Best  ^ |  |  | Best |
| Fuel Consumption |  | Best |  | Best |  | Best | Best  ^ | Best  ^ |
| Economic Indicators |  | Best | Best  ^ | Best  ^ |  | Best |  | Best |
| Total | 3 | 6 | 3 | 5 | 3 | 3 | 2 | 7 |

A numerical matrix was produced to ascertain the best option of both thermal storage within each centre and the best overall solution, taking into account Efficiency, CO2 Emissions, Fuel consumption and economic indicators. This is shown in Table 2.6. The thermal storage option within each centre that performed the best is indicated with ‘best’ and allocated 1 point. Those that are the best in within each category are allocated 2 points and denoted a ‘^’ symbol. It can be seen that in all the centres except in centre 3 the system with thermal storage performed the best. This is because thermal energy could be stored and used when needed as opposed to being wasted should the demand for heat drop, reducing costs and emissions. Centre 1 with conventional fuel source of natural gas performs the 2nd best out of all systems. This is due to it having a low number of units, good efficiency, and quite low fuel consumption. Centre 3 had an equal final score for centres with and without thermal storage, as they performed better in different areas. Overall, centre 4 performs the best out of all of the centres. This is a positive result as it means that it is feasible to move towards renewable heat sources for this centre. There are however compromises. The CO2 emissions of centre 4 are not the lowest, however this is likely due to occur in the construction phase. Therefore, efforts should be made to reduce these emissions. It should also be noted that costs for centre 4 are the highest of all the centres. Although this is not ideal, the main focus of this investigation is to move to a non-carbon-based fuel source and therefore Centre 4 with thermal storage provides the best option for this.

References

[2A] A. Mustafa Omer, “Ground-source heat pumps systems and applications,” *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 344–371, Feb. 2008, doi: https://doi.org/10.1016/j.rser.2006.10.003.

[2B] Carbon Trust, “Biomass heating A practical guide for potential users In-depth guide CTG012,” 2009. Accessed: Apr. 22, 2024. [Online]. Available: <https://cdn.forestresearch.gov.uk/2022/02/ct_biomass_heating_ctg012_2009.pdf>

# Task 3 – Lola Strout

## 3.1 Overview

Table 3.1: Technology Overview over the 4 Centres with and without Thermal Storage

|  |  |  |  |
| --- | --- | --- | --- |
| Centre | Available Technologies | Optimised Technologies | Number of Units Required over Project Lifetime |
| 1 – W/O | NG Engines | NG Engines | 13 |
| 1 – With | NG Engines | NG Engines | 9 |
| 2 – W/O | NG Engines + Biomass CHP | NG Engines | 14 |
| 2 – With | NG Engines + Biomass CHP | NG Engines | 9 |
| 3 – W/O | Biomass CHP + GSHP | GSHP | 22 |
| 3 – With | Biomass CHP + GSHP | GSHP | 20 |
| 4 – W/O | GSHP + EWF Incinerator | GSHP + EWF Incinerator | GSHP (8) EWF Incinerator (2) |
| 4 – With | GSHP + EWF Incinerator | GSHP + EWF Incinerator | GSHP (2) EWF Incinerator (1) |

Table 3.1 shows what each system is optimised to in terms of technologies used and the number of units required considering replacements over the project lifetime. The heat demand of the systems is 262.8 GWh and the power demand is 74.1 GWh.

For this task, the number of units, centre efficiency, CO2 emissions, fuel consumption, and economic indicators will be compared for each system, firstly for whether thermal storage is better for each centre, and which centre is better overall.

To begin, the centre with the fewest units over its project lifetime is centre 4 with thermal storage having only 3 units required. This is an important factor as having a low number of units lowers the complexity of the system, making operation and maintenance simpler. Another important point to consider is the use of multiple technologies reduces the risk of common mode failures, meaning if the supply of dry waste became unstable, the system could still produce heat.

## 3.2 DE Centre Efficiency

Table 3.2 has the necessary data required to calculate the centre efficiency as stated in the software handbook.

Table 3.2: Centre Efficiency Values for Task 3

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Total Heat Production GWh | 262.8 | 264.1 | 262.8 | 264 | 262.8 | 255.5 | 262.8 | 263.6 |
| Total Energy Production GWh | 216.1 | 217.1 | 216.1 | 217 | 0 | 0 | 19.7 | 108.3 |
| Total Fuel Consumption GWh | 573.7 | 571.1 | 576.2 | 570.6 | 90.7\* | 88.1\* | 413.6 | 653.6 |
| **Efficiency** | **83.5%** | **84.3%** | **83.1%** | **84.3%** | **40\*** | **40\*** | **68.3%** | **56.9%** |

For centres 1 and 2, the difference in efficiency is marginal with both having an under 1% change. Centre 1 has a higher efficiency with thermal storage at 84.3%, and centre 2 has the higher efficiency with thermal storage at 84.3% again.

Centre 4 has a lower efficiency at 68.3% and 56.9% as the one of the fuels used, dry waste, is a mixture of components, some of which will not produce much heat or energy. However, the inclusion of this dry waste into the system is important as otherwise this waste would have to go to landfill which we, as a planet, are running out of space for.

Centre 3 is a different system which cannot have its efficiency calculated by the formula provided in the software manual as there is no fuel on site consumed, it is fueled by imported electricity. If the formula was applied both systems would have over 100% efficiency, which is impossible, as the total of the heat and energy production is greater than the electricity required to create them, in addition to this, the software guidebook states that the efficiency for power plants supplying electricity is 40%. As a result, another metric is required to test the efficiency of these systems and the one of choice is to compare them solely to each other. Centre 3 without thermal storage requires 90.7 GWh of electricity to meet the same requirements as centre 3 with thermal storage, however the system with thermal storage requires less electricity at 88.1 GWh. So, it can be said that the centre with the thermal storage is more efficient than the centre without.

Overall, the centre with the best efficiency would be centre 3 with thermal storage, as the heat production is greater than the energy inputted by the electricity, with a second of both centres 1 and 2 with thermal storage.

## 3.3 CO2 Emissions

Table 3.3 contains the same data extracted for tasks 1 and 2 but for the 4 centres in task 3.

Table 3.3: CO2 Emissions for the 4 Centres Concerned in Task 3

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Fuel Emissions, t/yr | 107,137 | 102,647 | 107,593 | 102,546 | 0 | 0 | 89,171 | 141,282 |
| Emissions Credit, t/yr | 70,412 | 75,521 | 70,398 | 75,502 | 0 | 0 | 446 | 21,663 |
| Emissions Debit, t/yr | 557 | 5,679 | 557 | 5,720 | 80,463 | 79,240 | 26,477 | 4,485 |
| Global CO2 Emissions, t/yr | 37,281 | 32,805 | 37,751 | 32,765 | 80,463 | 79,240 | 115,202 | 124,104 |
| Percentage concerning Baseline Emissions, % | 70 | 61 | 71 | 61 | 150 | 148 | 215 | 232 |
| CO2 Emissions per unit of heat delivered, t/MWh | 0.162 | 0.143 | 0.164 | 0.143 | 0.351 | 0.345 | 0.502 | 0.541 |

For centre 1, the system with thermal storage is undoubtedly better in terms of overall lower carbon dioxide emissions as the fuel emissions, global emissions, percentage compared to baseline and emissions per unit of heat delivered are lower. More electricity is imported in thermal storage, as well as sold back to the grid. I believe that this second centre is the more environmentally friendly option out of the two as further work could be done to decrease the amount sold to the grid therefore making the import requirement lower.

Centre 2 was very similar to Centre 1 in terms of all the individual values and therefore the same conclusion was reached via the same thought process as described above.

Centre 3 presents a different outlook as there is no ‘fuel’ used in the system, the driving force for the ground source heat pump is 100% imported electricity. These present high values for the emissions per unit of heat delivered as well as the global emissions. The two systems, with and without thermal storage, as so similar that although thermal storage is slightly better, they could be considered the same.

Centre 4 is the highest out of the 4 centres for both options of thermal storage with no thermal storage providing slightly better emissions per unit of heat delivered.

Overall, Centres 1 and 2 are the most environmentally friendly when considering carbon dioxide emissions with the same value of 0.143 CO2 emissions per unit of heat delivered whilst Centre 4 with thermal storage provides the worst environmental choice with a value of 0.541 CO2 emissions per unit of heat delivered.

## 3.4 Fuel Consumption

Table 3.4 displays all the fuel types and consumptions of each of the centres. Centres 1 and 2 uses natural gas, which is a non-renewable source, at quite a large amount, with the lowest being centre 2 with thermal storage at 570.6 GWh. Centre 3 uses the least fuel out of all the centres with values of 90.7 and 88.1 GWh of electricity for without and with thermal storage respectively. However, this electricity is imported from the grid and most probably would be made from a non-renewable source such as the natural gas used in centres 1 and 2, therefore although this value is low, it is not the best option. Furthermore, centre 3 would be at the mercy of price fluctuations of electricity from the grid. Centre 4 presents the best fuel, a mixture of electricity from the grid and dry waste, with fuel consumption values of 413.6 and 653.6 GWh.

The best centre in terms of fuel type and consumption is centre 4 with thermal storage as although it has the highest consumption it is making use of waste which would ordinarily go to landfill. The use of electricity presents the same concerns as for centre 3, but having a dual fuel type means the operation of the centre is not fully reliant on the grid electricity.

Table 3.4: Fuel Consumption and Types of Fuel for each Centre

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Fuel Type | NG | NG | NG | NG | Electricity | Electricity | Electricity, Dry Waste | Electricity, Dry Waste |
| Total Fuel Consumption GWh | 573.7 | 571.1 | 576.2 | 570.6 | 90.7\* | 88.1\* | 413.6 | 653.6 |

## 3.5 Economic Indicators

Table 3.5 gives the annual costs and the minimum cost per unit of heat to break even. For each centre, the version with thermal storage provides lower annual costs and therefore a lower price required to break even resulting in higher profit margins. Overall, centres 1 and 2 with thermal storage have the best economics. Centre 2 has a marginally better annual cost at £10,004,770 compared to £10,014,966 for Centre 1, but the TAC is the same.

Table 3.5: Economic Indicators for Task 3

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Total Annual Costs, £106/yr | 12.3 | 10.0 | 12.7 | 10.0 | 24.9 | 24.3 | 18.6 | 14.5 |
| TAC per unit of heat delivered, £/ kWh | 0.08 | 0.07 | 0.081 | 0.07 | 0.134 | 0.132 | 0.107 | 0.089 |

## 3.6 Comparison of Results

Table 3.6 contains the findings from each of the previous sections, with a note of ‘Best’ for the choice of thermal storage of each centre, and a note of ‘^’ if that centre is the most favourable choice out of them all for that indicator. To create a quantitative score, no note is allotted 0, Best is allotted 1, and ‘Best’ with ‘^’ is allotted 2 points. These have been collected in the final row of the table.

Table 3.6: 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  ^ |  | Best | Best |  |
| CO2 Emissions |  | Best ^ |  | Best ^ |  | Best | Best |  |
| Fuel Consumption |  | Best |  | Best |  | Best | Best | Best  ^ |
| Economic Indicators |  | Best |  | Best ^ |  | Best |  | Best |
| Total | 0 | 7 | 0 | 8 | 0 | 5 | 3 | 5 |

Using this final quantitative approach, we can see that the most favourable centre is centre 2 with thermal storage which utilizes natural gas as a fuel source. Although this source is non-renewable it produces the least amount of carbon dioxide emissions with 0.143 tonnes CO2 Emissions per unit of heat delivered in MWh, having the least negative environmental impact. Furthermore, this centre is one of the most efficient with an efficiency of 84.3% and has the most attractive economic indicators with a TAC of 0.07 and an annual cost of £107.

# 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 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. An efficient way of producing power from geothermal energy is to produce steam, however at 99°C the steam produced will be very low pressure at 99°C and there is only a low amount of energy available for extraction. Electricity generation in this instance will have poor economic desirability when considering the cost of steam turbines; steam generation from GSHPs has not been considered in these centres). While the GHSP units can only produce heat, the gasifiers can produce electricity as well as heat, 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 which no longer meets the heat demand either.

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 CO2 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 NCV than its dry counterpart when compared by mass. However, it is self-sufficient in that anaerobic digesters operate optimally at ~30-45°C (mesophile). 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 mesophilic/thermophilic. 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. One way to improve efficiency is by utilizing the waste stream as a feedstock or by-product; while the efficiency of wet waste is quite low, it is converting an undesirable problem into a long-term sustainable solution for energy production.

## 4.3 CO2 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 CO2 Emissions, t/yr | 61477 | 51923 | 61477 | 51922 | 80463 | 79240 | -79147 | -86324 |
| Percentage concerning Baseline Emissions, % | 115 | 97 | 115 | 97 | 150 | 148 | -148 | -161 |
| CO2 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/CO2 | 692 | 698 | 692 | 698 | 1570 | 1424 | 267842 | 272065 |

Table 4.3: CO2 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 CO2 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). This means that 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. 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 may change the treatment required and can become another source of income.

## 4.5 Economic Indicators

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Centre 1 | | Centre 2 | | Centre 3 | | Centre 4 | |
|  | Without | With | Without | With | Without | With | Without | With |
| Total Annual Costs, £106/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: CO2 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 government so that they can 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 treatment 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 | - |  |
| CO2 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 enough temperatures (~565°C[4D]) which can be used to produce steam at high pressures. In turn, this can be expanded to a lower pressure and temperature and can then be directly used to extract latent heat or used to heat a secondary thermal fluid (i.e. district heating). Where cogeneration is not required, steam can also be passed through a condensing turbine; using only heat energy from the steam is less efficient than using the thermal fluid to directly heat the district fluid. Thermal storage increases the capital and operational costs. Construction materials will have their 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 cannot avoid heat losses 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 for with/without TS indicated by “-“which is not considered in the comparisons). Therefore centre 4 with thermal storage is the advised DE centre design.

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 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

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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).

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# Task 5

## 5.1 Hot Water Generation

Firstly, we will analyse the system with a dew point temperature of 110oC. 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.

0.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, that being that 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 m2, making the capital cost of the heat exchanger £52,245.

The piping cost correlation was a simple cost per metre, and the question stated 20km of piping was required at £2000 per metre. This gives an overall piping cost at £40,000,000. The total capital cost of these two parts were £40,052,245 , with an annual payment of £7,982,412 as stated by using the given annualization factor.

The operating cost of the system is the cost of the water, if 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. Therefore, we get an operating cost of £1,630,368 (£815,184 per hour).

Therefore, if the combustion gases' dew temperature is 110oC, the annual cost of water delivery is £9,612,780.

Now we will consider the system to have a dew point temperature of 160oC.

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 m2, 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 £1,390,608 (£695,304 per hour).

Overall, if the combustion gases' dew temperature is 160oC, the annual cost of water delivery is £9,373,020 after accounting for the pipe costs and the annualization factor for the overall capital costs.

The configuration of the heat exchanger in both scenarios is counter-current as it minimises the area required.

## 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 oC to be used for the production of superheated steam to 400 oC at 40 bar that will be used for steam supply to the steam turbine. The steam turbine efficiency is reported as 90%.

400°C, 4 bar

3 bar

Figure 1 Schematic of steam turbine

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

Where m = 120 kg s-1 and Cp = 1.11 kJ kg-1 K-1

Next the mass flowrate of steam into the steam turbine can be calculated using the Q value calculated and the enthalpy change.

However, the enthalpy-temperature graph shows that this is a completely unrealistic value because it violates the and both lines intersect. Therefore, the mass flowrate needs to be reduced so that is achieved. This is because drives heat transfer and is set at an optimised value to achieve target heat transfer rates.

Figure Enthalpy Temperature Graph for 160°C

The mass flowrate is limited by the pinch temperature which is at () 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).

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

Figure Corrected Enthalpy Temperature graph for 160°C

Steam exits the turbine at 3 bar.

Where Sin = Sout = 6.769, Sg = 6.993, Sf = 1.672

h2 = 561 kJ kg-1, hg = 2725 kJ kg-1, hIS = 2633.90 kJ kg-1.

∆h = 3214 – 2633.9 = 580.1 kJ kg-1

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

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

From this the quantity of hot water produced can be found.

The final results for 160°C: msteam = 12.19 kg s-1 , PowerST = 6364.3 kW, mhw = 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 and values as shown by the graph below.

Figure Temperature Enthalpy Graph for 110°C