DIGESTION AND GREENHOUSES – SYNERGISTIC RESOURCE RECOVERY

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Abstract

Digester gas is seen as a valuable resource because of its energy density, but it is frequently the case that most of this energy is wasted. A typical CHP will recover at best 40% of the available energy as electricity plus an amount used for digester heating. Old water industry assets suffered from low dry solids feeds leading to them needing all the heat, but newer advanced digestion assets and digesters fed on food waste only need a small amount of the recoverable heat from the CHP, leading to there being opportunities to use this heat. Furthermore, digester gas produces a CHP exhaust gas that is particularly rich in carbon dioxide and water vapour. This paper explores the synergy that exists between using otherwise wasted resources derived from digester gas in greenhouses for tomato production and is largely based on a DECC funded project at NWL's sludge centre at Bran Sands.

Keywords

Anaerobic Digestion, Greenhouses, CHP, Energy, Carbon Dioxide

Introduction

Overall Aim

This paper originated from a project, funded by Greenius, that sought to investigate the viability of utilising the waste heat and carbon dioxide (CO_2) from the Combined Heat and Power (CHP) and Thermal Hydrolysis (TH) plants associated with the Advanced Anaerobic Digestion (AAD) plant at Northumbrian Water's Bran Sands Regional Sludge Treatment Centre. The longer term goal of this project was to use these heat and CO_2 streams to promote the growth of salad crops under glass for local delivery. This would be very much in line with a large proportion of Europe's greenhouse crop production which is supplied with power, heat and CO_2 from dedicated CHP plants burning natural gas, but offers the benefit of in effect replacing the fossil fuel with renewable digester gas. Other sources of renewable biogas such as food waste digestion are also considered in this paper.

Northumbrian Water Background

Northumbrian Water (NW), as the result of its wastewater treatment activities in the northeast of England, generates in the order of 80,000 tonnes dry solids (tDS) of sewage sludge per annum. All this sewage sludge is fed into two almost identical AAD plants, one at Howdon on Tyneside and the other at Bran Sands on Teesside. This latter site was the focus of the original project, primarily because it has been operated for longer and therefore has more operational data available. The AAD plant at Bran Sands pre-treats the sewage sludge using Thermal Hydrolysis (TH) prior to using anaerobic digestion (AD) to produce biogas and a stable sludge product. The TH plant is used to enhance the efficiency of AD, allowing more biogas to be produced and improving the recyclability of the sludge product. Thermal Hydrolysis involves heating the incoming sewage sludge using steam under pressure to 160°C before abruptly reducing that pressure to pasteurise the sludge and render it more digestible by the AD plant. The resulting sludge is cooled to an appropriate temperature for AD to take place (40 °C) producing a large quantity of low grade waste heat in the process. The biogas from the AAD plant is currently burnt in CHP gas engines to produce electricity and heat. Some of the heat is re-cycled to the TH plant. However, the majority of the low grade heat from gas engine lubrication oil / jacket cooling water is lost to the atmosphere.

From the plant's original design (represented in the Sankey diagram below), it was known that approximately 40% of the 11.5 MW energy produced in the biogas is dissipated as waste heat from (i) the TH coolers and (ii) as un-utilised waste heat from the CHP. Note that the primary aim of the CHP plant is to produce renewable electricity, not renewable heat. Indeed, the current AAD installation at Bran Sands is producing in excess of 3.5MW of renewable electricity.

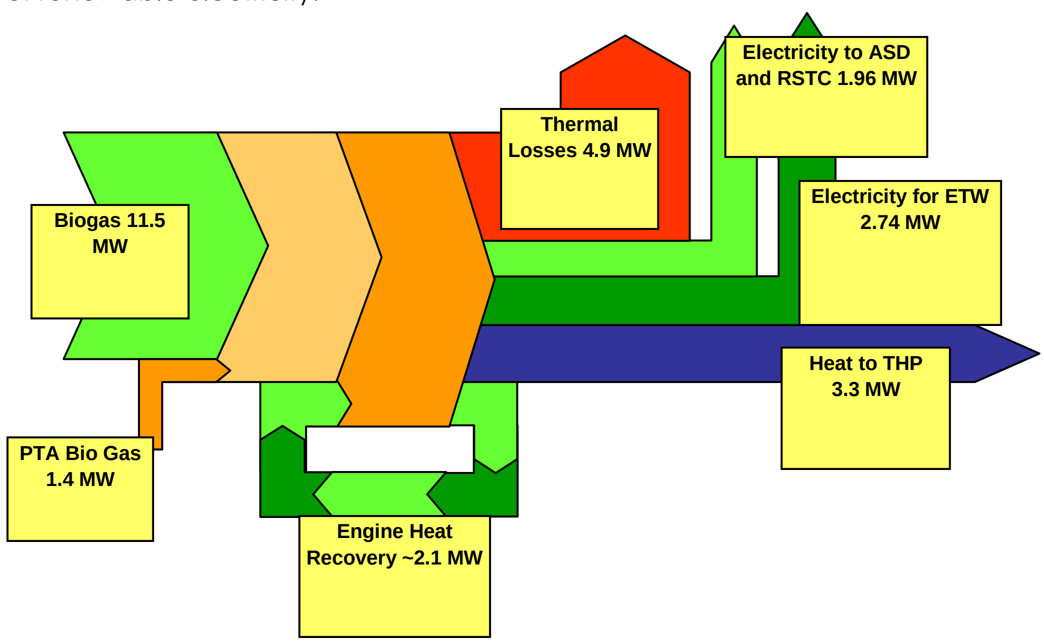

Figure 1: Sankey diagram to show the Energy balance (based upon 40,000 tDS sewage sludge Design Capacity)

Alongside the production of waste heat the AAD also produces CO_2 from the CHP and THP steam generation plant exhaust stacks. These exhausts are particularly rich in CO_2 because the biogas that is used as their fuel contains approximately 40% CO_2 which is normally lost to atmosphere from the CHP exhaust.

The site at Bran Sands also has a ready beneficial nutrient source in the form of sewage sludge digestate, which could be used as growing medium in horticulture because it is pasteurised and of consistent handling qualities

The idea of recovering heat and carbon dioxide in this way has the potential to keep bills down, saving money for consumers and creating jobs. As NWL is a regulated business, any return made from this new business activity will be to the benefit of the company's customers, resulting in lower water bills. Since the energy will be supplied to the glasshouses at a cost lower than the present market rate, local consumers will have the potential for buying lower-priced crops, grown locally, with a reduced carbon footprint that includes significant energy recovery. This form of Urban Farming will mean greater food production whilst actually reducing damage to the environment.

In pursuing this project, NW sought to support a supply chain of predominantly UK companies and a local labour market. Benefits would be obtained by the construction of this project and a partner horticultural company would benefit from running the glasshouse facility, providing jobs and income in the local community.

The Wider Picture

UK-wide, there is the potential for a great deal of AD related low grade heat energy from waste sources to be utilised in this way. According to DEFRA, current gas production from sewage sludge is 11,600TJ per year. However, most sewage sludge digesters require that practically all the heat that is produced is used for heating the digester. Only plants that manage the energy balance with a TH plant produce significant waste heat. We believe that there are currently 10 other TH plants in the UK, with a total estimated waste heat output of 24.5MW. Further DEFRA data gives low grade heat energy values from biogas sources other than sewage sludge (excluding landfill gas) of around 8,200 TJ per year. This is expected to rise to about 135,000 TJ per year. Of this, only the AD of foodwaste produces significant waste heat; so the numbers are 7,000TJ per year now and 34,750TJ per year in the future. Post CHP, the waste heat is about 40% of these numbers, and converting to MW, that is 90MW rising to 440MW.

Many of the principles and practice that apply to these large scale plants are transferrable to smaller AD plants, particularly those treating food waste or similar relatively 'dry' feedstocks, that produce waste heat at a level necessary for enhancing crop growing.

AD Resource Sources

From studies of the available process flow diagrams (PFDs), it was possible to determine where heat, carbon dioxide (CO_2) and effluent outlets occur at the AAD plant. These are listed as;

1. Heat sources;
    a. Adiabatic coolers
    b. Off-gas coolers
    c. Digested sludge
    d. CHP exhaust gas
    e. Steam boiler flue gas

   f. Wasted CHP hot water
   g. Unrecovered CHP hot water
   h. Bio-gas chilling plant
   i. Boiler blow-down
2. Carbon dioxide;
   a. Digester gas
   b. CHP exhaust gas
   c. Steam boiler flue gas
3. Effluent;
   a. Digested sludge centrate

An initial screening study was used to determine the viability of these sources for the purpose of greenhouse enhancement and concluded that only waste heat from the CHP cooling system, carbon dioxide from the CHP exhausts and nutrient rich liquor from the digested sludge centrate were viable. The others were either too small to be recovered economically or were intermittent. A description of each of these sources is given below for the Bran Sands case, but clearly, although the numbers will be different, the principles of these sources could be applied to any AD plant.

Wasted CHP Hot Water

There are four CHP units at Bran Sands, each equipped with heat recovery/cooling systems from the jacket water, oil cooler and intercooler. These are combined into a recirculating hot water system that is partially used (via a heat exchanger) to pre-heat the treated water used to raise steam and partially used (via an air blast cooler) to provide the CHP engines with cooling.

The pre-heat requirement of the water used to raise steam is only about 16% of the total heat the CHP units create when working at full power, hence there is clearly a large amount of heat in the form of hot water that is not used.

For the average case used in this study, the available hot water amounts to 2.49MW_{th} at around 85^{o}C. This is ideal for space heating. From the site visit, it was clear that obtaining this hot water could be relatively straight forward from a practical point of view.

CHP Exhaust Gas

The digester gas is burnt in the CHP unit to create carbon dioxide and water vapour as the principle products of combustion, plus small quantities of numerous other oxides arising from the various trace components of the digester gas.

To use this carbon dioxide in the envisioned greenhouses would require these trace oxides to be removed. This is normally achieved by using a catalytic converter to remove many of the problem by-products plus a urea tower/injection system to remove the oxides of nitrogen. This practice is widespread amongst tomato growers, particularly on the continent.

In practical terms, this is not too difficult if a standalone skid is used that includes an exhaust gas blower to prevent there being any backpressure on the CHP engines. Space to mount such a skid is at a premium around the CHP units at Bran Sands so this would require careful integration.

Given that a large component of the fuel (i.e. the digester gas) is actually carbon dioxide, the exhaust gases are actually unusually rich in CO_2. For the average case, the CHPs will produce around 3300kg/hour of CO_2 that could be treated and ducted to a greenhouse.

Depending on the design of the ductwork, this gas stream could also supply a considerable amount of heat (theoretically as much as >1MW for a kilometre of well insulated [expensive] duct or 0.3MW for a short length [50m] of bare metal [cheap] duct) and moisture to the greenhouse (over 1.7t per hour of water as either gas or condensate).

The recommendation of the screening exercise was to further investigate the use of the CHP exhaust gases as a carbon dioxide, water and heat source. This investigation is detailed below and came to the conclusion that the demand for CO_2 in the greenhouses would be considerably less than the amount that could be supplied. Hence, although possible and originally recommended for further investigation, the option to provide CO_2 from the steam boiler exhaust gases has been rejected as being unnecessary.

Digested Sludge Centrate

The quality of the centrate is microbiologically good because the thermal hydrolysis stage pasteurises (practically sterilises, actually) the feed sludge and the digestion stage produces a benign microbiological culture in the digested sludge. The centrate will contain useful quantities of readily available plant fertiliser in the form of nitrogen and phosphorous. Furthermore, the technology and know-how exists to modify the centrate into a well balanced fertiliser for any horticultural crop.

The recommendation of the screening exercise was not to consider this further unless the potential users express an interest in using such a product.

Greenhouse Demands

The previous paragraphs identify the possible supplies that could be produced at any AD plant, using the example of the AAD at Bran Sands. These next paragraphs describe the analysis of the demand side of the considerations – i.e. what is of value to a greenhouse operator and how much of the supplies would they take?

This analysis developed the optimum balance between the 3 potential outputs (heat, CO_2 and water/effluent) from the Bran Sands CHP plant. This consideration was then related to the area of greenhouse (greenhouses are normally described by their plan area – e.g. a "2.5Ha greenhouse" would be a fairly average size) that could be sustained by these potential supplies.

Heat

The Bran Sands Advanced Digestion plant is calculated from the above analysis to give a recoverable energy output (for the average case) in the region of 3.5MW (for 92% of the year – to account for downtime), which is equivalent to around 30million kWh/year. The official tomato industry website (The British Tomato Growers' Association www.britishtomatoes.co.uk) gives a rule of thumb of an average heat demand of 450kWh/m^2, implying these sources could supply enough heat for 7Ha of greenhouse. Clearly this heat demand is only required during the growing season (which is quoted from the same source to be from February to November) and hardly at all during summer (because of heat gained from insolation). Assuming a peaking factor of 2 to account for the spring and autumn peaks of demand hence gives a maximum area of 3.5Ha of greenhouse that could have its heat supplied by the identified sources.

Unfortunately this estimate is only based on a rule of thumb, so to validate it the next step taken was to consider where the heat would be used in a greenhouse. The heat sinks were identified to be;

1. losses through the glass,
2. losses to the air flow through the greenhouse,
3. and losses to evaporation/transpiration of water.

A complicated series of calculations and assumptions were used to quantify these losses, but in simplified terms, these losses are dependent on the outside air temperature and the number of air changes required to maintain the correct humidity and temperature for tomatoes.

To calculate the losses for a cold day in February, the Met Office long term average 24 hour minimum temperature in the north of England (0.6 °C) was assumed together with the recommended minimum number of air changes of 2 per hour to maintain the optimum humidity and working environment). This gives a maximum greenhouse area of only 1.1Ha. This assumes no heat is gained from insolation, which is considered reasonable for a grey day in February.

The equivalent calculations for summer are an external temperature of 11.0°C and 10 air changes per hour, giving a greenhouse area of 1.0Ha. However, it is clear that in summer, heat gained from insolation will be significant. In fact (assuming an insolation rate of 450W/m^2 – the July average for a sunny day in northern England) this raises the potential greenhouse area to infinity because the heat gained from the Sun exceeds all the losses (apart from the losses arising from the air change rate - which is, of course, how the temperature is controlled in an un-heated greenhouse).

The calculations of relative value (summarised later) show that the importance of the heat supplied from Bran Sands is more than the value to the grower of the CO_2. Hence the area of the greenhouse should be fixed by the area that the heat supply can support. In the simplistic case developed above, this varies from 1.1Ha in February to infinity in summer. As growers will be germinating seeds in February, barely using any water and generally apply insulation to the greenhouses, the heat losses will in reality be less than calculated above. By applying reasonable assumptions for this case, the calculations actually come to an area of greenhouse of between 2.5Ha and 3.5Ha. The upper limit here is on a par with the figure derived from the Tomato Growers Association rule of thumb. In the interests of erring on the side of caution, we have chosen 3.0Ha for the CO_2 calculations.

The heat would be delivered to the greenhouses in the form of hot water at 55 to 70°C, recirculated in a secondary water loop from a hot well adjacent to the CHP units. Within the structure of the greenhouse, the hot water would run through pipes to deliver the heat in a similar way to a domestic central heating system.

Carbon Dioxide

The OSHA (Occupational Safety and Health Administration) recommended limit for continual exposure to CO_2 is 1000ppm (the UK HSE equivalent limit is 5000ppm in an eight hour day). Maximum uptake rate for photosynthesis in the N of England is also 1000ppm (on a very sunny day), hence the calculations carried out for this feasibility study aim to maintain an atmosphere of 1000ppm in the greenhouse. Given the range of factors, this can be achieved by taking just the CHP exhaust gases and wasting between 35% and 80% of them – i.e. there is a massive excess of CO_2 produced compared to the heat. This implies to make a bigger greenhouse, the focus should be on providing more heat, rather than more CO_2.

To deliver the CO_2, a duct would be required that would pick up the exhaust gases at the base of the existing exhaust stack and carry a controlled fraction of the gas to the greenhouse. The precise arrangement for collecting this fraction adjacent to the CHP units depends upon the most efficient way of cleaning the gases to the required standard. The standard method of cleaning the exhaust gases is to provide a catalytic convertor to remove the trace levels of noxious gases arising from the fuel and a further stage of treatment to remove the NO_x produced from the nitrogen in the combustion air. The precise arrangement of components is complicated by the fact that a catalytic convertor is already fitted to each CHP unit to meet air quality requirements. These may be sufficient for our requirements but this cannot be determined because gas analysis to the level of detail required for the catalytic convertor manufacturers to provide guarantees has not been carried out. Furthermore, the use of the Steam Generators cools the exhaust gases to a level where the efficacy of a catalytic convertor is much reduced, so adding a second catalytic convertor to meet requirements may not be cost beneficial. Information from suppliers of such equipment has not been forthcoming because they are worried that the source of the digester gas being burned in the CHP units is sewage sludge. Without extensive gas analysis data, they are not willing to specify any particular catalytic converter. Finally, the choice of NO_x removal method is between a wet scrubber and a dry injection system. Each has its pros and cons and the choice ultimately depends on contractual/market/risk considerations. For this analysis we have assumed a dry injection system is used (to enable the recovery of heat in an economiser – more details below).

There are three options regarding the ductwork to carry the exhaust gases to the greenhouse;

1. Insulated so that the heat in the gases can also be delivered to the greenhouse
2. Un-insulated, which will be less expensive and will deliver warm clean water (condensate) to the greenhouse.
3. Compressing the exhaust gas so that the duct size can be reduced (and then more cost effectively insulated for health and safety reasons).

The choice depends on the economics of the situation and in particular the fact that supplying the CO_2 in an insulated duct has the potential to supply a considerable amount of heat. As heat has been established to be the main economic driver, this will also affect the potential size of the greenhouse, which then also affects the amount of CO_2 required and hence the heat supplied. This circular argument can be solved by making certain assumptions to derive a figure of about 875kW of additional heat that could be supplied via the insulated duct. The problem with this supply of heat is that it may be at a dangerously high temperature (depending upon the choice of catalytic convertor and NO_x removal combination, amongst other things). To reduce its temperature without wasting the heat requires either a gas to water heat exchanger (which will add hot water to the greenhouse heating system) or an air mixing system to allow ambient air to mix with the gas prior to injection into the greenhouses. The many pros and cons of these options would need to be further considered in conjunction with the potential users of the heat and CO_2 prior to making any investment decisions.

Water

The combustion product water that will condense from the exhaust gases from an un-insulated duct could, under certain circumstances, supply all the water required by the greenhouse. For the 3.0Ha greenhouse considered here, the CO_2 demand is only 66% of the total produced from the CHP, so the water available is reduced to about 48% of the annual requirement. Of course, the value of this water is rather low, so this is not a key driver

Nutrients

The use of centrate as a supply of nutrients could easily exceed the nutrient requirements of the tomatoes. However, a detailed analysis of this option has not been carried out.

Components Required

To recover heat from the CHP units' cooling circuits is relatively simple, requiring pumps, heat exchangers (to keep the cooling water and the greenhouse supply separate), pipework and a hot-well (to buffer the supply of heat to the greenhouses) at the AD site and connecting pipework to the greenhouses.

Efficient recovery of the CO_2 from the CHP exhausts is a combination of the treatment of the gas to a standard that is safe for the workers in the greenhouse, the conveyance of the gas to the greenhouse and the requirements of the (tomato) plants in the greenhouse. The maximum demand of the tomato plants in a 3.0Ha greenhouse was calculated to be 66% of the total produced by the four CHP units at the average design case. To convey this gas to the greenhouse, avoiding any back-pressure on the CHP engines that would reduce their power output, requires a fan or a blower or a compressor. The most cost-effective motive force in terms of the consequent pipe costs is a compressor because this allows relatively small pipes to convey the gas. The solution costed for Bran Sands was a 300kW compressor capable of 0.5barg (operating at 0.42barg), delivering into a 500mm insulated pipe of 200m length.

The compressor outlet would be connected to the inlet of the catalytic converter, to take advantage of the extra heat arising from the compression to boost the performance (and hence reduce the cost) of the catalytic converter. These catalytic converters are supplied as packages with a urea injection plant to remove the NO_x.

The recovery of the heat in the exhaust gases depends upon their temperature after the gas cleaning stage. These gases represent a potentially large, but highly variable heat source such that, when demand for CO_2 is low, then the heat available will consequently be low, and vice versa. One of the main drivers to recover heat from the exhaust gases is the health and safety issues of delivering hot gas to the greenhouse. These gases should be cooled to about 75°C at the exit from the BSAD plant so that further losses during conveyance and the final mixing with ambient air in the greenhouse reduce this temperature to safe levels. An economiser would achieve this and still produce hot water at 70°C for the hot well. The sizing of the economiser would be defined by the maximum flow of CO_2 to the greenhouse.

To deliver the exhaust gases to the greenhouses, it was clear from the prices received from the ductwork installers that the most economic approach is to compress the gas to deliver it through much smaller diameter pipework. The option to insulate this pipework then makes only a slight difference to the capex, but a considerable difference to the supply of heat to the greenhouses. The calculations applied to the Bran Sands case were based on an assumption of a 200m run of stainless steel, insulated, above ground pipework between the current CHP exhaust stack and the potential greenhouses. The gas was assumed to be compressed to 0.42barg using a 300kW compressor. This compressor would be capable of considerable downturn and would be used in conjunction with a valved by-pass (to the existing exhaust stack) in order to control the supply of CO_2 to the greenhouse.

The gas pipework has been priced on the basis of it being stainless steel (for corrosion resistance because the exhaust gas water vapour will condense) and mounted on plinths across open ground between the AD plant and the greenhouses. These same plinths would also be used for the hot water circuit pipework and the control cables.

Conceptual Design

In Figure 2 below;

1. Existing plant is shown in green, new plant in blue.
2. Dotted outlines represent options.
3. Pre-treatment coolers represent many potential sources of very low grade heat.

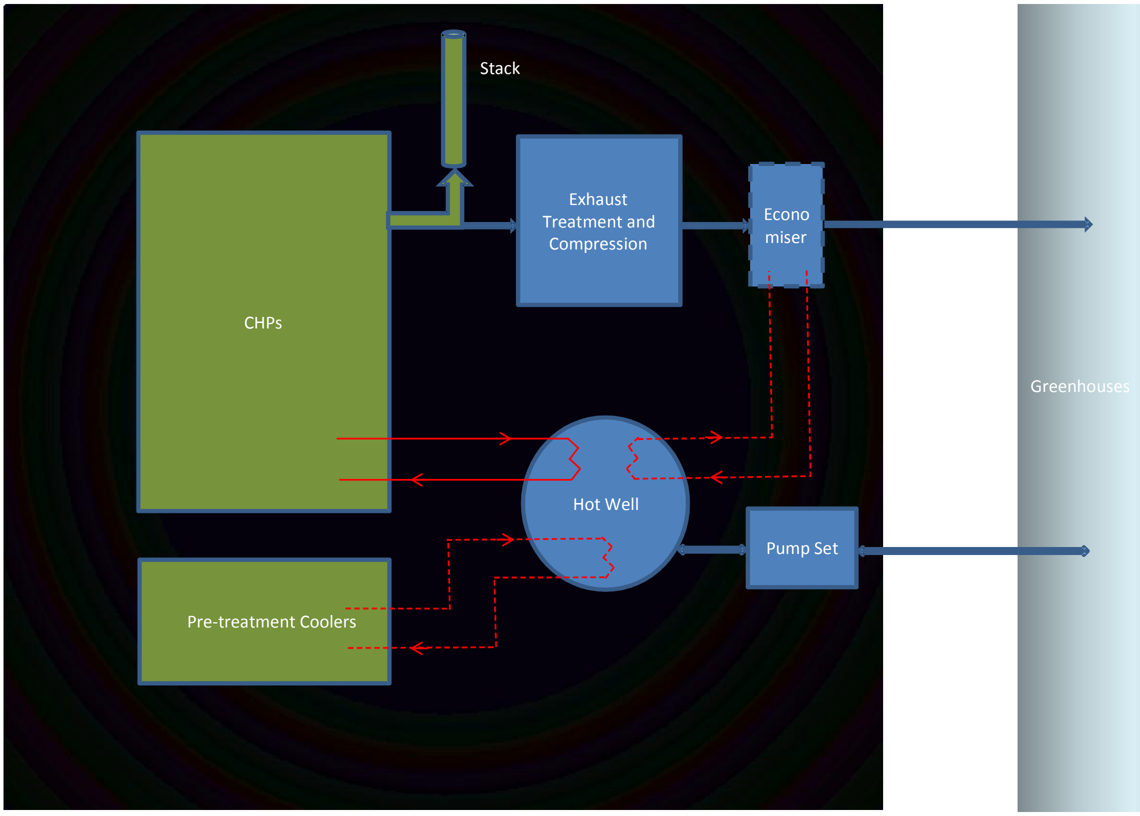

Figure 2: Design concept

Financial Analysis

Heat

The cost to the grower of the heat used in the 3.0Ha greenhouse used in this analysis would have an equivalent value if sourced from natural gas of around £500kpa (as opex assuming a gas price of £35/MWh, ignoring the maintenance costs and capex of the boiler/CHP unit being used to provide the heat in the greenhouse).

What the AD operator would charge the grower for this heat depends upon market forces, but the information considered for this paper would suggest a price for this heat of £15/MWh would be reasonable. This would give an income to the AD operator of between £200kpa and £270kpa, with the recommended option giving an income of £235kpa.

The cost to the AD operator of providing this heat is a combination of the capital cost of the required infrastructure and the operating cost of this infrastructure. These were calculated for the Brans Sands case to be £644k (as an outturn cost) and £8.4kpa respectively.

Carbon Dioxide

The value of the CO_2 is in the increased production of tomatoes that it engenders. From published data, this could increase the tomato production by 20 to 70%, but this is highly dependent on factors out of the control of the grower. Therefore, a more conservative approach of assuming a 30% increase in yield was chosen in this analysis. The value of tomatoes is monitored by DEFRA and using their data, an increase in production of 30% from a 3.0Ha greenhouse would be worth about £490kpa. This income benefit to the grower is directly proportional to the size of the greenhouse and therefore provides an incentive to build a larger greenhouse, which would be of benefit to the AD operator because of the consequent increased product (heat and CO_2) sales. In terms of the income potential of the CO_2 it has been assumed that the AD operator would receive payment equivalent to half the increased value of the crop, i.e. about £245kpa.

The cost to the AD operator of providing this CO_2 is a combination of the capital cost of the required infrastructure and the operating cost of this infrastructure. The estimated outturn cost for the Bran Sands case is £640k and the estimated operating cost is £82kpa comprised of £72kpa on electricity and £10kpa on urea.

Whole Life Cost

The above is a simplified view of the economics because there are a great many interdependencies. This fact also means there is considerable scope for optimisation and income enhancement depending upon the tomato grower's appetite for risk. However, the figures presented serve to show what orders of magnitude the value of the products could have and have generally erred on the side of caution.
Using the numbers presented, the whole life cost was calculated in terms of NPV and converted to an IRR to give the payback periods. The relevant numbers are;

- NPV of minus £1.8M (i.e. a net income)
- IRR of 12%
- Simple payback of 5 years
- Compound payback of 4 years

Conclusions

The recovery of spare heat and carbon dioxide from AD plants for use in greenhouses is technologically and financially viable.

AD plants generally produce far more carbon dioxide than can be used by the growers in greenhouses that are maintained at the ideal temperature using spare heat from the AD plant. In other words, if sizing a greenhouse to make use of the resources from an AD plant, it is the heat supply that defines the maximum size of the greenhouse.

Water and nutrients are available in abundance from AD plants, but growers have not expressed a wish to use these products.

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