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AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Tim Pratt
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Signature .... Date ....

Report authorised by:

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CONTENTS

GROWER SUMMARY

Headlines

- Natural gas combined heat and power (CHP) offers the cheapest source of CO_2 for greenhouses.
- Technology allowing CO_2 enrichment from biomass boilers is available now. The investment cost is likely to be significantly less than the £155 per tonne required to make it viable.

Background

Enhancing CO_2 levels is an important part of improving the growing environment for many crops. Most growers using the technique source CO_2 directly from the exhaust gas of their natural gas (NG) fired boiler. As NG burns cleanly and has low pollutant levels, the cost of doing this is low. CO_2 derived in this way is regarded as a 'free' by-product of NG boiler operation.

Two major things are affecting the status of CO_2 for this use. Firstly, the efficiency of energy use for heating is getting better. Thermal screens, better controls and better structures are reducing heating fuel use and this means there is less CO_2 available for enrichment. Secondly, there is likely to be a significant shift away from fossil fuel fired boilers as a result of Government subsidies for biomass systems. Because biomass boilers do not produce a clean exhaust gas, investment may be required in cleaning technology to enable CO_2 to be derived from this source.

Beyond the move to biomass, increasing global demand for fossil fuels and the prospect of carbon taxes are likely to push up gas costs, forcing growers to look at alternatives for heating and CO_2.

This project takes a broad look at the choices growers have if they wish to use CO_2 enrichment. As well as putting costs against conventional sources to provide a benchmark, the project looks at a wide range of alternative solutions, from boiler exhaust gas cleaning, to novel boiler design, gasification, fuel cells and even CO_2 extraction from the air.

Summary

Current sources and economics

At the moment growers don't often analyse the costs and benefits of CO_2 enrichment largely because CO_2 has been readily available as a 'free' by-product of heating. But as it becomes necessary to invest more in CO_2 enrichment and gas cleaning technology, understanding the value and costs of CO_2 and being able to compare costs of delivery systems becomes more important.

Understanding the true cost of CO_2 is not easy. It depends how it is valued against the heat and power which go hand in hand with its production. Clearly, if heat and power need to be generated and CO_2 is produced as a consequence, it effectively comes as 'free'. But if CO_2 is required when no heat is needed, then fuel cost for CO_2 production has to be apportioned to the CO_2 itself.

Similarly, when extra investment has to be made to allow, what would otherwise be unsuitable boilers, to deliver CO_2, then this capital has to be apportioned to the cost of CO_2 over an acceptable time.

The project has addressed these issues and produced some cost benchmarks to allow growers to gain a general idea of how much can be spent on CO_2 generation whilst working within the costs of a conventional system.

Table 1 below gives the most fundamental benchmark; that being the cost of CO_2 from burning gas where the heat from the process is not required in the greenhouse.

Table 1. Cost of CO_2 from NG boilers

Cost of natural gas		Cost of CO_2
Pence/therm	**Pence/kWh**	**£/tonne**
30	1.02	55.65
40	1.37	74.19
50	1.71	92.74
60	2.05	111.29
70	2.39	129.84
80	2.73	148.39
90	3.07	166.94

In terms of conventional fossil fuel combustion, the next step is to adopt combined heat and power (CHP) which has a higher capital cost, but a greater capacity to produce CO_2 (per unit heat required). The following graph relates CO_2 costs, to payback time on capital invested in CHP, and 'spark spread' – the difference between electricity cost and the gas required to generate it.

Figure 1. Cost of CO_2 from natural gas CHP

These figures, together with the raw energy costs for the generation of CO_2 set out in Table 1 give a set of benchmark costs against which other technologies can be compared.

Biomass boiler CO_2 economics

When considering biomass boilers it is possible, by starting with fuel cost savings, to state a notional saving per tonne of CO_2 produced and hence derive how much a grower could afford to spend on exhaust gas clean up whilst still producing CO_2 at a lower price than would be possible using gas.

Table 2. Biomass boiler CO_2 economics

Technology	Fuel cost per tonne of CO_2 minus RHI (where applicable)	Annual cost for 5 Ha greenhouse (1,780 tonnes of CO_2)	5 year saving over gas for 5 Ha site	Saving per tonne of CO_2 compared with gas
NG boiler	£111.29	£198,096	-	
Wood chip boiler	£24.91	£44,339	£768,765	£86.38
Straw boiler	-£43.85	-£78,053	£1,380,745	£155.14

Note. Straw is significantly cheaper than wood chip but only if it can be sourced close to the nursery.

So, a 5 Ha site with a straw boiler could afford to spend £1.38 m on gas clean up and still produce CO_2 as cheaply as burning gas (assumes five year payback). A further factor that has significant potential value is that you get at least twice as much CO_2 per MWh of heat from a biomass boiler than you do from a natural gas boiler i.e. similar to a conventional CHP installation.

How clean do CO_2 sources need to be?

This was investigated in detail in HDC Project PC 287 (2009) and identified NO_x, SO_x and ethylene as the main problem gases. Empirical relationships derived by PC 287 allowed a table of broadly ‘safe’ (economically tolerable) pollutant levels to be produced.

Table 3. ‘Safe’ concentration of pollutants in flue gas using volume ratio (CO_2:pollutant)

By volume	Threshold	CO_2 concentration	
		600 ppm	1,000 ppm
NO_x	250 ppb	2,000	3,809
	400 ppb	1,250	2,424
SO_x	100 ppb	5,000	10,000
	200 ppb	2,500	4,705
Ethylene	10 ppb	50,000	100,000
	20 ppb	25,000	47,058

By mass	Threshold	CO_2 concentration	
		600 ppm	1,000 ppm
NO_x	250 ppb	1,913	3,681
	400 ppb	1,193	2,301
SO_x	100 ppb	3,482	7,158
	200 ppb	1,741	3,221
Ethylene	10 ppb	80,526	161,052
	20 ppb	40,263	75,789

Note - these figures are approximations, given the accuracy of data available and assumptions made to convert them to a common format.

Current CO_2 enrichment requirements

To be able to specify / compare alternative CO_2 supplies it is useful to know:

- The design delivery rate tonnes/hour.
- The annual consumption tonnes/Ha.

Table 4 below details CO_2 delivery capacities currently found on UK nurseries.

Table 4. CO_2 delivery capacity

	m^3/hr/Ha of natural gas burnt	kg/hr/Ha of CO_2 delivered	tonnes/hour required by a 5 Ha nursery
NG boiler	100	209	1.0
	150	314	1.6
NG fuelled CHP	200	418	2.1
	250	523	2.6

HDC Project PC 265, (2007) determined a CO_2 use of 356 tonnes per Ha p.a. on a nursery where the CO_2 enrichment policy was to only derive CO_2 from the boiler when heat could either be usefully used or stored.

Potential sources of CO_2

Natural gas fuelled reciprocating engine CHP

This may not seem like an alternative source of CO_2 but few growers have a CHP installation. A new CHP installation can produce CO_2 at a relatively low cost per tonne. See Figure 1 above.

Biomass – combustion

Biomass combustion (wood chip and straw in particular) is becoming an important technology because of subsidies provided by the Renewable Heat Incentive. However, the flue gases are not clean enough to use for CO_2 enrichment without further treatment.

Investment in a high quality boiler/combustion system is vital to ensure the lowest possible pollutant levels in the first instance. This will reduce and possibly even eliminate the cost of any further treatment. Key design features are:

- Moving stepped grate – to deliver the most uniform combustion possible.
- Combustion air control – independent control of primary and secondary combustion.

- Well-designed combustion chamber – to ensure complete combustion of organic compounds.

Table 5. Biomass boiler: flue gas cleaning requirements

Particulates	A high standard of particulate removal is recommended. Bag or ceramic filters are best suited to this.
NO_x	A good quality wood chip boiler might deliver acceptable NO_x levels. A straw boiler will not. Ceramic filters impregnated with a selective catalytic reduction catalyst are a possible solution.
SO_x	SO_x removal is advisable. Dry scrubbing with sodium bicarbonate is possible.
Ethylene	The worst case ethylene concentration is borderline acceptable so should be checked.
Tars & other volatile compounds	Detailed flue gas analysis is required to determine if these are likely to be a problem. A flue gas condenser may provide sufficient removal.

Biomass – anaerobic digestion

The greatest problem with anaerobic digestion (AD) is the presence of hydrogen sulphide in the digester gas which leads to SO_x in the CHP engine flue gas. This significantly reduces the lifetime of selective catalytic reduction (SCR) NO_x removal equipment. The removal of SO_x using dry scrubbing techniques combined with a catalyst for NO_x removal seems possible. AD plants are not likely to become popular for greenhouses because of feedstock demands and digestate disposal issues.

Biomass – gasification

Gasification converts dry biomass into a combustible gas using heat in a low oxygen environment. The gas is partially cleaned and then burnt in a reciprocating engine CHP installation. This has similar pollutant removal issues (and solutions) to combustion and AD. Gasifiers of an appropriate scale are increasingly common in India and China. However, few are found in Europe. CO_2 enrichment aside, growers considering this option should include performance guarantees with associated penalties in any equipment supply contract.

Fresh air

Trials have demonstrated a small but practical wet scrubbing and heat driven regeneration concept which could be scaled up for horticulture. The inferred running cost (pumping and air compression) was £18.99 per tonne of CO_2. This excludes heat for regeneration which is expected to be low.

Gas cleaning technology

Particulates. A high level of particulate removal is recommended in all situations. In addition to removing some pollutants it also increases the lifetime/reduces the cost of many follow-on gas cleaning technologies.

Bag and ceramic filters offer the best potential for horticultural applications, especially biomass boilers. The ability to combine SCR NO_x removal with ceramic filters is particularly interesting.

NO_x and SO_x. The amount of NO_x and SO_x are largely determined by the amount of sulphur in the fuel. Subject to cost, low sulphur fuels should be the first step in any NO_x / SO_x reduction process. Straw contains much more nitrogen and sulphur than wood chip so the flue gases require more treatment to enable CO_2 enrichment.

SO_x can be removed by dry scrubbing using calcium hydroxide or sodium bicarbonate. NO_x can be removed by selective non catalytic reduction (SNCR) with ammonia. However, this requires a gas temperature of 850-1,000 °C (140 °C from a biomass boiler). Selective catalytic reduction (SCR), as used in conventional CHP installations, works best at around 400 °C. Conventional SCR material is easily 'poisoned' by SO_x and some other chemicals. However, the development of catalyst impregnated ceramic filters appears to have solved this problem and they claim to work at 250 °C.

The remaining issue is that flue gases from a biomass boiler are not hot enough to work with SCR. However, modifying the boiler or even re-heating the flue gases seems a viable solution.

All the technologies reviewed are:

- Available commercially.
- Proven in various applications and industries.
- Some are already proven in horticulture, albeit not specifically for CO_2 enrichment from biomass in particular.

The level of technical risk associated with these technologies, if correctly applied, should therefore be low. We have been unable to source indicative costs, for all of these technologies.

Carbon capture and storage (CCS)

CCS is subject to massive research and development investment to help decarbonise the power generation industry.

There are three main carbon capture technologies:

1. Absorption.
2. Adsorption.
3. Membrane separation.

Adsorption is closest to commercial application. CO_2 is absorbed by a solvent, typically an amine solution, and is then released by heating the solvent to around 140 °C. The solvents in question are not 100 % CO_2 selective, so some pollutants are absorbed as well. However, research suggests that they can be separated by ‘boiling them off’ at different temperatures.

Financial benefits

As this project was only intended to provide a broad overview of technologies, specific financial guidance is not provided.

However, in the “Current Sources” section of the grower summary the investment case for a natural gas fuelled reciprocating engine CHP installation is made. At a very competitive CO_2 cost of £30 per tonne a CHP installation will give a payback on investment within five years.

The financial case for investment in gas cleaning technology for a biomass boiler is much less certain. However, based on a five year payback our ‘typical’ 5 Ha nursery could afford to spend up to £1.4 m on capital and running costs to achieve this with a straw fuelled boiler. Ballpark capital costs provided by one equipment supplier to remove SO_x and NO_x using catalyst impregnated ceramic filters was £500 k. This provides sufficient room for on-going running costs and higher capital costs to remain interesting.

Extracting CO_2 from fresh air may be financially viable. A greenhouse scale system might cost upwards of £250 k and incur variable costs of £30 per tonne. This adds up to £517 k over five years for our 5 Ha nursery. So again, this leaves sufficient room for higher capital and running costs to remain interesting.

Action points

Key points for growers:

- Try to gain a greater understanding of true CO_2 generation costs and also the value derived from CO_2. This will help in the future when assessing capital investments on CO_2 enrichment and cleaning technology.
- Have a close look at natural gas (NG) driven combined heat and power (CHP) plant economics in tandem with the benefits of the extra CO_2 that can be derived.
- If a move towards biomass boilers is intended don't forget to consider the suitability of the plant for CO_2 enrichment. Ensuring the cleanest possible flue gas at this stage will reduce the cost of cleaning equipment in the future.
- Obtain flue gas analysis for plant using the same fuels you will be using and assess the minimum amount of gas treatment you'll need to do to make CO_2 extraction possible.
- With biomass boilers, consider using a cleaner fuel during the CO_2 production season to avoid or minimise the need for flue gas cleaning equipment.
- Keep an open mind to novel technologies. Interesting developments are taking place in combustion design, alternative fuels, gas cleaning and even CO_2 extraction. It's a fast changing area of technology - so keep up to date.

Further work

CO_2 from fresh air shows significant potential as a novel technology. The capital and running costs of a greenhouse scale installation should be explored in detail.

Biomass boilers will become a mainstream heat source in the near future. Comprehensive flue gas analysis should be carried out on commercially operated biomass boilers in the UK.

Detailed specifications and costs should be obtained from flue gas cleaning equipment suppliers. This will provide growers with greater certainty over likely costs and performance.

The economically optimum rate of CO_2 delivery. Growers lack readily interpreted information that allows accurate decisions to be taken. This is an issue with current CO_2 sources but even more so with alternative sources as it could have a significant impact on the capital investment required. As this is such a complex subject and it did not fall within the scope of this project means it is difficult to make specific recommendations as to how this might be addressed. However, it is clear that further work is required.

SCIENCE SECTION

Introduction

It is widely acknowledged that CO_2 enrichment delivers significant yield increases for many different crops and its use has become widespread, especially in protected vegetable production. For most users, CO_2 has been available as a by-product from their heating system. It has been effectively free; as a component of the flue gas from Natural Gas (NG) boilers. Even when gas was burnt solely for CO_2 production, low energy prices kept costs low.

More recently there has been significant financial, legislative and consumer pressure to reduce the amount of fossil fuel energy used in all aspects of life. The protected glasshouse industry has responded by introducing energy saving techniques such as thermal screens and optimised greenhouse climate control. They are also using more renewable energy sources in response to financial incentives which are lowering the effective price of biofuels and low carbon technologies.

All this means that ‘free’ CO_2 for glasshouse enrichment is not as abundant as it once was. It seems likely that as time goes on, it will become expensive to source. Growers must now contemplate burning natural gas for the sole purpose of CO_2 production or adopting techniques which can produce CO_2 in different ways. The costs are significant; NG burning for example can easily account for 100 kWh per m^2 energy use costing around £18,000 per ha. Biomass boilers are another potential source of CO_2. But the presence of pollutants stop the simple direct use of the exhaust gases and expensive and innovative gas cleaning technologies have to be applied to make this work.

HDC recognise the challenges that the de-carbonisation of protected crop production poses to the availability of cheap CO_2. Consequently this project was commissioned to examine some of the options available to growers now and in the future.

The project aims are to:

- Help in the progression towards alternative energy sources by exploring the changing economic and technical barriers imposed by the need to have a viable system to deliver CO_2.
- Identify alternative CO_2 supply options for use in protected horticulture in the UK.
- Provide growers with clear guidance on any further work required (if necessary) to deliver commercially proven and financially viable alternative CO_2 supplies.

The specific objectives were:

- Identify gas cleaning technologies which will enable alternative fuel systems to provide CO_2 from exhaust gas, with specific emphasis on wood fuelled combustion.
- Assess these technologies in terms of their effectiveness in removing pollutants which could affect plant growth or human health.
- Quantify, wherever possible, the likely capital and running cost of these systems and their impact on the viability of alternative heat sources.
- Provide guidance on the most promising technologies and the steps required (if any) to allow them to be adopted by growers.

Materials and methods

We have carried out this study as a desk based project with information based on:

- Information available largely in the public domain.
- Information provided by equipment suppliers.
- Analysis and projection of costs based on best available information on costs of CO_2, energy and equipment.

Current CO_2 enrichment practice and costs

In determining the suitability and the economic viability of a CO_2 delivery system it is important to have a starting position against which an alternative can be compared.

This section of the report sets some benchmarks based on current practice giving:

- A technical specification that any alternative system must satisfy.
- A current cost of CO_2 against which any alternative can be compared.

Where does CO_2 come from now?

At the moment CO_2 comes from one of three major sources:

1. **Flue gases from natural gas fuelled boilers** – uncleaned flue gas is piped into the greenhouse.
2. **Flue gases from natural gas fuelled combined heat and power (CHP)** - cleaned exhaust gas from the CHP engine is piped into the greenhouse.

3. **Pure (liquid) CO_2** – CO_2 is vapourised from tank stored liquid and piped into the greenhouse.

Most growers use either method 1 or 2.

Growers are concerned about three main issues relating to CO_2. These are:

1. Permissible concentration of pollutants that might affect plants. Clearly, where CO_2 is supplied as a by-product of combustion, then various levels of undesirable gases and particulates are produced, depending on the fuel and combustion process used.
2. Maximum CO_2 delivery rate. This determines the size of delivery plant needed.
3. Total amount of CO_2 required per annum. This will affect production costs whether it be fuel burned or CO_2 purchased.

How much pollutant can be tolerated?

Pollutants present in flue gases from the combustion of natural gas which are known to affect plants are oxides of nitrogen and sulphur and ethylene. Research to date has focussed on these compounds because they are present in the current CO_2 sources. Very little information is available about the effect of other compounds as, up until now, they have not been present in any CO_2 sources.

Table 6 below (PC 287, 2009) suggests maximum tolerable levels. Although this data is for tomato, it can be considered as reasonably representative for other crops which require CO_2 enrichment.

Table 6. Allowable pollutant concentration

Pollutant	Level harmful to tomato plants	Suggested 'safe' concentration
NO_x (NO, NO_2, NO_3)	250 ppb may reduce growth and yield.	Aim for less than 250 ppb. 400 ppb often tolerated.
Ethylene (C_2H_4)	50 ppb may reduce fruit set in some cultivars.	Aim for less than 10 ppb.
Sulphur dioxide (SO, SO_2)	Levels suggested vary from 100 ppb to 500 ppb.	Aim for less than 100 ppb. 200 ppb often tolerated.

In the case of ethylene, the safe figure is set well below the threshold figures as the effect on fruit set and flowering is very dramatic and comes on quickly beyond this level. Given that actual CO_2 and hence pollutant concentrations can oscillate quite significantly from the set point, a safe level well below the threshold is recommended. Having determined safe concentration levels for the greenhouse, it is necessary to translate these into equivalent safe levels in the flue gas. As the flue gas is substantially diluted within the greenhouse, the pollutants are also diluted. The relationship between greenhouse pollutant concentration and flue gas pollutant concentration is complex and dependent on the leakage of greenhouse and the level of CO_2 required.

We can draw empirical relationships between the concentration of CO_2 and pollutants in the greenhouse and their concentration in the flue gas. The relationships are described in PC 287. The project included short-term monitoring of the NO_x concentration within greenhouses alongside the composition of undiluted flue gases from a natural gas boiler.

Figure 2 below shows the relationship between NO_x concentration in the undiluted flue gases from a natural gas fuelled boiler (8 % CO_2) and the required greenhouse CO_2 concentration. The two lines are for a greenhouse NO_x threshold value of 250 ppb and 400 ppb.

So, for example, if a threshold of 250 ppb is chosen and 1,000 ppm of CO_2 is required in the greenhouse, there can be no more than 21 ppm of NO_x in the flue gases. PC 287 showed that this was regularly exceeded on commercial nurseries (400 ppb of NO_x was often recorded). The easiest solution is to set a lower target CO_2 level which will automatically reduce the NO_x. However, many growers believe that the negative effect of higher NO_x is more than compensated for by the benefit of higher CO_2 levels.

Note - that this relationship is also dependent on the concentration of CO_2 in the undiluted flue gas. So if the CO_2 concentration in the flue gas was halved (4 %) the 'safe' concentration of NO_x would also halve (10.5 ppm).

Similar relationships were also derived for SO_x and ethylene.

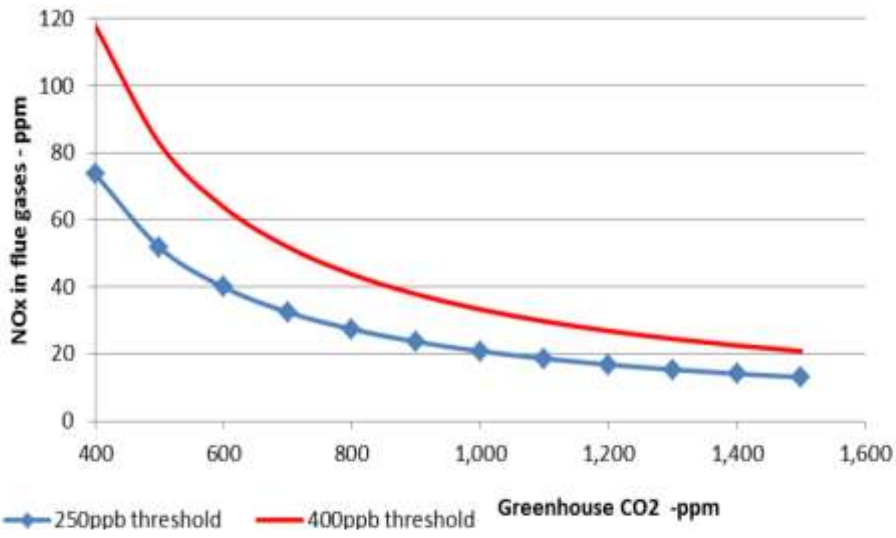


Figure 2. Relationship between NO_X (ppb) and CO_2 (%) and NO_x (ppm) in undiluted flue gases

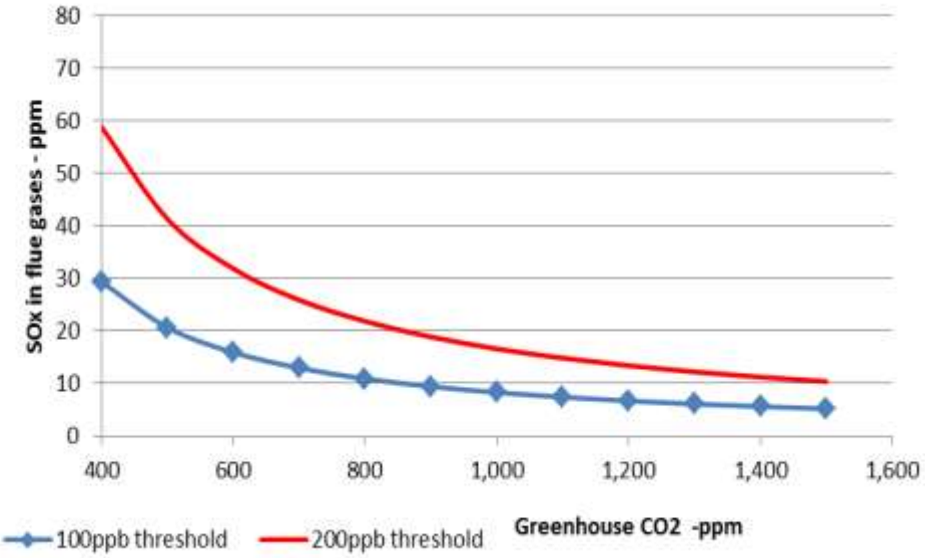


Figure 3. Relationship between SO_X (ppb) and CO_2 (%) and SOx (ppm) in undiluted flue gases

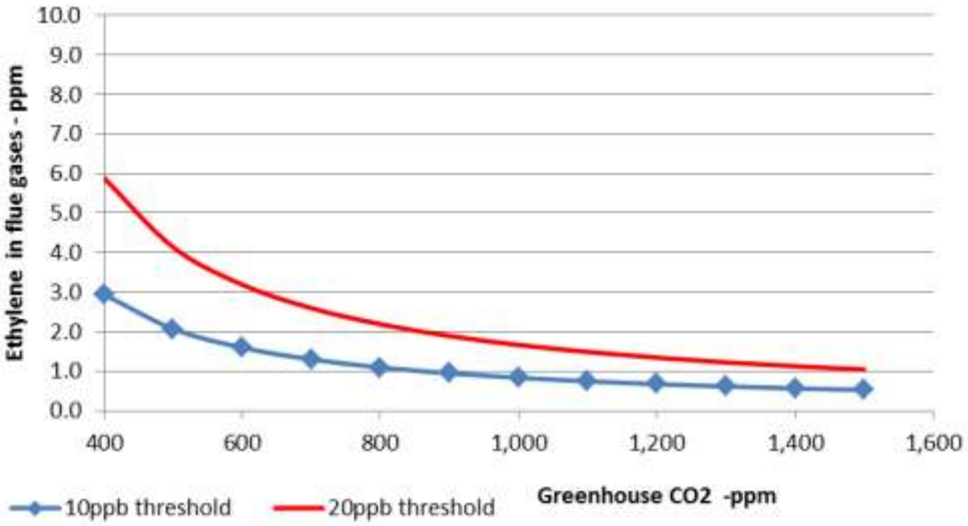


Figure 4. Relationship between ethylene (ppb) and CO_2 (%) and ethylene (ppm) in undiluted flue gases

Using the relationship from the graphs, Table 7 overleaf shows acceptable exhaust gas pollutant concentrations for two levels of greenhouse CO_2 and two levels of greenhouse gas pollution.

Table 7. 'Safe' concentration of pollutants in flue gas using volume (8 % CO_2 source)

	Threshold	CO_2 concentration	
		600 ppm	**1,000 ppm**
NO_x	250 ppb	40	21
	400 ppb	64	33
SO_x	100 ppb	16	8
	200 ppb	32	17
Ethylene	10 ppb	1.6	0.8
	20 ppb	3.2	1.7

The greenhouse CO_2 levels of 600 ppm and 1,000 ppm have been selected as representative of what might be typically used. The 600 ppm level is what might be achieved in the summer months when vents are open. The 1,000 ppm is a typical target figure for colder periods when ventilation is restricted.

The two greenhouse pollutant levels represent best practice (lowest figure) and levels that have been measured in commercial greenhouses. This data can also be expressed in terms of the volumetric ratio of pollutant to CO_2 concentration. This is more useful when considering exhaust gas sources which have varying concentrations of CO_2.

Table 8. 'Safe' concentration of pollutants in flue gas using volume ratio (pollutant: CO_2)

	Threshold	CO_2 concentration	
		600 ppm	**1,000 ppm**
NO_x	250 ppb	2,000	3,809
	400 ppb	1,250	2,424
SO_x	100 ppb	5,000	10,000
	200 ppb	2,500	4,705
Ethylene	10 ppb	50,000	100,000
	20 ppb	25,000	47,058

A third way to express the acceptable concentrations is as a mass ratio. This can be useful as it is common for the emission of pollutants in flue gas to be measured as a mass (mg/m^3). It can therefore be useful to consider the mass ratio of CO_2 to pollutants. You should note that this relationship varies with temperature so may need slight adjustment if temperatures are different from the datum.

Table 9. ‘Safe’ concentration of pollutants in flue gas using mass ratio (pollutant: CO_2)

	Threshold	CO_2 concentration	
		600 ppm	1,000 ppm
NO_x	250 ppb	1,913	3,681
	400 ppb	1,193	2,301
SO_x	100 ppb	3,482	7,158
	200 ppb	1,741	3,221
Ethylene	10 ppb	80,526	161,052
	20 ppb	40,263	75,789

Reference flue gas datum: 60 °C, 8 % CO_2 by volume (containing 129 g of CO_2)

What is the required CO_2 delivery rate?

There is considerable on-going debate about the economically optimum rate of CO_2 delivery. This has become increasingly relevant / important with on the vine tomatoes where an ‘overweight’ truss is worth no more than a ‘to specification’ truss. In addition, during the summer when the CO_2 supply capacity is ‘never enough’ the price for tomatoes, cucumbers etc. is often low. The answer to this question clearly has a significant impact on the cost and viability of alternative CO_2 supplies. It is beyond the scope of this project to explore this. Therefore table 10 below lists typical CO_2 delivery rates currently used on commercial nurseries.

The amount of gas (m^3) burnt per hour per hectare is often used by UK growers as it relates directly to their main source of CO_2 – that being from burning gas in a boiler. When assessing other CO_2 sources, this is not a particularly useful measure; kilograms of CO_2 per hour per hectare is a better measure.

The table also includes a figure for the amount of CO_2 required by a 5 Ha nursery.

Table 10. CO_2 delivery capacity

	m^3/hr/Ha of natural gas burnt	kg/hr/Ha of CO_2 delivered	tonnes/hour required by a 5 Ha nursery
NG boiler	100	209	1.0
	150	314	1.6
NG fuelled CHP	200	418	2.1
	250	523	2.6

The CO_2 delivery rate is higher for CHP installations than for a boiler because it consumes more gas per unit of heat delivered.

How much CO_2 is used per year?

Use varies with the characteristics of the crop, the heating and ventilation strategy and the availability of heat dump facilities. For a typical nursery, CO_2 demand is low in the winter because the ventilation rate is low and the internal atmosphere can be conserved. Demand rises in summer mainly because of the increased ventilation rate causing a constant demand on the CO_2 enrichment system.

Figure 5 below shows the amount of CO_2 used in tonnes per hectare per week on a typical nursery (PC 265, 2007). CO_2 enrichment policy on this site was to only derive CO_2 from the boiler when heat could either by usefully used or stored. The CO_2 used was 356 tonnes per Ha p.a.

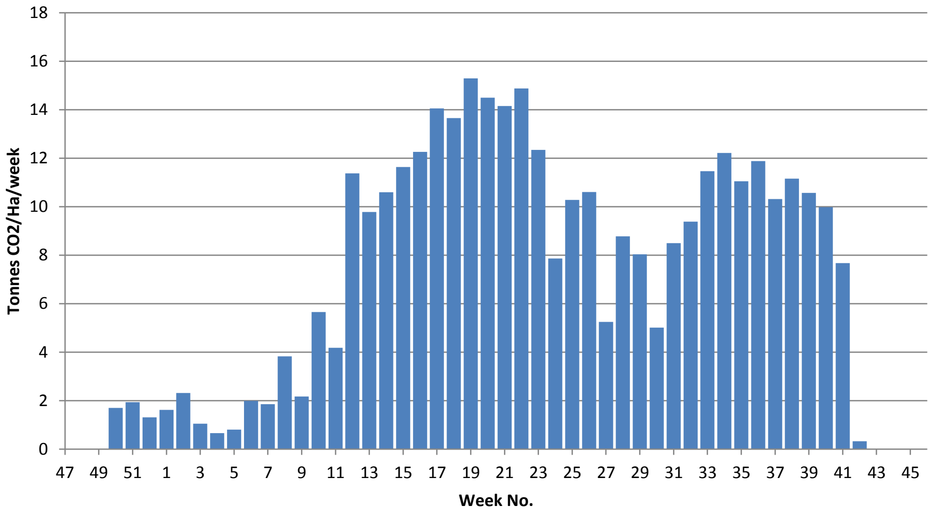


Figure 5. Weekly CO_2 usage

Diurnal supply and demand for CO_2 and heat storage

The diurnal demand for CO_2 is opposite to that of heating. That is, heat is required at night and CO_2 during the day. Since most CO_2 is a by-product of the glasshouse heating process this means that supply and demand for CO_2 are not ideally matched. In the absence of other strategies, growers are faced with throwing away exhaust gas CO_2 during the night, when high heating demands are high, and ventilating to dump the heat which is generated as a result of the production of CO_2 in the day.

Growers with low pressure hot water based heating systems cope with this in part by using heat storage. The heat generated in the production of the CO_2 during the day can be stored for use at night.

Basic heat store design parameters are:

- Volume - 150-200 m^3/Ha.
- Working temperature range – 45 °C to 90 °C.

Sources and costs of CO_2

Natural gas (NG) boiler

The clean burning characteristics of natural gas make the exhaust gas suitable for direct use in the greenhouse. Where all the heat produced is used to maintain temperature and give humidity control it is reasonable to say that the fuel cost of CO_2 production is effectively zero.

In reality, growers tend to use more heat than is strictly necessary for temperature and humidity control alone. This constitutes a cost which can be attributable to CO_2 enrichment. Table 11 below lists the cost of CO_2 when heat is destroyed for a range of gas prices.

Table 11. Cost of CO_2 from NG boilers

Cost of natural gas		**Cost of CO_2**
Pence/therm	**Pence/kWh**	**£/tonne**
30	1.02	55.65
40	1.37	74.19
50	1.71	92.74
60	2.05	111.29
70	2.39	129.84
80	2.73	148.39
90	3.07	166.94

Some useful figures:

- To produce 1 tonne of CO_2 you need to burn 5,435 kWh of NG.
- The amount of heat produced by a boiler (85 % efficient) alongside 1 tonne of CO_2 is 4,619 kWh.

Natural gas combined heat and power (CHP)

CHP uses gas to drive an engine and an electrical generator. A by-product of this is heat that can be used in the greenhouse. After the removal of pollutants CO_2 can be derived from the exhaust gases of the engine.

The advantage of CHP with regard to CO_2 enrichment is that it produces more exhaust gas per unit of heat delivered than a boiler. This is because 35-40 % of the energy content of the gas burnt is exported from the site as electricity. The need to 'dump' heat is therefore reduced and the production potential of 'free' CO_2 is enhanced.

Key figures:

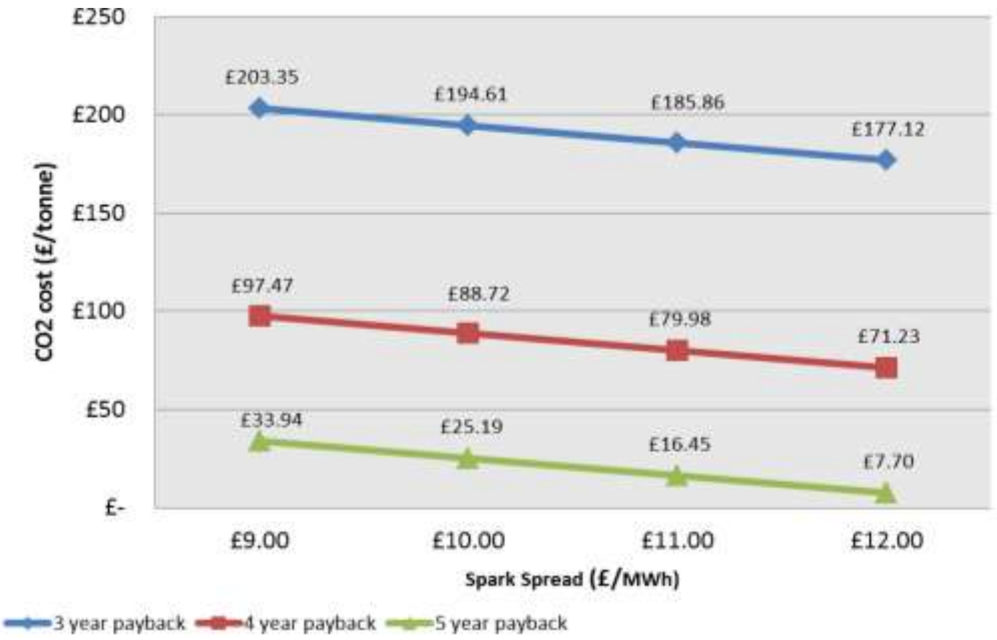
- Electrical efficiency of a modern reciprocating engine CHP installation – 41 %.
- Heat efficiency of a modern reciprocating engine CHP installation – 45 %.
- To produce 1 tonne of CO_2 you need to burn 5,435 kWh of NG.
- The amount of heat produced by a modern CHP alongside 1 tonne of CO_2 is 2,446 kWh.

The economics of operating an NG fuelled CHP installation are complex as it is necessary to take into account the cost of electricity and gas, and the value of heat and CO_2. Figure 6 provides a simple overview of the investment case for a new CHP installation.

Values are calculated on the basis of a CHP installation that replaces the operation of a conventional boiler. Figure 6 shows the implied cost of CO_2 assuming an investor in CHP requires a given payback period. The graph uses the concept of Spark Spread which is a commonly used measure indicating the gross margin from the generation of electricity from gas. It is the difference between the wholesale value of electricity and the cost of gas used to generate it for generation plant of 49 % efficiency.

Table 11. CHP assumptions

CHP installation (inc. flue gas cleaning)	£1,600,000
Grid connection cost	£500,000
Total capital cost of CHP installation	£2,100,000
Electrical efficiency	41 %
Heat efficiency	45 %
Gas consumption rate	8.0 MW
Electricity generation rate	3.3 MW
Heat production rate	3.6 MW
CO_2 production rate	1.5 t/hr
Alternative boiler parameters	
Boiler efficiency	85 %
MWh of gas required to produce 1 MWh of heat	1.18
Fuel	
Gas cost	60 p/therm
- or	£20.48 per MWh
CHP operating regime	
Operating hours (12 hours/day, every day)	4,380 hours p.a.
Electricity produced	14,454 MWh
Heat produced	15,864 MWh
Gas consumed	35,254 MWh
Extra CO_2 used/available	
Hours p.a. when CO_2 is useful (6 months p.a., 12 hours/day)	2,232
Extra CO_2 supplied compared to a boiler	1,653 tonnes p.a.



Note – the economics of an older CHP installation is notably different as the efficiencies of plant and operation/maintenance costs have improved.

Figure 6. Cost of CO_2 from natural gas CHP

Economies of scale mean that our ‘typical’ 5Ha nursery would opt for a reciprocating engine based CHP installation. Micro-turbine CHP (circa 100kW per unit) is used successfully on several UK nurseries and the flue gases do not require any cleaning prior to being used for CO_2 enrichment. These may be an alternative for smaller nurseries.

Pure CO_2

Pure (liquid) CO_2 is rarely used on nurseries as it tends to be more expensive than CO_2 derived from burning NG in a boiler, even when the heat is deemed as having no value – i.e. is effectively thrown away. It is however a proven source with no pollutant issues.

The cost of pure CO_2 comprises:

- Cost of the CO_2 itself – typically £100-£120 per tonne.
- Heat required to vaporize it – £3.28 per tonne (160 kWh/t, using gas at 60 p/therm).
- Tank rental/maintenance - £5,000 p.a.

If we assume that the 5 Ha nursery described earlier used pure CO_2 for all its annual requirement it would need 1,780 tonnes of CO_2. The total cost would be £106 - £126 per tonne.

The Renewable Heat Incentive and its impact on heat/CO_2 economics

The Renewable Heat Incentive (RHI) is a Government financial incentive for users of renewable heat. It is being introduced in late September 2011 for business customers and will pay a tariff per kWh of renewable heat used. The tariff rate depends on the technology used (biomass boiler, heat pumps etc.) and the maximum heat output of the installation. As a result of this scheme the investment case for a biomass boiler to satisfy winter heat demand is looking good at the moment. This has been investigated in a previous HDC project (PC 265, 2007) and more recently through workshops funded by Carbon Trust (presentations and economics calculators available from www.growsave.co.uk).

The untreated flue gases from a biomass boiler are not clean enough to use for CO_2 enrichment. The current assumption in most feasibility studies is that the biomass boiler will be turned off from mid-April to mid-October. The nursery’s existing NG boiler will be used to satisfy the CO_2 and heat demand during the summer months.

Table 12 below presents the variable costs of operating a biomass boiler on the assumption that CO_2 continues to be supplied by a NG boiler on a:

- 5 Ha nursery using 500 kWh/m^2 of heat.
- Using 356 tonnes per Ha p.a. of CO_2.

Table 12. Nursery heat demand

Nursery heat demand	
5 Ha x 500 kWh/m^2	25,000 MWh/a
Heat required for temperature support	16,777 MWh/a
Additional heat produced as a by-product of CO_2 enrichment	8,223 MWh/a
Cost if all heating is from a natural gas boiler	£602,289

Table 13. Natural gas boiler characteristics

Natural gas fuelled boiler characteristics	
Efficiency	85 %
Cost of gas - p/therm	60
Cost of gas - £/MWh	£20.48
MWh of gas required per 1 MWh of heat	1.18
Cost of 1 MWh of heat	£24.09
Amount of CO_2 produced per MWh of heat - tonnes	0.22
Cost of 1 tonne of CO_2 if the heat has no value	£111.29
Amount of CO_2 required for a 5 Ha nursery (5 Ha x 356 t/Ha)	1,780

Table 14. Biomass boiler economics

Biomass boiler	**Wood chip**	**Straw**
Capital (5 MW boiler + ancillaries)	£1,500,000	£1,500,000
Efficiency	85 %	85 %
Cost of 35 % m.c. wood chip / straw (£/t)	£80.00	£50.00
Energy content MWh/t	3.19	4.10
Fuel required per 1 MWh of heat – tonnes	0.37	0.29
Cost of fuel to produce 1 MWh of heat	£29.48	£14.35
Boiler operation & maintenance costs per MWh of heat	£3.00	£3.00
RHI income per MWh	£27.00	£27.00
Net cost of heat	£5.48	-£9.65
Total fuel costs		
Cost of gas use associated with CO_2 production (assuming gas boiler used)	£198,101	£198,101
Cost of biomass heat (no CO_2 available)	£91,876	-£161,947
Total nursery energy cost with biomass	£289,977	£36,154
Total fuel cost if all heat from a natural gas boiler	£602,289	£602,289
Net energy cost saving with biomass	£312,312	£566,135
Simple payback with no CO_2 from biomass	**4.80**	**2.65**

If an NG boiler is being used to produce CO_2 with no demand for heat (i.e. all heat wasted), then the marginal costs of the supply of 1 tonne of CO_2 is £111.29 per tonne. This cost figure is the starting point from which one can consider how much a grower could contemplate investing in cleaning up flue gases from a biomass boiler.

If we assume that renewable boilers have the same potential CO_2 yield per unit of heat produced as gas, then the fuel costs of CO_2 production are as follows:

Table 15. Biomass boiler CO_2 economics

Technology	**Fuel cost per tonne of CO_2 minus RHI (where applicable)**	**Annual cost for 5 Ha greenhouse (1,780 tonnes of CO_2)**	**5 year saving over gas for 5 Ha site**	**Saving per tonne of $C0_2$ compared with gas**
NG boiler	£111.29	£198,096	-	
Wood chip boiler	£24.91	£44,339	£768,765	£86.38
Straw boiler	-£43.85	-£78,053	£1,380,745	£155.14

Using a notional required payback of five years, the penultimate column in the table shows what a grower could afford to pay in capital and variable costs (other than for fuel) to convert and run a biomass boiler based CO_2 delivery system. The final column expresses this in pounds sterling per tonne of CO_2 delivered and could be used as a benchmark against which alternative source costs can be compared. For example a site using a straw boiler could afford to pay up to £155.14 per tonne for pure CO_2.

Potential alternative sources of CO_2

There are a host of potential alternative technologies for sourcing CO_2. Some are based on the treatment of existing flue gases to make them suitable for use; others are based on independent sources of CO_2.

The following sections look at each potential source and discuss:

- The source/process involved.
- Amount of CO_2 produced.
- Pollutants present.
- Any horticultural experience.
- Future developments.

- Gas cleaning requirements.

Alternative fossil fuel based sources

We already use natural gas and kerosene to produce CO_2. However, other fuels and/or alternative methods of releasing CO_2 from fossil fuels may be viable. As well as producing clean and useable CO_2 any proposed system needs to convert as much of the energy released into a form that can be exported/sold from the nursery. This is effectively what a traditional NG fuelled CHP installation does.

Two approaches have the technical potential to be applicable:

1. Steam methane reforming.
2. Fuel cells.

Steam methane reforming (SMR)

How does it work? - A processing device called a reformer reacts steam at high temperature with the fossil fuel to produce hydrogen, carbon monoxide and CO_2.

There are two main parts to the process:

1. Reformation of natural gas – methane is reacted with steam at 750-800 °C to produce a syngas. The syngas is primarily a mixture of hydrogen and carbon monoxide.

2. Shift reaction – the carbon monoxide is reacted with steam over a catalyst in two stages (one at circa 350 °C , the second at circa. 200 °C) to produce hydrogen and CO_2.

The CO_2 is removed from the final mixture using either liquid absorption or pressure swing absorption (covered in the section on flue gas cleaning).

Technically, SMR appears suitable for greenhouse CO_2 enrichment especially as the CO_2 stream is expected to contain very low levels of pollutants. However, the greatest difficulty with this technology is the lack of an established market for hydrogen.

Hydrogen is viewed by some as a fuel of the future and significant research and development (R&D) is being carried out. The development of small-scale SMR plants may enable the development of small-scale distributed hydrogen production and delivery infrastructure.

Is it viable? – Not yet. At best, this technology is one to watch in the future; perhaps 10 years from now. The greatest potential for the adoption of this technology in horticulture lies in locating a greenhouse next to an SMR plant.

Fuel cells

How does it work? - A fuel cell (FC) is an electrochemical cell that converts chemical energy into electrical energy. Electricity is generated from the reaction between a fuel supply and an oxidizing agent and CO_2 is produced as a by-product.

Fuels cells are like batteries but are fed by a constant supply of ‘fuel’ and they also produce heat. In a greenhouse application they can be thought of as CHP installations. The most significant differences between a FC and NG fuelled reciprocating engine CHP installation are:

- A fuel cell has very few moving parts and therefore low maintenance costs.
- The exhaust gas contains only low levels of pollutant so no cleaning is required before use in a greenhouse.

  FC development is focusing on using fuels derived from renewable resources such as bio-ethanol or hydrogen. However, they can also use natural gas and this is considered to be the first route to market by many FC manufacturers.

  The largest commercially available natural gas fuelled FC identified is the PureCell 400 manufactured by UTC Power. Key performance data are:

- Electrical efficiency 38 %.
- Thermal efficiency 52 %.
- CO_2 emissions of 500 kg/$MWh_{e.}$
- NO_x emissions of 9 g/$MWh_{e.}$

The electrical efficiency is similar to a conventional CHP whilst the heat efficiency is slightly better. NO_x levels are however much lower with a ratio of NO_x to CO_2 15 times lower than with a CHP installation.

Is it viable? - Fuel cells do not currently offer a financially viable source of CO2 for greenhouses but their development should continue to be monitored.

A budget installed cost for a suitable system is in the order of £600 k (£1,500 per kW). This compares with around £600 per kW for a reciprocating engine based CHP. Even if a FC had no operating and maintenance costs at all the higher capital cost remains a significant barrier.

As with many of the technologies being considered in this report FCs are attracting significant R&D funding. To give an indication of the targets/aspirations in this area, the United States Department of Energy has a capital cost target of £420 per kW (excluding installation) whilst improving the electrical efficiency to 50 %. If this can be achieved FCs will have significant potential for greenhouse applications.

Waste from other industries

CO_2 is a by-product of many industrial processes and it is potentially attractive to use this, especially where waste heat is also available. (Cornerways Nursery in Norfolk and the John Baarda Ltd Nursery in Teeside are examples of businesses using industrially derived CO_2).

To date the search for suitable sites has focused on finding a suitable source of heat first with the CO_2 supply being a secondary - but still important criteria.

In many cases sites are not suitable because either:

- There is not enough heat and/or the heating water temperature is too low to use in a greenhouse,

  or

- The source of CO_2 is too ‘dirty’.

The first issue was addressed to a large extent in PC 278 which showed that a heating water supply of only 50 °C can satisfy the year round heat demand of a nursery fitted with the correct heating infra-structure.

The pollutant problem is very much site/process specific. It is not possible therefore to give general guidance in this area. The section covering gas cleaning technologies discusses specific pollutants in more detail. The removal of CO_2 (leaving pollutants behind) is also considered.

Extraction from air

Perhaps the holy grail of CO_2 enrichment is a cost effective means of extracting CO_2 from the air around us. With CO_2 present at only 400 ppm in air, the cost of extracting CO_2 is likely to be high. Pollutant content is not an issue however.

CO_2 extraction technologies are discussed in more detail in the flue gas cleaning section. One particular technique using wet scrubbing has undergone laboratory scale trials with air as the source of CO_2.

The following data presents the results of laboratory scale trials carried out by WRK Design and Services Ltd (Raymahasay, 2010). In brief the system works by:

- Entraining air in a Venturi, mixing it with a solution of sea salt and water.
- The mixture is passed through the absorption tower.
- CO_2 is released from the salt solution by heating it to around 50 °C.

Energy used for salt solution pumping and compressed air supply was 211 kWh/t of CO_2 extracted which, at an electricity cost of 9 p/kWh, is £18.99 per tonne. The cost of heating the solution to extract the CO_2 needs to be added. However, it should be possible to recover much of this heat used in this process so the cost per tonne of CO_2 should be low.

Is it viable? - With apparently low operational costs compared to the threshold prices for CO_2 (£111 for NG with no heat use) and with no pollutant problems, extracting CO_2 from air using this approach appears to have significant potential and should be investigated.

To our knowledge this technique has not been tested in a greenhouse application.

CO_2 from biomass fuel

Biomass can be generally defined as:

> "Biological material derived from living, or recently living organisms."

For the purposes of greenhouse heating we are mostly concerned with plant or vegetable material.

The primary use of biomass is mainly for heating and/or electricity generation.

Biomass fuels are often considered in two categories:

1. Wet biomass – suitable for anaerobic digestion. Here a gas is produced for combustion in a boiler or engine.
2. Dry biomass – material is either burnt or processed to produce a gas/liquid (gasification or pyrolysis).

Wet biomass - anaerobic digestion (AD)

Here, biomass is ‘fermented’ in an oxygen free tank. The raw biogas produced is typically 60 % methane and 40 % CO_2. Hydrogen sulphide (H_2S) is also present at levels ranging from 0.5-5.0 % depending on the feedstock.

Biogas is most often used in a reciprocating engine CHP installation to generate electricity. The majority of the CO_2 and H_2S is removed from the raw biogas to optimise engine efficiency and lifetime. More recently, cleaning/upgrading the biogas to allow injection into the gas grid is being considered.

CO_2 can be derived from AD in 2 ways:

1. CO_2 produced by fermentation.
2. CO_2 from the CHP flue gases

To give an indication of the potential impact of AD from a CO_2 enrichment perspective, the data in Table 16 is based on a 250 kW_e AD plant.

Table 16. 250 kW_e AD plant – typical data

Raw biogas data			
Calorific value	24.1 MJ/m^3	CO_2	0.79 kg/m^3
Fuel required by a 250 kW_e CHP (35 % electrical efficiency)	714 kW	107 m^3/hr of raw biogas	
CO_2 in raw biogas	85 kg/hour		
CO_2 from CHP flue gas	136 kg/hr		
Total amount of CO_2 available	221 kg/hr		

Assuming that all the CO_2 could be utilised by a greenhouse a 1,131 kW_e AD plant would be required to provide 1 tonne per hour of CO_2 (equivalent to 5 Ha nursery using NG boilers for CO_2). An AD plant of this size requires approximately 30,000 tonnes p.a. of feedstock and will produce 1 MW of heat.

Pollutants - mainly H_2S and NO_x

Cleaning technology needs to:

- Almost completely remove H_2S from the biogas to allow existing SCR NO_x removal technology to perform reliably with engine flue gases.
- Selectively remove CO_2 from a mixture of CO_2 and H_2S.

- Remove SO_x from the flue gas before SCR NO_x removal.

Case study

Hanwell Environment & Energy were involved in a project where their $CODiNO_x$ (selective catalytic reduction) flue gas cleaning equipment was used to remove NO_x from a biogas fuelled CHP installation.

The installation delivered acceptable levels of NO_x removal initially. However, the effectiveness of the catalyst rapidly fell. This was caused by high levels of SO_x in the flue gas which are produced when H_2S goes through the combustion process. The maximum sulphur content in any fuel that Hanwell will currently work with is the same as natural gas (5 ppm).

Future developments

Research on biogas cleaning is mainly concerned with producing gas that is clean enough to be injected into the gas grid. This is already possible but the cost is high and only one or two such plants are running in the UK.

There is no information available regarding the use of CO_2 contained in the raw biogas for CO_2 enrichment.

Is it viable? - A 1.1 MW_e AD plant using around 30,000 tonnes p.a. of biomass material is required to make a significant contribution to the CO_2 demands of a 5 Ha nursery. Even if it is possible to get CO_2 for enrichment; the capital cost and likely biomass sourcing and planning issues alone mean that AD is unlikely to be a viable option for the majority of nurseries in the UK.

Wet/dry biomass – composting

CO_2 is produced when biomass is composted (aerobic treatment). Depending on the feedstock, pollutants and even fungal spores may be present in any CO_2 rich gas produced.

The first step was to assess the amount of CO_2 that could be produced and the potential cost. The data available was highly variable; wherever possible an optimistic view was taken.

- Straw – 45% carbon by weight (dry basis). Typically 0.85t of dry matter per tonne bought.

- Compost – 25% carbon by weight (dry basis).

On this basis, one tonne of straw composted will ‘lose’ 170 kg of carbon. If we assume this is all CO_2 this equals 623 kg of CO_2 per tonne of straw. Alternatively 1.6 t of straw will be required per tonne of CO_2.

Composting biomass is also likely to produce fungal spores and even H_2S from anaerobic zones. There is therefore potential for plant health problems without adequate precautions / gas cleaning equipment.

Case study

Several decades ago a cucumber grower on the south coast placed wet bales of straw underneath the crop. The CO_2 released as the straw composted is said to have delivered a significant yield increase (this was before any CO_2 enrichment was used at all).

Is it viable? - at £50/t for straw, CO_2 would cost £80/t excluding any other costs associated with a relatively large scale composting process. An all-inclusive variable cost of at least £100/t seems likely. The resulting compost may have some value that can be offset against this. Composting material such as garden waste could reduce the input cost but this enters the ‘waste disposal’ arena with associated legislation / costs that composting straw may avoid. Albeit simplistic, the above figures suggest that composting biomass for the main purpose of producing CO_2 is not a viable proposition.

Dry biomass

Dry biomass can be converted into usable energy by:

- Gasification.
- Pyrolysis.
- Combustion.

The summary of each of the above conversion technologies drew heavily on the Thermal Net project funded by Intelligent Energy Europe (Bridgwater, A.V., Hofbauer H., van Loo, S. 2009).

Gasification

Gasification is a process that converts organic material into carbon monoxide, hydrogen, carbon dioxide and methane. This is achieved by reacting the material at high temperatures

(>700 °C) with a controlled amount of oxygen and/or steam. The resulting gas is called syngas or producer gas.

Gasification is a relatively efficient way of converting solid biomass e.g. wood chip into a more refined, readily transported (by pipeline) and easily used fuel for end users. As such it is the subject of significant ongoing research at a global level. In spite of decades of research and development, gasification is still an immature technology. There have been a number of commercial plants operating for many years, some with good levels of reliability. There have also been a number of high profile failures.

Pollutants

Pollutants typically found in syngas include:

- Particulates.
- Tars.
- Sulphur compounds.
- Nitrogen compounds.
- Chlorine compounds.

Gas cleaning requirements to allow CO_2 enrichment

From a horticultural perspective the greatest opportunity lies with cleaning the flue gases produced by the CHP engine. The following is required:

- Particulate removal from the raw biogas.
- Removal of SO_x from the flue gas before SCR NO_x removal.
- SCR NO_x removal.

The amount of each of the above pollutants varies according to the fuel and specific type of gasifier used. The majority of recent installations (10s of MW) use reciprocating engine CHP installations to generate electricity. The pollutants listed above are therefore already removed to the standard required for efficient operation and long life of the engines. However, the resulting flue gas is expected to suffer from the same potential problems as AD.

The CO_2 and heat output of a gasification CHP installation will be at least equal to that from conventional NG fuelled CHP installations. Compared to AD, the amount of fuel required will be much less as the calorific value of say wood chip is higher than a wet biomass fuel. Gasification also leaves relatively little waste for disposal. Unlike AD where >90 % of the input volume remains after processing.

There is no information available on the use of CO_2 from gasification.

Future developments

Gasification continues to attract significant R&D investment. Occasionally, a 'new' smaller scale gasifier (250-500 kW_e) is promoted in the UK. However, uptake remains limited.

Is it viable? - If reliable gas cleaning can be obtained, gasification CHP could satisfy the heat and CO_2 demands of a nursery. However, very few commercial installations of an appropriate scale (500-1,000 kW_e) have been operating reliably in the UK for any length of time. Without this level of confidence in the underlying gasification technology the added risk associated with gas cleaning seems too high at this stage and we unlikely to see any significant uptake.

Pyrolysis

Pyrolysis is similar to gasification other than operating at a lower temperature (circa 450 °C). It produces a liquid fuel, along the lines of a crude oil, which can then be refined to other grades as required. This potentially offers a biofuel alternative to fossil oils, but in view of the benefits in combustion offered by a gaseous fuel it is unlikely to have widespread application in horticulture at present.

Combustion

The Renewable Heat Incentive (RHI) has brought the economics of the use of biomass boilers in line with conventional fossil fuel solutions. The capital cost of a biomass boiler producing low pressure hot water for heating is typically repaid within five years, even in the case where it is shut down during the summer months when an NG boiler is used to satisfy the summer heat and CO_2 demand.

Biomass boilers therefore represent a potential mainstream source of CO_2 for a nursery.

Table 17. Wood chip and cereal straw analysis

Element	**Units**		
Ultimate analysis (wt. %)		**Wood chip**	**Cereal straw**
C	% dry basis ash free	49	47.3
H	% dry basis ash free	6.3	5.87
O	% dry basis ash free	42	41.3
N	% dry basis ash free	**0.1**	**0.58**
S	% dry basis ash free	**0.02**	**0.07**
Cl	% dry basis ash free	**0.01**	**0.171**
K	mg/kg dry basis	**400**	**5,480**

Pollutants

Pollutants present in the flue gas from a biomass boiler are dependent on:

- The fuel used.
- The combustion system.

Table 17 above provides a breakdown of the main elements in wood chip and straw. Note - that the actual composition of individual fuel supplies can vary. Those of greatest interest with regard to pollutants are highlighted.

Nitrogen and sulphur are major factors influencing the amount of NO_x and SO_x in the flue gas. Higher levels are therefore present in the flue gases from straw combustion. SO_x can cause problems with the catalyst in SCR NO_x reduction equipment.

Chlorine produces hydrochloric acid as a vapour in the flue gas. The amount in wood chip is minimal but this can be a problem with straw.

Pottasium has a similar effect to SO_x on SCR equipment. But, as a non-volatile element it is possible to remove it with high levels of particulate filtering.

Particulates

In addition to potassium (discussed above) the flue gases produced by biomass combustion contain much higher amounts of particulate matter (PM) than NG boilers. The PM can contain a range of chemicals dependent on the fuel supply. Table 18 below lists the most common ones and their characteristics.

Table 18. Volatile chemicals in biomass fuels

	Typical elements found	**Destination**
Volatile	As, Cd Pb, Zn	Easily condense in the flue gas, largely found in the fly ash. <1µm particles may require bag or ceramic filters for removal.
Highly volatile	B, Cl, Hg	Tend to remain in gaseous form in the flue gas. If present at unacceptable levels a flue gas condenser may be required.

Tars

Tars are condensable organic compounds. Flue gas condensers tend to cool the gas sufficiently for the tars to condense. As tars can be difficult to remove/clean condensers are not normally fitted to biomass boilers.

Tars might be a problem for CO_2 enrichment as they will condense and deposit within the CO_2 enrichment system. Biomass boilers tend to produce relatively little tar. It is possible to predict the amount of tar using flue gas analysis data.

Biomass flue gas composition data

The data in Table 19 below was collected from multiple sources and converted into a common format. In some cases the data is a ‘best estimate’ so it should be used as an indication of levels likely to be encountered. Data for the straw fuelled boiler is based on one site only using damp fuel and therefore suffering from poor combustion.

Table 19. Biomass boiler flue gas analysis

FUEL		***CO_2 (%)***	***CO (mg/MJ)***	***NO_x (mg/MJ)***	***PM_{10}* (mg/m^3)***
Wood chip	Typical underfeed stoker, no feedback control	9.1	369	74.3	68.6
	Typical modern moving grate boiler	14.6	41.3	75.8	54.2
	Boiler with gas cleaning technology	15	206	21.3	6.0
Wheat straw	Typical modern moving grate boiler (damp fuel)	12.9	2,152	132	No data

* PM10 = particulates less than 10 µm in diameter

The amount of CO present can indicate:

- Low oxygen (lean) combustion to reduce combustion temperature and therefore NO_x production.
- Poor combustion – known to be the case with the straw fuelled boiler.

Other information

NO_x

Although high nitrogen content fuels are known to produce higher NO_x in the flue gas. The relationship is not linear as shown by the ratio of NO_x (1.8) compared to the ratio of N in the fuel (5.8).

SO_x

Specific information could not be found relating to the fuels in the table. The amount of SO_x will depend very much on the presence of sulphur in fuel. Values obtained for wood chip range from 20-100 mg/m^3 with an average of 71 mg/m^3.

The straw fuelled power plant at Ely uses lime injection to reduce acid gas emissions such as SO_x. Levels under these conditions are reported to be around 56 mg/m^3. No data for untreated flue gas was found.

Ethylene (C_2H_4)

The total amount of volatile organic carbon compounds averaged 1.95 mg/m^3. This was assumed to be mostly 100 % ethylene. No data for straw was found but it is reasonable to assume that the amount will be the same as with wood.

Trace elements and Poly Aromatic Hydrocarbons (PAH)

Where present in the fuel they may also occur in the flue gases. Table 20 below gives an indication of the levels encountered with wood chip. A literature review found no information about the effect of these substances on plants.

Table 20. Detailed wood chip analysis

Trace elements	mg/m^3	PAH	mg/m^3
Boron	0.063	Napthalene	0.05374
Arsenic	0.0001	Methylnapthalene	0.00563
Selenium	0.0005	Acenapthene	0.00032
Mercury	0.0127	Chloronapthene	0.00000
Formaldehyde	0.43	Acenapthylene	0.01420
Benzine	0.02	Fluorine	0.00027
Dioxin / Furan	0.000000005	Phenanthrene	0.01139
HCl	0.02	Anthracene	0.00104
Lead	0.0009	Fluoranthene	0.00461
Cadmium & Tellurium	0.005	Pyrene	0.00400
Silver	0.00114	Benzo(A)anthracene	0.00066
Barium	0.04564	Chrysene	0.00134
Beryllium	0.00011	Perylene	0.00009
Cadmium	0.00076	Benzo(B)fluoranthene	0.00156
Chromium	0.01126	Benzo(K)fluoranthene	0.00033
Copper	0.02726	Benzo(A)pyrene	0.00042
Manganese	0.23758	Benzo(E)pyrene	0.00102
Zinc	0.26147	Benzo(g,h,i)perylene	0.00082
Arsenic	0.00113	Indeno(1,2,3,cd)pyrene	0.00055
Nickel	0.00900	Dibenz(a,h)anthracene	0.00006
Lead	0.02201		
Selenium	0.00133		

Pollutant concentration in a greenhouse

It is possible to estimate greenhouse pollutant levels related to required CO_2 levels for specific biofuels using the methods discussed in the section covering safe levels of pollutants. With a greenhouse CO_2 concentration of 1,000 ppm, the following table shows the implied concentration levels.

Table 21. Biomass boilers – possible pollutant concentration in greenhouses

	NO_x	SO_x
Upper limit (from Table 6)	400 ppb	200 ppb
Wood chip, lesser quality boiler, no gas cleaning	407 ppb	484 ppb
Wood chip, higher quality boiler, no gas cleaning	257 ppb	300 ppb
Wood chip with gas cleaning	70 ppb	82 ppb
Straw, poor quality fuel	814 ppb	Unknown

Ethylene concentration was assumed to be 16.6 ppb across the board based on the limited information available (target <10 ppb).

Case history CO_2 enrichment experience - Wood chip

A Dutch company called Procede claims to be recovering CO_2 from a biomass boiler in British Columbia. The process involves stripping CO_2 from the flue gas using a solvent thereby leaving the pollutants behind. The CO_2 is released by heating the solvent to 140 °C. The actual solvent being used is not known. They are reluctant to provide detailed costs due to the bespoke nature of each installation. However, figures of £50 per tonne of CO_2 have been quoted inclusive of variable costs and capital write-down over five years.

Implied gas cleaning requirements

Based on the figures in Table 22 the implication for gas cleaning for wood and straw are:

Table 22. Biomass boiler; flue gas cleaning requirements

	Wood chip	**Straw**
NO_x	A good quality boiler should deliver acceptable NOx levels	NO_x removal is required
SO_x	SOx removal is advisable	Same
Ethylene	The worst case ethylene concentration is borderline acceptable but should be checked	Same
Particulates	A high standard of particulate removal is recommended	Same
Tars & other volatile compounds	More detailed flue gas analysis is required to determine if the amount of tar that accumulates over time is likely to present a problem. Other volatile compounds are unlikely to be present in sufficient quantity to be a problem	Same

Pollutant reduction technologies

Gas cleaning technologies are split into the following categories:

- Removal of particles / dust.
- Removal of water soluble gases: SO_2, HCl, HF and NH_3.

- Removal of NO_x.
- Removal of tars and other organic impurities.
- Removal of the very toxic substances dioxin and mercury.
- Removal of CO_2.

The importance of combustion systems

With regard to biomass combustion in particular the first step is to consider the impact of different combustion systems on the production of pollutants. At the very least, reducing the amount of any pollutant will reduce the cost of removing it. At the very best it may remove the need for further flue gas treatment completely.

Combustion basics

It is generally accepted that in order for combustion to occur the fuel must pass through three stages:

1. Drying.
2. Devolatisation (driving off volatile gas fractions).
3. Char burning.

The amount of combustion air required is significantly different for char and volatiles. To accommodate this, whilst ensuring maximum boiler efficiency and complete combustion, some quality biomass boilers have primary and secondary combustion air supplies.

NO_x formation

NO_x are formed in three ways:

1. Fuel - N in the fuel is released and can form NO_x.
2. Prompt - NO_x formation within the flame.
3. Thermal - N in the combustion air can convert to become NO_x due to high temperatures.

Within biomass combustion in boilers it is widely accepted that fuel NO_x is the only significant contributor. NO_x is dependent on the residence time, temperature, particle size and fuel to air ratio. With biomass boilers the aim is to ensure fast/uniform combustion (avoiding ‘hot spots’) whilst keeping the temperature and particle size low. These are largely dependent on the characteristics of the combustion system.

SO_x formation

SO_x formation is largely dependent on the amount of sulphur in the fuel. As a guide, kerosene (used for CO_2 enrichment) has a maximum sulphur content of 0.1 %.

Ethylene

Volatile organic carbons (VOCs) of which ethylene is one, are a product of incomplete combustion. Good combustion control and long residence time help to reduce these.

Combustion components and their effect on pollutants

Three parts of a biomass boiler affect combustion:

1. Grate.
2. Combustion air supply.
3. Combustion chamber.

Grate

As previously discussed, uniform combustion with good control over temperatures and the amount of combustion air delivered is key to achieving high boiler efficiency and the cleanest possible flue gases.

Single zone grates have only one air supply. Within this grate type there are two common sub-types:

1. Underfeed stoker.
2. Drop feed.

Grates of this type should be avoided if CO_2 enrichment is being considered.

Multi-zone grates have two independently controlled air supplies:

1. Primary air - enters from underneath the grate.
2. Secondary air - injected directly into the combustion chamber.

Multi-zone grates in biomass boilers tend to be stepped grates. There are two main sub-types:

1. Fixed –-rely on the addition of fresh fuel to push the burning fuel and ash through the boiler.
2. Moving grate - the grate is powered by various means to ensure positive movement of the fuel.

Moving grates are preferred if CO_2 enrichment is being considered as they avoid the formation of ‘dead spots’ and encourage more uniform combustion.

A final improvement is the addition of water cooling to the grate itself. This has three theoretical benefits:

1. Extends the life of the grate.
2. Lowers flame temperature leading to less $NO_{x.}$
3. In the case of straw it can reduce the likelihood of slag forming due to its lower ash melting point.

Water cooled grates are available but rarely used in the range that are likely to be relevant to horticultural use. No data is available to quantify the theoretical reduction in NO_x.

Figure 7. A moving stepped grate

Combustion air supply

The primary and secondary air supplies should be controlled separately according to the temperature and oxygen content at key points in the boiler.

A further step to help reduce NO_x in particular is flue gas recirculation (FGR). FGR mixes cool flue gas from the chimney with fresh air. This allows the combustion air flow rate to be increased without increasing the amount of oxygen supplied. This delivers more uniform combustion temperatures and reduces the occurrence of ‘hot spots’ where NO_x formation is highest.

Figure 8. FGR take off point

Combustion chamber

The design of the combustion (or secondary) chamber is critical to ensure that all volatile organic compounds (i.e. ethylene) are burned. High turbulence which reduces hot spots is key to both overall combustion efficiency and low NO_x levels.

Case study

The Kob boiler is an example of a sophisticated combustion chamber design. Gases enter the chamber at one end and then a reverse flame system with small fan and swirl plates ensures a helical flame pattern.

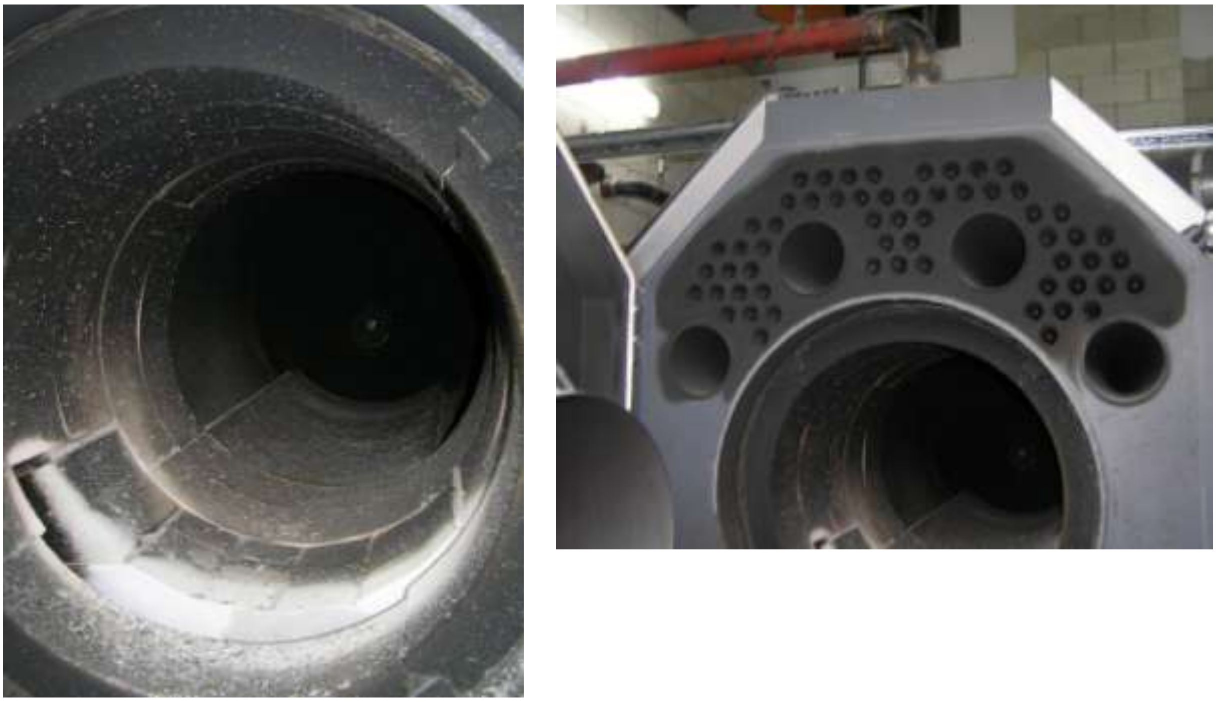


Figure 9. Combustion chamber in a Kob boiler

Part of the search for cost effective carbon capture and storage (CCS) solutions for the power generation industry includes modified/alternative combustion systems. Processes such as fluidised bed combustion, oxy-fuel and chemical looping are designed to produce less pollutants and/or a higher concentration of CO_2 in the flue gas. These may be a viable option for horticultural business at some point in the future. However, they have some way to go before being a commercial proposition to horticultural businesses.

Pollutant removal technology

Larsson (2008), Carlsson (2009) and Fleming *et al*. (2010) were used throughout this section of the report.

Removal of particles / dust

The removal of particles is important because they have the potential to:

- Contain harmful pollutants.

- Block CO_2 delivery systems over time.
- Leave an unsightly deposit on plants / fruit.
- Increase the capital and running cost of any further gas treatment equipment.

There may also be regulatory limits on particulate emissions from an installation. These set maximum limits in mg/hour (regardless of the particle size). An additional limit on particles less than 10 µm in diameter (PM_{10}) in mg/m^3 may also be set as these can be inhaled and contribute to respiratory disease.

Cyclones

The flue gas enters at a tangent to a cylindrical chamber which causes it to spin rapidly. This imparts a centrifugal force on the particles which are 'thrown' to the sides of the cylinder and then fall to the bottom.

Cyclones work best with larger and denser particle sizes. They typically remove >90 % of particles >10 µm but only 50 % of 5 µm particles.

A standard cyclone constructed from mild steel can handle gases up to 350 °C.

Figure 10. Cyclone on a fuel supply

Due to their low cost, simplicity and power consumption cyclones are often installed as standard equipment on biomass boilers.

Wet scrubbers

The gas stream is put into close contact with a liquid, the particles either absorb water thereby increasing in size and weight or become ‘trapped’ within a droplet. There are a variety of types of wet scrubber types:

- Column, open spray and packed bed scrubbers – remove 50 % of 1 µm particles.
- High velocity venturis – remove 50 % of 0.1 µm particles.

Wet scrubbers are most effective with moisture laden/saturated flue gas. Therefore colder gases are best, with temperatures under 70 °C preferred. A wet scrubber is best installed after a flue gas condenser.

Wet scrubbers offer the added benefit of removing some water soluble gas. However, the cost of water pumping and treatment can be high.

Bag filters

Also known as fabric filters, these comprise a number of woven mesh/perforated ‘bags’ suspended in a framework. As the particles themselves build up on the fabric, the pressure drop through the bags increases. Once it reaches a certain level the particle ‘cake’ is removed using either compressed air or vibration.

Bag filters have a very high particle removal efficiency (>99 %) including particles <1 µm. Standard bag filters generally have an upper temperature limit of 250 °C. But higher temperatures are possible if specialist material is used.

Bag filters provide a proven, established technological solution with relatively low operating costs and are widely used in many industries. The condensation of water and tars can be a problem if the flue gas cools too much. Teflon coating is sometimes used to counter this effect.

Figure 11. A bag filter ‘element’

Electrostatic precipitators (ESP)

The gas passes through high voltage electrodes which give an electrostatic charge to the particles. The gas then flows between earthed collection plates and the charged particles are attracted to them. The plates are cleaned by vibration.

There are two charging mechanisms:

1. Particles >1 µm are charged by field charging.
2. Particles <0.2 µm are charged by diffusion charging.

Between these two limits ESPs often have a low removal efficiency. An important point to note is that the removal efficiency of particles with high electrical resistivity is low because they not easily charged. This is especially significant for high chlorine content particles common in straw fuelled biomass boilers. This can be solved by using a wet electrostatic precipitator (WESP). This has two added benefits:

1. Particle size is increased (as in wet scrubbers) therefore helping to address the 0.5 µm ‘dead spot’.
2. Removal of water soluble gases can be incorporated.

In common with other wet scrubbers a wet ESP is best installed after a flue gas condenser. Similarly, the cost of water pumping and treatment can be high.

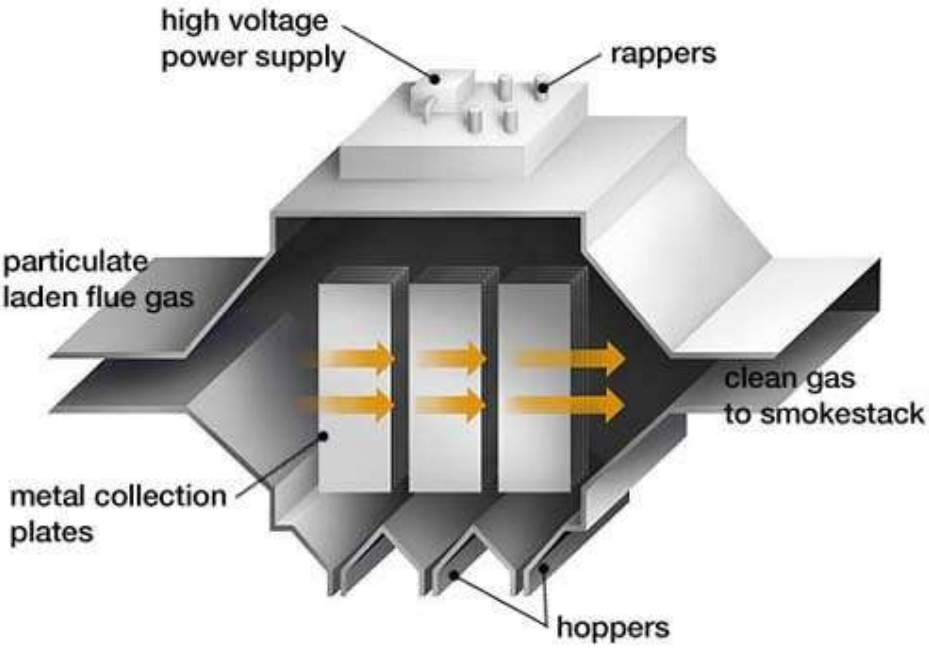


Figure 12. ESP schematic

Figure 13. Dry ESP on a 5MW boiler

Dry ESPs constructed from mild steel can work with gases up to 350 °C. Wet ESPs are similar to wet scrubbers and work best at <70 °C.

Particle removal efficiency is around 90 % for an ESP and as high as 95-99 % for a WESP. Dry ESPs are well established technology. Although only a few are installed on biomass installations they appear to be successful for this purpose.

Ceramic filters (CF)

Ceramic filters often take the form of a bank of cylinders with one closed end (candles). Exhaust gas is blown into the cylinder and is filtered through the ceramic material. They work in a similar way to bag filters but they are rigid (self supporting) and can be used at much higher temperatures (circa 600 °C).

Figure 14. Ceramic filter elements (candles) Image courtesy of A.B. Dust Control Ltd.

CFs can combine several gas cleaning processes into a single package. They can allow the simultaneous removal of particulates, acid gases and NO_x. This is discussed further in later sections of this report.

For particulate removal alone with lower temperature gases, CFs tend to be expensive compared to alternatives such as bag filters.

Removal of water soluble gases

Typical water soluble gases of interest are:

- Sulphur dioxide (SO_2).
- Hydrochloric acid (HCl).
- Hydrofluoric acid (HF).
- Ammonia (NH_3) which only tends to be present if it is used for SNCR NO_x removal.

There are two categories of removal system:

1. Wet absorption.
2. Dry absorption.

Wet absorption

This is a relatively old technology and tends to use wet scrubbers (described in the section on particulate removal). They combine particulate and water soluble gas removal in a single process.

The acid gases (SO_2, HCl, HF) are removed when placed in contact with either a calcium carbonate (limestone) slurry or sodium hydroxide (caustic soda) solution and oxygen. The resulting product (calcium or sodium sulphate) has little value and has to be disposed of.

Ammonia is soluble in water and can be neutralized with a range of common acids such as HCl. Ammonia can also be driven off the liquid by heating it.

The greatest disadvantage of all wet flue gas cleaning systems is the need for a water treatment plant to remove the pollutants accumulated and dispose of them.

Dry absorption

A dry absorbent is injected into the gas stream where it undergoes a chemical reaction with the pollutant. The products of the reaction are removed in the same way as particulates. The greatest benefit of dry versus wet absorption systems is that no water treatment systems are required. The disadvantage is that the chemicals tend to be more expensive.

For the removal of HCl, HF or SO_2 the chemicals used are:

- Calcium hydroxide (slaked lime) – requires moisture for the reaction to take place so is often added as a slurry or used with cool (saturated) gases (60 °C).
- Sodium bicarbonate – is much more reactive and does not require water. Gas temperatures of 150-300 °C are possible.

Sodium bicarbonate also reacts with NO_x at temperatures above 400 °C. Interestingly it also produces additional CO_2 as a by-product. Typical efficiencies of NO_x removal are 25 % but where a source gas is borderline ‘safe’ this could be used as a final ‘polishing’ treatment.

In commercial applications the resulting dry ‘dust’ is often removed with a bag filter. Ceramic filters are also starting to be used for this application.

Removal of NO_x

NOx normally comprises mostly of nitrogen oxide (NO) with a concentration of over 95 %. NO is a stable gas with low solubility in water but it can react with ammonia to produce nitrogen (N2) and water. This reaction takes place directly in the flue gas at a temperature of 850-1,000 °C and is called selective non catalytic reduction (SNCR). With the assistance of a catalyst the reaction can take place at 270-450 °C. This is called selective catalytic reduction (SCR).

SNCR requires stable conditions and a reasonable residence time for the reaction and an excess of ammonia is required for high NOx removal. The excess ammonia can be removed by a wet scrubber as described earlier. SCR requires much less excess ammonia.

SCR is used with conventional NG fuelled CHP installations on some UK nurseries and extensively in the Netherlands. In addition all new coal fired boilers on power stations have high dust SCR installed. In situations where biomass has been co-fired with coal SCR performance has suffered. This is caused by:

- Pores becoming blocked with fine particles.
- Reaction/poisoning with SO_x, sodium, potassium, arsenic or calcium.

The first issue can be solved relatively easily and reliably with filtration or scrubbing.

In the second case the presence of these compounds depends largely on the fuel composition. Calcium may be present if it is used to aid removal of acid gases so an alternative to this might need to be considered. SO_x can be removed using dry scrubbing techniques prior to high levels of particle filtration. This is also likely to remove potassium. Arsenic is only likely to be present (if at all) in very low concentrations so is unlikely to be a problem.

Ceramic filters impregnated with SCR catalytic material have recently become available and claim to work at temperatures as low as 240 °C. It is also possible to include SO_x removal before them. They claim a ‘one stop shop’ approach to the removal of SO_x, NO_x and particulates.

Removal of volatile organic carbons (VOCs)

VOCs cover a range of compounds. One of particular interest in greenhouses is ethylene which is highly volatile. Ethylene in the flue gases from NG fuelled CHP installations is removed by oxidation using a catalyst (OxyCat) immediately following the removal of NO_x using SCR. These catalysts have similar operating constraints to SCRs.

Where the temperature of the source gas is too low for SCR or OxyCat, its temperature can be boosted with a ‘clean’ heat source before treatment. For example, some waste incineration sites re-heat with direct combustion of NG. This may seem like a false economy but a relatively small amount of NG is required.

Removal of tars

Tars are defined as condensable organic compounds, with molecular weight greater than benzine, and poly aromatic hydro-carbons. They are a nuisance in various forms, viz. condensation, aerosol formation and polymerisation. They tend to be more of a problem in gasifiers than boilers.

If the flue gas cools sufficiently tars condense and can foul heat exchangers, particle filters etc. Biomass boilers tend not to have economisers fitted due to the potential for tars to form and block them. The greatest issue for horticultural CO_2 systems is likely to be the gradual accumulation of tars within the CO_2 distribution network.

Tars can be destroyed by heating the gas up to 1,200 °C for around 0.5 seconds (know as thermal cracking). They can also be removed using a catalyst at 400-900 °C. Wet scrubbing techniques using biodiesel can achieve very high tar removal efficiency. But they are relatively new processes developed primarily for gasification and little commercial information is available for them.

For biomass boiler flue gas, which is expected to have a low tar content the simplest solution may be to install a flue gas condenser and accept that it has to be replaced periodically. Cleaning the condenser may be possible but might prove uneconomic. One biomass boiler (wood chip) in the UK is known to have installed a flue gas condenser with no apparent problems in the 12 months since installation.

Removal of the very toxic substances dioxin and mercury

Mercury will only be present if it is in the fuel itself. It can be present in wood chip at very low levels.

Dioxins are not normally found directly after combustion. They tend to form by complex reactions in the boiler/gas cleaning part at around 200-450 °C. The presence of chlorine and organic precursors are necessary. Therefore no dioxin is formed after perfect combustion.

For completeness their removal is described briefly below:

- Dioxins – can be broken down by oxidation in the same way as VOCs.
- Mercury (Hg) – this can be present as particulates or in gaseous form. Hg particulates can be removed alongside other particulate. Gaseous Hg can be removed by condensing/washing in wet scrubbers.

Extraction of CO_2

So far we have considered sourcing CO_2 by accepting it as a component of an exhaust gas stream and taking out any polluting components. An alternative is to remove the CO_2 from the source gas (rather than removing the unwanted parts from the source gas) and simply venting what's left to the atmosphere. This has the benefit of producing a clean highly concentrated source of CO_2 which may even be considered for overnight storage.

The underpinning technology for CO_2 extraction has been the subject of massive research and investment in recent years. Primarily because it has the potential to decarbonise fossil fuel based electricity generation systems.

There are three fundamentally different processes being explored:

1. Absorption.
2. Adsorption.
3. Membrane separation.

This is a rapidly changing field of research. The contents of this section of the report are largely an extremely concise version of a book written by Mercedes Maroto-Valer M. (2009)

Absorption

Capture and separation of CO_2 from other gases is completed in two steps:

1. Absorption of the CO_2 in an aqueous solution of a solvent in an absorber (similar to a wet scrubber).
2. Separation of the CO_2 from the solvent in a stripper.

The absorption process is enhanced at low temperature and high pressure. As compressing the source gas is expensive it is usual to enhance the process by keeping gas temperature as low as possible. And to strip the CO_2 from the solvent using high temperature.

Solvents used in the aqueous solution are almost exclusively amines as they have a strong affinity for CO_2. Monoethanolamine (MEA) is the main solvent used. On-going research is concentrating mainly on using different amines to reduce the amount of heat required for stripping and to cut solvent evaporation loss.

A concern might be the effect of amines carried over into the greenhouse on plant health. No research was found that had investigated the effect of amines (in the aerial environment) on plants. However, fundamentals of plant physiology / nutrition suggest that amines should not present a problem.

Initially, the sources gas should be as cold as possible; well below 100 °C and ideally nearer to 40 °C. The gas should also be slightly above atmospheric pressure.

After absorption, the resulting CO_2 rich solution is heated to 120-140 °C for stripping and then cooled before being returned to the absorber.

For horticultural use the CO_2 gas which has been driven off in the process may need to be cooled before it can be added to a CO_2 enrichment system. Dilution with ambient air may be sufficient to do this.

One disadvantage of the absorption process is that other gases are absorbed as well as CO_2. Work continues to improve the selectivity of solvents. For example, Methyldiethanolamine (MDEA) which reacts more quickly with sulphur compounds than CO_2 can be used to remove highly reactive acid gases in a first stage absorber leaving the cleaned up CO_2 rich gas to be treated in a second MEA based absorber. Other approaches rely on a process akin to distillation where the solvent temperature is increased in stages to selectively remove gases. The gases are released in different parts of the stripper and can be handled separately.

Adsorption

Adsorption is the mechanism by which atoms or molecules of a gas or liquid adhere to the surface of another substance allowing their capture. Adsorption takes place at low temperature and high pressure in the presence of an adsorption material.

To ensure good performance, the adsorbents used should have an open pore structure and very large surface area in contact with the reacting gas (figures of 500-1,000 m^2 per gram are often quoted).

Where absorption is already thought to be close to its maximum potential, adsorption has not yet reached its performance potential. Lower costs and higher rates of gas transfer are expected as a result of further research.

Pressure swing adsorption (PSA) is currently the most popular technology for adsorption. However, it requires gas pressures around 20 bar. The energy required to compress the gas makes PSA unviable for horticultural application as the source gas is not generally available at high pressure nor is the CO_2 required at high pressure.

Temperature swing adsorption (TSA) is an area where significant research is being carried out but no commercially identifiable equipment has yet emerged.

As with absorption, other gases are sometimes extracted alongside CO_2 and these may need to be dealt with to attain the necessary CO_2 purity.

Membranes

These are molecular filters which only allow molecules of a tightly defined size to pass through them. High temperatures or pressures are used to drive the molecules through the membrane. As with many other CCS technologies membranes are the subject of considerable R&D effort. At this stage of their development they are not a commercially available/viable technology for horticultural applications.

Even if any of the above CO_2 extraction technologies extract pollutants such as SO_x alongside the CO_2 they may offer benefits. This is because the resulting CO_2 rich gas will have a much reduced volume which may make the cost of pollutant removal considerably cheaper.

Summary of pollutant reduction technologies

Table 23 below summarizes the current stage of development/market penetration of the different combustion technologies considered.

Table 23. Pollutant reduction technologies based on combustion system innovation (as applied to woody biomass)

		Early development stage	**Early commercial take-up**	**Mainstream commercial**
Boiler	Underfeed stoker			☐
	Vertical drop			☐
	Fluidised bed[a]		☐	
	Moving grate (with separate primary & secondary air)			☐
	Oxygen feedback control			☐
	Flue gas recirculation		☐	
	Oxy-burn	☐		
Gasifier	Updraught [b]		☐	
	Downdraught[c]			☐
	Fluidised bed [b]		☐	
	Plasma	☐		

[a] Mainstream in large industrial/power industry applications but not in horticulture.

[b] These are not flagged as mainstream despite being mainstream in India/China.

[c] This is flagged as mainstream due to the large numbers installed in India.

Even if no CO_2 enrichment is required, current best practice for biomass boilers is:

- Moving grate.
- Oxygen feedback control of combustion air.

The addition of flue gas recirculation should be seriously considered if CO_2 enrichment is being considered for the future. It may be expensive or not even possible to add at a later date.

Table 24 overleaf summarizes the current stage of development / market penetration of the different gas cleaning technologies considered.

Table 24. Gas cleaning technologies

			Maturity of the technology			
		Cost/MW	**General use (excluding biomass & horticulture)**	**Application to biomass**	**Current use in horticulture (non biomass specific)**	**Current use in horticulture (biomass specific)**
Particulates	Wet scrubber	n.a.	3	3	1	1
	Bag filter	£15 k	3	3	2	2
	Electrostatic precipitators	£25-£35 k	3	3	2	2
	Ceramic	£30-£50 k	3	2	1	1
Water soluble gases (SO_2, HCl, NH_3)	Wet scrubber	£10 k	3	3	1	1
	Dry scrubber	As for particulate filters +£5 k	3	3	1	1
NO_x	SNCR	£10 k	3	2	3	1
	SCR (conventional)	£100 k	3	2	3	1
	SCR + ceramic filter	£150 k	2	2	1	1
VOCs (ethylene)	OxyCat	£50 k	3	2	3	1
Tars	High temperature destruction	n.a.	2	2	1	1
	Catalytic cracking	n.a.	2	2	1	1
	Condensation	n.a.	3	3	1	1
CO_2	Absorption	£50 per tonne of CO_2 (capital over 5 years + variable costs)	2	2	1	2*
	Adsorption	n.a.	1	1	1	1
	Membranes	n.a.	1	1	1	1

* Believed to be one installation but no hard facts available

Key

1. Not proven/no known installations in the category.

2. Some commercial installations but not widespread.

3.Well established, many installations.

Discussion

Fossil fuel sources

It would be easy in this type of study to dismiss more conventional sources of CO_2 as not being worthy of mention, because they could be seen as too obvious a choice. Nevertheless, it is clear that **natural gas fuelled CHP,** although well established as a technology, is not as widely used as the costs associated with it appear to justify.

Compared with the Netherlands, growers in the UK have failed to embrace the potential benefits to the same degree. Even a relatively conservative analysis of costs shows that a modern CHP installation can produce CO_2 for around £30 per tonne - a good deal less than the benchmark fuel costs of £80-£110 per tonne, based on an NG boiler operating when no heat is required.

Steam reforming of natural gas is an established technology in the chemical industry which could theoretically be used in horticulture. Technically it can deliver CO_2 enrichment. But without a market for the hydrogen it produces it will always prove to be too expensive as a CO_2 source alone.

Technically, **natural gas fuel cells** appear very attractive indeed. They have few moving parts so are expected to have low maintenance costs. They also produce CO_2 with very low levels of pollutants. A 400 kW fuel cell CHP installation is available to buy now. But at around £600 k it cannot compete with a reciprocating engine CHP installation. The cost of fuel cells is expected to fall significantly in the next decade, so this is a technology to watch.

Fresh air

As fanciful as this might seem, ‘sucking’ CO_2 out of the air around us may be a viable proposition. Laboratory scale trials (backed by Technology Strategy Board funding) evaluated a **wet scrubbing CO_2 extraction** technology which appears to show that, although not particularly useful for global decarbonisation, the levels of CO_2 required for greenhouses could match well with the capability of this concept. The process itself is relatively simple so scaling it up should be straightforward and the capital cost should be low. The absence of any pollutants at all is also a major plus point. The technology deserves some more investigation.

Carbon capture and storage (CCS)

Although applied **CCS technology** in the power industry is huge, the trial equipment used in its development for coal and NG fuelled plant has been on a scale not dissimilar to that which would be useful for horticultural applications. The power industry need high levels of CO_2 concentration at lowest cost and this is not a bad starting point for horticulture. The CCS industry is targeting a cost of £50 per tonne of CO_2 for large installations, albeit at a much larger scale.

Absorption (capturing the CO_2 within a solvent) is the most mature CCS technology. This utilises various amine solutions. An installation using this technique is thought to be recovering CO_2 from a biomass boiler in Canada. A ballpark figure quoted for variable and capital costs over five years is £50 per tonne of CO_2. However, it was not possible to confirm how long the installation has been producing acceptable quantities and quality of CO_2.

Anaerobic digestion (AD)

CO_2 as a by-product of anaerobic digestion or more to the point, of the combustion of AD gases may be viable. However, AD can only be justified through the value of the energy it generates so the primary economics of installation for this reason have to be right. At the moment AD is best suited to those who:

- Have access to very large amount of organic waste or,
- Who can grow an energy crop, and
- Who have land to handle the digestate.

This does not constitute the best fit to horticultural businesses and as such it is felt that few growers are likely to adopt this technology.

Problems also exist with the high levels of SO_x in flue gases and although is it possible to solve, this is an added expense to those requiring CO_2 from the process.

Biomass boilers

The introduction of the Renewable Heat Incentive (RHI) makes the investment in biomass boilers look relatively attractive from a heating perspective alone. They are likely to become commonplace over the next few years, even if the flue gases cannot be used for CO_2 enrichment. Biomass boilers will therefore represent a potential source of CO_2 on many nurseries. However, the cost and practicality of pollutant control will be a key issue.

Available data shows that high quality boilers with a low nitrogen content fuel, such as wood, (low bark content) are close to meeting the acceptable limits of pollutants. However, much of the information in this area is anecdotal.

The addition of **ceramic filters** impregnated with a catalyst to remove NO_x (and SO_x if necessary) appears possible. Modifications to a standard boiler will be needed to achieve the temperature required for effective operation, but these would appear to be feasible.

There is some evidence to suggest that a standard (non-catalytic) ceramic filter could remove 20-25 % of NO_x. This may be adequate where the NO_x levels are borderline acceptable.

Higher nitrogen and sulphur content fuels, such as cereal straw, present more of a problem. However, the lower cost of straw compared with wood chip means that higher pollutant removal costs could be tolerated. As with wood chip fuelled boilers, catalyst impregnated ceramic filters appear to be a feasible solution. Another option to consider might be to run a biomass boiler on straw when no CO_2 is required, but on high quality wood chip when it is. This would require some innovative thinking with regard to fuel handling systems.

Gasifiers

There are no UK greenhouses heated with gasifiers at the moment and it is unlikely that this technology will become significant in the near future. Mainly as a result of high costs and lack of developed commercial systems. Nevertheless, gasification is becoming more widespread in India and China so we may see some development here as a result.

In the short-term it is more likely that a new greenhouse complex will be sited alongside a large scale gasification based biomass power station. Clearly, if such a development was to take place it would be necessary to install the required gas cleaning technology at an early stage to make such an idea viable.

Pollutant control technologies

The report details a host of developed pollution control technologies well capable of delivering the necessary CO_2 quality required for a horticultural environment. As such it is unlikely that there is any primary need to develop or even adapt existing systems to any great degree.

The big challenge will be taking appropriate measures which will deliver CO_2 at acceptable levels of purity, but at an acceptable capital and operation cost.

Clearly, the cheapest and simplest way to control pollutants is not to have them at all and as such the first level of pollution control takes place in the boiler itself. Growers need to have an eye on boiler design features as they may affect exhaust gas content. Also the type, consistency and quality of fuel feedstock needs to be considered.

If we concern ourselves with particulates NO_x and SO_x as the pollutants most likely to be a problem, each one of these has more than one established technological solution which can deliver the necessary levels of gas quality. The challenge is choosing a technology which is appropriate and cost effective. This is largely determined by defining what job has to be done and to what level cleaning has to take place. To establish this, what is most needed now is some real assessment and measurement of the levels and the ranges of exhaust gas pollution for real systems across a variety of fuel sources, boiler types and operational conditions.

Armed with this information it will be possible to draw up specifications for systems which are ‘fit for purpose’ without either posing any risk to plant growth by being underspecified or being so over-engineered that they become uneconomic.

Main technologies will be the cheapest, simplest and most appropriate to need, with systems like bag filters (particulates), dry scrubbers (acid gas removal inc. SO_x) and ceramic filters (particulates and NO_x) being paramount.

Conclusions

Natural gas fuelled CHP

Growers should revisit the economics of natural gas fuelled CHP installations. Instead of considering the additional CO_2 as ‘free’ a realistic value should be given to it.

CO_2 from fresh air

This may seem too good to be true. However, laboratory trials carried out are encouraging. This technology would be appropriate for any site especially where a biomass boiler is not feasible.

The capital and running costs of a greenhouse scale installation should be explored in detail.

Carbon capture and storage

Off the shelf solutions for horticulture are unlikely to come directly from CCS developments. However, spin-off greenhouse scale technology will no doubt happen at some point. This is one to watch for the future.

Anaerobic digestion

A dry scrubber based SO_x removal system combined with NO_x removal using catalyst impregnated ceramic filters has potential to supply sufficiently clean flue gases.

However, even if proven, the likely uptake of AD by the greenhouse industry is expected to be low. Further work using industry funds is unlikely to deliver sufficient industry wide benefits.

Biomass boilers

The potential is significant and the technical solutions to remove pollutants are available, albeit not proven in this specific application. To provide greater confidence in the cost and ability to deliver sufficiently clean flue gases:

- Comprehensive flue gas analysis should be carried out on commercially operated biomass boilers in the UK.
- Detailed quotes should be obtained from flue gas cleaning equipment suppliers, including projected running costs.

Gasifiers

As much as gasification may offer a solution, we question whether industry funds should be used to stimulate this market rather than wait until the technology has a better foothold and then examine the needs of systems with respect to CO_2 delivery.

If the technology is adopted in Europe, any one of a variety of application opportunities should present themselves to evaluate and consider the implication for exhaust gas quality and treatment.

The true value of CO_2

The true value of every extra tonne of CO_2 in terms of yield increase and the value of the produce, especially during the summer months, is not readily quantified by researchers never mind growers. As long as this remains the case, the true optimum with regard to CO_2 enrichment capacity and therefore capital/running costs of alternative CO_2 supplies will not be reached.

Knowledge and Technology Transfer

None at the time of completing the report. Activities already booked/committed to:

- HDC News – main article September 2011.
- Tomato Growers Association – presentation at the 2011 Annual Conference.

Glossary

AD	Anaerobic digestion. The process of ‘fermenting’ wet biomass in an oxygen free environment to produce a biogas containing methane.
CCS	Carbon capture and storage. A collection of technologies being developed primarily for the power industry to allow CO_2 to be captured and stored underground.
CHP	Combined heat and power. An installation that converts a fuel into electricity and useful heat.
CO	Carbon monoxide. Tends to be the product of incomplete combustion of fuels. Also present in raw syngas produced by a gasifier.
CO_2	Carbon dioxide.
FC	Fuel cell. An electrochemical means of converting fuel into electricity and heat.
FGR	Flue gas recirculation. Used to improve combustion and reduce pollutant formation, NO_x in particular.
H_2S	Hydrogen sulphide. Most frequently encountered in raw AD biogas and gasifier syngas.
kW_e	kilowatts electrical. The electrical generating capacity of a piece of equipment e.g. CHP or fuel cell.

kWh	Kilo-watt hour. The amount of energy produced/consumed by a 1 kilowatt ‘machine’ in 1 hour. 1 kWh = 3,600 MJ.
MDEA	Methyldiethanolamine. A solvent used in CO_2 absorption processes.
MEA	Monoethanolamine. A solvent used in CO_2 absorption processes.
MJ	Mega-joule. A unit of energy. 1 MJ = 1,000,000 joules.
NG	Natural gas.
NO_x	Nitrogen oxides. The collective name nitrogen monoxide, dioxide and trioxide.
PAH	Poly aromatic hydrocarbons.
PM_{10}	Particulate matter <10 µm. The total mass of particles that are <10 µm in $1m^3$ of flue gas (units mg/m^3). Particles of this size can be inhaled deep into the lungs. Units of mg/m^3.
ppm	Parts per million. The ratio, by volume, of a single gas in a mixture of gases.
ppb	Parts per billion. The ratio, by volume, of a single gas in a mixture of gases. 1 ppm = 1,000 ppb.
SCR	Selective catalytic reduction. A means of removing NO_x
SNCR	Selective non catalytic reduction. A means of removing NO_x
SO_x	Sulphur oxides. The collective name sulphur monoxide, dioxide and trioxide.
Therm	British thermal unit. A quantity of natural gas. 1 therm = 29.3 kWh
VOC	Volatile organic carbons. The collective name for a range of carbon compounds with the chemical formula C_xH_y.

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