Can Tomatoes Save the World?

by

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"I hereby declare that, except where specifically indicated, the work submitted herein is my own original work."

Date:…….. **Signature:……**

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Contents

1. Introduction

In recent years, the concept of carbon capture is considered as one of the vital instruments to combat the emission of greenhouse gases (GHG). However, the usual approach of dealing with captured CO_2 is to pump it into geological wells where it can be stored for many years and there has been little initiative to utilise this waste CO_2. The Can Tomatoes Save the World (CTSW) study aims to exploit the greenhouse's need of CO_2 to increase plant growth and/or quality and use crop photosynthesis as an alternative form of a carbon sink.

Volker Wessels is the main contractor for an upcoming project which involves the construction of a large Energy-from-Waste (EfW) plant as well as a 100 hectare greenhouse facility within the UK. The introduction of the Carbon Floor Price has brought about the unique proposition of combining the two facilities using carbon capture to reduce operation costs as well as the installations' carbon footprint. CO_2 enrichment will be achieved via extraction from waste flue gas by using carbon capture technology.

Before the introduction of the carbon floor price, carbon capture facilities have been deemed as economically unsustainable due to the loss in power generator efficiency and additional operational costs. As the carbon floor price is only limited to UK-based electricity generators (HMRC, 2011), GHG emissions used in agriculture would be exempted from the tax. (HMRC, 2011) have also indicated that they intend to introduce legislation that would ensure plants fitted with carbon capture would be eligible for relief from carbon price support rates. Hence, the carbon floor price could possibly offset the generation losses from using carbon capture.

The increasing nature of the carbon floor price means that the EfW plant operators will have greater incentive in the long term to reduce their carbon emissions. The rate of operational savings could be further enhanced as the CO_2 is captured and then reused in the greenhouses, relieving the need to purchase pure CO_2 or combustion fuel. Therefore, Volker Wessels wish to verify if the financial savings from installing carbon capture between the EfW plant and greenhouse facilities justify the total investment cost.

1.1 Aims and Objectives

The aims of this study are defined as follows:

- Determine whether the introduction of the carbon floor price results in the installation of carbon capture between the EfW plant and greenhouse becoming economically sensible
- Determine suitability of EfW as well as other popular power generation methods as the technology of choice with the greenhouse CO_2 sink setup
- Determine if the introduction of carbon capture to the combined system is environmentally beneficial

Consequently, the objectives to assess the defined aims are:

- Use common accounting practices (i.e. Net Present Value and Internal Rate of Return) to evaluate the prospective cash flows over a pre-set project lifetime to determine if there are increased savings with carbon capture after the carbon floor price has been introduced
- Evaluate the expected CO_2 utility rates of the greenhouse corresponding to individual power generation systems as calculated from their respective emission factors (EF)
- Use a life-cycle analysis (LCA) to evaluate the CO_2 footprint of the project as a whole and per kg of tomato produced under two scenarios: with and without carbon capture installed

1.2 Report Structure

The report will begin with a literature review, which will cover relevant material concerning the topics of investigation; this includes a case study on OCAP (the only such application of the setup), background on CO_2 enrichment, the introduction of the carbon floor price and prior works done similar to the study's objectives. The report will then reveal the methodologies used to achieve each of the objectives defined in **Section 1.1**. Following that, the results of each of them will be discussed individually, stressing key details from the data obtained and comparisons with applicable literature. The report will then close with the final conclusions, summarising the key messages revealed throughout the CTSW project.

2. Literature Review

Key literature for each element will be underlined, with further explanation and result comparisons included in their respective Results and Discussions section.

2.1 Case Study - OCAP

The Organic Carbon dioxide for the Assimilation of Plants (OCAP) is the only such example in the world that sources its CO_2 from refinery flue gases through carbon capture and directly transports them to greenhouses. As such, it will be used as our main case study to demonstrate the real world practicality of combining these technologies. OCAP is based in Rotterdam, Holland and is a joint venture between Volker Wessels and Linde Gas Benelux.

On the 3rd of Oct 2012, I had the opportunity to visit the Dutch branch of Volker Wessels in Holland where they gave us a presentation on the OCAP project. Figure 2.1 and 2.2 which shows the OCAP Process Flow and Distribution Network respectively, were taken from the slides shown during the presentation. CTSW is expected to have a similar process flow as OCAP shown in Figure 2.1 where the CO_2 is extracted from the "refinery" (EfW) and transported to the greenhouse facility after the gas has been cleaned and processed for agricultural use.

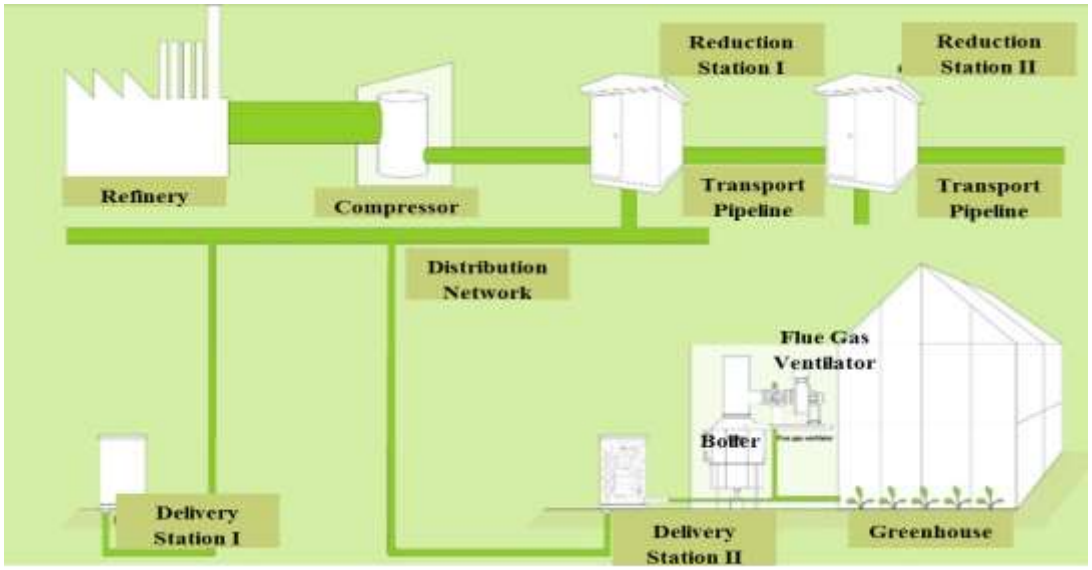

Figure 2.1: OCAP Process Flow (Source: OCAP Presentation Slides)

For OCAP, the CO_2 is sourced from 2 major locations, namely the Shell and Abengoa (Figure 2.2) refineries, where they are extracted from the flue gases and sent along the distribution "backbone", eventually branching into individual greenhouse locations. Along

the way, the CO_2 gas goes through multiple stages of compression and reduction for ease of pipeline transportation, though this would be minimal in CTSW as the greenhouse is located much closer to the flue gas source compared to OCAP.

For the greenhouse growers, the system provides them an alternative to burning hydrocarbon to produce CO_2, saving the greenhouse energy and potentially costs. It also provides the grower with an opportunity to use an alternative form of heating instead of fossil fuel (which is used for both heating and CO_2 production during winter), by using a combination of CO_2 delivery and renewable energy sources, such as geothermal energy or industrial waste heat. The extracted CO_2 is also used in other industries such as carbonated drinks and medicinal purposes in the OCAP example hence it would be expected to have a greater presence of quality control equipment compared to CTSW.

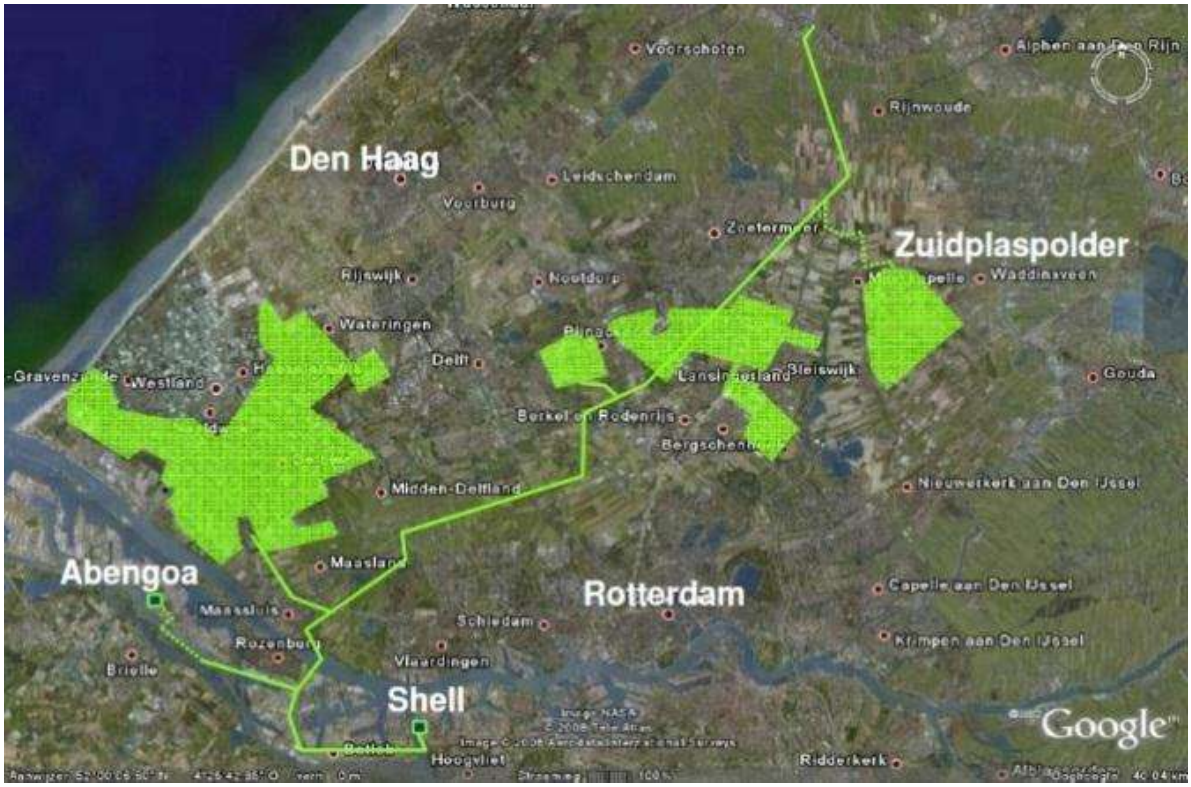

Figure 2.2: OCAP Distribution Network (Source: OCAP Presentation Slides)

The CO_2 is bought from the refineries at €5 per tonne and sold to the greenhouses at €50 per tonne. Thus far, €160m has been invested into OCAP and it generates a turnover of €20m per annum through CO_2 distribution alone (OCAP Factsheet, 2012). The OCAP system supplies a total surface area of 1,900 hectares of greenhouse area and has an average off take of 125 kg/hr per ha with some 1,800 full load hours, with a maximum off take of 500 kg/hr per ha

(OCAP Presentation, 2012). The annual environmental gains have been estimated at 115 million m^3 of natural gas savings and 205,000 tonnes of CO_2 emissions every year (OCAP Factsheet, 2012).

A technology that is more common place is the use of a greenhouse with a CHP system to provide the heating requirements for plant cultivation. The CHP is sited directly next to the greenhouse and waste heat is transferred to the greenhouse rather than dissipating the heat inefficiently using a cooling tower, reportedly increasing efficiencies up to 80%. Biogas which is made from digesting plant waste can also be used to power the CHP installations. (British Tomato)

It should be noted however that the greenhouse market is not as developed in the UK compared to Holland. It is also considerably more likely that there will be a CO_2 supply-demand mismatch between the EfW plant and the greenhouse installation as the CTSW system does not have a distribution network of the same scale as OCAP. Nevertheless, OCAP still exhibits the potential profitability of the CTSW project by combining the two installations through carbon capture and transport.

2.2 CO_2 Enrichment

Many studies have shown that increased CO_2 air concentration levels up to a certain degree have been found to be beneficial to plant growth and in some cases, even product quality (Calvert, 1972; Jacob et al. 1995; Sanchez-Guerrero et al. 2005). At CO_2 concentrations above 1000 ppm, the plant photosynthesis rate increases proportionately, producing more available sugars and carbohydrates available for plant growth and crop yield (Blom et al. 2002).

In contrast however, well-sealed greenhouses are particularly prone towards CO_2 depletion. Photosynthesis and CO_2 uptake by the plants will often result in the CO_2 concentrations dropping below the atmospheric ambient levels – approximately 350-380 ppm. For example, (Baille, 2001) reports that CO_2 levels drop to as low as 200 ppm in well-sealed plastic greenhouses. (Blom et al. 2002) estimates that the decrease in photosynthesis when CO_2 levels drop from atmospheric to 200 ppm is similar in magnitude to an increase from atmospheric to 1300 ppm. Sufficient air circulation within the greenhouse is therefore essential to prevent localised CO_2 deficiencies and maintain healthy plant microclimates.

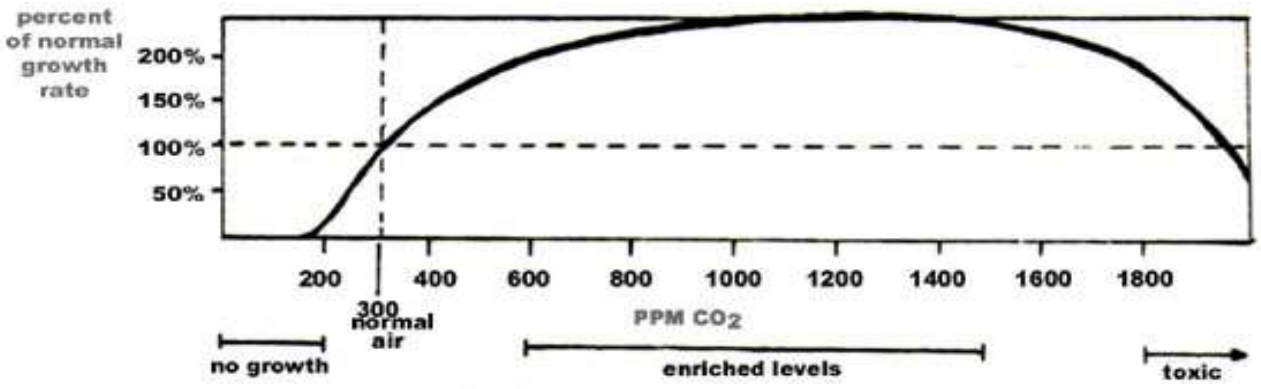

Figure 2.3: Effects of CO_2 enrichment on plant growth rates (Source: Hydrofarm.com)

The graph in Figure 2.3 highlights the effects of CO_2 enrichment and depletion on expected plant growth, where 100% represents the growth rate at ambient concentration. Generally, most greenhouse crops show the CO_2 enrichment benefits plant growth up until 1000 – 1500 ppm (Nelson, 2002); sometimes even doubling plant growth rates (Figure 2.3). There however, exists an upper limit cap at which further CO_2 enrichment is actually detrimental to plant growth. Above 2000 ppm, there exists a significant risk of plant toxicity (Vox et al. 2010) and levels above 5000 ppm could result potentially harmful effects in people such as dizziness and lack of coordination (Vox et al. 2010, Blom et al. 2002).

(Blom et al. 2002) have also indicated that other gases besides CO_2 can induce harmful effects to the crops. For instance, more than 0.2 ppm of SO_2 causes acute necrosis. Ethylene at 0.05ppm and propylene at higher levels can cause premature senescence on tomato plants. Incomplete combustion of some fuels produces ethylene while propylene is typically released from leaky propane pipes. High burner flame temperatures are also likely to produce nitrous oxides, which can cause diminished growth and necrosis at higher concentrations. It is also indicated that plants receive more phytotoxicity damage from low levels of both SO_2 and NO_x rather than a high level of either.

CO_2 can be supplied to the greenhouse through a few methods, with some of the more common methods being burning of hydrocarbon fuels, flue gas extraction, dry ice, yeast fermentation and decomposition of organic matter. The burning of hydrocarbon fuels proves to be the most popular out of all the CO_2 generation methods in larger greenhouse structures as it generates heat and moisture as a by-product of CO_2 and is relatively economical (Blom et al. 2002). The alternative method, which is of main interest, is extracting the CO_2 from the flue gases of the EfW plant. Utilising the waste CO_2 could possibly reduce the total carbon

footprint of the entire system as well as provide financial benefits due to the absence of hydrocarbon purchases and carbon tax (**Section 2.3**).

2.3 Carbon Floor Price

Ever since the Kyoto Protocol was established in 1997, developed nations have been consistently trying to reduce GHG emissions to combat global warming and climate change. The power generation industry has been identified as the most significant contributor to GHG emissions in the world (US EPA). Throughout the EU, governments have been adopting and reforming policies to encourage low-carbon investment in order to achieve climate goals.

One such measure is the introduction of the EU Emissions Trading System (EU ETS) in 2005 that gives industrial companies a specified number of carbon credits per year. These carbon credits have a market value, thus effectively making CO_2 tradable, which would allow companies to sell (and profit) from excess credits leftover. However, credits also need to be bought should the company exceed their credit allowances. Hence, the EU ETS system serves to promote carbon frugality within industry on top of establishing a CO_2 "market".

Although the EU ETS has been reported to be effective and is expected to reduce UK emissions by half by from 2010 to 2020 (HMRC, 2011), the decarbonisation rate still remains insufficient to meet the UK Climate Change Act's carbon reduction target of 2050. The current situation owes to the poor industrial activity levels as a result of the European Debt Crisis, leading to a large surplus of allowances and hence putting a downward pressure on the EU ETS carbon prices. The UK government has since responded by introducing a carbon floor price through means of the Climate Change Levy (CCL).

The CCL will add a support rate on the existing market carbon price identified by the EU ETS, effectively giving a minimum rate for CO2 emissions which is the Carbon Floor Price. The carbon floor price complements the EU ETS by strengthening the carbon price signal in the UK, enabling higher levels of investment for low-carbon infrastructure and therefore a faster rate of decarbonisation. Figure 2.4 shows – in 2009 real prices – that carbon floor price rate is expected to start from £16/tCO2 emitted and increase on a yearly basis to an expected value of £30/tCO2 by 2020 and £70/tCO2 in 2030 (HMRC, 2011).

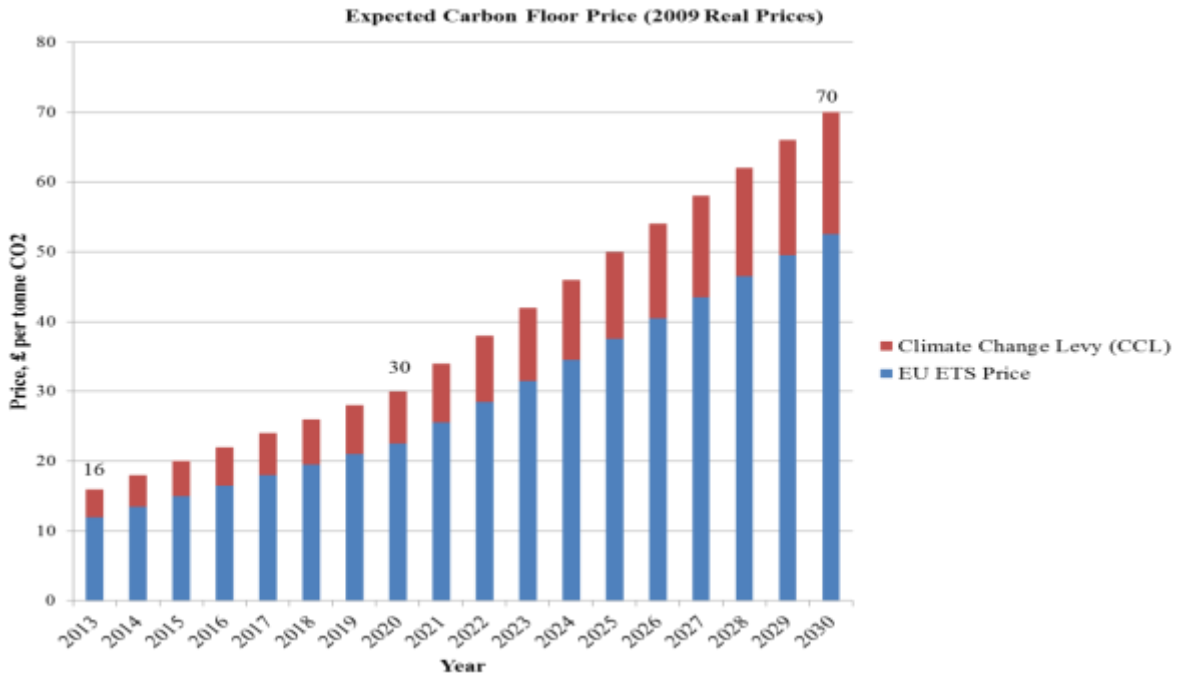

Figure 2.4: Expected Carbon Floor Price (2009 Real Prices)

However, there are some who have criticised the introduction of the UK carbon floor price. While respondents have acknowledged the need for CO_2 abatement, they believe the localised carbon tax will lead to price distortions and a loss of competitiveness in the UK compared to the rest of Europe (HMRC, 2011). Nevertheless – assuming there are no major changes to carbon floor price policies – the cost of CO_2 emissions is expected to increase in the UK in the long-run and power generation operators will be exploring various means of reducing costs to maintain their competitiveness.

2.4 Review of Advanced Carbon Capture Technologies

The various carbon capture technologies available are categorised to their type of carbon removal method and the most ideal method for CTSW which will be used for the models is consequently selected. There currently exist three main categories of carbon capture which are pre-combustion, oxyfuel and post-combustion capture.

2.4.1 Pre-Combustion Carbon Capture

Pre-combustion CO_2 capture is a process where the carbon in the fuel is separated, or removed, before the combustion process. It involves a gasification process whereby the fuel is reacted with insufficient O_2 for complete combustion in order to produce synthesis gases (syngas) which mainly consist of H_2 and CO (Florin-Fennell, 2010). The CO is then converted into CO_2 by reacting the synthesis gases with steam, while also producing more H_2

in the process. The CO_2 is then removed from the syngas mixture using a standard scrubbing process and can then be stored while the H_2 can be used as fuel in power plants or vehicles (Figure 2.5).

The two primary forms of pre-combustion CO_2 capture are through chemical absorbents and physical absorbents (Global CCS Institute, 2012; Florin-Fennell, 2010). Chemical absorbents (e.g. MDEA and other amines) are the same as those used in post-combustion carbon capture, which react with the acid gases to separate them from the syngas mixture. Physical absorbents (e.g. Selexol, Rectisol) work by dissolving the acid gases in the syngas mixture (Global CCS Institute, 2012). (Floren-Fennell, 2010) indicate that the physical absorbents combine less strongly with the CO_2 compared to their chemical counterparts, resulting in a lower energy penalty.

(Bellona) states that pre-combustion capture is capable of removing about 90 % of the CO_2 from a power plant. However, pre-combustion capture requires significant modifications of the power plant as the capture process has to be an integrated part of the combustion process. Hence, it is not suitable for older power plants and cannot be easily retrofitted. Pre-combustion technology has also been found to be less mature than post-combustion capture techniques, which contribute towards the high capital costs and energy losses (Global CCS Institute, 2012).

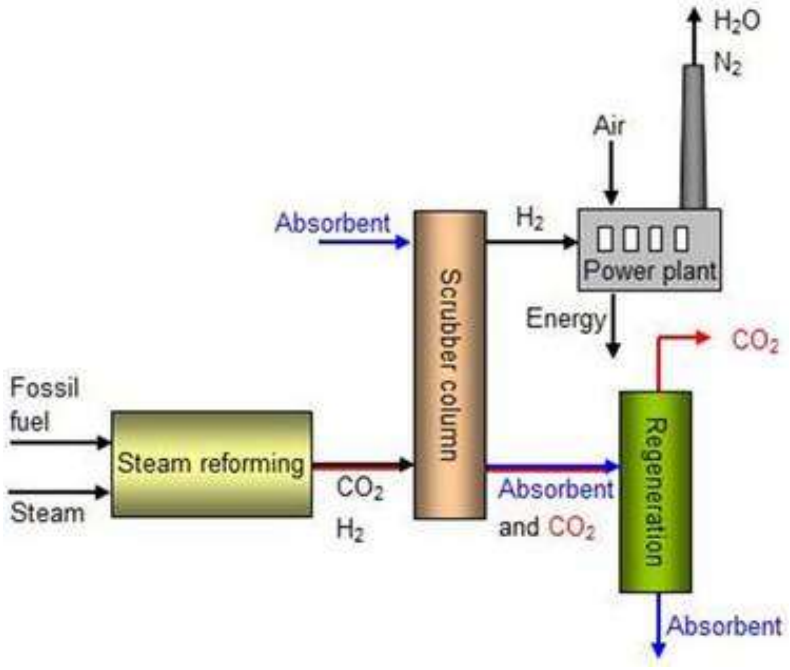

Figure 2.5: Pre-combustion Carbon Capture (Source: Bellona.org)

2.4.2 Oxy-fuel

Oxyfuel combustion involves combusting the fuel in pure O_2 instead, which produces a flue gas containing mainly CO_2 and water vapour as their concentration is not diluted by the presence of N_2 in the air (Floren-Fennell 2012). These two components are easily separated through cooling, following which the water condenses and a CO_2 rich gas-mixture is formed (Figure 2.6). The oxyfuel method's main advantage is its relatively simple CO_2 removal method as it eliminates the use of chemical/physical sorbents used in other methods as well as their associated environmental and monetary impact.

On the other hand, the benefits gained by the relatively simple oxyfuel CO_2 separation method are counterweighed by the need for O_2 separation. The most frequently used method to separate O_2 from air is cryogenic distillation, which is costly and energy-intensive (Floren-Fennell, 2012; Bellona). Combustion of pure O_2 fuel also results in higher operating temperatures (Floren-Fennell, 2012) and is consequently expected to result in high material stresses and failure; hence development of new materials is a necessary for oxyfuel deployment.

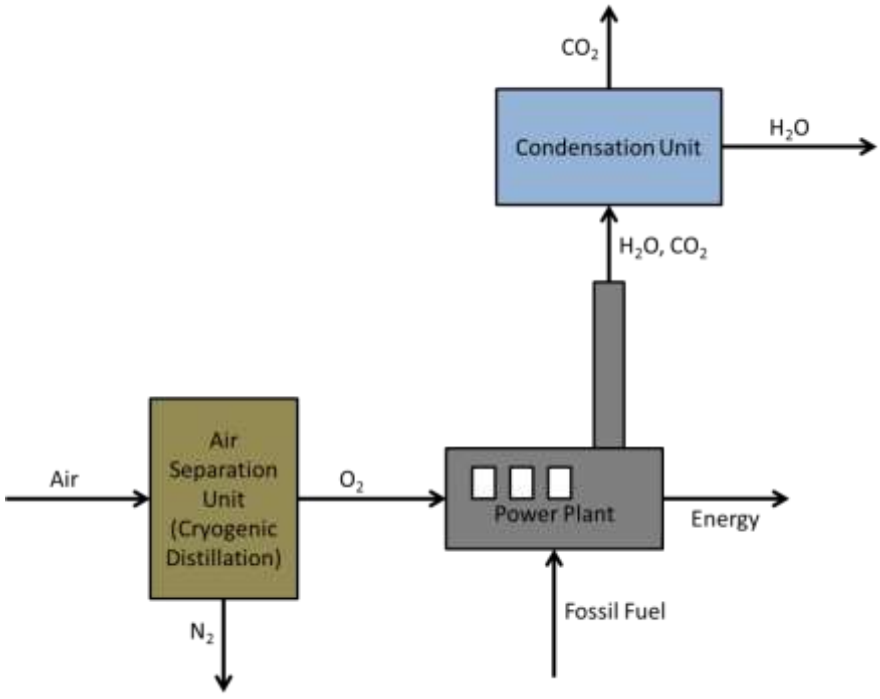

Figure 2.6: Oxyfuel Combustion CO_2 Capture (figure redrawn from Bellona.org)

2.4.3 Post-Combustion Carbon Capture

Post-combustion carbon capture is done by removing CO_2 from the flue gas produced during the combustion of fossil fuel and/or biomass in air. When fuel is combusted in a traditional power plant, the flue gas will typically contain between a few percent to ten percent of CO_2 gas, with the remainder of the gas mixture being mainly N_2 and water vapour (Bellona). The most commonly used technique to remove CO_2 from the flue gas is chemical solvent scrubbing, which is shown in Figure 2.7. Chemical solvent scrubbing segregated into two different methods – absorption, where the CO_2 reacts with a liquid chemical (absorbent) and adsorption, which uses a solid material that allows CO_2 molecules to attach directly to its (the adsorbent's) surface.

Between absorption and adsorption, absorption remains the more mature of the two technologies as there exists many years of experience in the chemical and oil industries to remove acidic gases from gas streams to meet industrial regulations (Kohl-Nielson, 1997). Aqueous amine capture of CO_2 using monoethanolamines (MEA) was first patented by R. R. Bottoms in 1930 (Wallace, 2005) and is currently seen as the primary candidate for large-scale post-combustion carbon capture. Calcium oxide (CaO) is seen as another potentially viable candidate due to the fact that it can be easily derived from natural limestone but still lacks the same technological readiness of MEA.

Many other alternatives for post-combustion capture have been suggested that include membrane separation, physisorbents (e.g. zeolites), activated carbons, chilled ammonia, etc., but they are relatively much less developed compared to MEA. On top of being a mature technology, amine scrubbing post-combustion capture can be easily retrofitted – granted sufficient space is available – to existing power plants and factories unlike pre-combustion and oxyfuel methods. Hence, it can be expected that post-combustion carbon capture will still remain a dominant CO_2 capture path even if pre-combustion and oxyfuel capture methods become more widely accepted.

There are some challenges towards the development of post-combustion carbon capture. The efficiency penalty proves to a significant deterrent to the deployment of carbon capture facilities. Energy is required during the regeneration cycle where heat is needed to separate the sorbents from the CO_2, depleting power plant resources (and revenue). In addition, large scale demonstration of the technology is still insufficient although the technology has been widely implemented in small pilot plants.

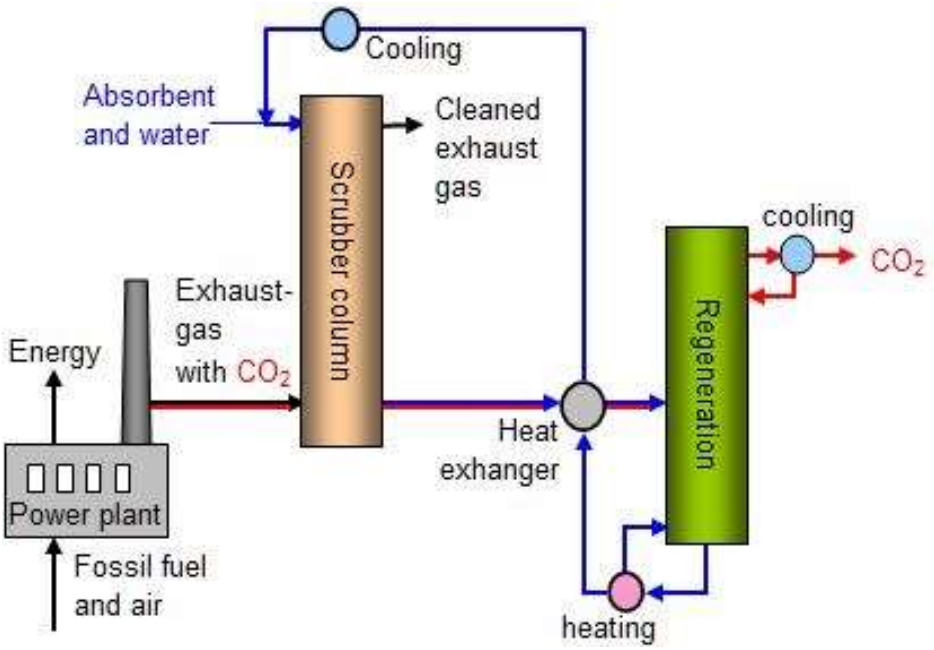

Figure 2.7: Post-Combustion Carbon Capture (Source: Bellona.org)

2.4.4 Selection of Carbon Capture Method

A key criterion for the most suitable carbon capture method for CTSW is that it can be retrofitted to any existing plant as the EfW plant is currently under construction, hence the carbon capture facilities have to be installed after construction is complete. On that basis, the pre-combustion and oxyfuel capture methods are immediately eliminated from the selection possibilities.

As mentioned in **Section 2.4.3**, there are many alternatives among post-carbon capture technologies but only a handful of them have sufficiently developed and tested in-field to be realistically considered as candidates. The following sub-sections will discuss the selection process further based on important performance criteria before coming to a final decision.

Technology Readiness Level

The technology readiness level (TRL) is used as a measuring scale to evaluate the development stage or maturity of a particular technology. The UK Advanced Power Generation Technology Forum has adopted the TRL method (UK APGTF, 2009), defining the readiness levels as shown in Table 2.1. Of the post-combustion capture methods, (Floren-Fennell, 2010) ranked MEA-based sorbent scrubbing as a 6, post-combustion calcium looping between 4-5, algae absorption between 3-4 and 2-3 for second generation sorbents (supported amines, ionic liquids, etc.) and membrane separation. Therefore, from a TRL

point-of-view, MEA remains the main contender for post-combustion carbon capture, with calcium looping a possible choice while the remaining methods can be effectively discounted as they still require more time to be properly deployed.

TRLs	Status
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Technology/part of technology validation in a laboratory environment
5	Technology/part of technology validation in working environment
6	Technology model or prototype demonstration in working environment
7	Full-scale technology demonstration in working environment
8	Technology completed and ready for deployment through test and demonstration
9	Technology deployed

Table 2.1: Summary of Technology Readiness Levels (TRLs) (Source: UK APGTF)

Cost of Absorbent

One key publication addressing the absorbent approximation was written by (Abanades et al. 2004), in which they estimate the cost of sorbent per kg of CO_2 removed from the flue gas (COS). From their study, they had also managed to estimate the degradation half-lives of each of the sorbents, $N_{1/2}$. Some of the results from the paper are shown in Table 2.2:

Sorbent	Cost of Sorbent per tonne of CO_2 removed (COS), €/tonne CO_2	Degradation half-life ($N_{1/2}$), Number of cycles
MEA	1.428	4561
CaO	1.430	12.9
Zeolites	1.295	1849
Hydrotalcites	1.430	33486

Table 2.2: Cost of sorbent per tonne of CO_2 removed and sorbent degradation half life

According to the results from (Abanades et al. 2004), MEA is only slightly cheaper per tonne of CO_2 removed compared to CaO. This is because MEA has to be industrially produced through a synthesis process between ammonia, NH_3 and ethylene oxide, EO while CaO can be cheaply obtained from natural limestone. However, the model by (Abanades et al. 2004) does not consider the additional costs of maintenance and downtime during sorbent replacement. Hence, it is expected that the operation costs of a calcium-looping system will be greater than the value shown in Table 2.2 due to its shorter half-life. Although the zeolites and hydrotalcites lack the technology readiness levels to be applicable, they do show exceptional qualities (COS for zeolites and $N_{1/2}$ for hydrotalcites), demonstrating the potential for future application should they be shown to work in the field.

Efficiency Penalty

The efficiency penalty from installing carbon capture to a power plant exists as the energy is required for the sorbent regeneration cycle and to compress the extracted CO_2. (UK APGTF, 2009) have released a summary which places the expected industry efficiency penalty of MEA-based carbon capture systems between 10-12 percentage point efficiency loss. Separate studies indicate that carbon looping is capable of delivering significant reductions in the efficiency penalty. (Epple-Strohle, 2008; Strohle et al. 2009) states that the efficiency penalty is as low as 6 percentage points for CaO-based systems, which agrees well with the estimates given by (Abanades, 2002) of 6-8 percentage points.

Carbon Capture Method of Choice

Considering all the factors above (TRL, cost of sorbent, efficiency penalty), it was believed that MEA would prove to be a more realistic choice compared to calcium looping. The technological readiness and industrial experience with MEA carbon capture made it a much more reliable selection compared to CaO at the time of this study, even though calcium looping was significantly less energy intensive. Calcium looping techniques will require considerably more testing to demonstrate its feasibility under operation as well as identify any potential obstacles before it could actually be considered.

2.5 Financial Model

There exist many methods to determine the potential profitability of a project which are commonly used in finance. Some of the more conventional methods include the payback period, average accounting return (AAR), profitability index, internal rate of return (IRR) and the net present value (NPV). These capital budgeting methods give managers and investors a better overview in the long-term on where allocate capital when selecting between different projects to develop. These methods use incremental cash flows to form a measurement criterion, from which the 'best' investment can be chosen.

(Graham, 2001) examined the capital budgeting practices among business firms in the US and Canada. He found that about three quarters of all firms use both the IRR (76%) and NPV (75%) methodology, followed closely by the payback period (57%) and less than 40% using other methods. IRR and NPV methods were the most used as they utilised a discounted cash flow methodology, where the time value of money is taken into account while many of the other methods used the book value (no discount rate applied). The two methods also have a well-defined measurement criterion which is easily comparable between different projects.

The NPV is known to be the more accurate measurement between the two but the IRR is much simpler as it uses a constant discount rate. Both these methods are chosen for the CTSW model to provide a means of corroborating our results between different capital budgeting methods.

Parameters of the EfW plant and the greenhouse from the model itself were mostly provided by the sponsoring company (Volker Wessels), including capital costs, expected cash flows and inflation/taxation rates. However, some parameters had to be sourced elsewhere. The municipal waste EfW plant CO_2 EF was approximated to be 1 kg of CO_2 per kg waste as past research showed that it was close to a 1:1 ratio (Johnke, 2001; Burnley, 2007) and allowed for simpler calculations. (Abanades, 2002) proved to be the key paper in determining the cost of sorbent used in carbon capture, as such studies proved to be relatively scarce. The cost of capital of a carbon capture facility was estimated from a similar sized coal power plant as the CO_2 emission levels were closer to that of an EfW plant (compared to natural gas and fuel oil). The (NETL) and (David and Herzog, 2000) provided reasonably similar estimations for the capital cost of carbon capture.

2.6 Comparing power generation EFs

GHG EFs were used to calculate the extent of environmental damage in terms of global warming potential per kWh produced for each power generation technology. The emission factors were mostly obtained from the UK's Department for Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC) GHG EFs report (Defra-DECC, 2012) as well as the Intergovernmental Panel on Climate Change Database (IPCC, 2006). To maintain result consistency, the EFs from (Defra-DECC, 2012) and (IPCC, 2006) were compared with one another, and compared again with a different set of results by the US Climate Registry (CR, 2012).

The EFs provided by some of the sources were calculated using the fuels' specific heat contents. As a result, the obtained EFs were much lower than industrial standards as the values were analogous to generating heat in a 100 % thermally efficient boiler (i.e. less fuel burned per kWh generated). Therefore, the efficiency factors had to be accounted for to find the 'actual' GHG emissions (the method is outlined in Annex 10).

2.7 Environmental Impact Analysis

The Life Cycle Analysis (LCA) is a method to assess the environmental performance of products, from the beginning to the end of their whole lifecycle and hence differentiate the environmental impact and consumption of resources among different systems with similar functions (Blengini and Busto, 2009). Hence, it is commonly used by producers of a certain product to manage and improve the ecoprofile of the related production system (Cellura et al. 2011). The benefits of the LCA is that it prevents a narrow outlook on the environmental impacts of a particular product by compiling all possible energy, material and environmental inputs and releases.

Another method of measuring environmental damage is by measuring the ecological footprint. The analysis approximates the amount of useful land or water area required to sustain a certain activity. The calculation typically converts resource usage into a measure of land area used in global hectares (gha) per capita. However, the LCA method was chosen over this method as the nature of per capita footprinting could lead to biased results, depending on the number of employees hired by operation. The measurement was also not easily comparable results from other papers as the results were usually given in kg $CO_{2(eq)}$.

Tomato production in greenhouses has attracted a lot of attention in similar studies, with papers such as (Carlsson-Kanayama, 1997; Andersson, 2000; Williams et al. 2006), being regularly cited. More recent papers (Cellura et al. 2011; Page et al. 2012) provide a good overview of the available literature on top of their own results to obtain more comparisons of LCA studies on tomato cultivation. (Kelly et al.2010; Page et al. 2012) also provided data for field grown tomatoes to compare with the greenhouse grown LCAs. The location of the study is also understood to have a significant effect on the ecoprofile, with warmer climates requiring less heating (hence energy). The more recent examples used a similar methodology based around the (ISO 14040, 2006) but have distinctive definitions of scope and boundaries.

Accordingly, there exists a range of global warming potentials (GWP) per kg tomato produced, varying between 0.08 to 9.4 kg $CO_{2(eq)}$ per kg tomato produced, depending on the plantation location, cultivation method and LCA definitions. Electricity and heat use is regularly reported to be the major contributor in greenhouse systems, representing between 54-97% of the total GWP impact. Further discussions of the LCA result comparisons between the CTSW output and the mentioned literature will be continued further in the **Results and Discussions** subsection for the CTSW LCA (**Section 4.3**).

3. Methods and Data

The following methods were designed investigate the objectives defined in **Section 1.1**.

3.1 CTSW Financial Model

The CTSW Financial Model aims to determine the economic gain of installing a carbon capture facility to extract and transport CO_2 emitted from the 10.15 MW, 100,000 tonne per year capacity EfW plant flue gases to a 100 hectare greenhouse facility where it is used to stimulate crop growth. The approach we have used is to calculate the Net Present Value (NPV) and Internal Rate of Return (IRR) of the project with and without the inclusion of the CO_2 capture resources. Both methods are frequently used in capital budgeting to measure and compare the profitability of investments. The key attributes of both models are listed below and the methodology is further discussed in the corresponding sub-sections:

- Construction time is negligible
- Discount rate assumed to be constant at 0.38% (UK 1-Year Government Bond Yield) with a project lifetime of 25 years
- Cash flows are in € currency and in nominal terms based on an inflation rate of 2.5%.
- Greenhouse heating cost is neglected as heat should be supplied by the in-built CHP facility, although cost of operating CHP is taken into account

3.1.1 Net Present Value (NPV)

The Net Present Value (NPV) calculated the sum of discounted cash flows throughout a given period. As stated earlier, we have used a project lifetime of 25 years, which is a reasonable timeline for a power generation facility before its closure. The discount rate is assumed to remain constant over the entire test period for ease of calculation, although this may be considerably unrealistic as real world discount rates fluctuate with the general economy and financial climate. All cash flows have been calculated on a nominal basis with an inflation rate of 2.5% per year but should otherwise maintain their real value from year to year. Real values take into account the effects of inflation on the currency value (i.e. cash flows will remain constant if not for inflation). The general rule behind the NPV criterion is if NPV is greater than 0, it will be a profitable project and the more positive the NPV, the greater the expected total returns from the project.

3.1.2 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is another commonly used capital budgeting method. The IRR is a constant discount rate that makes the NPV of all the cash flows from a particular project equal to zero. The IRR uses the same model as the NPV calculation hence similar assumptions apply (i.e. constant real values, inflation rate at 2.5%). Unlike the NPV method, using IRR necessitates the use of a constant discount rate. The minimum acceptance criterion for the project using the IRR method is if the IRR is greater than the actual discount rate (model discount rate at 0.38%). The IRR ranks individual projects, with the project having the highest IRR value being expected to generate the greatest rate of return on capital spent.

3.2 Comparison of Carbon Capture with other forms of power generation

To determine the GHG emissions from power generation systems, it was imperative to first find their EFs in per kWh terms. Assuming for a constant plant capacity of 10.15 MW and 92 % availability, it was then possible to calculate the amount of GHG emitted per year by multiplying the EFs (after accounting for the thermal efficiency) with annual power produced. Consequently, the greenhouse CO_2 utility rate can then be calculated by the expected greenhouse demand by the released CO_2 quantity.

3.3 Life Cycle Analysis (LCA) Model

The two case studies considered are the combined EfW plant and Greenhouse facility with and without the presence of carbon capture. Using the Life Cycle Analysis (LCA) methodology outlined by the international standards of series (ISO 14040, 2006), it is possible to assess the environmental impacts associated with all stages of the tomato fruit production.

3.3.1 Goal and Scope Definition

The main purpose of this LCA study is to determine if extracting CO_2 gas using carbon capture from the EfW plant flue gas for greenhouse enrichment has a reduced global warming impact compared to running them separately. The secondary goal would be comparing the estimated carbon impact per kg of tomatoes produced by the proposed CTSW project with available literature to estimate how it benchmarks against other greenhouse producers.

The scope of the CTSW LCA study is defined as follows:

- Only global warming potential is evaluated, ignoring other forms of environmental impact. The three GHG considered are CO_2, N_2O and CH_4 as they represent approximately 99% of global GHG emissions (IPCC, 2007)
- For the greenhouse, the only electrical and heating requirements are taken into account. The carbon capture facility is assumed to only have electrical power requirements and there are no emissions associated to the EfW power requirements. Emissions associated with the construction, maintenance and management of the EfW plant, greenhouse and carbon capture facilities are ignored
- It is assumed that CO_2 is fully extracted from the flue gas (i.e. 100 % extraction rate) and supplied to the greenhouse for CO_2 enrichment. Once transferred to the greenhouse, the CO_2 is either absorbed during plant photosynthesis or escapes through the air ventilation system.
- It is assumed excess heat from the CHP is transferable and can be used for other purposes besides heating the greenhouse
- CO_2 gases are sent to the greenhouse at ambient temperature
- The impact of fertiliser use in greenhouse is estimated using EFs by (Carlsson, 1997)
- Handling losses are considered by using the loss rates from (Carlsson, 1997). The waste is then assumed to go through Anaerobic Digestion (AD), through which the emissions can be calculated using the appropriate EF (Defra-DECC, 2012). Tomatoes are assumed to be transported to market before handling losses are taken into consideration.
- Seed production, waste production from packaging vegetables and pesticide use associated emissions are neglected
- Model parameters are adopted from CTSW Financial Model unless otherwise stated. Further explanations of calculations are available in the Appendix.

The functional unit for comparison between the two CTSW systems (i.e. with and without carbon capture) is the kg $CO_{2(eq)}$ released per year by both systems. The secondary functional unit under interest is the kg $CO_{2(eq)}$ released per kg of tomato produced that may be used to compare between the two systems or with results obtained in various literature.

3.3.2 System Boundaries

The system boundary determines which unit processes will be included in the LCA. For the global warming impact of the entire systems, the system boundary should include the whole system including power generation, carbon capture/hydrocarbon combustion and tomato

production from cradle-to-market. 'Cradle' refers to the pre-farm processes such as electricity and heating while market is the point at which the crop is sold to the consumer (typically involves transportation and packaging).

On the other hand, the system boundary to calculate the tomato's functional unit should only include CO_2 which is directly linked to the tomato cultivation – i.e. EfW emissions vented directly into the atmosphere should not be considered but CO_2 captured for enrichment will be considered. The CTSW system without carbon capture is assumed to use hydrocarbon combustion as a means of generation CO_2 and its carbon relevant inputs/releases should also be considered. Figure 3.1 and 3.2 details the proposed system boundaries for both scenarios:

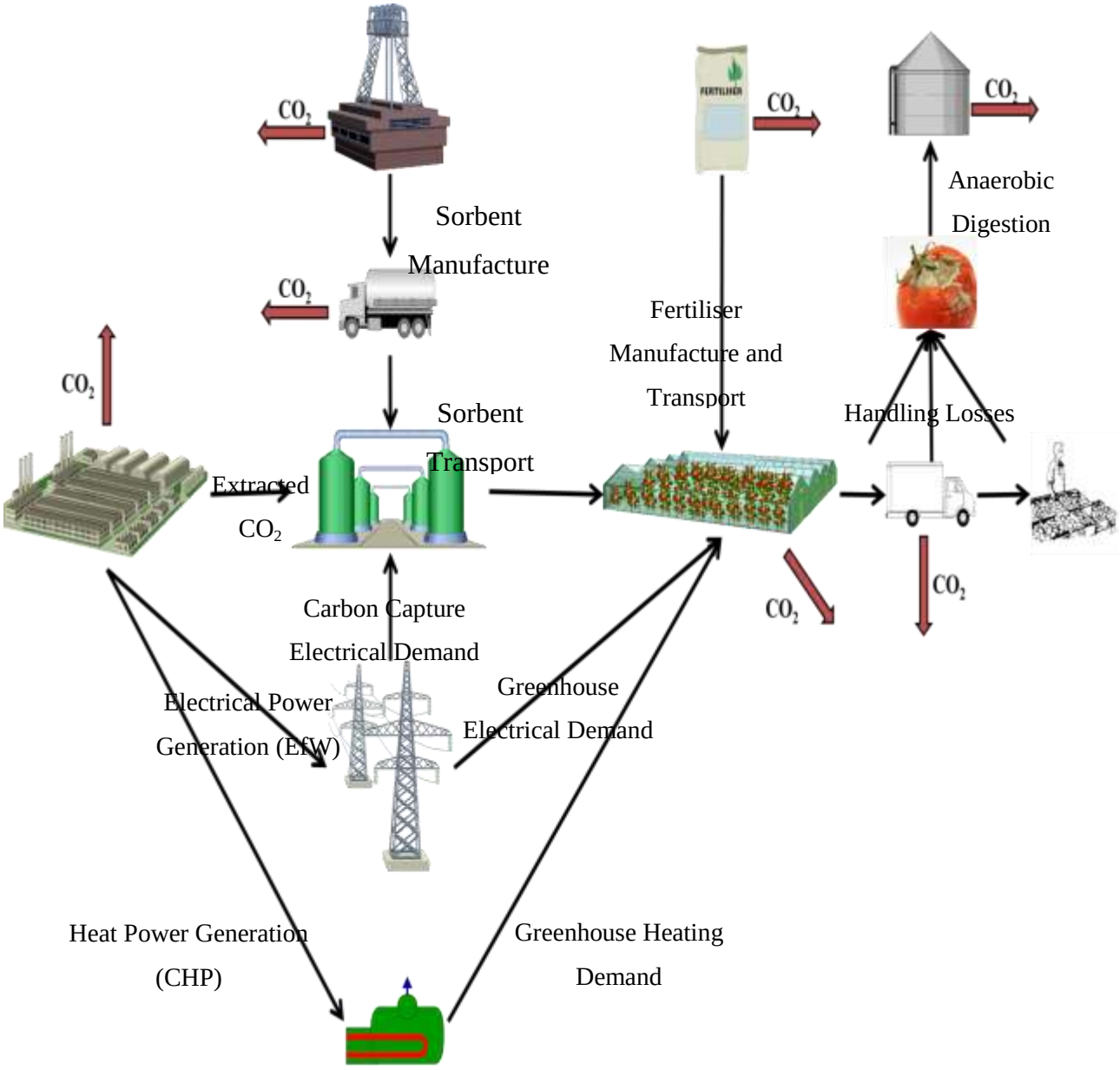

Figure 3.1: CTSW System Boundary (with Carbon Capture)

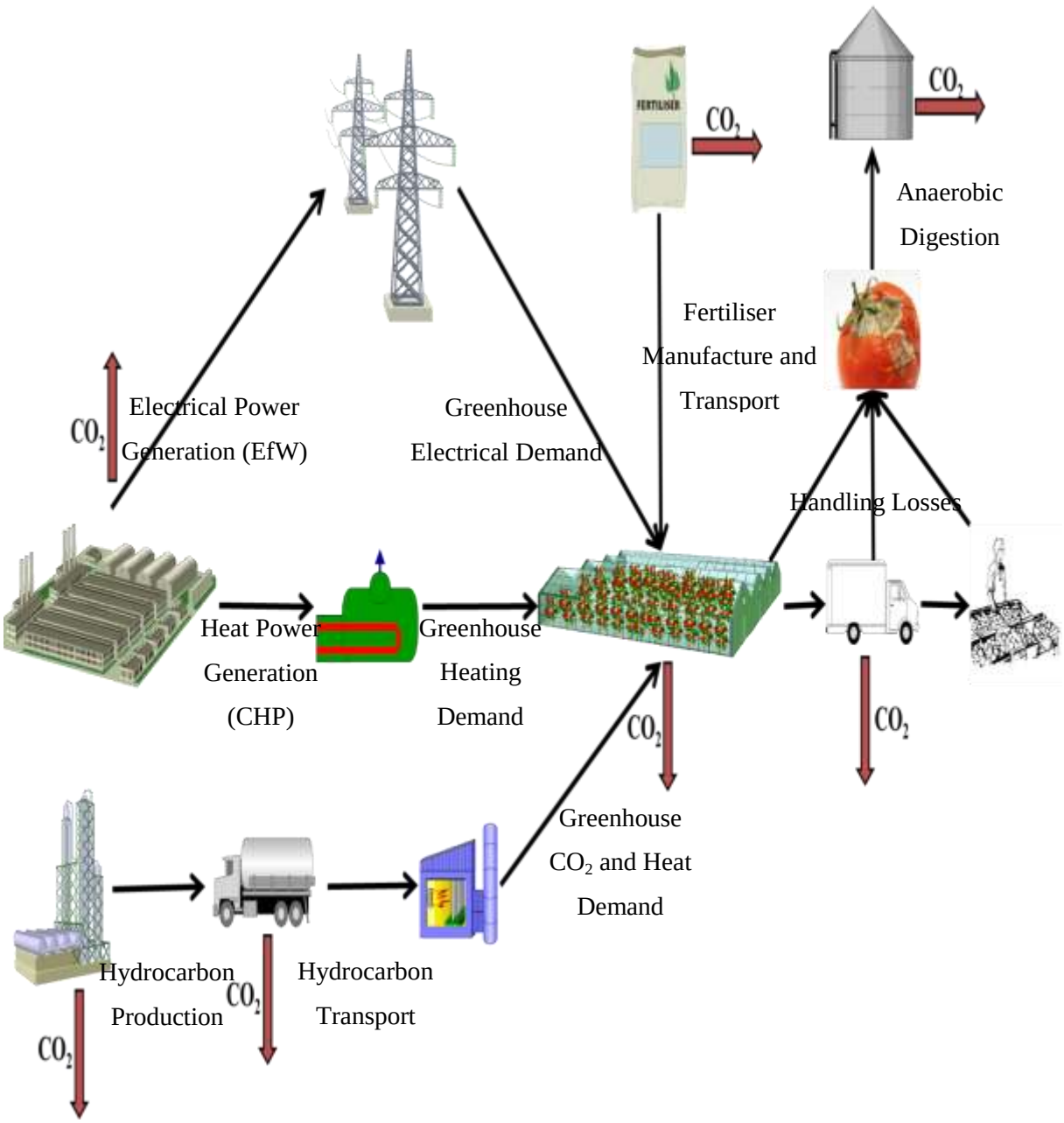

Figure 3.2: CTSW System Boundary (without Carbon Capture)

4. Results and Discussion

This section outlines the key results and discussions pertaining to the respective objectives of this study.

4.1 CTSW Financial Model

4.1.1 Results Comparison and Discussion

Table 4.1 below shows the NPV and IRR values for the CTSW project in four different scenarios, namely the EfW plant alone, Greenhouse alone, EfW plant and Greenhouse combined and lastly considering the EfW plant and Greenhouse connected by carbon capture.

Scenario	**NPV, €millions**	**IRR, %**
EfW Plant Only	169	9.33
Greenhouse Only	308	8.63
EfW Plant and Greenhouse Only	477	8.88
EfW Plant, Greenhouse and Carbon Capture	585	9.73

Table 4.1: CTSW Financial Model Results (with Carbon Floor Price)

The NPV results show some very significant details about the project. Firstly, both the EfW plant and the Greenhouse are "profitable" as stand-alone projects with positive NPV values. The combined EfW plant and Greenhouse also has a positive NPV value which is equivalent to the sum of the individual projects (i.e. 169 + 308 = 477). This is expected as the Present Values of the cash flows should be cumulative between the two projects. Most interestingly however is the fact that the project has the highest NPV value when equipped with the carbon capture facilities.

The IRR method also yields similar results, with all scenarios having higher IRR values than the 0.38% discount rate. The highest IRR value also indicates the EfW plant and Greenhouse combination being the most lucrative when equipped with carbon capture. However, it also shows that the EfW plant has a higher IRR value as a stand-alone installation compared to when combined with the greenhouse. This is likely due to the fact that the IRR method is particularly sensitive to the cost of capital of the project. The greenhouse has an expected capital cost of €199 million compared to the EfW plant's €124 million (including CHP), which could result in the lower IRR values. It also can be interpreted that IRR is a measurement for the project's expected growth rate (Sonin, 1991; Mas, 2005). Hence, the EfW plant would be expected to repay its cost capital earlier than the greenhouse and the

combined installation but the carbon capture retrofit would allow the combined installation to generate better returns in the long run.

The NPV and IRR results demonstrate the significance of the carbon floor price introduction to EfW plant operation costs. The EfW plant in question is expected to use municipal solid waste (MSW) as fuel, which usually contains between 33 to 50 % carbon content (Johnke, 2001; Burnley, 2007). (Johnke, 2001) indicates that the incineration of 1 tonne of municipal waste is associated with the production of about 0.7 to 1.2 tonne of CO_2. This agrees well with (Burnley, 2007) and the (US EPA, 2000) who estimate about 1.25 tonne of CO_2 and 0.985 tonne CO_2 is released per tonne of waste respectively. The high quantities of CO_2 content in the EfW plant flue gas results in a significantly higher operation cost due to the carbon floor price. Therefore, the rate of savings is sufficiently high enough to warrant the large investment costs and energy lost from using carbon capture. From the CTSW financial model, it is estimated that €0.03 is saved (in 2013) per kg tomato produced when carbon capture is used.

Scenario	**NPV, € million**	**IRR, %**
EfW plant and Greenhouse only	645	10.44
EfW plant, Greenhouse and Carbon Capture	658	10.36

Table 4.2: CTSW Financial Model Results (without Carbon Floor Price)

Table 4.2 shows the NPV and IRR results, for the combined EfW plant and greenhouse with and without carbon capture, without the presence of the carbon floor price. Although the NPV with carbon capture is still higher than without it, the difference between the two has significantly decreased. Furthermore, the IRR for the case without carbon capture is now slightly higher compared to when carbon capture is installed. Thus, the proposition of carbon capture is presumably less attractive without the presence of the carbon floor price, but still remains comparable. This was due to the savings from fuel purchases required for CO_2 enrichment offsetting the carbon capture operation costs. The NPV for fuel savings alone was calculated at €93.2 mn compared to the carbon capture operation cost of €63.5 mn per year.

However, calculations suggest that only a portion of the CO_2 released by the EfW plant is required for CO_2 enrichment. The greenhouse was estimated to only require 57.6 Gg of CO_2 per year while the EfW plant would be expected to produce 100 Gg of CO_2 (assuming 1 kg of CO_2 emissions to 1 kg of waste). The high CO_2 composition of the flue gas would result in an

excess of 42.4% of unutilised CO_2 emissions, which would still have to be stored or vented into the air. **Section 4.2** aims to address this issue by pairing the greenhouse with other forms of power generation technology via means of carbon capture to optimise the CO_2 supply and demand levels.

The CTSW financial model clearly demonstrates that there is a sound business case to link the two installations with carbon capture (assuming the carbon floor price continues to support the technology). In the case of CTSW, the EfW amalgamation with the greenhouse may be unsuitable due to the over-supply of CO_2 gas released by municipal waste incineration. But in general, results seem to demonstrate that carbon capture should be implemented with the EfW plant as it brings additional savings by negating the carbon floor price charges. Hence, the model demonstrates one possible example of how the CCL and government policies could influence the adoption rate of green-energy schemes within the UK.

4.1.2 Financial Model Limitations

Limitations within the model include those mentioned earlier in **section 3.1.1** and **3.1.2**. Both the NPV and IRR calculations assume a constant discount rate throughout the testing period which is a reasonably strong assumption. The continual development of carbon capture technologies could also possibly lead to improvements in efficiencies and lower costs. Such cases are difficult to account for as available literature is typically limited as the technology has yet to be properly tested. Additionally, parameter values vary between sources and would therefore probably lead to a degree of inaccuracy in the cash flow calculations.

4.2 Comparison of Carbon Capture with other forms of power generation

4.2.1 GHG Emission Factors (EF)

The EFs used and their respective source for the power generation comparison are shown (in highlight) in Table 4.3. The percentage difference of the IPCC and CR values with respect to the selected EF were then calculated. These EFs include other common GHG on top of CO_2 such as N_2O and CH_4. The global warming potentials (GWP) – which is a relative measure of how much heat a GHG traps compared to CO_2 – for N_2O and CH_4 have been determined range between 298 to 310 years and 12 to 25 years respectively (US EPA; IPCC, 2007) over a 100 year period. The GWPs used for this study are 298 for N_2O and 25 for CH_4.

In general, the percentage difference column shows most of the EFs match well across different sources. The exceptions to these are LNG (Defra-DECC against IPCC), MSW and Biomass (IPCC against CR) showing differences of -25.3%, 8.2% and 22.0% respectively. Between Defra-DECC and IPCC, this is due to the different approaches as IPCC uses the Net Calorific Value (CV) while Defra-DECC use the Gross Calorific Value instead (Webb et al. 2013, NAEI). Therefore, the IPCC EFs would be expected to be larger as a smaller calorific value is being used. The gross CV of LNG is about 10 % higher than that of its net CV, which would contribute to the discrepancy between the Defra-DECC and IPCC EFs.

(Note: [EF in kg $CO_{2(eq)}$/kWh] = [EF in kg $CO_{2(eq)}$/fuel quantity]/[Calorific Value])

With regards to the Climate Registry, the MSW and biomass values have the largest differences. This is likely due to the fact that the calorific values of MSW and biomass fuels vary depending on the composition of the fuel – i.e. individual locations have different fuel mixtures with its own distinctive energy content. MSW incineration EFs are found to vary between 0.4 to 2 kg of $CO_{2(eq)}$ per kg of waste (IEA, 2012), with MSW net CVs ranging from3.5 kJ/kg to 15 kJ/kg (Johnke, 2011). On the other hand, biomass net CVs are reported to be around 17 to 20 kJ/kg for softwood, with the lower limit extending to15 kJ/kg if other forms of biomass fuel are included (Jenkins, 1993). The IPCC values were chosen as they represent a global sample size but the CR values were constrained to the US.

Total GHG Emissions (in kg CO2(eq) per MWh emitted)					
	Source			Percentage Difference	
Fuel Type	DECC	IPCC	CR	IPCC	CR
Coal	899.63	930.84	924.85	-3.47%	-2.80%
Fuel Oil	626.78	653.16	589.95	-4.21%	5.88%
LNG	353.45	442.81	345.25	-25.28%	2.32%
LPG	501.26	531.21	502.10	-5.97%	-0.17%
MSW	N/A	1348.44	1237.92	0.00%	8.20%
Biomass (Wood and Wood Chip)	N/A	1171.97	914.45	0.00%	21.97%

Table 4.3: GHG EFs and Source Comparison

4.2.2 Annual GHG Emissions Comparison and Greenhouse Utility Rate

The breakdown of GHG emissions by each of the power generation systems are shown in Table 4.4. In the left most column, is the net release of GHG which is not transferred to the greenhouse for CO_2 enrichment. These values are always greater than zero even if the CO_2 demand is greater than the amount produced during fuel combustion as the N_2O and CH_4 have to be separated from the CO_2 stream and are released into the atmosphere.

The results show that the MSW incinerators have the largest amount of GHG emissions, followed closely by biomass and then coal. These fuel types are seen as carbon-rich, hence generate a high proportion of CO_2 in their flue gases. MSW and biomass combustion also generate large amounts of secondary GHGs; significantly greater compared to the fossil fuels. Among the fuel types which have an under supply, fuel oil has the greatest effect on global warming due to higher secondary GHG emissions.

Annual GHG produced in 10.15 MW plant with 92% availability (kg CO2(eq) per year)					
Fuel Type	CO2	CH4	N2O	Total	GHG Emitted
Coal	72,969,613	12,853	636,232	73,618,698	16,039,102
Fuel Oil	51,104,772	43,975	141,485	51,290,232	185,460
LNG	28,864,477	42,165	17,178	28,923,820	59,344
LPG	40,952,266	19,120	47,799	41,019,184	66,919
MSW	108,057,357	883,784	1,404,628	110,345,769	52,766,172
Biomass (Wood and Wood Chip)	94,270,322	631,274	1,003,306	95,904,902	38,325,305
CTSW Plant (MSW)	100,000,000	817,884	1,299,891	102,117,775	44,538,179

Table 4.4: Annual GHG Emissions in 10.15 MW plant (92% availability)

The CO_2 utility rate results (Table 4.5) seem show that the two most ideal candidates to be paired with the 100-ha greenhouse are fuel oil and coal. Fuel oil has the closest utility rate to a 100%, with a deficiency of 12.7%. The required CO_2 supply can be delivered using an independent hydrocarbon burner. Alternatively, the coal before plant only produces about 20% more CO_2 than is required (compared to about 40% by MSW and biomass), hence the hydrocarbon burner will not be required as the excess CO_2 produced would act as a buffer between the generator and greenhouse.

The utility rate estimates should be used very cautiously as a form of comparison, as other following factors would affect the choice of power generation:

- The greenhouse in CTSW is a particularly large facility at 100 hectares. Its size puts it on par with the total greenhouse area in entire province of Alberta, Ontario of 117 hectares (Chaudhary, 2011). (Hackman, 1998) denotes that commercial greenhouses in California typically lie between 0.14 to 0.33 hectares in area while the average greenhouse area in Netherlands is about 3.3 hectares (OCAP Factsheet, 2012).
- Only the GHG emissions were considered in this study. There exist many other gaseous components in the exhaust gas which could be harmful to plant growth – i.e. Hg, SO_x, NO_x, etc. The composition of these particles would differ between fuel types and within

MSW itself because of the inconsistency of its mixture, requiring a more complicated clean-up system.

- Both the CO_2 supply and demand are cyclic within a daily and yearly basis. Plant CO_2 demand is expected to be the highest during the summer months but consumer power demand would decrease during this time. This is also true in the opposite direction during winter months, as plant CO_2 demand is low but consumer power demand is at its peak, which can cause supply-demand matching issues. There are fewer complications on a daily basis, as peak power and plant CO_2 demand typically occur during the day.

The results should hence only be used as a simple guidelines but serves to provide a method of comparison to the suitability of a power generation form and can be extrapolated to incorporate different greenhouse sizes and parameters should it be required. For CTSW, the poor choice of MSW creates an excess of CO_2 which is still vented into the atmosphere, adding to the installation carbon tax cost and footprint.

Utility rate for CO2 in Greenhouse		
Fuel Type	Utility Rate	Excess/Deficiency Percentage
Coal	78.9%	21.1%
Fuel Oil	112.7%	-12.7%
LNG	199.5%	-99.5%
LPG	140.6%	-40.6%
MSW	53.3%	46.7%
Biomass	61.1%	38.9%
CTSW Plant (MSW)	57.6%	42.4%

Table 4.5: Utility Rate and Excess/Deficiency Percentage for CO_2 by Greenhouse

4.3 Life Cycle Assessment Model

4.3.1 Overall System GWP

GWPs of the case studies' process units with and without carbon capture are shown in Table 4.6 and 4.7 respectively. Comparing the two, the scenario with carbon capture has a 4.62 % smaller global warming impact compared to the scenario using a hydrocarbon combustor, amounting to 11.6 Gg of GHG emissions a year. Hence, results suggest the use of carbon capture to meet the CO_2 enrichment needs appears to be the more eco-friendly alternative compared to burning hydrocarbon fuels. However, the difference may not be substantial enough to convince sceptics of the setup's viability.

The reason for this is the greenhouse heating requirement through the year, comprising of 64.2 % of the greenhouse's GHG emissions. This is equivalent to approximately 2.06 kg $CO_{2(eq)}$ or 7.43 kWh per kg tomato for heating alone. (Carlsson, 1997) indicates that the EF attributable to heating vary between 3.5 to 5 kg $CO_{2(eq)}$ per kg tomato produced in various Scandinavian countries. (Page et al. 2012) states that the average heating emissions in lie roughly around 1.43 to 1.56 kg $CO_{2(eq)}$ per kg tomato, contributing 83-85% of emissions at farmgate and 54-83% from cradle-to-plate. (Williams et al. 2006) suggests that 97 % of energy consumption is due to heating and electricity. It is thought that the differences between the obtained results and the above literature owes to the inclusion of CO_2 enrichment into the LCA, contributing 26% of the overall emissions.

In the hydrocarbon combustor scenario, heat is supplied in situ with the CO_2, reducing the severity of the greenhouse heat demand. It was noted that the CO_2 gas contains low levels of heat when first exhausted but this would be lost during the extraction by the CHP infrastructure.

With CCS	Units (kg CO2e/yr)
EfW Plant	
EfW Emission (uncollected)	44,538,179
Carbon Capture	
Carbon Capture Adsorbent Production	780,948
Carbon Capture Adsorbent Transportation	104,128
Carbon Capture Electrical Energy Demand	7,946,186
Greenhouse	
Greenhouse Electrical Energy Demand	8,847,300
Greenhouse Heating Energy Demand (CHP)	144,505,900
CO2 required for enrichment (from EfW Flue Gas)	57,579,597
CO2 absorbed by Tomato Plants	(10,512,000)
CO2 associated with Produce Waste (Anaerobic Digestion)	5,665,800
CO2 associated with Tomato Transport	4,968,460
CO2 associated with Fertiliser Usage	3,528,000
Total Emitted GHG	267,952,498

Table 4.6: Breakdown of individual process unit GHG emissions (with carbon capture)

Without CCS	Units (kg CO2e/yr)
EfW Plant	
EfW Emission (uncollected)	102,117,775
CO2 Enrichment (Propane Combustion)	
Hydrocarbon Combustion (CH4 and N2O only)	94,078
Hydrocarbon Production	7,217,676
Hydrocarbon Transport	9,217,593
Heat Supplied by Hydrocarbon Combustion	(53,661,378)
Greenhouse	
Greenhouse Electrical Energy Demand	8,847,300
Greenhouse Heating Energy Demand (CHP)	144,505,900
CO2 required for enrichment (from Hydrocarbon Combustion)	57,579,597
CO2 absorbed by Tomato Plants	(10,512,000)
CO2 associated with Produce Waste (Anaerobic Digestion)	5,665,800
CO2 associated with Tomato Transport	4,968,460
CO2 associated with Fertiliser Usage	3,528,000
Total Emitted GHG	279,568,801

Table 4.7: Breakdown of individual process units GHG emissions (without carbon capture)

4.3.2 Per kg Tomato GWP

As a whole, the systems generate 2.37 and 2.54 kg $CO_{2(eq)}$ per kg of tomato produced. Several studies of the LCA of tomato cultivation provide benchmarks to which the CTSW estimates can be compared to. In general, environmental burdens between different sources were found to be largely inconsistent as a consequence of cultivation techniques, local environments and system boundaries used. (Cellura et al. 2011) compiled a list of global warming potentials (GWP) of relevant studies in Europe, which was combined with (Page et al. 2012) and the CTSW values to produce Table 4.8.

The CTSW GWPs correlate reasonably well with (Carlsson, 1997), probably due to the similarities in climate however (Williams et al. 2006) shows GWPs nearly four times higher than the CTSW results in a comparable sample area (possibly due to the auxiliary heating system). Tomato cultivation is shown to have the least environmental burden in the Mediterranean case studies as shown by (Cellura et al. 2011; Anton et al. 2005), having GWPs nearly 30 times smaller than the CTSW estimates. (Page et al. 2012) indicates that field-grown tomatoes contribute 0.66 kg $CO_{2(eq)}$ per kg tomato on average from cradle-to-market including the increased transportation effects by reason of the field's outlying locations. This agrees well with (Kelly et al. 2010) who determined field grown tomatoes to have GWPs of 0.645 kg $CO_{2(eq)}$ per kg tomato.

Therefore, CTSW grown tomatoes show competitive GWPs compared to greenhouses under similar climates but field-grown and tomatoes grown in greenhouses under warmer conditions have been reported to exhaust significantly smaller carbon footprints. It is thought that this is mainly due to the lesser heating and electricity demand during the warmer months or in more temperate countries.

Functional Unit Index (kg $CO_{2(eq)}$ per kg tomato)	Details	Reference	LCA Steps Included
0.74	Mediterranean greenhouses	Cellura et al. 2011	Greenhouse Structure; Tomato Production (Land treatment, seeding, fertilization, irrigation); Harvest, transport and packaging; Transport to retailer; Waste management
9.4	Northern European Greenhouses	Williams et al. 2006	Greenhouse Structure; Tomato Production (Auxiliary heating and ventilation on are taken into account)
0.0814	Mediterranean greenhouses, spring-summer cycle	Anton et al. 2005	Greenhouse Structure; Tomato Production (Use of fertiliser and CO2 absorbed by groves are estimated)
3.3	Swedish (or countries nearby) greenhouses	Carlsson-Kanayama, 1997	Production of fertilisers; Tomato Production (Fertilisation, seeding and crop); Transports (refrigeration considered); Sale to retailer
2.28	South-Eastern Australia greenhouses	Page et al. 2012	Greenhouse Structure; Tomato Production (Fertilization considered); Harvest, transport and packaging; Transport to retailer; Waste management; Consumer use phase considered
Carbon Capture: 2.37 Hydrocarbon: 2.54	Based on Dutch greenhouses	CTSW Model	Tomato Production (Fertilization and CO2 absorbed by plants estimated); Adsorbent/hydrocarbon production; Transport to retailer; Only tomato handling losses considered; (Anaerobic digestion used as waste treatment method)

Table 4.8: Comparison with literature LCA studies on tomato cultivation, adapted from (Cellure et al. 2011)

5. Conclusion

'Green' government policies, such as the carbon floor price in the UK, serve as the fundamental motivating factor for industry players to reduce their total environmental impact. Although both crop CO_2 enrichment and carbon capture practices have been around for many years, only recently have their possible synergies become potentially viable from an economic point of view. OCAP have demonstrated that CO_2 enrichment can be supplied through extraction from industrial flue gases, utilising waste CO_2 to increase crop yield instead of polluting the environment. CTSW has tried to emulate the OCAP example and some of the highlights derived from this study include:

- Only post-carbon capture was possibly viable in the CTSW project due to its ability to be retrofitted into the EfW instalment. Among post-carbon carbon technologies, MEA was selected as the CO_2 capture method of choice as had respectable performance qualities across the board and was the closest to a market technology with a TRL of 6. Research has shown that other methods have the potential to achieve greater returns compared to MEA. For instance, CaO-based carbon removal only has an efficiency penalty of between 6-8 percentage points (compared to MEA-based with a loss of 10-12 percentage points) but only has a TRL around 4-5, therefore requiring further development before it can be reasonably considered.
- The CTSW Financial Model results seem to suggest the inserting carbon capture between the EfW plant and the greenhouse is a worthwhile investment, yielding greater NPV and IRR results (€585 mn, 9.73%) compared to the similar system without carbon capture (€477 mn, 8.88%). This is partially due to the use of MSW in the EfW plant, which has a (approximately) 1:1 waste to CO_2 mass release ratio, therefore resulting in superior savings from the CO_2 emission channelled to the greenhouse. The carbon floor price proves to be the key stimulating factor, increasing the cost of polluting which compels power generation operators to look for means to reduce GHG emissions. Without the presence of the carbon floor price, it is shown that the NPV and IRR values of the system with and without carbon capture are (€658 mn, 10.36%) and (€645 mn, 10.44%) respectively. Although the installation of carbon capture does become less attractive because of this, it also shows that the savings from the absence of fuel procurement (for CO_2 enrichment) presents a noteworthy incentive for the operators to install carbon capture, even without the carbon floor price.

- On comparing the greenhouse and carbon capture with different forms of power generation, it was found the MSW EfW plants are among the more unsuitable candidates to be connected to a greenhouse. This is because of the high levels of GHG emissions lead to a surplus of unused CO_2 which still has be stored or vented into the air (in excess of 40%). Biomass also suffers from a similar situation of releasing large quantities of GHG, resulting in excess rates of close to 40% and thus making it unsuitable. On the other hand, LNG and LPG are also incompatible but for the opposite reason of producing too little CO_2, with deficiency rates of -99.5% and -40.6% compared to the 100ha greenhouse demand. The utility rates for fuel oil and coal were much more promising, having deficiency and excess rates of -12.7 % and 21.1 % respectively. It should be noted these results should be considered preliminary due to the specific nature of the CTSW system.
- The LCA model showed the use of carbon capture does indeed lead to a lower environmental burden by the system, releasing 11.6 Gg $CO_{2(eq)}$ less per year. However, the magnitude of the difference is limited by the heating requirements (~ 64.2 % of energy demand) of the greenhouse, as hydrocarbon combustion produces nearly 40% of the required heat concurrently with CO_2 gas but the flue gas CO_2 carries little or no heat. Similarly, the per kg of tomato produced gives a GWP of 2.37 kg $CO_{2(eq)}$ with carbon capture compared to 2.54 kg $CO_{2(eq)}$ without. The results also agreed reasonably well with various LCAs from available literature. In general, the CTSW tomatoes have less GWPs compared to similar Northern European greenhouses (between 3.3 – 9.4 kg $CO_{2(eq)}$ per kg) but tomatoes grown in more temperate regions showed significantly reduced carbon footprints (0.0814 – 0.74 kg $CO_{2(eq)}$ per kg). Field-grown tomatoes are also found to have lower GWPs of 0.645 – 0.66 kg $CO_{2(eq)}$ released per kg of tomato produced. It is eminent that results from different literature LCAs are taken with caution as cultivation methods, system boundaries, local climate and season during the test period all have significant effects on the final GWP and conditions differ between papers.

6. Further Research

The development of CaO and other CO_2 removal methods presents an opportunity for greater research of the technology as more pilot plants are installed and they become better understood, possibly replacing MEA-based techniques in such setups. Given more time, it would have been interesting to properly deconstruct the flue gas compositions of each power generation systems to determine the degree of cleaning required and hence further dividing ideal and non-ideal candidates. For the LCA model, the system boundary could be expanded to include other inputs (i.e. construction, maintenance, waste management, etc.) to gain insight into the overall environmental impact of tomatoes grown in the CTSW system. Comparisons should also be done between the environmental burden of similar crops grown in the CTSW setup with those grown in Mediterranean countries and transported to the UK to establish the more eco-friendly form of tomato cultivation.

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8. Appendix

Annex 1: Method of Calculation for CO_2 Supply to Greenhouse

Description of method used to calculate quantity of CO_2 needed in kilograms to be supplied to 100 m2 area of greenhouse per hour (i.e. kg CO_2 per 100 m2 per hr) and total annual CO_2 supply needed.

The Enrichment Standard is the additional concentration in ppm of CO_2 required in the greenhouse to reach ideal levels of CO_2 enrichment for plant growth.

[Enrichment Standard] = [Ideal CO_2 Concentration] – [Atmospheric CO_2 Concentration]

Therefore, kg CO_2 to bring enclosed room to ideal CO_2 concentration is

[kg CO2 needed to reach ideal CO_2 concentration] = [Enrichment Standard in ppm]*[Room Volume]*[Density of CO_2]

The concentration of CO_2 is reduced mainly due to the exchange of air between the inside and outside of the greenhouse as well as CO_2 absorption during the plant photosynthesis process. Hence, the mass of CO_2 supply per 100 m2 per hour required is:

[kg CO_2 supply per 100 m2 per hr] = [Enrichment Standard in ppm]*[Greenhouse Volume per 100 m2]*[Density of CO_2]*[Number of Air Exchanges per Hour] + [kg CO_2 lost through photosynthesis per 100 m2 per hr]

Therefore, the total annual CO_2 supply needed for the greenhouse is found as:

[Annual CO_2 Supply] = ([kg CO_2 supply per 100m2 per hr]*[Area of Greenhouse in m2]*[CO_2 supply uptime per day]*365)/100

Annex 2: Method for Calculating quantity of CO_2 released in EfW Plant flue gas

Description of method used to calculate CO_2 EF from energy derived through municipal solid waste (MSW) combustion in terms of kg CO_2/MWh produced

(Johnke, 2001) states that 1 Mg of municipal solid waste combustion in incinerators is associated with the production of 0.7 – 1.2Mg of CO_2 output. A separate report by the US Environmental Protection Agency (US EPA) provides agreeing values, averaging at 0.985 Mg CO_2 per 1 Mg of municipal waste combusted. For this study, an emission factor of 1 Mg of CO_2 released per 1 Mg of municipal waste combusted is used for ease of calculation.

Therefore,

[Annual CO_2 Production from EfW Plant] = [EF]*[Total Annual Mass of Waste Processed]

Annex 3: Method of Calculation for CO_2 Sorbent Cost

Description of method used to calculated cost of sorbent (in €) per kg CO_2 removed from flue gases

(Abanades et al. 2004) describes a method of quantifying the sorbent cost per kg CO_2 removed from flue gases by using the molar flows of CO_2 sorbent during CO_2 removal. Sorbent costs are converted to the nominal prices of their respective years by using an inflation rate of 2.5%.

Annex 4: Method of Calculation for Carbon Capture Capital Costs

Description of method used to estimate the capital cost for the carbon capture facilities

A paper by the (NETL, 2008) estimates that the incremental cost of capital of installing carbon capture in a pulverised coal plant would be 1321 $/kW (averaged). Similarly, (David and Herzog, 2000) estimated that the incremental cost for pulverised coal in 2000 would be 1140 $/kW, which agrees relatively well with the NETL's result. Pulverised coal was used as the high CO_2 content in the flue gases would better represent the EfW plant flue gases.

As it was deemed more prudent to account for the worst case scenario, the NETL's result of 1321 $/kW was used in this study. The effects of inflation and technological development are ignored as their effects on the incremental cost would cancel each other out to a certain degree. The EfW plant in question is expected to provide, on average, 10.15 MW of power.

Hence Capital Cost of Carbon Capture Facility = 1321*0.76*10.15*1000 = 10.19 million €

Annex 5: Method of Calculation for Carbon Floor Price

Description of method used to estimate the carbon floor price (i.e. carbon tax) in € per kg CO2 released

According to (HMRC, 2010), the carbon floor price begins at around £16/tCO_2 in 2013 and follows a straight line trajectory to £30/tCO_2 in 2020, rising to £70/tCO_2 in 2030. These values are in 2009 real prices and thus have to be converted into a nominal price for its respective year before being used in the CTSW financial model. Real values adjust the nominal values for inflation; hence any differences are then attributed to actual changes in the carbon floor price and not to monetary time effects (i.e. inflation). To convert the real values to nominal values, an inflation rate of 2.5% is used to calculate the nominal carbon floor prices of the time period considered. For example:

The nominal price for a specific year would be the [Real Price]*$(1.025)^n$, where n is the number of years between 2009 and the year in question. So, the 2013 nominal floor price would be equal to (16)*$(1.025)^4$ = £17.66/tCO_2. Similarly, for 2020, the nominal floor price would be (30)*$(1.025)^{11}$ = £39.36/tCO_2. The values are then converted into Euros using an exchange rate of 1.17€/£ to give €20.66/tCO_2 and €46.04/tCO_2.

For years beyond 2030, it was assumed that the carbon floor price would increase by about £4/year in real prices, following the same rate of increase between 2020 and 2030.

Annex 6: Method of Calculation for CO_2 Utility Rate in Greenhouse with different generation technologies

Description of method used to calculate CO_2 utility rate of the greenhouse compared to the total CO_2 produced from the flue gases of different power generation technologies.

The results allows the comparison of the degree of excess CO_2 produced which cannot be absorbed by the greenhouse and hence determine more suitable technologies which the greenhouse can be paired with using carbon capture**.** The carbon EFs were mainly found from the (Defra-DECC, 2012) except for Municipal Solid Waste (MSW) and Biomass which were obtained from the (IPCC, 2006) as they were unavailable in (Defra-DECC, 2012)

Note: The EFs provided assume 100% thermal efficiency. The EFs used also only consider the direct GHG emitted from the power generation operation which is typically fuel combustion while indirect emissions from other activities (i.e. transport and fuel processing) were ignored.

The obtained EFs in kg $CO_{2(eq)}$ per kWh energy produced are shown in Table 8.1:

Emission Factor (kg CO2(eq) per kWh)					
Fuel Type	CO2	CH4	N2O	Total	Source
Coal	0.341	0.00006	0.00297	0.34366	Defra/DECC
Fuel Oil	0.267	0.00023	0.00074	0.26826	Defra/DECC
LNG	0.185	0.00027	0.00011	0.18521	Defra/DECC
LPG	0.214	0.00010	0.00025	0.21454	Defra/DECC
MSW	0.330	0.00270	0.00429	0.33711	IPCC
Biomass	0.403	0.00270	0.00429	0.41019	IPCC

Table 8.1: EFs for different power generation technologies

Accounting for thermal efficiencies of each of the power generation systems:

To produce E MWh of energy, let us say we have to burn *x* amount of fuel at 100% thermal efficiency. However, the actual thermal efficiency is η, where $0<\eta<1$, so burning *x* fuel will only provide ηE MWh worth of energy. Hence, to produce E MWh with thermal efficiency, η, the quantity of fuel combusted needs to increase by the order of $(1/\eta)$. Assuming there is no change in CO_2 equivalent emitted per kg fuel burned with thermal efficiencies, the quantity of CO_2 equivalents emitted per useful/real MWh produced is also increased by $(1/\eta)$.

The thermal efficiencies used to calculate the actual EFs and the actual EFs themselves are shown in Table 8.2 and 8.3:

Efficiency of Generation Systems		
Fuel Type	Thermal Efficiency,η	Source
Coal	38.2%	Klassen, 2011
Fuel Oil	42.8%	Klassen, 2011
LNG	52.4%	Klassen, 2011
LPG	42.8%	Klassen, 2011
MSW	25.0%	Defra, 2007
Biomass	35.0%	Eurelectric, 2003

Table 8.2: Power Generation Thermal Efficiencies

Emission Factor (in kg CO2(eq) per MWh emitted)				
Fuel Type	CO2	CH4	N2O	Total
Coal	891.70	0.16	7.77	899.63
Fuel Oil	624.51	0.54	1.73	626.78
LNG	352.73	0.52	0.21	353.45
LPG	500.44	0.23	0.58	501.26
MSW	1320.48	10.80	17.16	1348.44
Biomass (Wood and Wood Chip)	1152.00	7.71	12.26	1171.97
CTSW Plant (MSW)	1222.02	9.99	15.88	1247.90

Table 8.3: EFs for Different Power Generation Systems with thermal efficiencies considered

Note: CTSW Plant EFs calculated from case study values

The EFs are then paired with power plants of similar power capacity as the EfW plant in question (i.e. 10.15 MW) with an availability = 0.92 to find the amount of CO_2 emitted by each form of generation.

From Annex 1, we can find the annual CO_2 supply required by the greenhouse facility. By dividing the annual quantity of CO_2 produced by each power generation system with the total CO_2 supply required by the greenhouse, we can find the CO_2 utility rate of the greenhouse as well as the excess/deficiency percentage between the greenhouse and generation form.

e.g. for the greenhouse, [Annual CO_2 Supply] = $57.6 * 10^6$ kg/yr
Therefore, Utility Rate for Coal = $(57.6 * 10^6)/(79.6 * 10^6)$ = 72.3% and the Excess Percentage = 27.7%

Annex 7: Method of Calculating CO_2 outputs in Carbon Footprint Model

Description of methods used to calculate CO_2 equivalent output from various sources in the EfW plant and Greenhouse system (with and without the presence of Carbon Capture)

A7.1 CO_2 emission from energy (electricity and heat) consumed in greenhouse

The Dutch Greenhouse industry benchmark for electricity energy intensity was found to be 15 kWh/m2 [Energy Benchmarks and Saving Measures for Protected Greenhouse Horticulture in the UK] of greenhouse area. Therefore,

[Greenhouse Electrical Energy Consumption] = [Electrical Energy Intensity]*[Total Greenhouse Area]

Using the CO_2 EF (Defra-DECC, 2012), total annual emissions can be found:

[Annual Electrical $CO_{2(eq)}$ emissions] = [Greenhouse Electrical Energy Consumption]*[Emission Factor per kWh Electricity Consumed]

As the EfW plant is equipped with CHP facilities, heat and electricity can be produced simultaneously and hence, the emissions are not mutually independent (i.e. emissions are associated with both electricity and heat energy production). CO_2 emissions are expected to be pre-dominantly due to heat generation, therefore annual $CO_{2(eq)}$ emissions due to heating:

[Annual Heating $CO_{2(eq)}$ emisions] = [Heating Energy Intensity]*[Total Area]*[Emission Factor per kWh Heating Consumed] – [Annual Electrical $CO_{2(eq)}$ emissions]

Note: Electrical CO_2 emissions are subtracted from the heating emissions so as not to double-count the emissions. Heat emitted during propane combustion should also be taken into account for the case without carbon capture.

A7.2 CO_2 emission from CO_2 Enrichment

The net CO_2 emissions from the carbon dioxide enrichment process is the total amount of CO_2 which leaks out from the greenhouse compound. It is assumed that all CO_2 supplied to the greenhouse is either absorbed by the plants photosynthesis or leaks through the ventilation/windows during air exchanges between the greenhouse and outside air. Hence, [Net CO_2 emissions due to CO_2 Enrichment] = [CO_2 supplied to greenhouse] – [CO_2 absorbed during plant photosynthesis]

A7.3 CO_2 emission from greenhouse miscellaneous activities (Handling Losses, Tomato Transport, Fertilisers)

(Carlsson, 1997) states that approximately 50g of $CO_{2(eq)}$ are released during production and transportation of fertilisers needed per kg tomato consumed. The total GHG impact is then found by multiplying this with the total tomato output per year – i.e. 70,000 tonne.

A7.4 CO_2 emission from Carbon Capture Activities (Production, Transportation and Operation)

Production

The total mass of sorbent used per year is estimated to be approximately 210 tonnes of monoethanolamine (MEA) by dividing the total cost of sorbent used per year by the cost per unit mass of sorbent (i.e. €1.97/kg sorbent). According to (Ruehl et al., 1997), a 10:1 molar ratio of ammonia (NH_3)/ethylene oxide (EO) can be used to produce virtually a composition of virtually all MEA. The EFs for both NH_3 (US EPA) and EO (NEAA, 2006) were then used to calculate an estimate for the EF for MEA production.

Transportation

The total mass of sorbent is also used to calculate the total emissions from MEA transportation (over a distance 700km) to the EfW plant by multiplying it with the EF of a 5.5 tonne (average) Freight Truck in units kg $CO_{2(eq)}$ per km per kg (Defra-DECC, 2012).

Operation

Carbon capture operations are expected to subject the operating power plant to an energy penalty of 0.135 kWh/kg CO_2 removed. This energy is used power the carbon capture process as well as compress the CO_2 gas extracted from the flue gas. Therefore, the carbon capture energy demand is (0.135)*(100*10^6) = 13.5*10^3 MWh/yr. The total $CO_{2(eq)}$ emission attributed then calculated by multiplying the energy demand with the EF per kWh electricity consumed

A7.5 CO_2 emission from Hydrocarbon (Propane) Combustion

Production

To calculate the quantity of propane fuel needed, [Quantity of fuel] = [Required CO_2 supply]/[Direct CO_2 emission factor]. The indirect GHG EF from (Defra-DECC, 2012) for propane (LPG) production were used and multiplied by the total quantity of fuel needed.

Transportation

Similar to transportation of Carbon Capture Sorbent, propane fuel is transported over a distance of 700 km and utilises a similar carbon EF (5.5 tonne averaged freight truck).

Combustion

The difference between the carbon enrichment method using carbon capture and hydrocarbon combustion is that hydrocarbon combustion produces heat as well as additional GHG emissions (N_2O and CH_4). The N_2O and CH_4 emissions are simply calculated by multiplying their respective EFs during propane combustion by the total amount of fuel.

The heat content of propane (CR, 2012) could be multiplied by the total fuel combusted during the course of the year to calculate the amount of heat supplied to the greenhouse. Assuming the combustion system is located relatively close to the greenhouse, heat transfer losses should be minimal and hence it can be assumed that the full proportion of heat emitted is absorbed by the greenhouse. This results in a lower greenhouse heating demand from CHP when the hydrocarbon combustion system in used.