# The Feasibility of Biomass CHP as an Energy and $CO_2$ Source for Commercial Glasshouses

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**Abstract:** A techno-economic modelling tool has been developed to examine the feasibility of biomass combined heat and power (CHP) technologies to provide the energy and $CO_2$ demands of commercial horticultural glasshouses. Using the UK as a case study, energy and $CO_2$ demands of candidate glasshouse installations on an hourly basis are established using both measured and benchmark datasets. Modelled electrical and thermal generation profiles for a number of commercially available small-scale biomass CHP systems of rated outputs of 0.1-5MW$_e$ are also derived, and the results of their application within the modelling tool to carry out multi-parametric techno-economic analyses for various operational scenarios are presented. The impacts of both capital grant and generation tariff-based support mechanisms upon economic feasibility are investigated, along with that of variations in feedstock fuel prices. Net $CO_2$ reductions accruing from the implementation of biomass CHP are also assessed. Finally, technical options, marginal costs and sale tariffs for $CO_2$ recovery and supply are evaluated for specific scenarios. The results indicate that feasibility is very sensitive to the relationship between specific biomass CHP power:heat ratios and temporal electrical and thermal energy demand profiles, along with economic factors such as specific levels of capital and tariff-based support. With the utilisation of currently available financial support mechanisms, biomass CHP offers significant promise for realising economically viable significant $CO_2$ emission reductions in this sector.

**Keywords:** Biomass, Biofuel, CHP, Glasshouse, Economics, $CO_2$ Recovery.

## 1. INTRODUCTION

Intensive horticulture is a key component of the EU's agricultural sector, with significant land areas occupied by glasshouse operations. In the Netherlands and Spain alone, around 10,000Ha and 50,000Ha respectively are currently dedicated to glasshouse operations [1]. In the UK, the horticulture sector has a value of over £2bn and accounts for around 12% of agricultural output [2]. Intensive horticulture is very energy intensive; combined energy consumption values for UK glasshouse operations can exceed 600kWh/m$^2$/year, resulting in annual $CO_2$ emissions for the sector in excess of 2 million tonnes [3]. In financial terms, for a sector characterised by a preponderance of small businesses operating within the context of rising energy prices, this intensive energy use represents a significant financial burden.

For commercial glasshouses, heat is the majority energy requirement, and is used to maintain internal temperatures within specified limits in order to facilitate optimal growth regimes for up to 12 months of the year, depending on the specific contexts [4]. Electrical energy is used for pumps, supplementary crop lighting and environmental systems, whilst $CO_2$ is often utilised to enrich the glasshouse atmosphere and increase crop yield [5]. Commonly, heat and $CO_2$ is supplied by natural gas-fired boilers (where available) whilst natural gas-fired Combined Heat and Power (CHP) with flue gas catalyst cleaning can also be utilised to additionally provide electricity, heat and $CO_2$. Due to the daytime requirement for $CO_2$, in specific cases, hot water thermal storage can be used to overcome the mismatch between night-time heat and day-time $CO_2$ demands, although this is not commonly utilised in the UK context [6,7]. With commercial glasshouse operators coming under increased pressure to reduce both operational costs and $CO_2$ emissions, biomass CHP (with $CO_2$ recovery where viable) offers a potential means to achieve these goals, especially where grants or enhanced tariffs for small-scale renewable electricity and heat generation are available. A number of small-scale (0.1-5MW$_e$) biomass CHP technology platforms are currently at or near commercial status. In addition to capital and operational costs, biomass CHP viability depends largely on operational efficiency, thermal/electrical energy generation characteristics and site-specific energy demand profiles. However, there has been very little recent research focussed upon the techno-economic analysis of biomass CHP technologies in practical applications [8,9], whilst one study has been carried out on biomass heat-only applications in a glasshouse context [10]. Thus, as biomass CHP technologies mature towards wider commercial availability, the need for evaluation of applications of the technology within specific sectors such as glasshouse horticulture becomes more pressing in order to inform and educate stakeholders of the realistic potential of the technology.

Within this context, the aim of the present work is to develop a model suitable for multi-parametric techno-economic analysis of various biomass CHP platforms as a source of electricity, heat and $CO_2$ for commercial glasshouse applications, using the UK as a case study. Specific objectives of the work include (a) to develop a methodology to assess and model glasshouse demand profiles for electricity, heat and $CO_2$ along with associated $CO_2$ emissions; (b) to carry out discounted cash flow net present value (NPV) and $CO_2$ reduction analyses for candidate biomass CHP technologies and glasshouse applications and (c) to assess the potential of $CO_2$ recovery from biomass CHP and evaluate associated cost scenarios.

# 2. MODEL DEVELOPMENT AND METHODOLOGY

## 2.2. Heat Demand Analysis

The protected crops sector currently accounts for around a quarter of the direct energy use in UK agriculture, and this is primarily for heating and humidity control [11]. Heat is required to temporally maintain crop-specific temperature regimes within the internal glasshouse environment, and typical set points range from 16°C to 25°C depending upon crop requirements. Previous empirical and simulation studies have been carried out in the UK in order to model energy consumption profiles and propose specific energy demand reduction scenarios [4,10,12]. Glasshouse structures typically comprise a single layer of 3mm thick glass set within an aluminium framework, and the majority of heat loss occurs via conduction and ventilation mechanisms [13]. Conduction losses depend on the glasshouse material conductivity (defined by elemental U-values), whilst ventilation losses depend on the age, type and condition of the glasshouse along with the nature of any active ventilation system [9]. A previous heuristic modelling study, validated against measured fuel use data [14] has quantified glass house heat loss, and this is the basis for the current fabric heat loss model, given by Equation (1).

$$\frac{Q_f}{t} = UA(t_i - t_o) - K \qquad (1)$$

where $\frac{Q_f}{t}$ is the rate of heat loss [W], U is the thermal transmittance of the material, also known as the U-value [$Wm^{-2}K^{-1}$], A is the elemental area [$m^2$] and $t_i$ & $t_o$ are the internal and external temperatures respectively [°C] and K is the net short wave radiation [$W/m^2$]. $K$ may be inferred by using sol-air temperature values given by equation (2)

$$t_{sol-air} = t_0 + \frac{(a.I - \Delta Q_{ir})}{h_0} \qquad (2)$$

where $a$ is the solar radiation absortivity of a surface [-], I is the global solar irradiance [$W/m^2$] and $\Delta Q_{ir}$ is the extra infrared radiation due to difference between the external air temperature and the apparent sky temperature [$W/m^2$]. In practice, solar radiation estimates can be made based on meteorological observations, and sol-air temperature reference datasets are available for applications such as this [15]

The effective U-Value of the glasshouse material also depends on incident wind speed [16], and this relationship is given below by Equation (2).

$$U_v = U_c + 0.6336\, w \qquad (2)$$

Where $U_v$ is the elemental U-Value including wind effects, $U_c$ is the constant U-Value of the material and $w$ the wind speed [$ms^{-1}$]. To determine the heat losses due to ventilation, a value for the glasshouse air change rate, expressed as air changes per hour (ACH) is needed. This depends on the type and condition of the glasshouse and the incident wind speed [9]. Roof vents are also used to actively control the internal temperature during sunny days and thus the air change rate will change as the vent position is varied. Equation (3) gives the ventilation heat loss rate.

$$\frac{Q_v}{t} = 0.33NV(t_i - t_o) \qquad (3)$$

Where $\frac{Q_v}{t}$ is the heat loss due to ventilation, $N$ the air change rate per hour and $V$ the glasshouse volume [$m^3$]. The total heat loss rate from the glasshouse can be calculated by combining the fabric and ventilation heat loss components as shown in Equation (4).

$$\frac{Q_T}{t} = \frac{Q_f}{t} + \frac{Q_v}{t} \quad (4)$$

For modelling purposes, material U-values and measured meteorological data for the England Midlands were used to calculate total hourly annual heat demand, and subsequently an average daily demand profile was generated for each month. Validation was carried out via comparison with metered energy demand data from glasshouse operators along with published benchmark datasets [3].

### 2.3. Electricity Demand

Electricity is primarily required to operate pumps, fans and ancillary equipment which control the internal glasshouse environment, whilst lighting is also often used to aid continued crop growth during periods of low lux levels. For the purposes of this study, electricity consumption data was obtained from a number of commercial glasshouse operators, and this was used to model an hourly demand profile to represent a typical day in each month per square meter. Validation of modelled data was subsequently carried out via correlation with published benchmark data for UK glasshouse energy consumption [3]. Modelled data for both heat and electricity demand were then used as a reference and scaled according to specific glasshouse size parameters.

### 2.4. $CO_2$ Demand and Supply Modelling

Carbon dioxide ($CO_2$) is required for plant photosynthesis, and increased $CO_2$ concentrations of typically 1000vppm within the glasshouse atmosphere can lead to improved crop productivity and fruit yields [4,17,18]. The rate of $CO_2$ supply required depends on the type of crop, the rate of photosynthesis and the ventilation rate. To determine the hourly glasshouse $CO_2$ demand the supply rate of $CO_2$ kg/hr/hectare and associated light intensity for the user's specific growing strategy is specified as model input variables, together with a daily solar radiation profile for each month. For the purposes of this study, the maximum $CO_2$ demand was set at a typical value of 250 kg/hr/hectare [4] and proportionally reduced when radiation levels fall below 400 $W/m^2$.

The ability to use biomass CHP exhaust gases as a source of crop-growth promoting $CO_2$ can potentially add economic benefits to a scheme provided $CO_2$ sales revenue offset the increased capital costs. However, as biomass exhaust gas contaminants significantly exceed permitted levels (table 1), feedstock fuel quality control combined with primary (pre-combustion) or secondary (post combustion) gas treatment. In the current study, the maximum additional capital cost of $CO_2$ recovery equipment acceptable whilst maintaining a least the corresponding base-case NPV for each platform was modelled in order to assess the feasibility of specific primary or secondary gas treatment proposals.

For exhaust gases to be suitable for glasshouse applications, it must meet strict purity requirements. As can be seen from table 1, untreated biomass combustion gases are not appropriate for direct injection into a greenhouse atmosphere [7]. Under complete combustion 1MWh of energy provided by cellulose biomass would typically produce 308kg $CO_2$, whilst natural gas produces 184kg $CO_2$. Therefore biomass has the potential to provide a greater rate of $CO_2$ per MWh at a competitive cost provided gas purification can be carried out economically.

**Table 1 Glasshouse Exhaust Gas Contamination Limits and typical solid biomass fuel content [19,6]**

### 2.5. Biomass CHP System Modelling

To model the technical and economic performance of a number of current commercial biomass CHP systems, data was obtained from both published sources and manufacturers for systems with an electrical power output of 0.1-5$MW_e$ [20,21]. System descriptions, identifier codes and performance data are given below and in Table 2.

#### *2.5.1. Solid Biomass Gasifier with Internal Combusiton Engine (Gas-IC)*

Solid dry biomass is converted in to a combustible gas by heating in a reduced oxygen environment. The gas is then cleaned to remove particulates and other contaminants before it is combusted in a modified or specifically designed spark ignition engine. As for other biomass CHP platforms, heat can be recovered from the gas generation plant, from the engine and the engine exhaust plant.

#### *2.5.2. Liquid Biomass-fuelled Compression Ignition Engine (Liq-IC)*

Virgin vegetable oil or processed used cooking oil is combusted in a modified compression ignition engine. Fuel prices are generally higher compared to solid biomass and more susceptible to price variations. However, capital costs are typically lower due to the lack of a dedicated fuel processing sub-system.

#### *2.5.3. Direct solid biomass combustion with ORC (Sol-ORC)*

Organic Rankine Cycle (ORC) platforms use solid dry biomass fuel which is combusted directly and used to evaporate a secondary organic fluid which drives a small turbine. ORC is similar to a traditional steam turbine system, but the working fluid has a much lower boiler point and can therefore achieve higher efficiencies in smaller systems.

*2.5.4. Direct solid biomass Combustion with Air Turbine (Sol-AT)*
Solid biomass is combusted directly and used to heat air *via* a heat exchanger. The heated air is then expanded through a turbine which is used to generate electricity.

*2.5.5. Combined Cycle biomass Gasification CHP (Gas-CCST)*
Combined cycle biomass gasification CHP is a development of standard biomass gasification technology together with an internal combustion (IC) engine. The exhaust gases pass through a heat recovery steam generator, and the steam is then used to generate further electricity. Potential benefits include improved electrical efficiency and enhanced combustion of CO components.

**Table 2 Biomass CHP System Details. Economic data is shown in GBP (£).At the time of writing, exchange rates for 1GBP were 1.60USD and 1.18Euros respectively.**

### 2.6. Economic Analysis

Assessment of economic viability was carried out using a discounted cash flow net present value (NPV) analysis for each scenario. NPV is a measure that expresses the initial capital investment and all subsequent cash flows arising from avoided electricity costs and sales of exported energy (and $CO_2$ where relevant) as an equivalent amount at time zero. This approach is particularly appropriate when the cash flows associated with a project vary over time, as is the case with a biomass CHP investment. The net present value of a cash flow at time $t$ is given by:

$$NPV = \sum_{t=0}^{n} \frac{A_t}{(1+d)^t} \quad (5)$$

where $A_t$ is the project's cash flow (revenues minus costs) in time $t$, with $t$ taking values from year 0 to year $n$ and $d$ is the discount rate (an interest rate used to calculate the present value of future cash flows). When the calculated NPV is positive, the investment results in a rate of return greater than the minimum rate $d$, and in the absence of alternatives this would be a profitable investment. However, when the NPV is negative, the investment would not give a return at the minimum rate $d$, and indicates a non-profitable investment. To assess candidate biomass CHP feasibilities, temporal glasshouse energy and $CO_2$ demand profiles along with CHP performance and capital/operational cost data were used to carry out the NPV analyses for the candidate systems. The model allows for the selection of glasshouse size, commodity and financial costs and CHP operating regime making the model flexible for all glasshouse applications and future use. For the purpose of this study a 40,000m$^2$ glasshouse is considered. An initial 'base case' economic analysis was carried out, and a subsequent mulit-parametric analysis was achieved by investigating the effects of varying fuel price, capital grants and $CO_2$ costs. The effects of enhanced generation tariffs was also investigated, in light of current schemes such as the UK renewable electricity feed in tariffs (FITs) and renewable heat incentives (RHI). Finally, the economics of recovering $CO_2$ from biomass CHP and the minimum $CO_2$ sale price required to maintain viability were analysed. Table 3 shows the base case economic parameters used in the study. It should be noted that base case net electricity export prices include generation benefits available in the UK renewable energy generation, including Renewable Obligation Certificates (ROCs) and Climate Change Levy Exemption Certificates (LECs).

**Table 3. Basecase Modelling assumptions**

In common with other EU states, to access the financial incentives available to CHP in the UK the scheme must meet quality criteria as set down in the EU CHP Cogeneration Directive and the UK CHP Quality Assurance Scheme (CHPQA) [22]. The quality score is dependent on the electrical efficiency and the useful heat generated from the scheme on an annual basis. CHP performance is optimised in cases when a relatively constant heat demand is present throughout the year; the plant can then be sized according to this demand and the CHP operated continuously. However, glasshouse heat demand is seasonal and CHP system flexibility is an important consideration. Compared to natural gas fuelled technology, solid biomass-fuelled CHP has lower operational flexibility, and therefore any modelling approach needs to take into account the different operating regimes and system sizing needed to maximise returns. Where beneficial generation tariffs are the key driver for biomass CHP, this partly decouples profitability from purely the export electricity price alone. For thermal energy supply, solid fuel biomass CHP for glasshouse applications needs to be sized to meet the base load heat demand, and therefore minimise any surplus heat and maintain good quality CHP status under the UK CHPQA scheme. Liquid fuel CHP has much greater flexibility in terms of system modulation and is comparable to natural gas fuelled CHP in terms of flexibility. This enables liquid fuel CHP to operate in either base load or peak load mode or indeed any profile in-between.

# 3. RESULTS & DISCUSSION

## 3.1. Heat & Electricity Demand Analysis

Electricity, heat and $CO_2$ demands for the 40,000m$^2$ base case glasshouse are shown in Fig.1. For the base case scenario, modelled space heating winter power demand peaks at 148 W/m$^2$, and is generally higher during day time due to the higher internal temperature requirements for optimal crop growth compared to night time. Monthly heat energy consumption ranges from 21kWh/m$^2$ in the summer to 84kWh/m$^2$ in winter. The calculated annual heat demand of 625 kWh/m$^2$ is consistent with accepted benchmarks for glasshouses in the UK [3]. For the baseline analysis, the cost of supplying heat loads via a gas-fired boiler operating at 90% nominal efficiency was calculated.

Electricity demand profiles were modelled using half hourly glasshouse electricity consumption data over a two year period to create typical daily profiles for each month. Electrical demand varies from a minimum of 0.5W/ m$^2$ in the winter to a maximum of 2.5W/m$^2$ in the summer, owing to the added operation of $CO_2$ forwarding fans. The annual electricity demand was calculated to be 13.5 kWh/m$^2$ . Again, this is consistent with industry benchmark data [3].

## 3.2. $CO_2$ Demand

$CO_2$ requirements increase during daylight hours and reach a peak around midday. During the growing season, $CO_2$ demand correlates with crop growth rates and is greater in the summer months due to the higher solar irradiance and longer daylight hours. $CO_2$ is commonly provided by natural gas-fired boilers, and in some cases can be utilised at concentrations of typically 1000vppm together with heat storage to increase the combined efficiency of $CO_2$ and heat production [6]. As natural gas is one of the cleanest fossil fuels, the $CO_2$ produced is suitable for directly supplying the glasshouse. [3] Alternatively, bottled $CO_2$ can also be used for direct glasshouse enrichment, offering high gas purity and operational flexibility [7], but this incurs an extra gross cost of typically £100/tonne $CO_2$.

**Figure.1 40,000m$^2$ Glasshouse Monthly Electricity, Heat and $CO_2$ Demands**

## 3.3. Economic Analysis

An initial discounted cash flow simulation analysis was carried out using typical current UK market base case parameters shown in table 3. The simulation results are shown in Fig.2, and indicate that feasibility for all systems is related to the extent to which glasshouse electrical and thermal energy requirements match the generation capabilities of each candidate biomass CHP system. Reductions in NPV as module numbers increase are predominantly due to the relatively low CHP electrical:thermal generation ratios, resulting in increasing amounts of excess heat being generated for which no value is received. Base case profitability is marginal or poor for all systems except the liquid fuelled IC-based system, the viability of which is largely due to the lower equipment capital cost compared to other platforms.

**Figure. 2 Base Case Economic Analysis**

### *3.3.1. Effect of Capital Grants*

Various capital and generation-based incentives exist across the EU for CHP and renewable energy equipment [23]. In the UK, the Government's Enhanced Capital Allowance scheme enables businesses to claim 100% first year allowance against tax for investments in equipment that meets specific energy-saving criteria, including good-quality CHP. Therefore, using current (2010) UK corporate tax rates, the analysis was repeated assuming a 25% effective capital grant is available, and the results are shown in Fig 3. In this case, assuming bas-case variable costs, all systems are profitable (showing a positive NPV) up to a specific number of modules installed, after which point excess wasted heat generation rapidly reduces viability. Improved profitability is especially marked for systems with higher specific capital cost due to the proportionally greater reduction in up-front investment for these systems.

**Figure.3 Base Case Economic Performance Including 25% Capital Grant**

*3.3.2. Effect of enhanced electrical generation tariff*

A number of EU states currently offer enhanced generation-based tariffs for renewable electricity generation, including Germany and Spain [24,25]. Although biomass CHP is currently excluded from UK feed-in tariff (FIT) support, the technology was originally included in proposals for the scheme with a proposed tariff of £140/MWh for combined generation and export [26]. Therefore, given the UK government's ongoing programme of periodic reviews of the FIT scheme and eligible technologies, a sensitivity analysis was carried out to investigate potential benefits of a FIT for biomass CHP operators, and evaluate tariff rates required to maintain profitability (a positive NPV). The results are shown in Table 4. As is the case for capital grants, specific factors such as electrical:thermal efficiency and specific capital cost for each platform have a strong impact on profitability and minimum required FIT levels. Furthermore, the range of FITs required to maintain a positive NPV for the various technologies under consideration show that banding of FITs for different sub-technologies (such as combustion and gasification) may be beneficial at a policy level.

**Table 4. Gross generation tariff required for positive NPV**

*3.3.3. Effect of enhanced thermal generation tariff*

The UK Government's renewable heat generation incentive (RHI) scheme offers thermal generation-based support for biomass system operators at proposed rates ranging from £16-£90 per MWh depending on system scale. In order to assess the potential value of RHI incentives, sensitivity analyses were carried out for all candidate systems, and the results are shown in Fig 4. It is evident that a significant positive effect on the NPV for all systems accrues for an RHI level as low as £5/MWh. The systems that benefit most by the RHI are those that have lower electrical power to heat ratios, and an RHI value in the range of £10 – 15/MWh would increase NPVs for all candidate biomass CHP technologies, especially for those systems with relatively low electrical:thermal efficiencies. Furthermore, the availability of a thermal generation incentive of this level would also help to reduce fuel price sensitivity, and help reduce risks associated with volatility in biomass CHP feedstock fuel prices.

**Figure.4 NPV sensitivity to level of heat generation tariff**

*3.3.4. Fuel Price Sensitivity*

Analysis of the effects of variations in fuel price on NPV for the base case scenario show that systems with higher electrical efficiencies and power to heat ratios (resulting in higher revenues from sales of electrical energy) were found to be the least sensitive to fuel price increases. Fuel price sensitivity was then investigated assuming enhanced heat generation tariffs of £10 & £15 respectively are available. In this case, greater benefits accrue for those systems with relatively low power to heat ratios. The maximum fuel prices that return a positive NPV are shown in Table 5.

**Table 5. Maximum fuel price for positive NPV with two heat generation tariffs (HGT) £/MWh$_{th}$**

*3.3.5. Site $CO_2$ Reductions*

For the base case scenario, the energy consumption for a 40,000m$^2$ glasshouse with heat provided by natural gas boilers and grid-derived electricity results in annual $CO_2$ emissions is calculated at approximately 6660 tonnes, based upon current $CO_2$ emission indices for natural gas and grid-derived electricity respectively. Against this benchmark, and in light of current and forthcoming EU carbon reduction commitments and compliance targets, $CO_2$ emission reductions for each candidate biomass CHP system were calculated, and the results are shown in Fig 5. Although $CO_2$ reductions increase with the number of biomass CHP modules (and hence renewable energy capacity) installed, in an operational setting, $CO_2$ reductions must also be considered in light of economic performance. Without capital grants or enhanced generation tariffs, the analysis indicates that a 45-60% $CO_2$ saving can be achieved using gasification and liquid fuelled IC platforms respectively while maintaining a marginally positive NPV, whilst the availability of financial incentives up to levels currently available or proposed within the EU [17,18] improves both financial and $CO_2$ reduction viability for all candidate platforms.

**Figure.5 Effect of system type and number of modules on glasshouse $CO_2$ reduction.**

### 3.4. Glasshouse $CO_2$ Recovery

With an assumed glasshouse $CO_2$ sale price of £35/tonne, The analysis shows that for $CO_2$ recovery capital costs up to £1m/MWe, all systems exhibit an increase in NPV. Subsequently, the sensitivity of the $CO_2$ sale price was investigated assuming a fixed gas recovery capital cost of £1m/MWe. The results are shown in Fig 6, and indicate all systems exhibit profitability for $CO_2$ sale prices ranged from £5 to £35/tonne depending on the specific biomass CHP platform under consideration.

**Figure 6. Effects on NPV due to variation in Glasshouse $CO_2$ Sale Price with $CO_2$ Recovery Equipment Investment at £1,000k / MWe.**

### 3.5. The role of energy storage

Due to the demand mismatch between heat, electricity and $CO_2$ generation, thermal stores (including aquifer buffers) offer the potential to store excess heat generated during $CO_2$ and electricity production, as is currently utilised in the Netherlands [27]. However, within the UK context, glasshouse heat storage is much less commonly utilised, and numerous commercial and technical barriers need to be overcome prior to its widescale implementation in the UK [28]. Therefore, in the current work, the economic viability of energy storage technology was not analysed as a means for utilising wasted heat generated as a result of energy and $CO_2$ mismatch. However, this is the focus of current ongoing effort, and an analysis of the potential viability of thermal storage will be the subject of future publications.

## 4. CONCLUSIONS

A modelling tool has been developed in this work that facilitates the feasibility assessment of biomass CHP options for commercial glasshouse operators world-wide. By varying input parameters including local climactic data, energy/$CO_2$ consumption profiles and tariffs, and biomass CHP cost and performance data, profitability assessments can be carried out on a location and application-specific basis in light of any available support subsidies.

For the UK case study presented in this paper, the analysis shows that careful selection of the type and scale of biomass CHP platform for a specific glasshouse application is crucial in order to maximise project profitability. The majority of solid biomass CHP technologies are characterised by relatively high capital costs, and whilst liquid biofuel IC-based systems exhibits relatively low capital cost (and hence the shortest payback periods for base case cost assumptions) this technology is also the most sensitive to fuel price fluctuations.

For the case study, sizing of the biomass CHP system to meet the average summer heat demand and electrical base load provides the most favourable techno-economic solution. For a typical 40,000$m^2$ glasshouse, the optimal base-case analysis shows that approximately 45% of annual heat demand, 90% of electricity demand and a 45-60% reduction in site $CO_2$ emissions is achievable.

The analysis also suggests that the availability of a 25% capital grant can result in project profitability, due to offsetting relatively high capital costs for biomass CHP technology. An enhanced thermal energy generation tariff at a minimum price of £10/MWh provides significant benefit to biomass CHP viability by improving overall project profitability and reducing sensitivity to fuel price increases, whilst an enhanced electrical generation tariff of approximately £140/MWh provides increased forward economic visibility. It should be noted that these support levels are consistent with those currently being implemented in a number of EU states and beyond.

Although biomass CHP exhaust gases are not directly compatible for use in glasshouses, it may be feasible to utilise these for $CO_2$ enrichment purposes with further treatment. By realising $CO_2$ values of around £35/tonne (either via direct sale on site of via carbon trading mechanisms) an additional investment of up to £1m/MWe for $CO_2$ recovery equipment is feasible. Therefore, glasshouse $CO_2$ demand provides a unique opportunity for the development of biomass gasification CHP with pre $CO_2$ recovery, and warrants further investigation.

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## 6. GLOSSARY

ACH – Air changes per hour
CHP - Combined Heat and Power
EU – European Union
FIT – Feed-in tariff
IC – Internal combustion
NPV – Net Present Value
ORC – Organic rankine cycle
UK – United Kingdom
IC – internal combustion

**Figure 1**

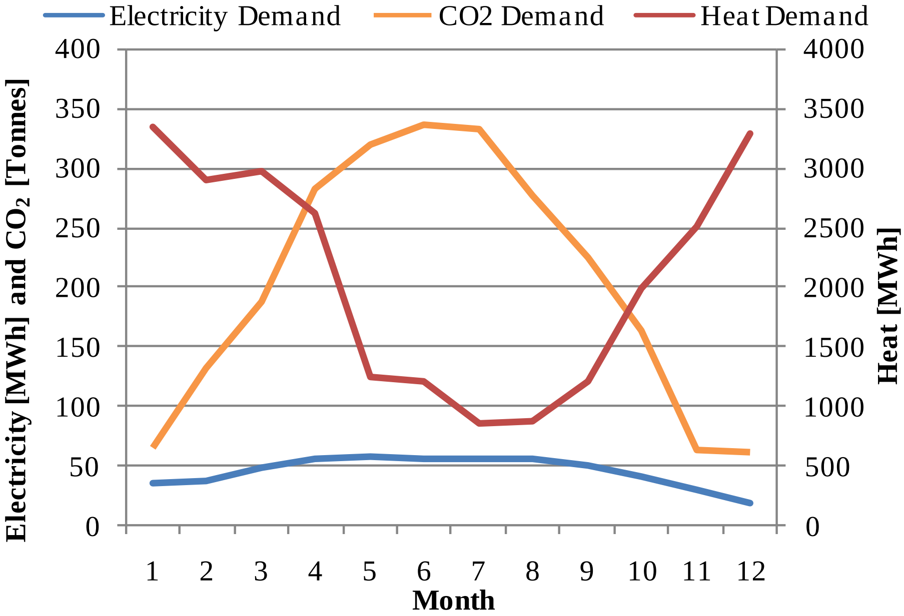


**Figure.1** 40,000m$^2$ Glasshouse Monthly Electricity, Heat and $CO_2$ Demands

**Figure 2**

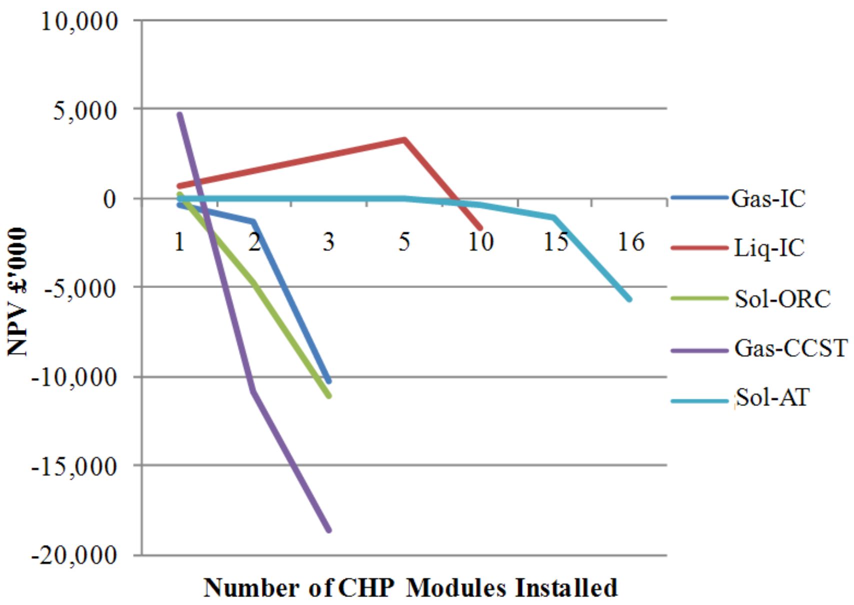


**Figure. 2** Base Case Economic Analysis

**Figure 3**

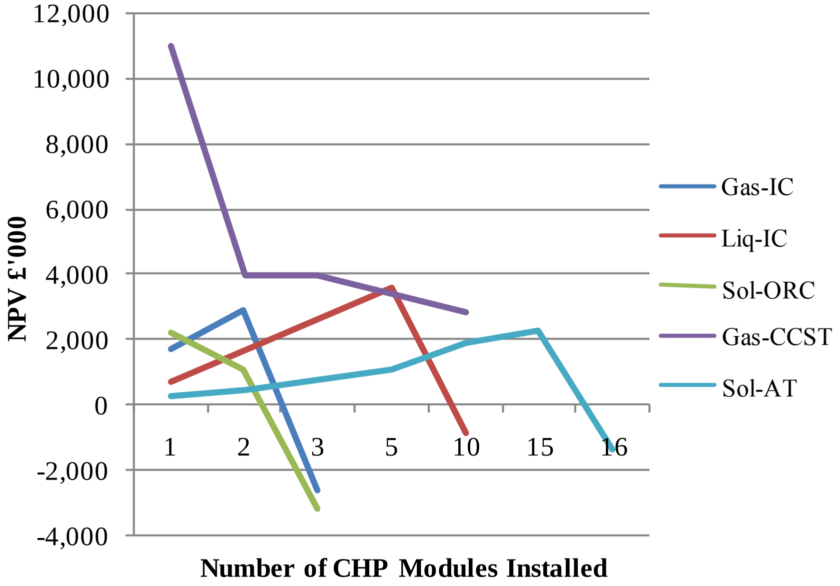


**Figure.3** Base Case Economic Performance Including 25% Capital Grant

**Figure 4**

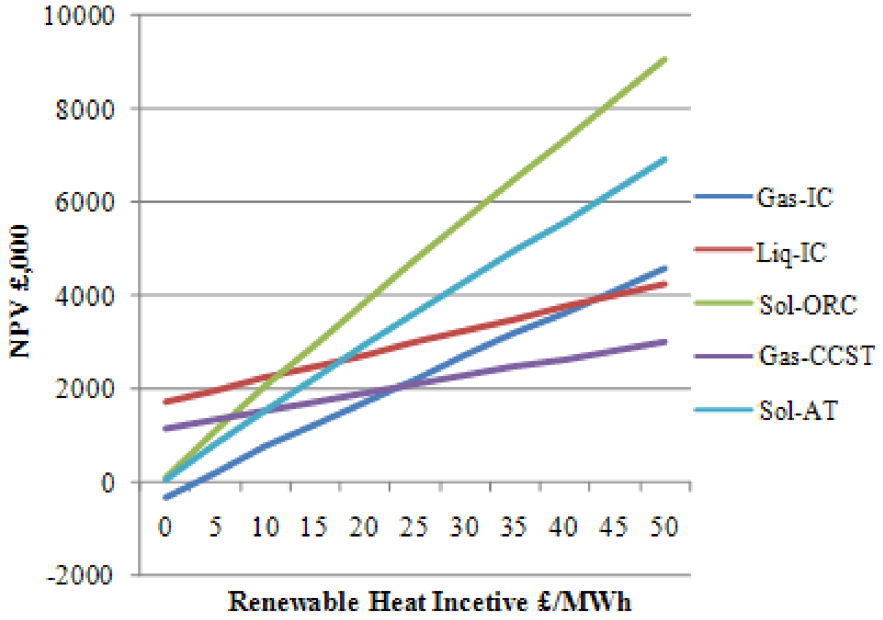


**Figure.4** NPV sensitivity to level of heat generation tariff

Figure 5

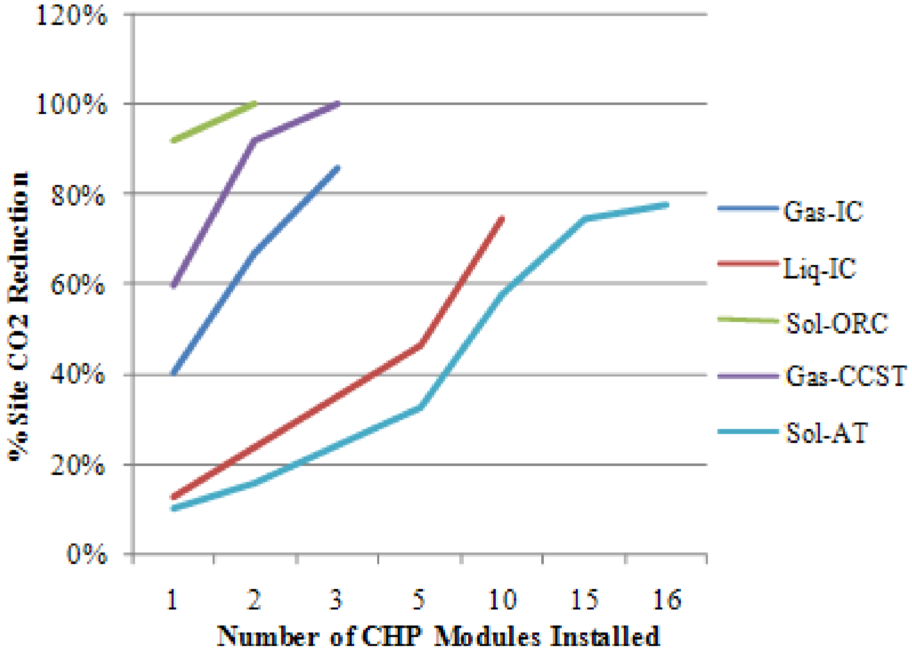


**Figure.5** Effect of system type and number of modules on glasshouse $CO_2$ reduction.

Figure 6

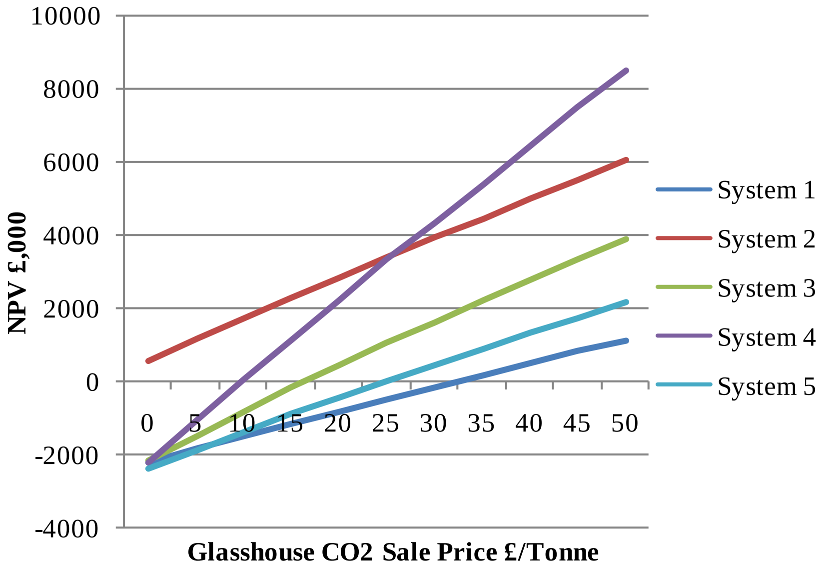


**Figure 6.** Effects on NPV due to variation in Glasshouse $CO_2$ Sale Price with $CO_2$ Recovery Equipment Investment at £1,000k / MWe.

**Table 1**

**Table 1**
Glasshouse Exhaust Gas Contamination Limits and typical solid biomass fuel content [6, 19]

| | **Statutory Limit** | **Biomass** |
|---|---|---|
| Sulphur Dioxide [$SO_x$] | <0.2ppm | 8 to 29 ppm |
| Ethylene [$C_2H_4$] | 0.2 to 0.4 ppm | 4 to 11 ppm* |
| Carbon Monoxide [CO] | 1 to 5 ppm | 109 to 1746ppm |
| Nitrogen Oxide [$NO_x$] | 12 to 34 ppm | 86 to 180 ppm |

**Table 2**

Table 2

**Biomass CHP System Details. Economic data is shown in GBP (£).At the time of writing, exchange rates for 1GBP were 1.60USD and 1.18Euros respectively.**

| **Name** | Description | Electrical Output ($MW_e$) | Thermal Output ($MW_{th}$) | Electrical Efficiency | Overall Efficiency | Power:Heat Ratio | Aprox Installed Cost (£) | Specific Cost (£/MWe) |
|---|---|---|---|---|---|---|---|---|
| **Gas-IC** | Woodchip fuelled downdraft gasifier with IC engine | 1.00 | 1.26 | 23% | 58% | 4.4:6.3 | 4.90 | 4.90 |
| **Liq-IC** | Vegetable oil fuelled IC engine. | 0.40 | 0.30 | 40% | 85% | 4:3 | 0.15 | 0.37 |
| **Sol-ORC** | Woodchip direct combustion ORC | 1.25 | 4.00 | 19% | 90% | 1.2:4 | 5.02 | 3.96 |
| **Gas-CCST** | Woodchip combined cycle gasification IC & steam turbine | 4.00 | 2.00 | 40% | 61% | 2:1 | 16.5 | 4.02 |
| **Sol-AT** | Woodchip direct combustion air turbine | 0.1 | 0.2 | 21% | 83% | 2:5 | 0.52 | 4.77 |

**Table 3**

**Table 3.** Basecase Modelling assumptions

| Parameter | Base Case Value |
|---|---|
| Solid Biomass Heating Value | 19 GJ/Tonne |
| Solid Biomass Heating Cost | £50/ODT |
| Liquid Biofuel Heating Value | 37 GJ/Tonne |
| Liquid Biofuel Heating Cost | 500£/Tonne |
| Availability | 90% |
| Average Electricity Base load Net Export Price | 145£/MWh |
| Average Electricity Peak load Net Export Price | 150 £/MWh |
| Electricity Onsite Sale Price | 55 £/MWh |
| Electricity Import Price | 68£/MWh |
| Gas Import Price | 17.4£/MWh |
| Heat Sale Price | 20 £/MWh |
| Glasshouse $CO_2$ Sale Price | 65 £/Tonne |
| Waste Disposal | £10/Tonne |
| Project Period | 15 Years |
| Inflation Rate (RPI) | 3 % |
| Discount Rate | 10 % |
| Loan interest rate | 9 % |

**Table 4**

| System | Gas-IC | Liq-IC | Sol-ORC | Gas-CCST | Sol-AT |
|---|---|---|---|---|---|
| Tariff (£/MWh) | 147 | 120 | 117 | 135 | 148 |

Table 4. Gross generation tariff required for positive NPV

**Table 5**

| System | Base Case | HGT@£10/MWh | HGT @£15/MWh |
|---|---|---|---|
| Gas-IC | £46 | £59 | £65 |
| **Liq-IC** | £598 | £628 | £643 |
| **Sol-ORC** | £51 | £83 | £90 |
| **Gas-CCST** | £65 | £71 | £74 |
| **Sol-AT** | £50 | £65 | £72 |

Table 5. Maximum fuel price for positive NPV with two heat generation tariffs (HGT) £/$MWh_{th}$