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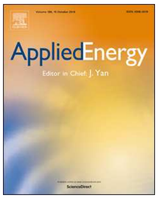

Agricultural greenhouse CO_2 utilization in anaerobic-digestion-based biomethane production plants: A techno-economic and environmental assessment and comparison with CO_2 geological storage

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HIGHLIGHTS

- Design of CO_2-enriched greenhouses using captured CO_2 from a biogas to biomethane upgrading unit.
- Economic and environmental assessment of the proposed CO_2 Utilization route.
- Comparison with CO_2 geologically stored plant configurations.
- CO_2 utilization route exhibits better economic performance than the CO_2 storage case.
- Net greenhouse gas emission savings for the Utilization case are strongly dependent on system/boundary assumptions.

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ABSTRACT

Anaerobic digestion plants enable the production of power, heat and fuel. Biogas can be upgraded to biomethane fulfilling grid injection requirements by separating CH_4 from CO_2. By- product CO_2 could be geologically stored or utilized as a feedstock to produce valuable goods, enabling in both cases negative climate change impact fuel production. CO_2 utilization could as well improve plant economics, as a consequence of the profits related to the commercialization of the final products whilst allowing further emission reductions.

In this paper, a techno-economic assessment of the use of the CO_2 by-product in CO_2-enriched agricultural greenhouses for tomato production is discussed. The results of the research show that, depending on the operating mode and the design approach, the use of a greenhouse enables the recovery of 14–67% of the by-product CO_2 when the internal CO_2 concentration is kept at 1000 ppm. In addition, it is estimated that the associated heat and power demand ranges from 0.097 to 0.138 kWh_{th}/kg of used CO_2 and 0.04–0.05 kW_e/kg of used CO_2, respectively. Revenues related to the tomato production are partially offset by the greenhouse capital investment and operating costs; however, a net profit between 16 and 19 p/kg of used CO_2 was calculated, leading to a net profit of 1.3–1.6 p/kWh of injected biomethane. These results show that CO_2 utilization is technically feasible and economically more convenient than CO_2 storage. While both geological storage and CO_2 utilization would allow negative climate change impact fuel production, the net greenhouse emission savings for the utilization configuration were found to be strongly dependent on the assumptions regarding fuel substitution for the produced biomethane.

1. Introduction

Anaerobic digestion (AD) plants enable the use of organic wastes such as food and farm waste for heat, electricity, fuel and bio-fertilizer production [1]. In AD reactors, metabolic bacteria break down organic matter into simpler chemical compounds such as CH_4, CO_2, NH_3 and H_2S in the absence of oxygen [2]. Because of the bacteria metabolic processes, waste is converted into biogas and digestate [3]. The digestate can be used directly on land as fertilizer or further processed into compost to increase its quality and value [3]. The biogas can be used as a fuel for electricity and heat production or upgraded to biomethane [1]. Biogas from agriculture waste exhibits CH_4 mole fraction in the range 50–60% and CO_2 mole fraction between 40 and 50%; CO_2 must therefore be removed from the biogas stream to fulfil CH_4 requirements

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Nomenclature

Acronym	Variable name [Unit]
A	area [m^2]
a_a	constant for Eq. (8) [m^3/J]
a_{canopy}	canopy light efficiency [g_{CO2}/J]
a_{leaf}	leaf light efficiency [g_{CO2}/J]
$ASEC$	area-specific electricity consumption [kWh_e/m^2]
$ASHC$	area-specific heat consumption [kWh_{th}/m^2]
b_a	constant for Eq. (8) [$m^2\,s/J$]
$\dot{biogas}$	biogas consumption [g/s]
$BOSC$	boiler specific cost per installed kW [£/kW]
C	concentration [ppm]
CEC	cost for yearly electricity consumption [£]
CHT	cost for heat consumption [£]
CHT	capital investment cost [£]
$\dot{CO}_{2in}$	CO_2 inlet flow [g_{CO2}/s]
EC	electricity consumption [kWh_e]
$EF^{IPCC}_{CH_4}$	CH_4 emission factor for diesel combustion – using IPCC 2006 Guidelines for National Emission Inventories – expressed in CO_{2eq} [kg CO_{2eq}/TJ]
$EF^{IPCC}_{CO_2}$	CO_2 emission factor for diesel combustion – using IPCC 2006 Guidelines for National Emission Inventories. [kg CO_2/TJ]
$EF^{IPCC}_{N_2O}$	N_2O emission factor for diesel combustion – using IPCC 2006 Guidelines for National Emission Inventories – expressed in CO_{2eq}
EF_{DEFRA}	greenhouse gas emission factor for UK grid electricity-published by DEFRA [kg CO_{2eq}/kWh_e]
EF^{PROD}_{GHG}	greenhouse gas emission factor for diesel oil production [kg CO_{2eq}/TJ]
FIT	feed-in tariff for biomethane [£/$kWh_{injected}$]
GHG	greenhouse gas emissions [kg CO_{2eq}]
$GHUKPR$	area-specific greenhouse cost in the UK [£/m]
$\hat{h}$	mass specific enthalpy [J/g]
I	global solar radiation [W/m^2]
k	extinction coefficient for light [–]
L	leaf area index [–]
LC	levelized cost per kg of used CO_2 [£/kg_{CO2}]
$LCBM$	levelized cost of biomethane [£/$kWh_{injected}$]
LHV	low Heating Value [J/g]
m	leaf transmission coefficient for light [–]
MTF	maximum thermal flow for each design option [J/s]
N	infiltration rate [1/s]
PARor$\bar{PAR}$	photosynthetically active radiation (PAR) at the top of the canopy or average PAR during previous week [W/m^2]
p	UK pence [–]
P_g	gross photosynthesis rate [$g/m^2\,s$]
P_n	net photosynthesis rate [$g/m^2\,s$]
$\dot{Q}$	heat flow [W]
r	respiration rate [$g/m^2\,s$]
r_d	discount rate [–]
RHI	Renewable Heat Incentive (revenue paid to the farm) [£]
SEC	specific electricity consumption [kWh_e/kg_{CO2}]
SHC	specific heat consumption [kWh_{th}/kg_{CO2}]
U	heat transfer coefficient [$W/m^2\,K$]
$\dot{Ventilation}$	ventilation flow [g/s]
V	volume [m^3]

Greek symbols

β	absorbed radiation ratio [–]
ε_{boiler}	biogas fired boiler efficiency [–]
τ	CO_2 stomatal conductance [m/s]
ρ	density [g/m^3]

Subscripts

in	internal or inlet conditions
$AD\ plant$	related to the anaerobic digestion (AD) plant
CO_2	per unit of mass of CO_2
cul	cultivated
el	electrical related unit/variable
ex	external conditions
in	internal or inlet conditions
th	thermal related unit/variable
y	yearly variable or value

Superscripts

$\cdot$	flow (variable per unit of time)
atm	related to atmospheric value for the variable
ave	related to average value for the variable
BO	related to biogas boiler related variables
GH	related to greenhouse related variables
max	related to maximum value for the variable
min	related to minimum value for the variable

for biomethane injection [4].

Biomethane upgrading has been assessed in several works in the literature [5–10]. CO_2 is separated from the biogas using solvent or sorbent-based technologies. In the case of solvent based separation using amines, CO_2 is absorbed in the solvent which is thermally regenerated in a stripper column. A CH_4-rich stream, with a dry mole fraction between 95% and 97%, is obtained in the top of the absorber whilst a CO_2-rich stream (96–98% mole fraction) is produced downstream of the condenser of the stripper. Consequently, the dry CO_2-rich stream from the condenser of the stripper could be used as a way of increasing the CO_2 concentration in agricultural greenhouses.[1]

The productivity of agricultural greenhouses is influenced by solar radiation, CO_2 internal concentration and temperature [11,12]. Different models have been developed and experimentally validated to quantify CO_2 crop uptake in CO_2-enriched greenhouses [13–15]. A compilation of results for different species was carried out by Nederhoff [16], who showed that larger CO_2 concentrations lead to significantly larger crop production rates for internal CO_2 greenhouse concentrations lower than 1000 ppm. Agricultural greenhouses are recommended to operate at temperatures between 20 and 25 °C for the whole year [17]; ventilation or external heating may therefore be required. Ventilation must be supplied when the heat associated with solar radiation is higher than the heat transfer to the surroundings [18]. Heating is mainly needed in winter or during the night. Ventilation involves adding air (with atmospheric CO_2 composition) to a CO_2-enriched greenhouse, causing a dilution effect. There is therefore a strong dependency between CO_2 internal composition, energy balance and CO_2 ventilation flow.

Previous studies have quantified the energy consumption associated with the operation of agricultural greenhouses in several locations in Europe. A selection of these articles was analysed as part of the literature review [11,19–23]. In these works, ventilation and heating duties were estimated throughout the day for the different seasons;

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[1] The dry condenser stream exhibits a CH_4 mole fraction between 1 and 2%, which could be toxic for the crops, thus it is advisable to install a boiler downstream the gas separation unit. By doing so, the remaining amount of CH_4 can be converted into CO_2.

these values were integrated over the year and the specific duties per unit of covered surface were presented.

Georgiou et al. [23] studied different greenhouse types in terms of isolation and geometrical design in the United Kingdom context, investigating the influence of the afore mentioned parameters with the associated yearly energy demands. A period of 20 years (1995–2015) was considered with the aim of accounting for meteorological variability. The mean heat demand (during the 20-year period) was estimated to be close to 350 kWh_{th}/m^2 y with a minimum value of around 275 kWh_{th}/m^2 y and maximum value close to 500 kWh_{th}/m^2 y, with the assumption of single glass-sealed covers and typical infiltration rates. The mean power consumption for ventilation was found to be 50 kWh_e/m^2 y (with a minimum of 15 kWh_e/m^2 y and maximum of 110 kWh_e/m^2 y). Heat requirements were reported to be significantly lower when double glass-sealed covers were analysed (with a minimum of 100 kWh_{th}/m^2 y, a mean of 150 kWh_{th}/m^2 y and a maximum of 275 kWh_{th}/m^2 y). These results were validated through continuous measurements in operational greenhouses. Agricultural greenhouses in Mediterranean countries exhibit average thermal duties of around 90 kWh_{th}/m^2 y while this value reaches 1000 kWh_{th}/m^2 y in Northern European countries [22].

Several works have focussed on the optimal design, operation and control strategy for CO_2-enriched greenhouses [24–27]. In these articles, the authors presented an analysis of the economic performance of the operation of CO_2-enriched greenhouses. Two sources of CO_2 were considered: pure CO_2 [24] and CO_2-rich combustion effluents [25]. In both cases, CO_2 was a non-free commodity and the CO_2 internal concentrations were quantified to guarantee economic profit for the operation of a greenhouse for a specified area.

As previously underlined, the existent literature always assumed a price for the required CO_2 (pure or from combustion effluent). This is not the case for greenhouses installed downstream of the gas separation unit in AD biomethane plants because CO_2 is obtained as a by-product, and the use of the separated CO_2 would enable these plants to obtain

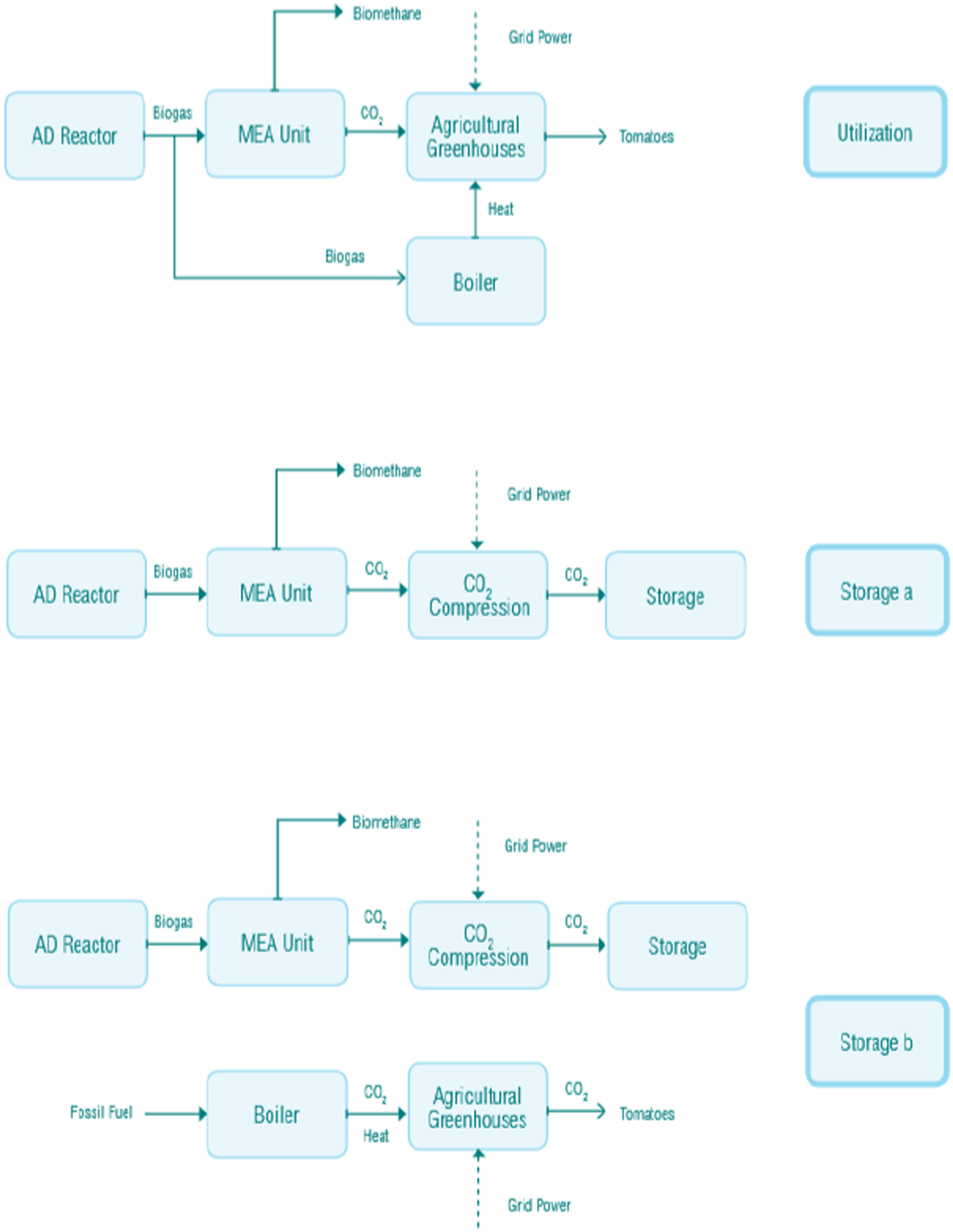

Fig. 1. Configurations investigated in this work.

extra profits due to the sales of the cultivated crops. Heat and power demands associated with the operation of the greenhouses can be envisaged as the energy penalty for the CO_2 utilization process. The associated levelized costs for the greenhouse construction and maintenance can be considered as an expense per kg of used CO_2. The increase in crop yield resulting from the CO_2 enrichment of the greenhouse leads to additional profit and the difference between this income and the cost per unit of used CO_2 can be defined as the net profit per mass unit of used CO_2.

CO_2 utilization from fossil and biogenic fuelled energy conversion plants is the subject of ongoing research; for instance, CO_2 utilization is part of the latest European Union strategy to mitigate climate change [28]. CO_2 can be used as feedstock in the synthesis of fuels, chemicals and materials. Works assessing the techno-economic and environmental feasibility of CO_2 to chemicals and fuels have recently been published [29–33]. These studies showed that converting CO_2 into valuable products requires a very high energy consumption due to the CO_2 non-reactivity. This leads in some cases to marginal economic benefits and environmental trade-offs when comparing it with the conventional process configurations to produce these goods and CO_2 geological storage. Enriched CO_2 agricultural greenhouses could then be envisaged as an alternative CO_2 utilization route, allowing a lower energy demand for CO_2 transformation into a valuable final product. In particular, when applied to AD based biomethane production plants, by-product CO_2 utilization in agricultural greenhouses would enable fuel production with negative CO_2 emissions, with the potential of offering economic and environmental advantages in comparison with CO_2 geological storage.

In this work, a techno-economic and environmental assessment of CO_2 utilization from biogas to biomethane upgrading AD plants is the subject of investigation. The paper analyses the scenario of biomethane production from a UK plant fed by a 125-cow herd farm and producing CO_2 as a by-product. The work is divided in four sections: this Introduction, Methodology, Results and Discussion and Conclusions. In the Methodology greenhouse design options, mass and energy balances and performance indicators are defined to assess the effectiveness of the proposed configuration and to enable comparison with the CO_2 geological storage cases. The Results and Discussion section presents the findings of the conducted research in terms of energy consumption, CO_2 absolute and specific net profits and greenhouse gas (GHG) emissions, analysing as well potential sources of uncertainty and recommendations for the deployment of this technology. The Conclusions section summarizes the outcomes of this work in terms of possible economic and environmental advantages of the CO_2 utilization option and highlighting the relevance of its implementation.

2. Methodology

2.1. Configurations under study

The techno-economic performance and GHG emission reduction potential of by-product CO_2 utilization route in agricultural greenhouses (Utilization case) were confronted against CO_2 geologically storage options in which CO_2 is compressed up to 150 bar at the energy plant and long distance transported to the storage place [34]. This exercise presented conceptual definition problems which were addressed by the case studies, presented in Fig. 1. These definitions problem arose from the fact that in the Utilization case, biomethane but also tomatoes were produced thus the comparison with a plant in which by-product CO_2 were solely stored (Storage case a) may seem unfair or punitive in regards with the Utilization configuration. However from an utility or energy industry prospective, this comparison may be the most useful, considering the need of reducing power plant emissions or making them "negative" at a lower cost.

From a system prospective, Storage case b, may offer the best comparison case against the utilization design options. This is because tomato production in CO_2 enriched agriculture greenhouses using CO_2 obtained from fossil fuel combustion was taken into account. It was also assumed that the share of biogas which was burned to provide thermal energy in the greenhouse was replacing fossil fuel originally used for heat supply within the farm.

The technical and economic assessment in this paper focussed on the Utilization case and employed data from our previous works for an AD based biomethane plant, which use dairy cow slurry as feedstock. In these articles [8,35], technical performance indicators as well as capital investment and operating costs for biogas to electricity, heat and biomethane were discussed. For the storage cases, the CO_2 compression train was modelled based on the configurations presented in [34,36] and using commercial process simulation software [37].

2.2. Technical assessment of the utilization case

2.2.1. Greenhouse mass and energy balances

In this work, greenhouses were assumed to be operated at a constant CO_2 internal concentration and temperature. Consequently, the greenhouse energy consumption and the CO_2 uptake in the greenhouses were quantified by solving the steady state version of the mass and energy balance equations. It was also assumed that the air in the greenhouse was well mixed which enabled to employ the stirred tank model reported in [39] and shown in Eq. (1). The steady state model for greenhouse operation has previously been used in other works [23] despite changes in external temperature and solar radiation: this is because it can be assumed that the temperature control system acts fast enough to make transients very short.

$$\begin{aligned}0 = C\dot{O}_{2in} &+ (ventilati\dot{o}n_{in} \times C^{atm}_{CO_2}) - \left(ventilation_{ex} \times C^{GH}_{CO_2}\right)\\ &+ [(\rho \times N \times V_{green}) \times \left(C^{atm}_{CO_2} - C^{GH}_{CO_2}\right)] - P_n \times A_{cul}\end{aligned} \tag{1}$$

$C^{GH}_{CO_2}$ refers to the CO_2 internal concentration in the greenhouse and $C\dot{O}_{2in}$ represents the mass flowrate which is fed to the greenhouse. The amount of inlet CO_2 may be equal to or lower than the CO_2 by-product flow from the gas separation unit of the AD biomethane plant. The ventilation flow accounts for the mass of air that enters the greenhouse in order to maintain a given internal temperature and can be estimated using the energy balance (Eq. (2)). The term $[(\rho \times N \times V_{green}) \times (C^{atm}_{CO_2} - C^{GH}_{CO_2})]$ represents the difference between the mass of CO_2 entering and leaving the greenhouse, as a result of air infiltration. P_n is used to quantify the mass of CO_2 taken by the tomatoes and it is a function of the solar radiation, the CO_2 internal concentration and the greenhouse temperature (Eq. (5)) [24,25], as further described in this section.

Eq. (2) displays the steady state energy balance for the greenhouses. The term $\beta \times I \times A_{rf}$ refers to the heat flow from solar radiation, whilst $U \times A_{trf} \times (T_i - T_o)$ accounts for the heat transfer to the surroundings. Enthalpy flow associated with the infiltration rate is quantified by the term $[\rho \times N \times V_{green} \times (\widehat{h_{ex}} - \widehat{h_{in}})]$. Greenhouses are assumed to be operated at a constant temperature (25 °C), which can be reached if an external enthalpy flow is supplied in order to compensate for the difference between heat gains and losses.

During the daytime, especially during summer, the heat gain associated with solar radiation is expected to be higher than the heat transfer to the surroundings; consequently, $\dot{Q}_{ex}$ must be negative. Negative values for $\dot{Q}_{ex}$ can be reached by adding cooler air (ventilation flow) and the greenhouse temperature can thereby be prevented from increasing or it can be reduced due to the mixing effect. At night and during winter, the heat gain associated with solar radiation may not be enough to compensate the negative enthalpy related to the air infiltration and the heat transfer to the surroundings and so $\dot{Q}_{ex}$ must be positive. This heat can be obtained by burning a part of the biogas from the AD plant and circulating the hot water or steam in a pipe network inside the greenhouse. The required amount of ventilation air and biogas related to$\dot{Q}_{ex}$ was estimated by Eqs. (3) and (4). Low heating value (LHV) efficiency for biogas boilers ranges between 75 and 90% [40]. In this work, an average LHV efficiency of 82.5% was considered.

$$0 = -U \times A_{trf} \times (T_{in} - T_{ex}) + (\beta \times I \times A_{rf}) + [\rho \times N \times V_{green} \times (\widehat{h_{ex}} - \widehat{h_{in}})] + \dot{Q}_{ex} \tag{2}$$

$$ventil\dot{a}tion = \frac{|\dot{Q}_{ex}|}{\widehat{h_{ex}} - \widehat{h_{in}}} \tag{3}$$

$$biog\dot{a}s_{heating} = \frac{|\dot{Q}_{ex}|}{LHV_{biogas} \times \varepsilon_{boiler}} \tag{4}$$

The solution of the energy balance equations requires input data related to external weather conditions such as temperature, humidity and solar radiation [11,12,23]. This information is available from the UK Met Office [41] and from websites that report meteorological data from different measurement stations [42]. This data enables the development of an hourly profile for the meteorological variables throughout the year. For each month, the average of the meteorological variables at a given time - for the different days of the month - was estimated, resulting in an hour-by-hour average for the external temperature, solar radiation and humidity.

CO_2 tomato uptake is also influenced by variables such as solar radiation and CO_2 internal concentration in the greenhouse as displayed by Eqs. (5)–(8). This set of equations was proposed by Nederhoff and Vegter [13]: it is based on correlations from experimental studies and allows the quantification of the mass of photosynthetically adsorbed crop CO_2. The canopy net photosynthesis rate (P_n) can be estimated using Eq. (5) accounting for the difference between the gross photosynthesis rate (P_g) and the respiration rate($r \times L$). The leaf area index, defined as the one-sided green leaf area per unit ground surface area, was assumed to be in the range 1–1.3 [43] using the most conservative values for this parameter, which changes over time according to the tomato growth. The gross photosynthesis rate (Eq. (6)) is a function of the canopy light efficiency (a_{canopy}), the solar radiation via the photosynthetically active radiation (PAR), the CO_2 internal concentration ($C_{CO_2}^{GH}$) and the CO_2 stomatal conductance (τ). The canopy light efficiency (Eq. (7)) and the CO_2 stomatal conductance (Eq. (8)) are variables that account for how much CO_2 and solar radiation can be absorbed during the photosynthesis process. These correlations have been employed in previous works [24,25] aiming to attain an optimal design of CO_2-enriched greenhouses.

$$P_n = P_g - (r \times L) \tag{5}$$

$$P_g = \frac{a_{canopy} \times PAR \times \tau \times \rho_{CO_2} \times C_{CO_2}^{GH}}{a_{canopy} \times PAR + \tau \times \rho_{CO_2} \times C_{CO_2}^{GH}} \tag{6}$$

$$a_{canopy} = a_{leaf} \times \left(1 - \frac{\exp(-k \times L)}{1 - m}\right) \tag{7}$$

$$\tau = \frac{a_a}{b_a \times k} \times \ln\left(\frac{(1 - m) + b_a \times k \times P\bar{A}R}{(1 - m) + \exp(-k \times L) \times b_a \times k \times P\bar{A}R}\right) \tag{8}$$

As it can be appreciated from Eqs. (1)–(8), there is a clear relationship between the meteorological conditions, the ventilation flow and the internal CO_2 concentration. This means that during different times of the day and of the year, different CO_2 internal concentrations and masses of CO_2 uptake can be reported. Therefore, in order to achieve a constant internal CO_2 concentration in the greenhouse, different CO_2 flow rates should be fed into the greenhouse, as it is discussed in the next section.

2.2.2. Greenhouse design

In this work, it was assumed that the greenhouses operate with a fixed target CO_2 concentration (1000 ppm); this concentration was selected by considering previous studies for CO_2-enriched greenhouses [16]. As it was previously stated, this can be reached by controlling the amount of CO_2 inlet flow and by an adequate estimation of the covered/cultivated area. Two options for defining the greenhouse area were considered:

Option 1: *Estimation of greenhouse cultivated area using maximum yearly values for area specific global solar radiation.*

A larger value for area specific global solar radiation involves a larger amount of heat to be removed from the greenhouse (via ventilation) leading as well to a larger area specific CO_2 uptake rate. Consequently, the maximum yearly area specific value for global solar radiation corresponds to the maximum yearly value for the area specific ventilation flow and the maximum area specific tomato CO_2 uptake rate. The system of equations resulting from the mass and energy balances can be solved dividing Eqs. (2) and (3) by the greenhouse cultivated area. By doing so, the area specific ventilation flow can be obtained and then used for the quantification of the cultivated greenhouse area via algebraic replacing and reordering of Eq. (1). The quantified area represents the minimum cultivated area that could be enriched without the need for an external CO_2 source. Considering that ventilation losses and CO_2 uptake flows were estimated using extreme maximum values, a lower amount of CO_2 (in comparison with the CO_2 by-product from the AD-based biomethane plant) should be incorporated into the greenhouses for a considerable fraction of the year.

Option 2: *Estimation of greenhouse cultivated area using the average yearly values for area specific global solar radiation.*

Average yearly value for area specific global solar radiation was estimated for 2016 using the previously cited UK statistics for meteorological variables [41,42]. Using this data, it is possible to obtain the area specific ventilation flow (Eqs. (2) and (3)) and then quantify the greenhouse area via Eq. (1) (employing analogous algebraic procedures than for Option 1). For those periods in which the required ventilation flow and the CO_2 uptake by the tomatoes were lower than the yearly average values, the CO_2 internal concentration was kept at 1000 ppm by enabling a lower CO_2 flow rate into the greenhouse. For those periods in which a CO_2 deficit was calculated (highest ventilation losses and highest CO_2 uptake rates), part of the produced biogas was burned and then cooled down in order to use the combustion effluents as a CO_2 source for the greenhouse.

Both options were analysed in terms of tomato production, CO_2 utilization, energy and economic performance.

2.2.3. Geometry, area and volume estimation

In this work, the greenhouse was assumed to be gable-shaped, with the walls built using a single polyethylene layer. The cultivated area was calculated according to the methodology described in the previous sections. Lateral and roof areas were based on case studies presented in [15]. The roof area was assumed to be 33% of the cultivated area, door areas 14% and lateral (faces) area was set at 44% of the cultivated area, based on the designs reported in [18].

2.2.4. Quantification of the greenhouse energy performance

In this article, the power consumption associated with ventilation flow and the heat duty required to maintain the greenhouse internal temperature were considered as an energy penalty for the CO_2 usage. It is common to report specific energy consumption per area unit (Eqs. (9) and (10)). These equations can be re-arranged to quantify the specific energy consumption per mass unit of used CO_2, as shown by Eqs. (11) and (12).

$$ASHC = \frac{|\dot{Q}_{ex}|_{year}}{A_{cul}} \tag{9}$$

$$ASPC = \frac{PC_y}{A_{cul}} \tag{10}$$

$$SHC_{CO_2} = ASHC \times \frac{A_{cul}}{CO_2 used_y} \tag{11}$$

$$SPC_{CO_2} = ASPC \times \frac{A_{cul}}{CO_2 used_y} \tag{12}$$

Tomato yield can be quantified by considering that 1 mol of carbon, assimilated as CO_2, would lead to 0.4 mol of harvested carbohydrate, 12 g of biomass or 200 g of fresh mass (assuming a 6% dry-matter content in tomatoes) [43]. This conversion factor was estimated by considering a 72% biochemical conversion efficiency, a 17% loss of accumulated respiration, a harvest index of 67% and a fruit dry-matter content of 6%.

2.3. Economic assessment of the Utilization case

2.3.1. Estimation of the capital investment cost

The capital investment cost for the greenhouse was quantified using the cultivated area estimated for Option 1 and Option 2. Using an average of 90 £/m^2 [44], the capital investment costs for the greenhouse were calculated using Eq. (13).

$$CIC^{GH} = GHGUKPR^{ave} \times A_{cul} \tag{13}$$

As it was previously mentioned, a faction of the produced biogas is assumed to be combusted to supply the required heat for the operation of the greenhouse. If the incorporation of the greenhouse were considered during the design phase then the farm, the greenhouse, the AD reaction system and the upgrading unit thermal duty could be generated using the same biogas fired boiler. Consequently, the capital cost associated with the heat production for the greenhouse (CIC_{BO}) can be estimated (Eq. (14)) by considering the installed cost per kW presented in [45] and the yearly maximum thermal flow (MTF) for each option. It must be noted that the obtained result represents the added cost for a projected boiler so that the heat provision of the greenhouse can be delivered; it is not the cost of an individual boiler. Using the maximum thermal flow for each design option guarantees that heat can be supplied the whole year; enabling heat to be provided during winter nights but also during summer (at a lower operational load).

$$CIC^{BO} = BOSC^{ave} \times MTF \tag{14}$$

Air circulation to and within the greenhouse was enabled using ventilators. It must be noted that the ventilator models were selected so that the maximum air flow for each design option can be provided. Ventilator diameters in the range between 36 and 60 in. were considered as well as cost data provided by vendors [46].

2.3.2. Quantification of operating costs

Greenhouse operating costs were mainly associated with the energy consumption for ventilation and heating. In the case of ventilation, costs associated with power consumption were quantified by considering the UK electricity price and the total electricity consumption during the year (Eq. (15)). The UK electricity price is forecasted to increase during plant life because of higher values for UK climate change levy, this cost evolution was presented by the former UK Department for Climate Change [47].

Costs related to heating were based on the non-obtained profit due to the burning of a share of biogas instead of upgrading it to biomethane. This profit reduction can be estimated (Eq. (16)) as the difference between the injection revenue of the biomethane and its associated levelized cost [8]. Biomethane injection tariff is guaranteed for the entire plant life time and it depends on the commissioning date [48]. The biomethane production plant was assumed to be commissioned in the last quarter of 2017 whilst the levelized cost of biomethane was estimated using the values reported in [8].

$$CE^{GH} = ELUKPR_y \times EC_y \tag{15}$$

$$CHT^{GH} = \left(\frac{biomethane\ \ mass\ \ flow}{biogas\ \ mass\ \ flow}\right)_{plant} \times (FIT - LCBM) \times biogas_{heating_y} \tag{16}$$

The thermal energy employed in the greenhouse qualifies as useful heat under the renewable heat incentive (RHI) definition [49] thus the plant may receive an extra profit (negative cost, RHI^{GH}) related to this heat production (Eq. (18)). The RHI fare (RHI^{biogas}_{fare})paid to the farm for this thermal output will be guaranteed as well for the whole plant life time.

$$RHI^{GH} = RHI^{biogas}_{fare} \times biogas_{heating_y} \tag{17}$$

The economic performance of the use of CO_2 in greenhouse was quantified using the levelized cost of CO_2 utilization, as displayed by Eq. (18).

$$LC^{GH}_{CO_2} = \frac{\sum_n \frac{CIC^{TT} + CEC^{GH} + CHT^{GH} - RHI^{GH}}{(1 + r_d)^n}}{\sum_n \frac{CO_2 utilization_n}{(1 + r_d)^n}} \tag{18}$$

Gross profit associated with the use of CO_2 in greenhouses is a consequence of the sale of the produced tomatoes and can be estimated by using Eq. (19). An assumed yearly tomato price average was used in this estimation, based on the data reported in [50]. Net profit (Eq. (20)) is defined as the difference between the gross profit and the levelized cost of CO_2 use.

$$GP_{CO_{2use}} = TP_y \times TUKPR_y \tag{19}$$

$$NP_{CO_{2use}} = \left[\left(\frac{CO_2 used_y}{TP_y}\right) \times GP_{CO_{2use}}\right] - LC^{GH}_{CO_2} \tag{20}$$

2.4. Environmental assessment

Net GHG emission for the Utilization and the Storage configurations were quantified by considering: a) the non-emitted by-product biogenic CO_2 emissions from the biogas upgrading unit, b) the indirect emissions associated with electricity supply, c) the fossil fuel employed for traditional enriched CO_2 greenhouses and which may be as well replaced by the share of biogas used for greenhouse heat supply and d) combustion and production emissions. It must be noted that the scope of this work is not to present a life cycle assessment study for the configurations under study but understanding the environmental advantages of the utilization case when comparing it against the CO_2 geological storage and conventional CO_2 enrichment for agriculture greenhouses. GHG emissions per kWh_e for the UK electricity grid are based on the data published by DEFRA [51], as shown in Eq. (21).

$$GHG\ \ emission_{power} = (Power_{consumption}) \times EF_{DEFRA} \tag{21}$$

It was assumed that in conventional greenhouses, liquid fossil fuels, manly diesel oil types, would be burned to produce the required CO_2 flow for the greenhouse enrichment. Knowing the latter, the amount of diesel to be burned can be quantified using Eq. (22).

$$Diesel\ \ oil\ \ consumption_y = \frac{CO_2\ \ used_y}{EF^{IPCC}_{CO_2}} \tag{22}$$

Apart from CO_2 emissions, diesel combustion will generate other greenhouse gas emissions including CH_4 and N_2O, which also contribute to global warming and can be expressed in terms of CO_2 equivalent, as stated in Eq. (23). It can be assumed that the non-CO_2 species were not absorbed by the crops and removed to atmosphere by the ventilation flow. Emission factors have been extracted from the 2006 IPCC Guidelines for National inventories [52].

$$Non\ \ CO_2\ \ GHG\ \ diesel\ \ oil\ \ combustion\ \ \ emissions_y \\ = Diesel\ \ oil\ \ consumption_y \times (EF_{CH_4}^{IPCC} + EF_{N_2O}^{IPCC}) \tag{23}$$

Diesel oil production also involves greenhouse gas emissions which are avoided when CO_2 enrichment of agriculture greenhouses is undertaken with by-product CO_2 from other activities. These emissions were estimated using Eq. (24). The specific greenhouse gas emissions per mass unit of produced diesel oil is based on the survey conducted by [53].

$$GHG\ \ diesel\ \ production_y = Diesel\ \ oil\ \ required_y \times EF_{GHG}^{PROD} \tag{24}$$

3. Results and discussion

This section of the paper presents the results for each of the techno-economic and environmental indicators employed for the feasibility and profitability analysis of CO_2 utilization for AD plants in agricultural CO_2-enriched greenhouses. Section 3.1 presents the main technical outputs whilst Sections 3.2 and 3.3 summarize the results for the economic and environmental performance parameters. Section 3.4 shows the monthly evolution of the afore mentioned indicators while Section 3.5 analyses possible sources of uncertainties and gaps in the modelling assumptions in this work. Section 4 highlights the main findings of this work, underlining key messages and possible uses for technology deployment.

3.1. Technical indicators

3.1.1. Input to the greenhouses

As previously mentioned, greenhouses were designed to use the CO_2 by-product from an AD biomethane plant installed in a 125-cow dairy farm. Data for the plant and the CO_2-rich stream is based on the process design presented in [8] and [40]. Table 1 summarizes the key parameters of these previous works that were employed in the current research exercise.

3.1.2. Solar radiation, temperature profiles and energy demand

In this work, mass and energy balances for the greenhouses were solved for area and energy duty quantification. Heat consumption and ventilation are function of the meteorological conditions. It was observed that maximum solar radiation took place between 1 pm and 5 pm, whilst minimum temperatures occurred during the morning time, when solar radiation was close to zero. Results for the area-specific monthly heat and power demands are shown in Fig. 2. Higher values for electricity consumption were seen during summer due to larger ventilation flows, required to maintain an internal temperature of 25 °C due to the higher temperature and higher solar radiation values. As expected, larger heating demands were calculated for the winter period. The heat demand was assumed to be supplied by part of the biogas produced in the AD plant. The cumulative yearly specific power demand accounted for 14.9 kWh_e/m^2 y, whilst the cumulative yearly specific heat demand was around 357.4 kWh_t/m^2 y. These values were in agreement with results presented by [19] for greenhouses in the UK.

3.1.3. CO_2 absorption by tomatoes and total CO_2 uptake

Total CO_2 uptake (Fig. 3) in the greenhouse was a consequence of tomato CO_2 absorption (6%) and CO_2 ventilation losses (94%). Tomato CO_2 absorption was directly influenced by the meteorological conditions. For those periods with larger values for global solar radiation, larger CO_2 absorption by tomatoes were found. During these periods, larger ventilation flows were also required, resulting in larger CO_2 losses through ventilation. These losses were offset by the CO_2 inlet flow and therefore, due to the loss CO_2 in the ventilation flows, a considerably lower area of cultivated tomatoes or vegetable crops was served with the same CO_2 inlet flow.

Table 1
Main input and output data for AD and upgrading plant.

AD reaction system	
Biogas produced (kg/year)[1]	337,625
y_{CH_4}[2]	0.6
y_{CO_2}[2]	0.4
Biogas produced molar flow (kmol/year)[3]	12,413
Energy consumption: AD reactor + farm (MJ/year)[4]	160,834
Biogas consumption: AD reactor + farm (kg/year)[5]	9112
Net biogas produced: AD reactor (kg/year)	328,513
MEA upgrading unit	
Specific energy consumption ($kJ/Nm^3_{biogasinput}$)[6]	1607
Specific energy consumption ($kg_{biogasfuel}/kg_{biogasinput}$)[7]	8.1E−2
$y_{CO_2}^{biomethane}$[8]	4.0E−2
$y_{CH_4}^{biomethane}$[8]	9.6E−1
$y_{CO_2}^{CO_2richflow}$[8]	9.9E−1
$y_{CH_4}^{CO_2richflow}$[8]	1.0E−2
Biogas inlet flow, excluding biogas used as fuel for thermal duty of the MEA unit (kg/year)	
CO_2 rich stream flow (kmol/year)[9]	4254
CO_2 rich stream flow (kg/year)[10]	185,945
Biomethane flow (kmol/year)[11]	7247
Biomethane flow (kg/year)[12]	115,945
Greenhouse	
CO_2 greenhouse inlet stream (kmol/year)[13]	4254
CO_2 greenhouse inlet stream (kg/year)	187,176

[1] Based on the figures presented in [35]. Biogas was quantified using average ultimate analysis for dairy cow slurry and the Buswell Boyle equation [54].

[2] Typical composition for biogas obtained as a product of the anaerobic digestion of dairy cow slurry. Rounding to close integer for the mole fraction used in [8] Simplification to two component mixture for easing the analysis in this article.

[3] Using a molar mass of 27.2 g/mol for the biogas (weighting average of the biogas mole fractions and the molar mass for the components of the mixture).

[4] Heat required for the operation of the anaerobic digester and for the farming activities [35,55,56].

[5] Calculated using the thermal duty mentioned in 4 and a low heating value of 17.65 MJ/kg biogas. LHV based on weighting average of mass fractions and LHV of pure compounds.

[6] Specific energy consumption for a 30% mass MEA (mono-ethanol amine) upgrading unit, data published in [8]. This figure is equivalent to a thermal duty of 3.85 MJ/kg CO_2, which is consistent with previous works assessing the use of this separation agent for CO_2 removal.

[7] Heat for the operation of the solvent based unit. The thermal duty for the separation can be obtained by combusting part of the produced biogas. Biogas LHV estimated as described in 5.

[8] Mole fractions based on the simulation presented in [8]. Biomethane refers to the stream leaving the absorber of the MEA unit (injected to the grid) whilst CO_2 rich stream makes reference to the stream leaving the stripper of the MEA unit downstream the condenser.

[9] Molar flowrate from the process simulation results published in [8] for the rich CO_2 stream.

[10] Mass flowrate converted using the molar mass for the gaseous stream (weighting average using the mole fraction of the mixture components and the molar mass of CO_2 and CH_4).

[11] Molar flowrate from the process simulation results published for the biomethane stream in [8].

[12] Mass flowrate converted using the molar mass for the gaseous stream (weighting average using the mole fraction of the mixture components and the molar mass of CO_2 and CH_4).

[13] It was assumed that the rich CO_2 stream is burned in excess of air so that the remaining CH_4 is converted to CO_2 and H_2O. This is because the presence of CH_4 could be toxic for the crops in the greenhouse. Considering the low mole fraction of CH_4 thus the low thermal flow, the heat generated by the combustion was considered negligible.

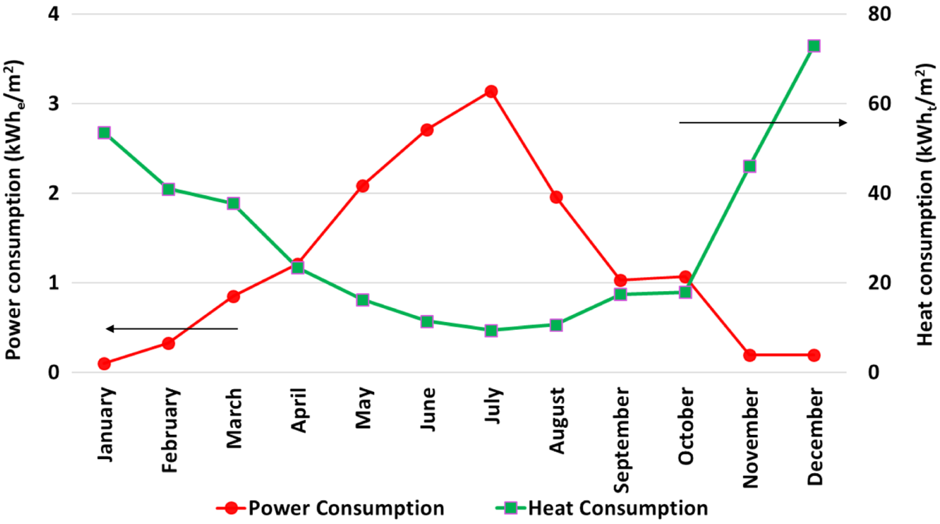

Fig. 2. Specific power and heat consumption per month.

3.1.4. *Greenhouse design*

As explained in the methodology section, two options were considered for the greenhouse design. For the first option (**Option 1**), the greenhouse area was calculated based on the maximum area specific ventilation flow and the maximum area specific CO_2 tomato absorption therefore gave the lowest resultant area. For the second option (**Option 2**), the greenhouse area was estimated by using the yearly average area specific solar radiation and temperature and so a larger area could be served by using the AD biomethane by-product CO_2. It must be noted however that there were periods of the year for which an extra source of CO_2 was required due to the larger ventilation flow and larger CO_2 uptake. It should be highlighted that for both options, the greenhouse internal CO_2 concentration was kept at 1000 ppm. Table 2 displays the main technical inputs and production yields for the two design options.

It can be seen that the cultivated area in **Option 2** was approximately 6.73 times larger than for **Option 1**, thus enabling a larger CO_2 by-product usage and also allowing a larger tomato production yield, despite having higher heat and electricity demands. Extra CO_2 was needed for **Option 2** in order to offset the losses for ventilation, with the demand for extra CO_2 occurring during late spring and summer months. This is because it did not seem feasible to store the excess CO_2 from winter times to be used during summer.

The area specific energy consumption for both design options was almost identical; **Option 2** involved a larger area and no difference was expected to be found. In the case of specific CO_2-related performance parameters, two values are presented for **Option 2**: the value on the left refers to the specific values (only considering the CO_2 flow that was fed to the greenhouse) whilst the value on the right was normalized by accounting for the total amount of used CO_2.

Fig. 4 shows specific tomato yield per unit of covered area for CO_2-atmospheric and CO_2-enriched (1000 ppm) greenhouse operation. The results from the model developed in this research exercise were compared against published data [11,13]. Small differences between the results presented in this article and in previous literature were observed. A significant increase on the tomato production yield (50%) in CO_2-enriched greenhouses was reported.

3.1.5. *Comparison of energy demand with storage case*

Power consumption for the CO_2 compression train is highly influenced by the number of compression and intercooling stages considered in the compression train, the assumed efficiency for the compressors and the temperature for available cooling water. If long distance

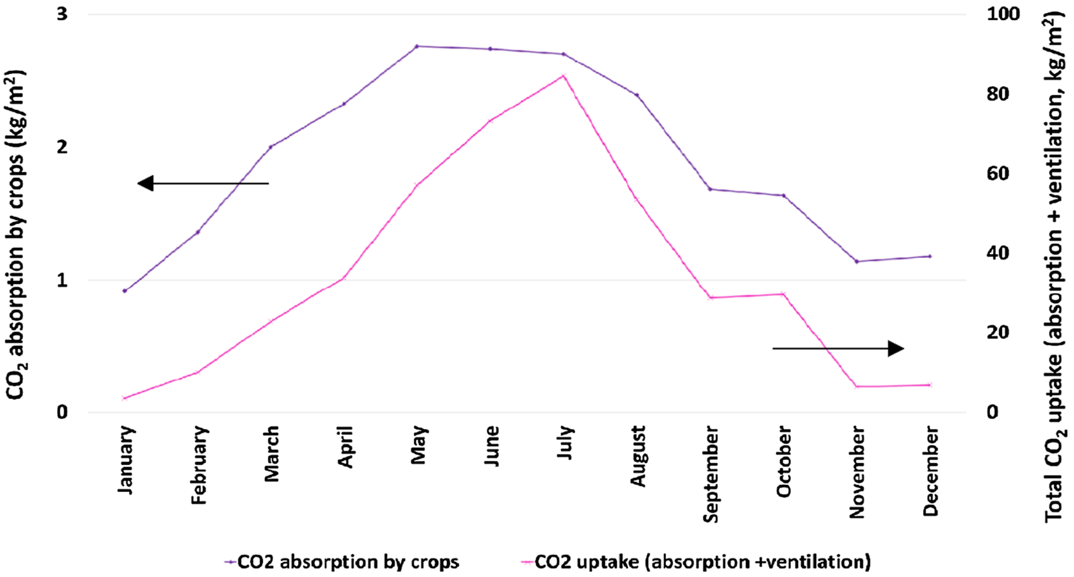

Fig. 3. CO_2 Uptake: tomato absorption and ventilation.

transport were considered, as it was in this work, the final pressure should be around 150 bar in order to compensate possible pressure drops along the transport network. Main design assumptions and technical performance indicators are displayed in Table 3.

Table 2
Main technical inputs and yields for the two greenhouse options analysed greenhouses.

	Option 1	Option 2
Covered area (m^2)[1]	72	485
CO_2 crop uptake (kg/y)[2]	1645	11,074
Total CO_2 loss for ventilation (kg/y)[3]	24,876	167,463
CO_2 used from upgrading unit (kg/y)[4]	26,521	125,160
Extra CO_2 required (kg/y)[5]	–	53,571
Percentage (%) of used CO_2 (in comparison with the AD biomethane CO_2 by-product)[6]	14	67
Tomato production (kg/y)[7]	7589	51,072
Electricity consumption (kWh/y)[8]	925	6228
Thermal duty (kWh/y)[9]	25,745	173,623
Biogas consumption for heating (kg/y)[10]	6365	42,661
Equivalent biomethane, heating (kWh/y)[11]	26,352	176,625
Biogas consumption for extra CO_2 (kg/y)[12]	–	31,775
Equivalent biomethane, for extra CO_2 (kWh/y)[13]	–	131,547
Total equivalent biomethane (kWh/y)[14]	26,352	308,172
Specific electricity consumption per covered area (kWh_e/m^2)[15]	13	13
Specific heat consumption per covered area (kWh_{th}/m^2)[16]	358	358
Specific tomato production per covered area (kg tomato/m^2)[17]	105	105
Specific electricity consumption per kg of used CO_2 (kWh_e/kg CO_2) * 100[18]	4	5/4
Specific heat consumption per kg of CO_2 (kWh_{th}/kg CO_2) * 100[19]	97	139/97
Specific tomato production per kg of used CO_2 (kg tomato/kg CO_2)[20]	29	41/29

[1] Estimated based on the methodology described in Sections 2.2.1 and 2.2.2 - solving Eqs. (1)–(8).

[2] Quantified by considering the methodology described in Section 2 and using meteorological data (Eqs. (5)–(8)).

[3] Employing the methodology explained in Section 2 via the energy and mass balance.

[4] Total CO_2 used in the greenhouse, accounting for the CO_2 absorbed by the crops and by the ventilation losses.

[5] Extra CO_2 that yearly must be incorporated to the greenhouse in addition to the CO_2 by product from the upgrading unit. CO_2 flow is used for fulfilling the summer CO_2 peak demands in Option 2.

[6] Considering the ratio of the sum of the CO_2 absorbed by the crops and lost by ventilation and the total by product CO_2 from the upgrading unit.

[7] Calculated using the ratio between the mass of CO_2 and tomato reported by [43] and explained in Section 2.2.4.

[8] Using a specific power consumption of around 0.15 kJ_e/Nm^3 (information provided by the vendors).

[9] Based on the methodology described in Section 2, as result of the energy balance using average meteorological data input.

[10] Estimated by considering the thermal duty for the greenhouse (see 9), using LHV thermal boiler efficiency of 82.5% and biogas LHV of 17.65 MJ/kg biogas.

[11] Quantified by employing the separation performance indicators (recovery and purity) presented in [8].

[12] Obtained by solving the system of equations arising from the mass and energy balance as well as an emission factor of 1.617 kg CO_2/kg of biogas.

[13] Idem 24, calculated by employing the separation performance indicators (recovery and purity) presented in [8].

[14] Sum of the biomethane equivalent for employed biogas for heating purposes and biomethane equivalent for biogas burned to produce extra CO_2.

[15] Obtained dividing the yearly power consumption by the cultivated/covered greenhouse area (Eq. (10)).

[16] Calculated as the ratio between the yearly thermal consumption and the greenhouse covered area (Eq. (9)).

[17] Estimated dividing the tomato production yearly production by the greenhouse cultivated covered area.

[18] Result of employing Eq. (11).

[19] Quantified using Eq. (12).

[20] It must be noted that the denominator of this ratio includes the CO_2 which is lost due to ventilation.

As it can be observed the specific power consumption was two times higher than the one corresponding to the utilization case. Based on that, both economic and environmental benefits would be expected for the latest option as it will be further explained in the next subsections.

3.2. *Economic indicators*

3.2.1. *Capital investment costs*

For both design options, capital investment costs were calculated. These capital investment costs include the cost of the greenhouses, the cost of the required ventilators and the cost of the biogas-fired boiler, as shown in Table 4.

It can be noted that the greenhouse infrastructure was the main driver for the capital investments for both design options, followed by the ventilators, the biogas boilers and CO_2 flow inlet blowers.

3.2.2. *Operating costs*

Operating costs considered in this work were related to the heat and electricity consumption in the greenhouse. As previously explained, heat was assumed to be supplied by burning a fraction of the produced biogas, meaning that using this share of biogas would reduce the amount of biomethane to be injected to the natural gas network. Consequently, it was decided to account for this loss of profit. The need for extra CO_2 for **Option 2** led to additional burning of biogas to produce the required CO_2. Costs related to power consumption in ventilation were also accounted for, with values for 2017–2018 reported in Table 5.

3.2.3. *Levelized cost of used CO_2 and net profit*

As mentioned in the introduction, the economic feasibility of the use of the by-product CO_2 was assessed by employing the levelized cost of used CO_2 and the net profit per kg of CO_2 as performance indicators. Fig. 5 shows the main contributions to the levelized costs of CO_2 usage for both options.

As it could be observed, the levelized cost associated with the unobtained profit for the biomethane injection accounted for the largest portion of the levelized cost of CO_2 usage, followed by the levelized CIC. The net profit per kg of used CO_2 was also calculated based on the tomato sales and the levelized cost of biomethane, as explained in the methodology section. The extra profit per kWh of injected biomethane is shown in Table 6.

Both utilization options may have potential to show economic advantages over the storage case. For the latter, operating costs associated with CO_2 compression - based on the power consumption estimated in Section 3.1.5 and the UK price for grid electricity in 2018 [38] - are around 1 p/kg of CO_2 whilst storage costs may range from 0.1 to 0.7 p/kg of stored CO_2 (on-shore) and 0.6 to 2 p/kg of stored CO_2 (off-shore) [38].

3.3. *Environmental indicators*

Greenhouse gas (GHG) emissions were quantified and compared for the CO_2 storage and the CO_2 utilization options. Table 7 shows the values for GHG emissions associated with different aspects related to the operation of the by-product CO_2 enriched greenhouse and with the storage configurations. Net GHG emissions per kWh_{LHV} of biomethane are as well presented. The exercise was conducted, considering that the amount of stored CO_2 is equal to the one utilized in **Option 1.**

When undertaking this research exercise, the focus was to confront the environmental performance of the utilisation case against the two storage options. This is why the results in Table 7 are presented only for the utilization case Option 1. If the utilization Option 2 were

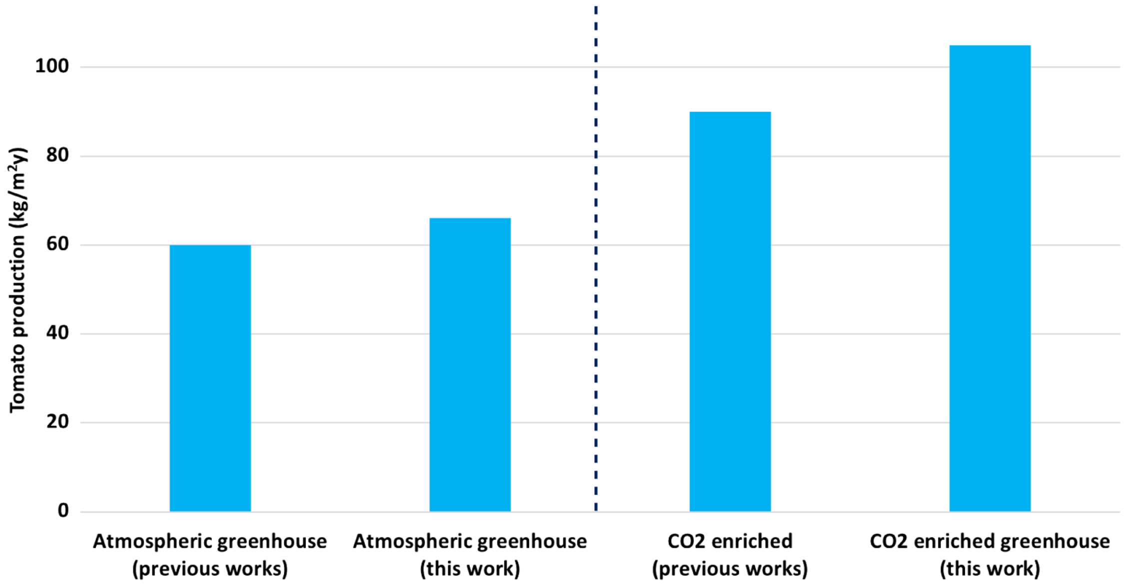

Fig. 4. Tomato production per unit covered area.

Table 3
Main technical inputs and outputs of the compression train.

Technical design parameters	
Compression stages	6
Compressor adiabatic efficiency (%)	84
Technical performance indicators	
Specific performance (kWh_e/kg of CO_2) * 100	8.2

Table 4
Capital investment costs.

	Option 1	Option 2
CIC^{GH}[1] (£)	5763	42,811
CIC^{BO}[2] (£)	1057	6981
CIC^{VN}[3] (£)	4748	32,234
CIC^{TOT} (£)	11,568	82,026

[1] Capital investment cost, estimated using an average of £90/m^2, as described in Section 2.

[2] Cost associated with an increase in boiler size to supply the maximum heat flow for each design option; estimations were carried out using capital investment cost of £140/kW based on data in [45].

[3] Based on the information from industrial ventilator vendors.

Table 5
Operating costs and profits (2017–2018).

	Option 1	Option 2
CPW^{GH}(£)[1]	122	821
CIC^{GH}(£)[2]	1081	7075
CEX_{GH}(extra CO_2)[3](£)	–	5393

[1] Using UK electricity price presented in [47], based on 2018 forecasted values published by DECC.

[2] Estimated considering the economic loss associated with the amount of non-injected biomethane equivalent to the biogas which is employed for greenhouse heating. Calculations were based on the methodology described in Section 2.2.2. Assumed biomethane feed in tariff corresponds to the one published for the second quarter of 2018 whilst the levelized cost of biomethane was based on the data presented by Oreggioni et al. [8].

[3] Estimated considering the economic loss associated with the amount of biomethane equivalent to the biogas which is employed for greenhouse heating. Calculations were based on the methodology described in Section 2.2.2.

considered, the net GHG emitted per kWh_{LHV} would be different - consequence of a larger CO_2 greenhouse recovery rate. In both cases, a fair comparison with the storage case would require that the amount of CO_2 being stored and utilized to be the same.

Going further into the analysis – using the data displayed in Table 7- it could be observed that GHG indirect emissions associated with power consumption for CO_2 compression were higher than indirect GHG emissions related to the electricity consumed for the greenhouse ventilation.

Given the fact that the fuel consumption for CO_2 enrichment in Storage B case was a few times higher than the fuel required for the greenhouse heating, it was assumed that part of the heat generated in the boiler - employed for producing the required CO_2 for the enrichment- could as well be used for greenhouse heating. This explained why only the direct non-CO_2 GHG emissions and the indirect GHG emissions for diesel production related to CO_2 enrichment are shown in Table 7. The advantage of the CO_2 utilization case over Storage B case was strongly dependent on the assumptions regarding the fuel, being replaced by the share of non-upgraded biogas combusted to provide heat to the greenhouse. If diesel oil were considered, higher net absolute emissions- meaning larger emissions- would be reported by this configuration. However, if that share of biogas were used for replacing woody biomass or natural gas, the Utilization case would exhibit an advantage from a GHG emission saving point of view. If biogas were substituting natural gas, the associated direct GHG emissions would be 27% lower thus net GHG emitted per kWh of biomethane would be lower than for Storage B case. For the case of replacing assumed carbon neutral woody biomass, the Utilization Case would show even further GHG emission savings.

3.4. *Monthly performance indicators*

As it could be observed from the results presented – in special in Section 3.1- a monthly dependency for the energy consumption and for the extra CO_2 needs in the greenhouse were reported. This is consequence of a monthly variation of temperature and solar radiation – influencing the ventilation flows and the CO_2 uptakes by the tomatoes. As examples of these trends, Figs. 6 and 7 display the monthly evolution of economic and environmental performances for the CO_2 Utilization 1.

As expected, during winter months, larger costs for greenhouse heating – since a share of biogas is not upgraded to biomethane- were quantified. During summer, higher operating costs related to the

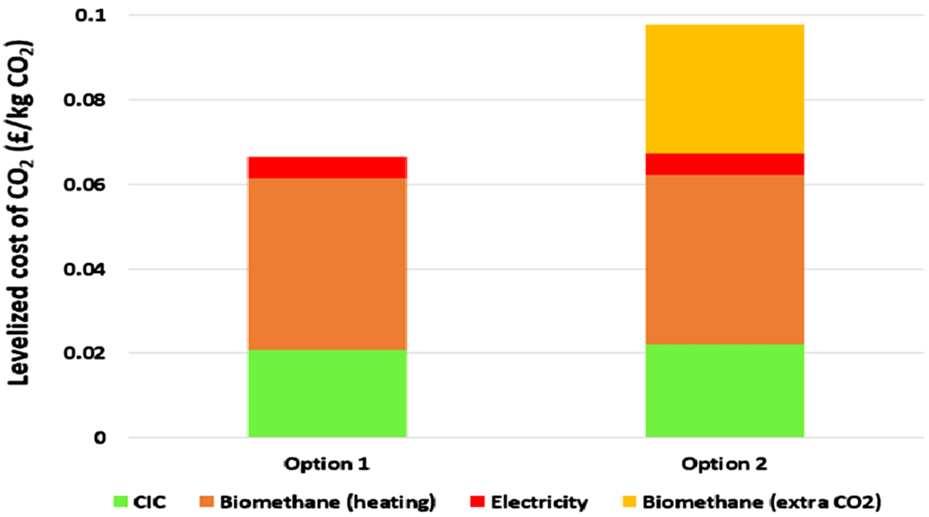

Fig. 5. Levelized cost of CO_2 usage for both greenhouse design options.

Table 6
Profits for design Options 1 and 2.

	Option 1	Option 2
Net profit (p/kg_{CO2})	11.7	11.2
Added profit (p/$kW_{biomethane}$)	1.6	1.3

consumed power for ventilation were estimated. However, the net profits resulted to be positive for the twelve months of the year.

In terms of GHG emissions for the operation of the CO_2 enriched greenhouses, larger GHG emissions associated with fuel substitution – consequence of biogas being burned for greenhouse heating- were reported for winter months in which a larger thermal demand was quantified. Indirect GHG emissions for power supply were observed in the summer months alike the CO_2 usage – for compensating for a larger amount of CO_2, being absorbed by the crops and lost by ventilation.

3.5. Discussion

Data input for the mass and energy balances for the greenhouses mainly relies on meteorological data, presenting variations according to the year in which the study is carried out. These variations in temperature and global solar radiation may lead to different values for the specific heat and power consumption. Estimates were carried out using the 2016 meteorological data for the UK, giving an area-specific heat demand of 357.4 $kWht/m^2$ y, whilst the area-specific power demand was calculated as 15 $kWhe/m^2$ y. These values are in agreement with the results published by Georgiou et al. [19] for the UK covering the last 20 years. It must also be noted that the steady state assumption for the mass and energy balances was considered: it was assumed that, independently of the daily temperature changes, heat or ventilation was supplied to keep the internal greenhouse temperature constant. This ignores possible transients, but greenhouse temperature control would be designed so that the transient duration is minimal.

CO_2 absorption by tomatoes was calculated using the experimentally based correlations presented by Nederhoff and Vegter [13]: this set of equations is based on CO_2 uptake experiments in greenhouses in the Netherlands. It was assumed that these correlations could be applied to the UK when using local meteorological conditions. Results in terms of tomato yield per unit of covered area also aligned well with published data; the quantified tomato yield was close to 66 kg_{tomato}/m^2 y, whilst

Table 7
Greenhouse gas emissions among the utilization and the storage cases.

	CO_2 utilization Option 1	CO_2 Storage A	CO_2 Storage B
Power consumption – GHG indirect emission (kg_{CO2eq}/kg_{CO2})[1]	1.13E−2	–	1.13E−2
Diesel non-CO_2 GHG combustion emissions – CO2 enrichment (kg_{CO2eq}/kg_{CO2})[2]	–	–	6.29E−3
Life cycle emissions diesel production GHG emissions – CO_2 enrichment - (kg_{CO2eq}/kg_{CO2})[3]	–	–	1.92E−1
Total GHG emissions -operation greenhouse (kg_{CO2eq}/kg_{CO2})	1.13E−2	–	2.09E−1
Indirect GHG emissions CO_2 compression – GHG emissions associated with power consumption, (kg_{CO2eq}/kg_{CO2})[4]	–	2.26E−2	2.26E−2
Fossil fuel substitution- combustion GHG emissions (kg_{CO2eq}/kg_{CO2})[5]	2.89E−1	–	–
Fossil fuel substitution- fuel life cycle production GHG emissions (kg_{CO2eq}/kg_{CO2})[6]	5.51E−2	–	–
GHG emission – fossil fuel substitution ($kgCO_{2eq}/kgCO_2$)	3.44E−1	–	–
Total GHG emissions (kg_{CO2eq}/kg_{CO2})	3.55E−1	2.26E−2	2.32E−1
Gross GHG emitted per kWh of biomethane (kg_{CO2eq}/kWh_{LHV})[7]	4.57E−3	4.57E−3	4.57E−3
Net GHG emitted per kWh of biomethane (kg_{CO2eq}/kWh_{LHV})	2.95E−3	4.47E−3	4.47E−3

[1] Based on the specific power consumption reported in Table 2 and specific greenhouse gas emission factor for UK grid electricity reported by DEFRA [51].

[2] CO_2 emission factor from the 2006 IPCC Guidelines for National Gas Inventories were used for quantifying the fuel to be combusted for producing the required CO_2 mass for greenhouse enrichment. Once fuel was estimated, non-CO_2 greenhouse emission factors were employed for the quantification of these emissions.

[3] Considering the fuel consumption previously estimated and the life cycle greenhouse emissions for diesel production presented by Berglund and Borjesson [57].

[4] Based on the power consumption presented in Table 2 and using DEFRA GHG emission factor for UK grid electricity [51].

[5] Considering that biogas employed for greenhouse heating is replacing diesel oil for thermal energy supply in the farm.

[6] Using the assumptions pointed out in 45 and using the emission factor from Berglund and Borjesson [57].

[7] These emissions were quantified employing the CO_2 inlet to the greenhouse – which was accounted as stored in the cultivated tomatoes in the greenhouse- and considering a global warming potential of −1 for being biogenic utilised or stored CO2 emissions.

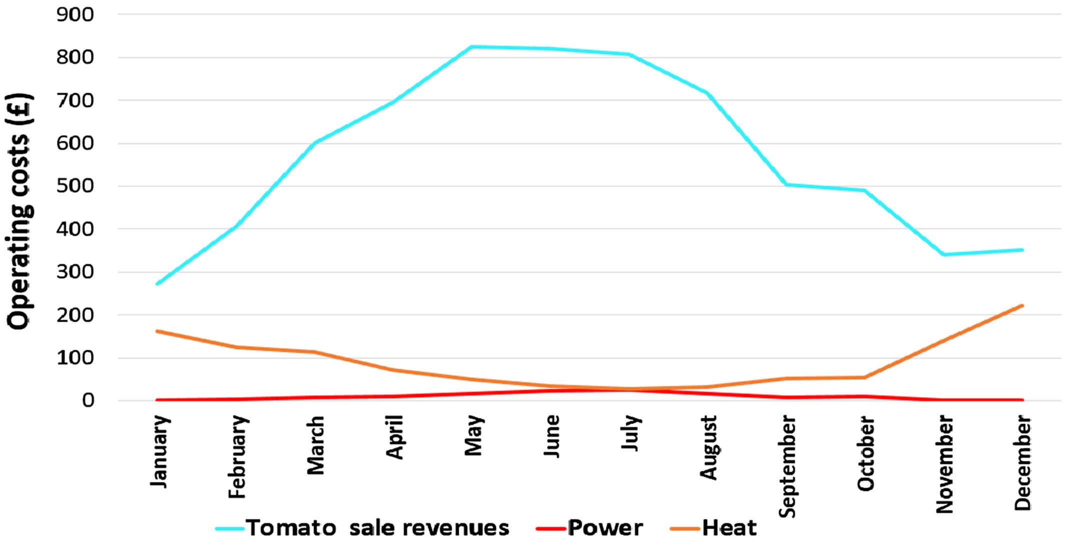

Fig. 6. Monthly operating costs and revenues for CO2 Utilization Option 1.

Nederhoff and Vegter [13] reported area-specific production rates of around 60 kg_{tomato}/m^2 y.

CO_2 enrichment in agricultural greenhouses proved to be a viable CO_2 utilization route, enabling the recovery of a meaningful share of the CO_2 by-product from the AD biomethane plant. The power consumption per unit mass of utilized CO_2 was found to be 0.04 kWh_e/kg of CO_2, whilst the thermal duty was estimated to be 0.97 kW_{th}/kg of CO_2. Despite the capital and operating costs, a net profit per kg of CO_2 was returned.

The two design options for the Utilization case were found to exhibit net economic benefits when comparing with an anaerobic digestion based biomethane production plant in which the same amount of by-product CO_2 was geologically stored. GHG emissions for each configuration was quantified by considering the combustion and the indirect emissions associated with grid electricity and fuel replacement and production. Net GHG savings for the Utilization option were observed to be function of the fuel, which the biogas employed for greenhouse heating- was replacing. When effectuating these estimations, the same global warming potential factor for stored and utilized biogenic CO_2 emissions was considered This simplification may lead to an over estimation of the benefits associated with the Utilization case because it implies that the CO_2 absorbed by the tomatoes is permanently stored alike geologically stored CO_2 however this is not the case. The amount of CO_2 sequestrated by tomatoes is part of the carbon cycle and it is likely to be re-emitted to the atmosphere but the effects in global warming potential factors cannot easily be assessed and its associated quantification would be quite uncertain.

Considering the significant level of interest in CO_2 utilization routes as a way to decarbonize the energy and industrial sectors, this article contributes to the knowledge base of these technologies and it is hoped that it may encourage the deployment of these technologies, both in fossil and biogenic plants.

4. Conclusions

In this work, the techno-economic performance of the use of AD biomethane by-product CO_2 in agricultural greenhouse was studied. The main outcomes of the conducted research are:

- Agricultural CO_2-enriched greenhouses enable CO_2 recovery rates between 14% and 67%.
- Specific power consumption per unit of covered area in the greenhouses was found to be approximately 15 kWh_e/m^2 y, whilst specific thermal duty per unit of covered area was close to 357 kW_{th}/m^2 y, leading to an associated power consumption per kg of used CO_2 of around 0.04 kWh_e/kg_{CO2} y and specific thermal duty in the range of

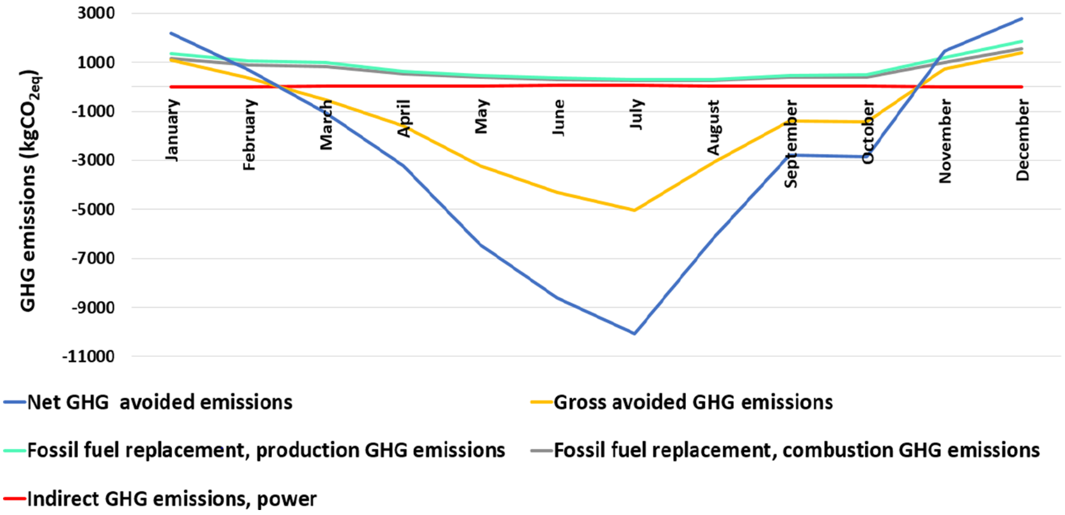

Fig. 7. Monthly operating GHG emissions.

$1\,\mathrm{kWh_{th}/kg_{CO2}}$ y.

- CO_2 utilization in CO_2-enriched greenhouses enables a maximum net profit of between 0.16 and 0.19 £/kg_{CO2}, leading to a maximum net profit close to 1.6 p/kWh of injected biomethane. It was shown that the CO_2 utilization case is more convenient than the CO_2 storage case, given the fact that the latter involves an additional net cost per mass unit of compressed, transported and stored CO_2.
- From a GHG emission savings, both CO_2 storage and CO_2 utilisation-based configurations would enable "negative CO_2 emissions" fuel production in a biogas to biomethane upgrading facility. When comparing GHG emission savings between the utilization and the storage cases, it was observed that the utilisation cases were largely influenced by the assumptions regarding the fuel to be substituted by the biogas, which is employed for greenhouse heating.

The results presented in this article highlight the economic feasibility and profitability of the use of CO_2 by-product or rich CO_2 combustion effluents in agricultural greenhouses. The outcomes of this work are expected to act as a tool or guide for the further development of this technology.

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