# Anaerobic Digestion as a Carbon Capture, Storage, and Utilization Technology

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It is expected that European biogas production will double by 2030 and quadruple by 2050. There are currently more than 18,943 biogas plants operating in Europe. With the emergence of biogas upgrading technologies, biogas is upgraded into biomethane with carbon dioxide as a byproduct. A common practice in biomethane plants is to release carbon dioxide ($CO_2$) into the atmosphere instead of utilizing it as an input for greenhouses or algal farming. In this study, the unutilized 1,900,000 $m^3$/y carbon dioxide from the biogas plant in Bruck an der Leitha (Austria) will be used for greenhouse crop farming. This study aims to determine the number of hectares of greenhouses that can be enriched with this $CO_2$. An optimal greenhouse enriched with $CO_2$ will be designed for the production of local crops to reduce the biogas plant carbon dioxide emissions. The daily daylight, solar radiation, crops carbon dioxide uptake rate and the 5,200 $m^3$ of carbon dioxide daily available were utilized to calculate the optimal greenhouse areas with and without onsite $CO_2$ storage for completely closed greenhouses and partially opened greenhouses with double polyethylene walls and standard glass walls.

## 1. Introduction

Biogas has been considered the cleanest renewable fuel for transportation by the European Union (EU) and the United States (Li et al., 2017). The EU biogas accounts for 12 % of all primary bioenergy, making it the second-largest form of bioenergy (ECOFYS, 2019). Biogas is a mixture of approximately 70 % methane ($CH_4$), 29 % carbon dioxide ($CO_2$), and 1 % other gases (Rasi et al., 2007).

According to the European Biogas Association 2020 statistical report, there are 18,943 biogas and 725 biomethane plants operating in Europe (EBA, 2020). Biogas plants are utilized for electrical and thermal energy production by burning the biogas in combined heat and power units. In more recent years, biogas upgrading technologies have emerged to purify the biogas into biomethane with a purity between 95 % to 99 %, which is either used as a transport fuel or injected into the grid.

To upgrade the biogas, carbon dioxide must be removed from the mixture. If the removed carbon dioxide is captured and stored or utilized in a contiguous process, $CO_2$ is obtained at a low cost since it's a by-product of biomethane upgrading and it also closes the carbon loop. This carbon dioxide can be utilized for horticulture, algae farming, or the soft drinks industry.

The biogas plant in Bruck an der Leitha (Austria) produces 5,200,000 $m^3$ of biogas per year, out of which 3,300,000 $m^3$ are upgraded to biomethane and 1,900,000 $m^3$ of carbon dioxide are released into the atmosphere. This unutilized carbon dioxide can be utilized for greenhouse crop production or sold as feed for the algae production facility Jongerius Ecoduna (Jongerius Ecoduna, 2022), located 400 meters from the biogas upgrading facility. The $CO_2$ can also be utilized for a methanation process or to disinfect foodstuffs instead of poisonous elements like N-Hexane (Aghel et al., 2022). This study aims to determine the number of hectares of greenhouses that can be enriched with this $CO_2$.

In horticulture, greenhouses are used to ensure the presence of regionally farmed vegetables throughout the year despite the adverse meteorological conditions or the season of the year (Vox et al., 2010). An advantage of horticultural greenhouses is that completely out-of-season crops can be obtained or the normal season production can be advanced by increasing crop prices (Adaro et al., 1999).

Carbon dioxide enrichment improves crops yield, which improves the overall efficiency of greenhouses (Huber et al., 2021). Greenhouses protect crops from adverse meteorological conditions, improve productivity and quality of crops, and ensure the presence of floricultural and vegetable products throughout the year to meet the demands of consumers and the needs of trading organizations (Russo et al., 2014). The most grown greenhouse crops are tomatoes, lettuce, zucchini, peppers, cucumbers, spinach, strawberries, and carrots. Plants are grown through photosynthesis, a process that requires sunlight, humidity, temperature, water, $CO_2$, and nutrients.

Greenhouses are designed to provide, control, and maintain the temperature, solar radiation, humidity, and carbon dioxide levels in an artificial environment (Panwar et al., 2011). The parameters to control in a greenhouse are daily solar radiation, mean air temperatures, and average vapor pressure deficit. Other parameters involved are crop nutrition (fertilizer) and crop protection (pesticides). Within crop nutrition, carbon dioxide plays an important role in photosynthesis. To make $CO_2$ enrichment effective, ideal growing conditions like humidity, temperature, moisture, nutrition, and proper lighting must be maintained (Poudel and Dunn, 2017). In this study, the main parameter considered to determine the size of the greenhouse production area is the carbon dioxide uptake rate. Other parameters, such as water evaporation, lightning, air circulation, energy, and heat demand must be considered for the design of an artificial indoor crop growing facility.

For water evaporation, the Penman-Monteith method is recommended by the FAO as the standard method of measuring evapotranspiration to determine crop water usage (Smith et al., 1998). The protective environment drastically increases yield, while lowering water consumption and pesticide use as compared to conventional farming (Ravishankar et al., 2021).

Plants need air circulation to remove humidity, and heat and to receive $CO_2$. The air renewal rate is the main parameter of greenhouse ventilation, which refers to the total volume of fresh air supplied in an hour (Mashonjowa et al., 2013).

Light energy is one of the main parameters in photosynthesis, artificial light can be utilized when there is insufficient sunlight or to modify the plant's natural cycle. A reduction of 1 % in light will decrease the crop yield by 1 % (Kong and Zheng, 2019). High-performance greenhouses carefully control the daily light integral by activating supplemental lighting when there is insufficient daylight and using screens when excess insolation exists (Bambara, 2018).

For closed heated greenhouses, energy is needed for ventilation, illumination, and heating. The energy demand can be met with solar energy or wind for electricity and geothermal energy for heating. The energy demand depends on an energy balance that contemplates the thermal requirements specified for each crop and the temperatures inside the greenhouse (Chiriboga et al., 2021). The following forms of energy can be utilized to meet the demand of the greenhouse:

- Wind: The Energie Park Group, owner of the biogas plant has 54 operational wind turbines in Bruck an der Leitha, whose installed capacity is 167 MW.
- Solar: Energie Park Group, also has experience with Solar Energy. Their installed capacity is approximate 77 MWh. Ravishankar et al., (2021) proposed to integrate semi-transparent solar cells into the structure of greenhouses to lower the energy footprint by capturing part of the light, while the remaining is utilized for crop production.
- Geothermal heat pump: the heat flow depends on the soil temperature, the exchange area, thermal properties of the soil, and the water content (Chiriboga et al., 2021).

## 2. Materials and methods

Crop modelling typically employs simplified approaches, although detailed crop modelling is possible when sufficient growth parameters are known. Simpler models estimate crop production by calculating the net photosynthesis rate of the crop (amount of dry matter produced by the plant). Complex models such as the Gembloux Dynamic Greenhouse Climate Model consider heat and mass balances, flux densities of solar radiation, far-infrared radiation, convection, phase change, conduction, ventilation leakage, ventilation, and max flux densities, and the heating system (Pieters and Deltour, 1997). Mao et al. (2016) developed an intelligent greenhouse control system based on a mathematical model of neural network control with the global variable predictive model to guarantee the best state for crop growth.

For this study, the carbon dioxide assimilation rate will be used to determine the optimal size of the greenhouse with $CO_2$ enrichment. The carbon dioxide consumption rate varies with every crop, its stage of development, nutrient level, light intensity, temperature, and nutrient level (Blom et al., 2002). An average carbon dioxide consumption level is estimated to be between 0.12–0.24 kg/h/100 $m^2$, where the higher rate corresponds to sunny days and fully-grown crops (Blom et al., 2002).

The $CO_2$ concentration of outside air by volume is approximately 340 parts per million (ppm), while in closed greenhouses with little ventilation the $CO_2$ concentration is 200 ppm (Blom et al., 2002). For this reason, $CO_2$

enrichment is a common practice in horticulture. According to Mortensen and Strømme (1987), the optimal $CO_2$ concentration for growth and yield seems to lie between 700 and 900 ppm. It has been reported that net photosynthesis increases when the $CO_2$ concentration lies between 700 - 1,000 ppm for tomatoes and 600 - 1,100 ppm for sweet peppers (Elings et al., 2007). Under ideal circumstances, the crop saturation point is reached between 1,000 - 1,300 ppm (Blom et al., 2002).

When natural air exchange through ventilation is utilized to keep the optimal temperature levels, it is estimated that about 0.50 - 0.60 kg of $CO_2$/h/100 m² must be added to a standard glass greenhouse to maintain 1,300 ppm (Blom et al., 2002). For glass greenhouses, $CO_2$ enrichment is mainly utilized to compensate for the dilution due to air infiltration. The monthly average climatological data from Bruck an der Leitha presented in Table 1 was utilized for the calculation of the optimal size of the greenhouse with $CO_2$ enrichment.

*Table 1: Monthly average climatological data of Bruck an Der Leitha. Data extracted from* ("WeatherSpark," 2022)

| Month | Solar Radiation (MJ) | Daily Daylight (h) | Air Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) | Cloudiness (%) |
|---|---|---|---|---|---|---|
| January | 4.68 | 8.9 | -3 / 3 | 89 | 4.43 | 57 |
| February | 7.92 | 10.3 | -2 / 5 | 84 | 4.65 | 57 |
| March | 12.6 | 12 | 2 / 10 | 72 | 4.52 | 56 |
| April | 18 | 13.7 | 6 / 16 | 64 | 4.34 | 52 |
| May | 21.96 | 15.2 | 10 / 20 | 65 | 4.07 | 49 |
| June | 23.76 | 16 | 14 / 24 | 59 | 3.93 | 43 |
| July | 23.76 | 15.6 | 16 / 26 | 55 | 3.80 | 35 |
| August | 20.52 | 14.2 | 15 / 25 | 54 | 3.62 | 37 |
| September | 15.12 | 12.5 | 11 / 21 | 64 | 3.80 | 45 |
| October | 9.72 | 10.8 | 7 / 14 | 76 | 3.98 | 51 |
| November | 5.4 | 9.2 | 2 / 8 | 88 | 4.16 | 61 |
| December | 3.96 | 8.4 | -1 / 3 | 88 | 4.25 | 61 |

## 2.1. Fast calculation

The number of available sun hours per month, shown in Table 1, is utilized to calculate the number of hours in which $CO_2$ can be utilized for greenhouse crop production by multiplying the daily daylight hours by the days in every month. The number of hours in which $CO_2$ can be utilized for greenhouse crop production is utilized in Table 2 to obtain the potential yearly $CO_2$ utilization and the number of hectares of greenhouse that could be enriched. The $CO_2$ consumption rate applied for completely closed greenhouses and partially opened was taken from (Blom et al., 2002). The potential yearly $CO_2$ utilization is obtained by the sum of the potential monthly $CO_2$ utilization. Finally, the greenhouse area that can be $CO_2$ enriched is obtained by dividing the yearly available $CO_2$ from the biogas plant in Bruck an der Leitha by the potential yearly $CO_2$ utilization.

The $CO_2$ potential yearly usage and the potential greenhouse area that could be $CO_2$ enriched are shown at the bottom of Table 2. Considering the 1,900,000 m³ of $CO_2$ available and the rates applied by Blom et al. (2002), a partially opened greenhouse of 2.39 to 4.78 Ha and a completely closed greenhouse of 11.95 Ha can be built.

## 2.2. Detailed calculation

As mentioned above, the yearly production of the biomethane plant of Bruck an der Leitha is 5,200,000 m³/y of biogas, 3,300,000 m³/y of biomethane, and 34,000 m³/y of Terra Juva Fertilizer (Biogas-Energiepark, 2022). The biomethane produced accounts for 63.46 % of the total biogas, leaving the remaining 36.34 % of $CO_2$. The 1,900,000 m³/y of unutilized $CO_2$ gives a daily availability of 5,205.48 m³/d. The two different types of greenhouses that were considered for this study are completely closed and partially opened. The main parameter used is the carbon dioxide uptake rate per 100 m².

*Table 2: Potential yearly $CO_2$ use by month based on sunshine hours at Bruck an der Leitha. Based on Blom et al., (2002).*

| Month | Number of hours applied (h) | CO$_2$ Applied Rate (kg/ha/h) | | | | | |
| | | Completely Closed | | | Partially Opened | | |
| | | 12 | 18 | 24 | 45 | 65 | 90 |
|---|---|---|---|---|---|---|---|
| January | 275.9 | 3,310.8 | 4,966.2 | 6,621.6 | 12,415.5 | 17,933.5 | 24,831 |
| February | 288.4 | 3,460.8 | 5,191.2 | 6,921.6 | 12,978 | 18,746 | 25,956 |
| March | 372 | 4,464 | 6,696 | 8,928 | 16,740 | 24,180 | 33,480 |
| April | 411 | 4,932 | 7,398 | 9,864 | 18,495 | 26,715 | 36,990 |
| May | 471.2 | 5,654.4 | 8,481.6 | 11,308.8 | 21,204 | 30,628 | 42,408 |
| June | 480 | 5,760 | 8,640 | 11,520 | 21,600 | 31,200 | 43,200 |
| July | 483.6 | 5,803.2 | 8,704.8 | 11,606.4 | 21,762 | 31,434 | 43,524 |
| August | 440.2 | 5,282.4 | 7,923.6 | 10,564.8 | 19,809 | 28,613 | 39,618 |
| September | 375 | 4,500 | 6,750 | 9,000 | 16,875 | 24,375 | 33,750 |
| October | 334.8 | 4,017.6 | 6,026.4 | 8,035.2 | 15,066 | 21,762 | 30,132 |
| November | 276 | 3,312 | 4,968 | 6,624 | 12,420 | 17,940 | 24,840 |
| December | 260.4 | 3,124.8 | 4,687.2 | 6,249.6 | 11,718 | 16,926 | 23,436 |
| Total (kg) | | 53,622 | 80,451 | 107,244 | 201,082.5 | 290,452.5 | 402,165 |
| Greenhouse Area (Ha) | | 17.92 | 11.95 | 8.96 | 4.78 | 3.31 | 2.39 |

### 2.2.1 Completely closed greenhouse

Knowing that on a sunny day a fully-grown crop has a carbon dioxide consumption level of 0.24 kg/h/100 m$^2$ and that the $CO_2$ uptake rate of a small crop on a shady day is 0.12 kg/h/100 m$^2$, based on the monthly solar radiation the monthly $CO_2$ uptake rate was extrapolated from these values. The crops $CO_2$ uptake per every 100 m$^2$ was utilized to determine the number of hectares of a completely closed greenhouse that could be $CO_2$ enriched. Since June and July have 16 hours of daylight, the lowest availability of $CO_2$ per hour was during this time of year, hence the smallest plantation area values were obtained for these months. The optimal greenhouse area without carbon dioxide storage tanks obtained by the plantation areas for June and July was 7.03 Ha, while when utilizing 368,989 m$^3$ of $CO_2$ storage, the resulting area was 11.31 Ha. The results for the completely closed greenhouse with and without $CO_2$ storage are presented in Table 3.

### 2.2.2 Partially opened greenhouses

2.2.2.1 Double polyethylene
Utilizing the $CO_2$ rates directly based on the monthly sun hours, it was determined that 6.14 hectares can be fed at a rate of 35 kg/ha/h and 8.6 hectares at a rate of 25 kg/ha/h. Correlating the 25 – 35 kg/ha/h rate with the monthly solar radiation of Bruck an der Leitha (Table 1), a more real consumption can be obtained. Based on the month with the most sunlight, 4.82 hectares can be enriched with $CO_2$, with no $CO_2$ storage needed. If the exceeding 277,000 m$^3$ of $CO_2$ are stored and utilized during the sunny months, 6.97 hectares of double polyethylene greenhouses can be $CO_2$ enriched. These results are presented in Table 3.

2.2.2.2 Standard glass
Utilizing the $CO_2$ rates directly based on the monthly sun hours (Table 1), it was determined that 3.58 hectares can be fed at a rate of 60 kg/ha/h and 4.30 hectares at a rate of 50 kg/ha/h.
Correlating the 50 – 60 kg/ha/h rate with the monthly solar radiation of Bruck an Der Leitha (Table 1), a more real consumption can be obtained. Based on the month with the most sunlight, 2.81 hectares can be enriched with $CO_2$, with no $CO_2$ storage needed. If the exceeding 233,000 m$^3$ of $CO_2$ is stored and utilized during the sunny months, 3.85 hectares of standard glass greenhouses can be $CO_2$ enriched.

*Table 3: Summary of results*

| Concept | Completely Closed | Partially Opened Double Polyethylene | Standard Glass |
|---|---|---|---|
| Greenhouse with No CO$_2$ Storage (Ha) | 7.03 | 4.82 | 2.81 |
| Greenhouse with CO$_2$ Storage (Ha) | 11.31 | 6.97 | 3.85 |
| CO$_2$ Storage (m$^3$) | 368,989 | 276,515 | 232,791 |
| CO$_2$ Uptake Rate (kg/h/100m$^2$) | 0.12-0.24 | 0.25-0.35 | 0.5-0.6 |

## 3. Conclusions

In this study, optimal greenhouses capacity designs were evaluated for carbon enrichment with unutilized carbon dioxide ($CO_2$) from the biogas plant of Bruck an der Leitha located in Lower Austria. Optimal greenhouse area values were obtained for completely closed greenhouses and partially opened with double polyethylene walls and standard glass walls.

Two methodologies were used to calculate the optimal greenhouse area. First a fast calculation utilizing a standardized $CO_2$ application rate. The second was a detailed calculation based on the daily daylight, solar radiation, crops carbon dioxide uptake rate and the daily available carbon dioxide.

The greenhouse area values for the fast and detailed calculation for the completely closed greenhouse and partially opened greenhouse are in agreement. In the fast calculation for a completely closed greenhouse, a greenhouse of 11.95 Ha can be built, which presents similar dimensions to the 11.31 Ha obtained in the detailed calculation for the completely closed greenhouse with a $CO_2$ storage system. For partially opened greenhouses, the greenhouses without $CO_2$ storage in the detailed calculation, 4.82 Ha, and 2.81 Ha are in agreement with 4.78 Ha and 2.39 Ha from the fast calculation.

For a completely closed greenhouse, the optimal greenhouse area without carbon dioxide storage tanks obtained by the plantation areas for June and July was 7.03 Ha, while when utilizing 368,989 $m^3$ of $CO_2$ storage, the area was 11.31 Ha. For a partially opened double polyethylene greenhouse, the optimal greenhouse area without carbon dioxide storage tanks was 4.82 Ha, while when utilizing 277,000 $m^3$ of $CO_2$ storage, the optimal area was 6.97 Ha. For a partially opened standard glass greenhouse, the optimal greenhouse area without carbon dioxide storage tanks was 2.81 Ha, while when utilizing 233,000 $m^3$ of $CO_2$ storage, the optimal area was 3.85 Ha.

Further design parameters were outside the scope, but they were briefly mentioned. Another use for the $CO_2$ by-product of the biomethane plant of Bruck an der Leitha is algae farming, there is currently an algae production plant 400 meters from the biomethane upgrading facility.

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