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CO_2 in greenhouse horticulture

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Preface

The importance of carbon dioxide (CO_2) in plant growth is common understood. The absence of carbon dioxide in the atmosphere would lead to zero plant growth and consequently no animal or human life on earth. However, carbon dioxide does have a negative side as well. According to experts, the large increase in carbon dioxide in the atmosphere during the past 150 years, from 280 parts per million (ppm) to 360 ppm, will lead to global climate changes and a considerable rise in sea levels. This could be associated with various environmental disasters. To prevent this politicians have reached global agreements, such as Kyoto (1997), to reduce carbon dioxide emissions. The current rate of increase by 1.5 ppm per annum must be reduced! Greenhouse horticulture shares this responsibility. A reduction in carbon dioxide emissions through more efficient use of natural gas, the primary CO_2 source in greenhouse horticulture, has been given maximum priority. This brochure can contribute to the above. It deals with the botanical, technical and managerial aspects of CO_2, with the aim of gaining an understanding of how to use CO_2 more efficiently and how to improve the production of a high quality product. Should you have further queries about the use of CO_2 after reading this brochure, please contact the Internet of PPO: www.ppo.wur.nl.

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1. CO_2 IN GREENHOUSE HORTICULTURE

1.1 INTRODUCTION

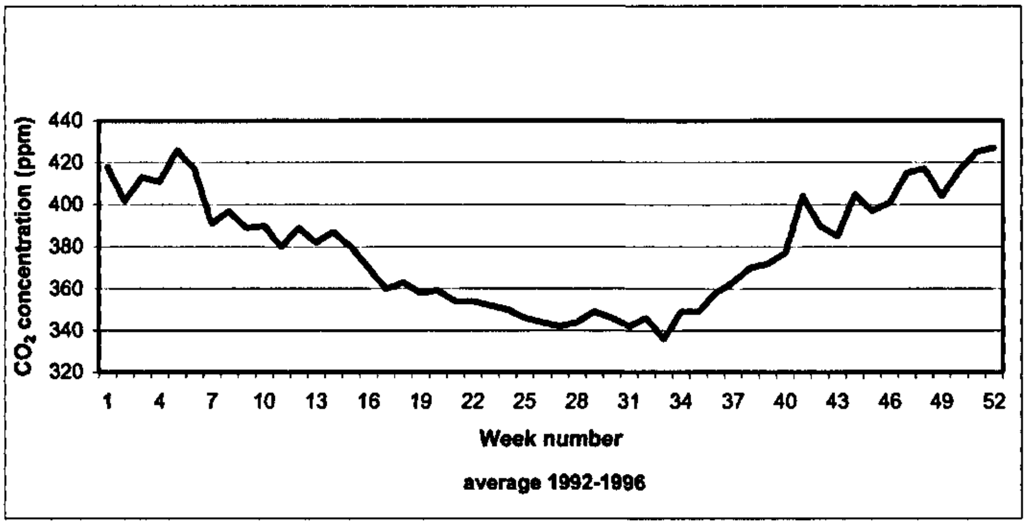
Carbon dioxide dosing has become an integral part of greenhouse horticulture. Additional carbon dioxide or CO_2 promotes crop growth and increases production and/or improves quality. In 1995, approximately 80% of greenhouse horticulture businesses used CO_2 dosing. 50% of companies dose even in the absence of heat demand.
Even though CO_2 dosing has been used for some time, there are still some unanswered questions around this technology. Some questions are new, the answer to others has become obscured over time. There is a great deal to be said about CO_2 and CO_2 dosing. Since our previous brochure in 1988, there have been many new developments in the area of CO_2.
This brochure explains all the latest advances in knowledge about CO_2 and CO_2 dosing. Authors from a wide range of disciplines were involved in putting the brochure together. The information it contains will help you to make decisions on CO_2 and CO_2 dosing.

1.2 WHAT CAN YOU EXPECT FROM THIS BROCHURE?

The brochure consists of five chapters that detail the botanical, technical, control and economic aspects of CO_2 dosing in greenhouse horticulture as well as providing general information. Environmental and government requirements also play an increasingly important role. Section 1.4 briefly describes the environmental aspects of CO_2 dosing. Chapter 2 describes the botanical aspects of CO_2. The last section of this chapter covers the possible adverse effects of CO_2 dosing, such as damage caused by overdosing and/or pollution. Chapter 3 describes the technical aspects of CO_2 dosing and the various sources of CO_2. Chapter 4 discusses the control aspects of CO_2 dosing. CO_2 demand and heat demand do not always coincide. Economic factors will determine how this situation is approached. Various options and strategies are calculated on the basis of two examples of crops in chapter 5.
Most sections in the brochure can be read independently. As a result, it is inevitable that some information is repeated. However, this prevents the reader from having to constantly search through the document for information.

Outside value
The brochure refers to the outside CO_2 value. This concentration rises annually by 1 to 1.5%. The annual national average for the outside value in 1996 was 0.036% or 360 ppm according to data from the KNMI (Royal Dutch Meteorological Institute). The outside CO_2 value fluctuates strongly both during the day and throughout the seasons. In winter, the outside concentration is higher than 360 ppm, but during the summer it is lower. Figure 1 shows the average weekly value between 1992-1996 measured at PBG in Naaldwijk. The outside concentration is also affected by wind direction, wind speed and exhaust fumes, so there may be huge differences between local values and the national average. Most of the example calculations in this brochure are based on an outside value of 350 ppm. In terms of the conclusions that can be drawn, it is more or less irrelevant whether 340, 350 or 360 ppm is used as a guideline. 350 ppm is close to the summer outside value.

Figure 1 Chart showing the average outside value of the CO_2 concentration per week between 1992 and 1996, measured at PBG in Naaldwijk.



1.3 WHAT IS CO_2?

CO_2 or carbon dioxide is a colourless, non-flammable, non-toxic gas with a tingling taste and smell. It is used to carbonate soft drinks and in other applications. It occurs naturally in the air in concentrations of 350-360 ppm (parts per million or ppm). This concentration is increasing by 1-1.5% every year, in particular as a result of high CO_2 emissions from an increasingly industrialised world! In chemical terms, CO_2 is a compound consisting of 1 carbon atom and 2 oxygen atoms. In gas form CO_2 is easily soluble in water (sparkling water). Liquid CO_2 is stored in steel tanks. When the liquid evaporates on contact with the air, the sudden increase in volume causes a cooling effect which produces white flakes. This is called carbon dioxide snow or dry ice. The specific gravity of CO_2 at 0 °C and 1013 kPa (1 atmosphere) is 1.97 kg per m^3. Its boiling point (at 1013 kPa) is -78.5 °C.

CO_2 is approximately 1.5 times the weight of air. This is not a problem as gas aims to achieve a balanced distribution in the space. CO_2 does not drop to the ground. One m^3 of outside air contains approx. 0.7 g CO_2.

CO_2 calculations

At 20 °C and 1013 kPa the following applies:

CO_2 in air

1 ppm = 1 vpm= 1.53 mg CO_2/kg air = 1.83 mg CO_2/m^3 air
= 41.6 μmol/m^3 = 0.101 Pa
1 vpm (volume part per million) = 0.0001 volume % = 1ml/m^3 = 1μl/l
1 ppm (part per million) = 1mmol/kmol
1 mg/kg (milligram per kilo) = 0.0001 weight %

CO_2-absorption by the plant

Fully grown active crops absorb up to 5-8 g CO_2 per m^2 per hour.
1 g/(m^2.h) ≈ 6.3 μmol/(m^2.s)

CO_2 dosing

1 litre CO_2 weighs 1.78 g at 20 °C
1 kg CO_2 is equivalent to 555 litres at 20 °C
1 m^3 natural gas produces 1.78 kg CO_2, rounded to 1.8 kg (based on Dutch Slochteren natural gas)
1 kg CO_2 is derived from 0.56 m^3 gas

A greenhouse with an average height of 5 m has a volume of 50,000 m^3 and, at the same CO_2 concentration as the average outside air, contains approximately 35 kg CO_2. This is the same as the amount of CO_2 in 20 m^3 combusted natural gas.

Dosing standards for spring/summer

Greenhouse vegetables: 40 - 80 m^3 per ha per hour; with buffer 80 - 120 m^3
Cut flowers: 40 - 60 m^3 per ha per hour; with buffer 40 - 90 m^3
Pot plants: same as cut flowers
A gas consumption of 60 m^3/(ha/h) equals 100 kg CO_2/(ha/h)
Burner position low; 25 m^3 gas/(ha/h) = 45 kg/(ha/h) = 4.5 g/(m^2/h) is usually sufficient to maintain 350 ppm.
Approximately 32.3 kg/m^2 is dosed annually.

1.4 ENVIRONMENTAL ASPECTS OF CO_2

In 1993, a long term energy agreement (MJA-E) was set up between the government and the horticulture industry. The objective of the energy agreement was to improve energy efficiency by 50% by the year 2000 with 1980 as the base level. Energy efficiency was defined as the primary fuel consumption per product unit. The energy agreement target was based on the national CO_2 target in the Dutch government's National Environmental Policy Plan Plus (NMP+). The government wanted absolute CO_2 emissions in 2000 to be 3% lower than in 1990. The target for 2010 is a 10% reduction on 1990 levels. If the efforts made by the sector are not sufficient to meet expectations, there is a real chance that the government will impose mandatory requirements. In order to meet the objectives and avoid the imposition of mandatory requirements, it is essential that CO_2 and energy are used carefully.
By the end of 1997, the result of the energy agreement was 42%. This meant that there was another 8% to attain by 2000. As a result, CO_2 efficiency (i.e. the CO_2 emissions per product unit) is also improving and therefore contributing to the national CO_2 target. Table 1 shows the various sources of carbon dioxide emissions with their annual CO_2 output. In the meantime, long-term agreements have been set up with a number of these producers to limit CO_2 emissions.
The horticultural industry was responsible for emitting 8.0 million tonnes of CO_2 in 1996. This was 12% more than in 89/90! (source: LEI-DLO).

Table 1. Annual CO_2 emissions from various sources in million kg (1000 tonnes)
source: CBS 1995

CO_2 source	CO_2 emissions (10^6 kg)
Transport sources	32,838
of which: - road traffic	27,365
- agricultural equipment	1,100
Furnaces (total)	123,274
of which: - agriculture (including horticulture)	9,096
- industry	42,354
- energy companies	42,431
- domestic	21,230
Total annual emissions	156,112
of which: - agriculture total	10,196
- percentage (%)	6.5

Why limit CO_2 emissions?

It is estimated that CO_2 is responsible for 55% of the greenhouse effect. This occurs when substances in the atmosphere retain heat radiated by the earth, which results in an increase in temperature and possible changes in the climate. Calculations have shown that an increase in CO_2 in the outside air to approximately 600 ppm results in a temperature rise of 1.5 to 4.5 °C. In 1987, the average annual increase in CO_2 concentration in the air was 1.5 ppm, based on global energy consumption at the time.
CO_2 also acts as a weak acid. This dissolves lime, which results in the weathering of monuments and buildings. Other elements in flue gas emissions such as CO, NO and NO_2, also have a negative impact on the environment. Nitrogen oxides damage plants and contribute to acid rain. Ethylene and associated substances contribute to smog formation. Smog can cause breathing problems in humans.

CO_2 is always released in the combustion of carbon compounds, such as gas, to generate electricity and/or heat. The best way to limit CO_2 emissions is to use energy as efficiently as possible and to limit energy use as much as possible.
An important development in this area is the use of Heat-Power-Links (H/PL or H/P) with flue gas purification. These allow electricity, heat and CO_2 to be derived from natural gas and then used, resulting in reduced air pollution. An H/PL and heat buffer combination, and successful agreements with electricity suppliers are required to be able to use these products (heat, electricity and CO_2) to maximum effect. The use of clean combustion methods, such as Low-NO_x burners, is also essential.

CO_2 dosing

The use of CO_2 dosing can be split into two general situations. In the first situation, CO_2 released from fuel being burned to heat the greenhouse is used. In the second situation, there is no heat demand but there is still a requirement for CO_2.
It is often the case in the first situation that too much CO_2 is released: for example, the light intensity may be low or the crop cannot use all the available CO_2. The ideal solution would be

to store this CO_2 surplus for sunnier periods. Unfortunately, this type of storage is still too expensive. In this situation, the only way to limit CO_2 emissions is by saving energy. There are a number of ways to use energy efficiently, including:
- using residual heat from third parties;
- the use or improved use of energy screens;
- achieving good climate distribution in the greenhouse;
- the use of the most suitable operating equipment.

In the second situation, where the energy demand is not sufficient to supply the CO_2 demand, it would seem that the only way to limit CO_2 emissions is to reduce or stop dosing. However, this is not always advisable. This situation occurs under conditions where there is a very high light intensity. By dosing under these conditions, the production per unit of energy consumed increases and, as a result, energy efficiency increases.

CO_2 is produced by additional burning of fuel or by supplying pure CO_2 rather than purified flue gases from elsewhere. During the burning of fuel, heat is released that cannot always be used. In this case, improving energy efficiency is at odds with saving energy and the limitation of CO_2 emissions. Fortunately, there are various options for resolving this dilemma.

Heat storage tank or heat buffer

Protecting the environment

The use of heat storage represents the simplest solution. Gas is burned during the day. The flue gases are used for CO_2 dosing and the heat is stored in the buffer tank. This heat is used at night to heat the greenhouse. The use of a buffer has many benefits from both an economic and environmental point of view if a minimum water temperature is used to dose CO_2. In the latter case, heat that is of no use at that particular point in time is released. However, few horticulture businesses have heat buffers with sufficient capacity. Research carried out by the Institute of Agricultural Economics (LEI) showed that in 1995 only 14% of greenhouse horticulture businesses had a buffer, mostly used by vegetable growers. A quarter of the vegetable growers had a buffer, but three quarters of the buffers were too small for the most effective use. This means that there are further opportunities for the sector to make savings if more companies purchase a buffer or install a buffer with adequate capacity. So far, only heat storage in a 24 hour period is cost-effective. It is not a question at the moment of storing summer heat for use during the winter, but we are working on it.

A second option is the use of purified flue gases from an H/P system. An H/P system produces less heat per CO_2 unit as compared to a standard boiler. This means that heat surpluses occur less frequently. This method only works if the electricity produced at the

same time is also used, either in the nursery itself or by supplying third parties. Purification of H/P flue gases also contributes to a reduction in NO_x emissions. In the future, the regulations relating to electricity supplies will be broadened, so that the in-house management of an H/P station in conjunction with colleagues or even in a horticultural area will become a more attractive proposition.
In situations where there is no buffer and/or no flue gas purification on the H/P, ventilation can be limited if there is plenty of light. This reduces ventilation loss and increases the CO_2 concentration in the greenhouse air. The temperature increases slightly as a result, but this can often be compensated for by maintaining a slightly lower temperature at night. Marginally less fuel then needs to be burned at night in order to achieve the required temperature over the 24 hour period. This is referred to as temperature integration. Again this contributes to cuts in emissions and energy consumption. Research has shown that for most crops the average 24 hour temperature is more important for plant growth and development than the precise day and night temperatures.

A fourth option is the use of pure CO_2. One of the major advantages of this method is that the risk of crop damage (e.g. from NO_x and ethylene) is minimised. Pure CO_2 is still expensive but major efforts are being made to obtain and/or to distribute cheaper CO_2. Large industries in the 'Rijnmondgebied' (Rhine delta area) are interested in supplying their surplus CO_2 to Westland. They are investing in research into new methods of obtaining pure CO_2 from industrial flue gases (e.g. membrane technology) and into new distribution methods such as a pipeline below the 'Nieuwe Waterweg'.

New horticultural areas have significant opportunities to save energy and reduce CO_2 emissions, by using residual heat and purified flue gases from power stations or other industrial producers. In fact, restrictions should be imposed to prevent residual heat projects from starting up if a solution for CO_2 supplies has not been found. A combined residual heat project (heat and CO_2) turns the market gardener into an energy waste consumer instead of an energy waste producer. The use of primary energy in horticulture is decreasing, therefore improving energy efficiency and reducing CO_2 emissions. This is a very attractive option from an environmental, financial and social standpoint. In 1996, the heat share from third parties was 8%, so that there was a good 5% saving on primary use by the sector (Source: LEI-DLO).

The point is often made that the horticulture industry, as opposed to other 'energy burners', has the opportunity to utilise some of the CO_2 released. In the most favourable circumstances, this is only about 10% of the CO_2 produced by horticulture in a year, the rest escapes through windowvents or chimneys. CO_2 is stored by plants and is not released into the atmosphere directly. However, this cannot be seen as reducing emissions. When the crop decays (e.g. on a compost heap, in waste combustion or in the stomach), CO_2 is still released. In terms of the greenhouse effect it does not matter whether the CO_2 is released directly during combustion or later when the plant material decays. 'Feeding' CO_2 to plants does not limit emissions, it merely postpones the emission.

2. BOTANICAL ASPECTS OF CO_2

2.1 PLANT PHYSIOLOGY

Photosynthesis and assimilation

Carbon dioxide (CO_2) and water (H_2O) are the basis of all organic compounds. Plants absorb CO_2 through the stomata in the leaves. Water and carbon dioxide are then converted into sugars ($C_6H_{12}O_6$) in the green leaves. This process generates oxygen (O_2). This conversion process occurs with assistance from energy provided by (sun)light. The entire process of converting light energy into chemical energy (sugar) is referred to as photosynthesis. The formula below shows this process in a very simplified way (proceeds from left to right):

☼**light**

↘

Formula 1 $6\,H_2O + 6\,CO_2 \Rightarrow C_6H_{12}O_6 + 6\,O_2$

Water Carbon dioxide Sugar Oxygen

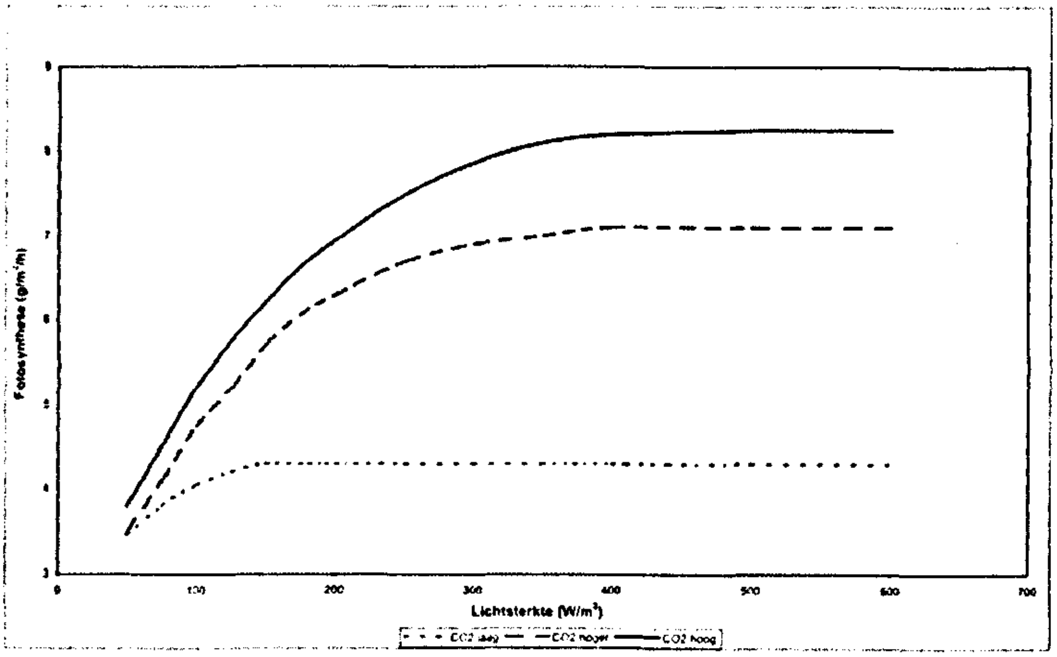
The production of energy rich sugars is often referred to as assimilation. The sugars are used to produce new plant material and as an energy source. Chemical energy is stored in the sugars. This energy is released when the sugars are broken down. This is often incorrectly referred to as 'burning'. This energy is needed to produce other substances such as proteins and fats. Humans and animals cannot produce chemical energy themselves as plants do. They need plants to supply energy rich food.

The following conditions are essential for photosynthesis:
1 Water and carbon dioxide must be available.
2 The plant must have green parts.
3 The green plant parts must trap light.

Water and CO_2 are the building blocks for photosynthesis and light supplies the necessary energy. Photosynthesis improves as the light intensity increases and, with light available, also improves as the CO_2 concentration around the leaves increases, as shown in figures 2 and 3. In this case, more sugars are produced. More sugars implies more growth.
The substance that gives leaves their green colour is referred to as chlorophyll. Chlorophyll occurs in chloroplasts. These are the parts of the plant cell in which photosynthesis occurs. The presence of chloroplasts, and therefore chlorophyll, is detectable from the green colour of that part of the plant. Non-green plant parts do not contain chlorophyll and do not contribute to photosynthesis.
Photosynthesis can be affected by the greenhouse climate. This section includes a brief description of the effects of light, CO_2 and temperature. The relationship between water, photosynthesis and CO_2 absorption is described in section 2.3.

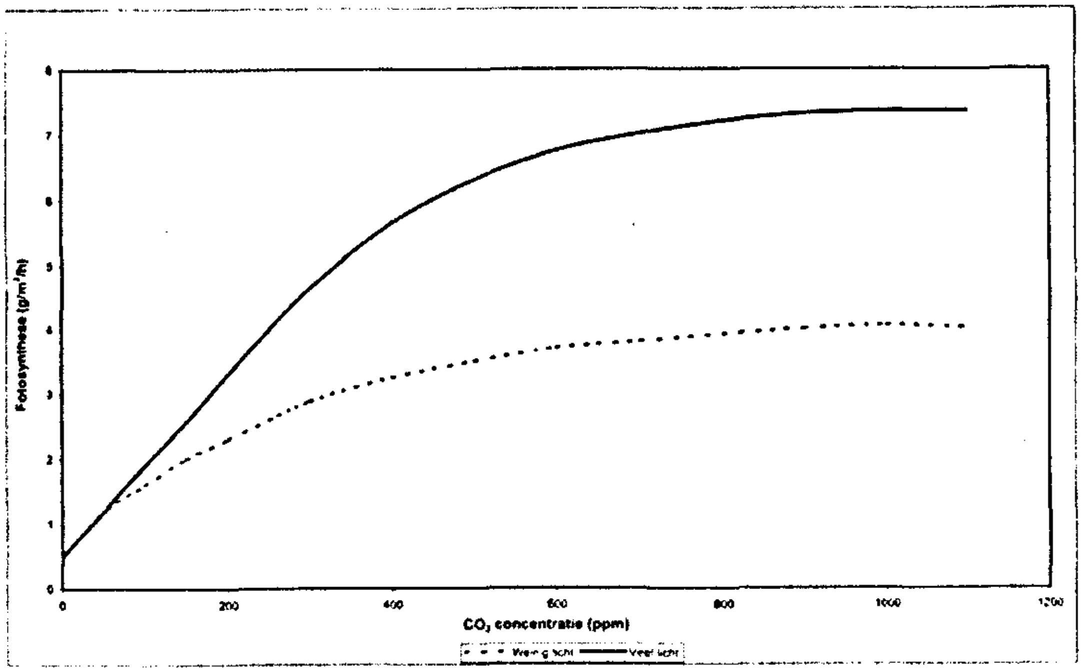
Respiration

Respiration involves the absorption of oxygen and release of carbon dioxide. Chemically, this process is the opposite of photosynthesis, i.e. proceeds from right to left in formula 1.



Translation: Fotosynthese = Photosynthesis, Lichtsterkte = light intensity

Figure 2 Photosynthesis increases as the light intensity increases. With high CO_2 concentrations photosynthesis increases more than with low CO_2 levels.



Translation: Fotosynthese = Photosynthesis, CO_2 concentratie = CO_2 concentration

Figure 3 Photosynthesis increases as the CO_2 concentration rises. With a high light intensity, photosynthesis increases more than with low intensity of light.

This is referred to as dissimilation. The sugars that have formed are oxidised ('burned') using oxygen to create water and carbon dioxide. The process does not require energy, as with photosynthesis, instead it releases energy, which is the light energy stored up in the sugars during photosynthesis. The energy is used in various energy demanding growth and maintenance processes. Part of this energy is released as heat. The carbon dioxide produced during the process is released into the greenhouse air. Respiration continues day and night. This is why the CO_2 concentration increases in the greenhouse when it is dark, when there is no dosing. Respiration increases as the temperature rises.
In addition to the respiration processes that occur in light and dark conditions, another specific respiration process takes place only under light conditions. This is referred to as photo respiration (photos = light and respiration = respiration). During this process the plant also absorbs oxygen and releases carbon dioxide, but it is not the same as normal respiration. This is in fact a 'deficiency' in photosynthesis. The enzyme Rubisco, that normally binds the CO_2 from the air 'mistakenly' takes oxygen from the air instead of CO_2. As a result, photorespiration diminishes the efficiency of photosynthesis. Photorespiration increases with high light intensities, high temperatures or low CO_2 concentrations.

Types of photosynthesis
The process of photosynthesis is common to all green plants. There are three different types of photosynthesis. The route from CO_2 and H_2O to sugars is through a range of intermediate products. For the first intermediate product produced a distinction is made between C_3 and C_4 photosynthesis.

Type 1

C_3 photosynthesis, also referred to as the Benson-Calvin cycle, has 3-phosphoglycerol acid as the primary intermediate product. This acid contains **three** C-atoms. The Benson-Calvin cycle is named after the researchers who identified the process. The unique aspect of this process is that eventually it forms its own starting substance again, but in larger quantities. In favourable conditions the plant can then increase its photosynthesis capacity.

Type 2

C_4 photosynthesis has C_4-dicarbon acid (usually malic acid) as the first product with **four** C-atoms. Hence the name C_3 and C_4 photosynthesis. Other than that, the photosynthesis of C_4 plants is identical to that of C_3 plants.
There are a number of essential differences between C_3 and C_4 plants that relate in particular to the use of CO_2. C_4 plants use CO_2 very efficiently. The stomata are usually smaller, this allows C_4 plants to reduce transpiration significantly. The CO_2 compensation point is usually lower as well. The compensation point is explained under photosynthesis and carbon dioxide. C_4 plants have no or poor photorespiration. C_4 plants often grow in drier, hotter areas where these characteristics are very useful.

Type 3

Crassulacean acid metabolism, abbreviated to CAM. This type occurs in green parts of succulents, such as Kalanchoe, other succulents and various orchids. Succulent plants with CAM can be found in hot, dry areas. Their typical characteristic is that the stomata close during the day and open during the night. The plant absorbs CO_2 when it is dark and binds it to malate, also referred to as malic acid. During the day, the CO_2 is released in the plant again and assimilated under the influence of light via the Benson-Calvin cycle. C_4 and CAM photosynthesis use more energy and CAM plants also need more biochemical 'hardware'. That is why most plants, including nearly all greenhouse crops, use C_3 photosynthesis.

CO_2 dosing during the day produces fuller plants with more flowers in Kalanchoe 'Singapore'

Measuring photosynthesis

CO_2 absorption is the easiest element to measure in the entire photosynthesis process. It shows the net photosynthesis, i.e. photosynthesis minus the respiration. This is often measured on a single leaf. It is not a good indicator for the CO_2 absorption and consumption of the entire crop. The actual CO_2 consumption of the crop is always lower than can be calculated on the basis of the number of individual leaves. This is due to the fact that the plant has a large number of parts that breath, but cannot fix CO_2. Shadows cast by leaves above or on neighbouring plants also have the effect of reducing photosynthesis, while the leaf that is in shade continues to breath. In general, the larger the plant mass, i.e. the older the crop, the greater the impact from respiration. The crop's efficiency declines as it gets older.

The amount of CO_2 fixed, or dry matter, in the plant can only increase if photosynthesis fixes more CO_2 than the plant breaths in a 24 hour period. This also applies to plant growth and, therefore, to the crop. In low intensity light, a crop with lots of leaves grows less than a young crop with few leaves.

Photosynthesis and light

Photosynthesis does not take place in the dark. Photosynthesis starts as soon as it becomes light (figure 2). Photosynthesis increases as the light intensity rises. At even higher light intensities, the rate levels off as the saturation level has been reached. Other factors (carbon dioxide, water), the size of the photo-chemical hardware (the 'factory'), or the discharge and processing of produced sugars have a limiting effect.

At a specific light intensity, the CO_2 quantity absorbed for assimilation is equal to the CO_2 quantity released during respiration. This is referred to as the light compensation point. The light compensation point is different for each type of plant. Above this light intensity, more CO_2 is absorbed than is released.

Shade loving plants are plants that thrive naturally in shady conditions. They have a lower light compensation point than light loving plants. The saturation level is usually lower for shade loving plants than for light loving plants.

The composition of the light and the spectrum also affects photosynthesis, but this will not be discussed here.

Photosynthesis and carbon dioxide

CO_2 also has a compensation point. This CO_2 compensation point is the CO_2 concentration at which the absorbed quantity of CO_2 equals the released quantity. In fact the CO_2 quantity in the plant does not change. This implies that no assimilates are added and the plant cannot grow. If the CO_2 concentration outside the plant increases (e.g. because of dosing), the plant can absorb more CO_2 and therefore produce more sugars (see figure 3). The CO_2 compensation point rises if the air temperature increases and drops at higher light intensities. Fruits on the plant also increase the CO_2 compensation point. The compensation point is an indicator for the efficiency of CO_2 absorption. The lower the compensation point, the greater the efficiency. The efficiency indicates the percentage of absorbed CO_2 that remains in the plant.

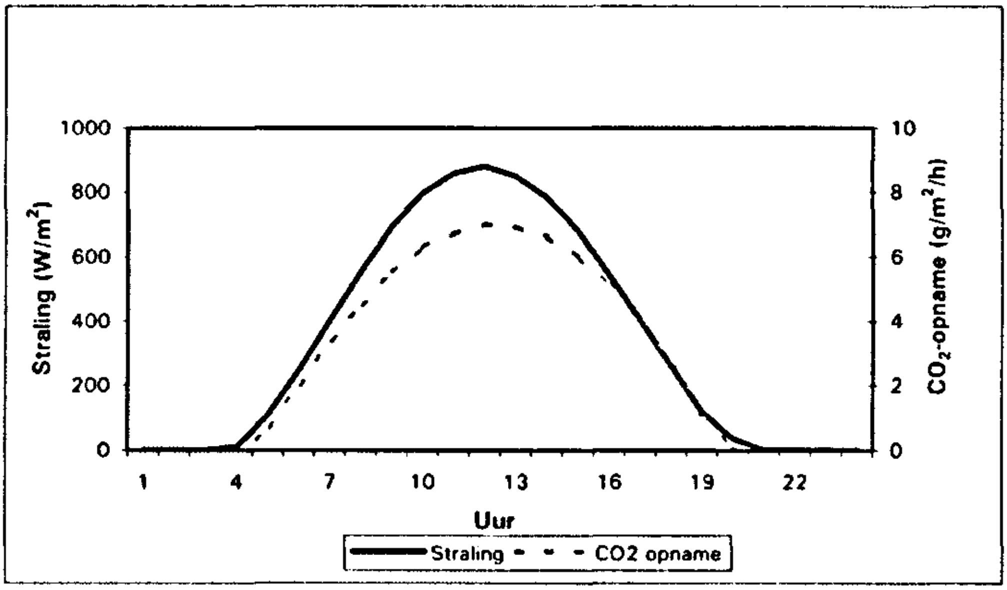
Photosynthesis increases with a rising CO_2 concentration until the saturation level is reached. This happens sooner at low light intensity than at high light intensity, as shown in figure 3.

Photosynthesis and temperature

Photosynthesis is slow at low temperatures. Photosynthesis increases as the temperature rises until an optimum level is reached above which the net photosynthesis declines. This is also the result of increasing respiration, which reduces the efficiency of photosynthesis. The optimum temperature shifts in line with the light intensity. It is higher at a high light intensity than at a low light intensity. Temperature only has a marginal effect on photosynthesis, as long as there are no extreme temperatures in the greenhouse.

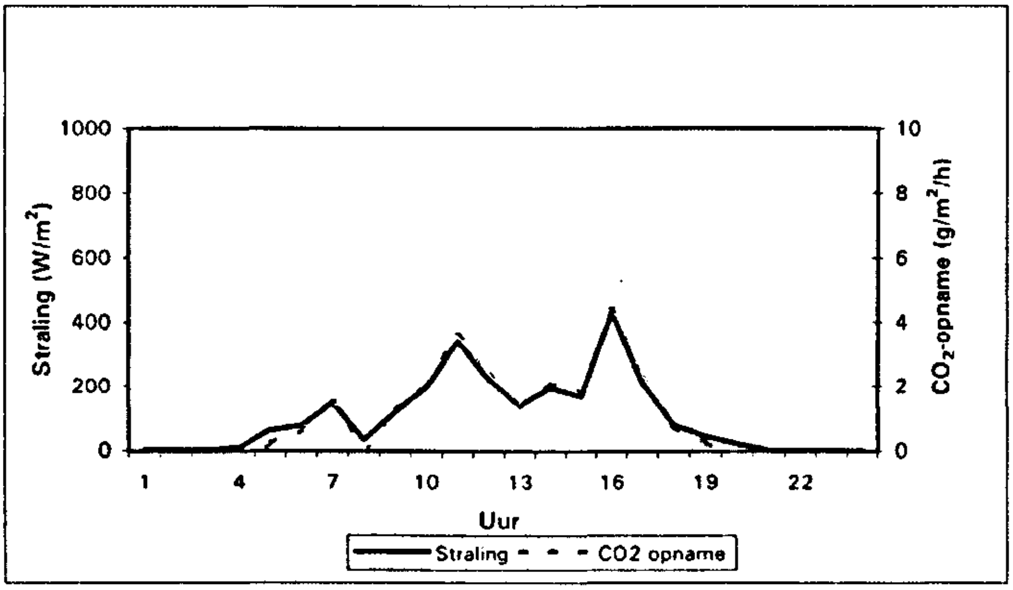
Summary

- *The production of sugars via photosynthesis is a unique process that only occurs in plants.*
- *Photosynthesis requires green plant parts, water, carbon dioxide and light.*
- *In the conditions in the Netherlands, more light and carbon dioxide increase photosynthesis and usually improve production.*



Translation: Straling = Radiation, Uur = Houre, CO_2 opname = CO_2 absorption

Figure 4 Radiation and CO_2 absorption on a light day



Translation: Straling = Radiation, Uur = Houre, CO_2 opname = CO_2 absorption

Figure 5 Radiation and CO_2 absorption on an overcast day

2.2 CO_2 UTILISATION DURING THE DAY

CO_2 dosing is useful on sunny days. Usually the air vents are open, so CO_2 escapes from the greenhouse. Therefore, the quantity of CO_2 for dosing is often also limited. This poses the question of how much, and when, CO_2 should be introduced into the greenhouse. This depends upon the reaction of the plant and the degree of ventilation.

The Research station in Naaldwijk has carried out extensive measurements on the photosynthesis of tomatoes, peppers and cucumbers. Photosynthesis can be measured using the CO_2 absorption of the crop. This is the only correct measure for the activity of a crop. Scientifically, it is expressed as μmol CO_2 per m2 leaf per second, but in horticulture it is more practical to use 'gram per square metre per hour' ($g/m^2/h$). This is because dosing is calculated in weight.

The CO_2 absorption was measured under varying conditions on many spring and autumn days. Unfortunately, this was not possible during the summer for technical reasons. Photosynthesis ran in parallel with the radiation on all the days on which measurements were taken. Figures 4 and 5 illustrate this once again for a light and an overcast day.

Photosynthesis often declines considerably at the end of the afternoon causing the CO_2 concentration in the greenhouse to rise. This is frequently attributed to saturation of the crop with sugars and starch, or it is assumed that the crop will collapse. However, there is usually a much simpler explanation. Radiation decreases at the end of the afternoon. This results in a reduction in photosynthesis and CO_2 absorption. There is also less ventilation and therefore less CO_2 escapes to the outside. These two processes (decreasing photosynthesis and closing vents)

cause the CO_2 concentration in the greenhouse to rise if the dosing rate stays the same. The decrease in evaporation at the end of the afternoon is also a result of the drop in light intensity and is not connected to collapsing plants, providing the correct humidity is maintained. Temperature, humidity and CO_2 concentration are often different in the morning and afternoon. This makes it quite difficult to compare crop activities. The extensive measurement data demonstrates, however that, under similar conditions, photosynthesis is virtually the same in the morning and in the afternoon. There is no indication that vegetable crops function better in the morning than in the afternoon.

Ventilation

Increased ventilation results in more CO_2 escaping from the greenhouse. It is always necessary to weigh up whether to open the vents less wide to save CO_2 or to open the vents wide to discharge the excess heat and/or humidity.

In the morning it is still cool in the greenhouse. After a day of sunshine the greenhouse will have heated up considerably. If the set point for ventilation is not adjusted, the vents are usually opened wider in the afternoon than in the morning, if the amount of light remains the same. During the summer, however, it is better to increase the ventilation in the morning by lowering the ventilation line in the morning close to the heating line, or by setting a minimum air quantity. This stimulates evaporation and reduces the risk of fungal disease.

Ventilation can often be restricted to some extent in the afternoon.

Day dosing

As long as the heating is active during the day, dosing to the required CO_2 concentration in the greenhouse is acceptable. As soon as the heat demand disappears during the day, the dosing needs to be adjusted. In this case, the quantity of CO_2 available is limited and needs to be distributed correctly over the day.

The simplest method is to apply the same target value throughout the day, i.e. to maintain the outside concentration. However, this is not the best approach. It is better to distribute the limited quantity of CO_2 over the day to gain maximum benefit for the plant and consequently for production. The best solution is to divide the day into four periods:
1 - in the morning, with increasing light and relatively low level of ventilation;
2 - middle of the day, the most light intensive period with high level of ventilation;
3 - afternoon with decreasing light and high level of ventilation;
4 - (early) evening, relatively low light intensity and little air.

Period 1: morning, starts with a high CO_2 content, exhaled by the crop during the night. The heating often remains active to prevent dew formation on the plants. Initially, CO_2 is not a problem. CO_2 is not particularly useful to the plant yet, as the radiation, and consequently photosynthesis, is low. More CO_2 results in a significant increase in photosynthesis, but in absolute terms the effect (in gram CO_2 absorption per m^2 per hour) is not great. Later on, the light increases and photosynthesis increases considerably. The effect of CO_2 dosing also intensifies significantly. However, the ventilation and ventilation loss also increase. The CO_2 target value can be high (maximum 1000 dpm) in the morning, but must drop with increasing ventilation.

Period 2: the most important period for dosing; the lightest period in the middle of the day. Photosynthesis is so high that a small increase in
CO_2 absorption has a major impact on photosynthesis. Always try to keep the CO_2 concentration at the outside value during this period. Even with the vents open, this is a low cost option and provides considerable benefits. If the CO_2 concentration is below the outside value this always results in production loss.

Period 3: at the end of the afternoon the light intensity is often comparable to that in the morning. But as the vents are opened wider, more CO_2 is required to maintain the concentration. CO_2 dosing up to the outside value is always advisable during this period.

Period 4: in the evening, when the vents are closing, it is easy to achieve a high concentration again. It will not be particularly useful to the crop, however, as the light intensity is decreasing rapidly. CO_2 dosing is less effective at this time and is definitely not a priority. Once it gets dark, CO_2 dosing is no longer useful.

2.3 CO_2 EFFECTS ON EVAPORATION

With higher CO_2 concentrations, evaporation is sometimes inhibited because the stomata are partly closing. Why then does CO_2 dosing continue to stimulate growth? There is no simple answer to this. To answer this question three areas need to be addressed:
1 How far do the stomata close under the influence of increased CO_2?
2 How does this affect evaporation?
3 What is the effect of all this on photosynthesis?

Stomata

The stomata are pores in the surface of the leaf. Moisture escapes and CO_2 enters the leaf via these pores. Stomata are able to close up almost completely during the night, for example. They act as a block to evaporation and the absorption of CO_2. When the stomata are wide open the resistance to evaporation and the absorption of CO_2 is low.

Any number of opening positions are possible in between. Opening and closing happens gradually but, if necessary, the plant can close the stomata very quickly.

Light is the most important factor by far in controlling the stomata. Plants aim to keep sufficient CO_2 in their stomata cavity to maintain photosynthesis. As the light increases, the plant has to allow more CO_2 in via the stomata for photosynthesis. As a result, the stomata will open wider when the light intensity is higher. Halfway through the afternoon, the stomata often start to close as a result of a drop in radiation.

The second most important factor is water supply and humidity. If the plant lacks water or the air becomes drier, the stomata opening decreases in size to protect the plant from drying out. In addition, the stomata may partially close due to excessively high leaf temperature, ageing, a high CO_2 concentration, air pollution or when specific pesticides have been applied.

Stomata open wide when the light intensity is high, when the leaf receives sufficient water, when the humidity is high and the CO_2 concentration low.

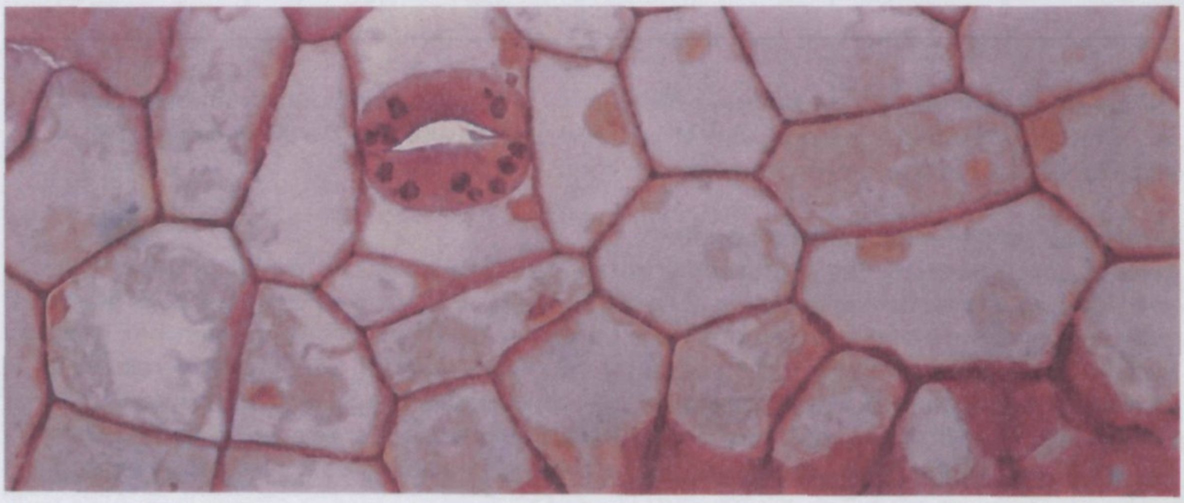
Reactions of stomata to CO_2

The CO_2 concentration in the air has less impact on the opening of the stomata than light and humidity. As the CO_2 in the environment increases, it penetrates the plant more easily. In this case, CO_2 absorption remains adequate even if the stomata opening is small. The stomata will close further as the CO_2 concentration rises. This process starts at a low CO_2 level and continues to a relatively high CO_2 level (approximately 2000 ppm). Above this limit, the stomata will close completely. At even higher levels (thousands of ppm), the stomata may lose their capacity to react. They may open at inappropriate times allowing moisture to escape too quickly and allowing air pollution to penetrate. These very high concentrations do still occur during the winter in hot air crops where there is no flue gas extraction.

The stomata opening on peppers, tomatoes, cucumbers and aubergines at 350 and 700 ppm CO_2 respectively has been measured under various conditions at the Research Station in Naaldwijk. The results can be summarised as follows.

As the CO_2 content increases the stomata close further. As a result, evaporation decreases. Because of the drop in evaporation less moisture is brought into the air and as a result the humidity decreases. The lower level of humidity causes the stomata to close even more. Sometimes the stomata closed by 40%. This was triggered not just by a high CO_2 level, but also by the change in humidity.

How much is actually caused by CO_2 could be measured if the humidity and leaf temperature could be stabilised. This is not possible, but the actual CO_2 effect on the stomata can be calculated. For tomatoes, cucumbers and peppers this was approximately 10% closed at 700 ppm relative to 350 ppm. This is approximately 3% for every 100 ppm increase in CO_2. Aubergines react three times more strongly to increased CO_2. The stomata on some aubergine leaves were sometimes almost completely closed at midday.



Anthurium leaf stoma

Effect on evaporation

CO_2 dosing causes the stomata openings to be smaller, resulting in less evaporation and lower humidity. The leaf temperature also rises as there is less cooling. The rise in leaf temperature is usually limited to approximately one degree Celsius. The leaf/air humidity deficit increases as a result of the decrease in humidity and increase in leaf temperature. The increased humidity deficit strongly stimulates evaporation, because a higher difference in the humidity of the leaf and of the air has a greater drawing force on the moisture in the pores. These two influences (stomata opened less and increased humidity deficit) work in opposition to each other. This means that the evaporation is inhibited less than could be expected due to the stomata closing. These complicated influences are referred to as feedback. The strength of the feedback also depends on the vent opening, wind speed and crop size.

This makes it impossible to calculate the evaporation change percentage with a specific change in stomata, or a specific change in CO_2 concentration. We can, however, show the average measurement percentages. In general the results of CO_2 dosing for the evaporation were relatively insignificant. The total effect of an increase in CO_2 concentration from 350 to 700 ppm was approximately 40% less stomata opening and still approximately 10% less evaporation. In aubergines, the effect was much more pronounced: sometimes the evaporation dropped by a good 25% with an increase in CO_2 concentration from 350 to 700 ppm.

In roses, the stomata's reaction to the CO_2 concentration depended on the cultivated variety. Some varieties reacted strongly, others hardly at all. As a result, the effects on evaporation also differed.

Photosynthesis, evaporation and stomata

It is often assumed that evaporation is the same as growth. Growth is seen as being as a result of evaporation. However, this assumption is incorrect. Evaporation occurs when the plant releases moisture into the ambient air. Growth and production are the result of photosynthesis and assimilation. This is absorption of CO_2, in addition CO_2 is converted into sugars and incorporated into the plant, so that the amount of dry matter increases. Photosynthesis and evaporation are entirely different processes, but both are connected to the stomata. Successful humidification is important for both processes.

Furthermore, both photosynthesis and evaporation increase as the sun's radiation rises. Photosynthesis reacts to sunlight and evaporation reacts to heat from the sun. Plant evaporation can be stimulated without increasing growth. A typical example is crop 'activation' using a minimum water temperature. This increases evaporation, but does not promote growth as the photosynthesis process hardly changes at all.
Closing of the stomata means higher resistance to the air exchange between the leaf and the environment, i.e. less air inflow. Because of the increased CO_2 concentration, the stomata close slightly so that less air flows into the stomata. But, because the air has a higher CO_2 content, more CO_2 penetrates as a whole. Consequently, CO_2 dosing results in increased photosynthesis, even though the stomata close slightly and the evaporation may drop slightly.

Importance of evaporation

Evaporation is important for crop cooling and water and nutrient absorption, particularly calcium. It is not clear what is the minimum amount of evaporation for successful growth and production. Provided there is adequate humidity and nutrients, low levels of evaporation do not seem to cause significant problems. The main factor related to evaporation is radiation from the sun. If the weather is overcast for long periods, evaporation levels are also low for a long time. Using CO_2 dosing inhibits evaporation and than may have an adverse effect. Neither is it useful to maintain a high CO_2 level if the light intensity is low.
In sunny weather, evaporation also has to be monitored, as it is required mainly to cool the leaves. This is not usually a problem for healthy crops. In this case, it is not useful to lower the CO_2 concentration with the aim of stimulating leaf cooling. The closing of stomata due to a high CO_2 concentration will only have adverse effects in very sensitive crops or if there are problems with water absorption. Evaporation levels drop even further and the leaf temperature may increase (in excess of 30 °C) and humidity decrease (below 50% RH) significantly as a result. This could lead to leaf damage. So far this phenomenon (including yellowing of the leaves) has only been clearly observed in aubergines. Despite yellowing of the leaves, the production of aubergines was higher at 700 ppm than at 350 ppm. It is advisable to limit the dose if there is serious leaf damage.

Recommended CO_2 dose

The general advice during longer periods of overcast weather (mainly in the winter) is to select a CO_2 target value below 700 ppm. Even if the crop struggles with evaporation, 700 ppm should be the maximum. This may be the case if the root system is poorly developed and the plant load heavy, or if there is a sudden change from overcast to bright weather. If the sun shines regularly, there are no specific problems with the crop and no increased risk of high NO_x levels, the ideal CO_2 value is approximately 1000 ppm. In spring and summer, it is beneficial for the plant to have as high a level as possible (but not above 1000 ppm). There is no real danger of additional leaf burning, as the temperature of the top leaves rises no more than one degree Celsius as a result of CO_2 dosing. High CO_2 levels will only carry some risk with aubergines. Therefore, it is always better to maintain 700 ppm instead of 1000 ppm as the maximum for aubergines.

Summary

- *CO_2 dosing causes the stomata to partially close (approximately 3% per 100 ppm CO_2 and 10 to 11 % for aubergines).*
- *For each 10 % the stomata closes, CO_2 dosing will inhibit evaporation by 1.5 to 3% at high radiation levels and by 4 to 6% at low radiation levels.*
- *The humidity drops slightly and the leaf temperature increases by approximately 1 °C.*
- *Evaporation does not directly promote growth, but it does promote the supply o nutrients.*
- *CO_2 dosing increases photosynthesis and consequently also increases growth.*
- *700 ppm CO_2 is advisable in overcast weather and 1000 ppm during periods of high intensity light.*
- *The effect of CO_2 on the stomata and evaporation is more intense in aubergine crops. It is advisable, therefore, to dose CO_2 carefully up to a maximum of 700 ppm.*

2.4 DEFINING THE EFFECT OF CO_2 DOSING ON PRODUCTION

The more sugars a plant produces, the larger and heavier it will become. The plant can also produce more and/or heavier fruits. Plant production increases as a result. The effect of CO_2 on growth and production is not the same for every crop. The average effect of CO_2 on production can be illustrated by a wide curved line, the CO_2 curve (see figure 6). This curve applies to many crops. This graph was produced in 1987 from the results of Dutch and international research on CO_2 in vegetable and ornamental plant crops, and adapted for vegetable crops in 1994. Most of the research was carried out under conditions of low intensity light (winter/spring).
Production at 340 ppm was set at 100%. Around the outside value, and this also applies to the current outside value of 360 ppm, the concentration plays an important part in determining production. A lower concentration in the greenhouse, which soon occurs during the day if there is no dosing, has a major impact on production.
An increase in greenhouse concentration, to just above the outside value, quickly results in significant production gains. As the concentration in the greenhouse rises, additional increases result in gradually lower production gains.

Global effect

A general guideline or rule of thumb to estimate the average effect of CO_2 on production simply and quickly was worked out in 1994 on the basis of research results. The general guideline is used to estimate the effect of CO_2 dosing, similar to the general guideline for light. The effect of light on production is estimated using the 1% rule, i.e. "1% light = 1% production". This rule has been applied since the early eighties and is still as effective as ever. As with all general guidelines, there are always exceptions to the rule. But, it is an ideal way of making a quick estimate of the global effect of a reduction or increase in light intensity.
A large amount of photosynthesis data has been used in order to define a general guideline for the effect of CO_2. The assumption is that the CO_2 effect is mainly the effect of CO_2 on photosynthesis. Depending on the conditions, the effect of CO_2 on production may deviate somewhat in reality.

CO_2 general guideline

The effect of additional CO_2 on photosynthesis is highest at low CO_2 levels: the plant reacts very strongly to CO_2 dosing. At higher CO_2 levels, the effect diminishes and at even higher CO_2 levels the effect of additional CO_2 becomes virtually nil. This is illustrated in figures 3 and 6. The general guideline has to express this diminishing effect. Unfortunately, this means that the CO_2 general guideline is more complicated than the 1% rule for light, where the effect does not decrease under conditions prevalent in the Netherlands.

The following formula calculates the effect of CO_2: $\mathbf{X = (1000/CO_2)^2 \times 1.5}$

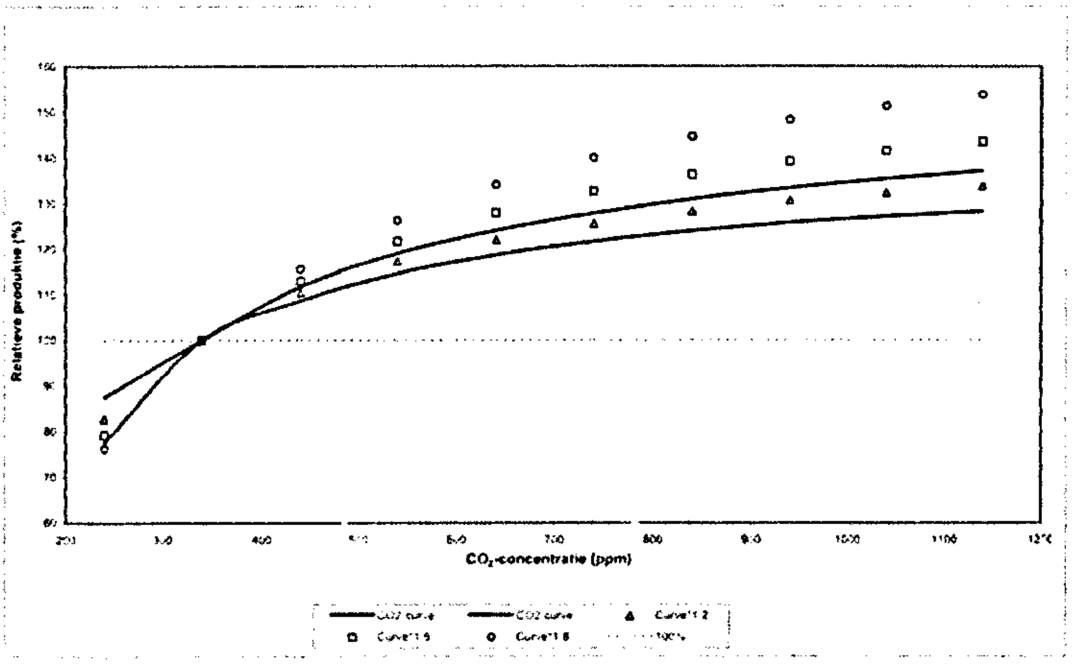
X indicates the rise in production as a percentage following a rise in the current CO_2 concentration by 100 ppm.
The calculation is as follows: 1000 is divided by the current CO_2 concentration, the square of this quotient is multiplied by 1.5.

The following are a few examples:
1 at 200 ppm CO2: $X = (1000/200)^2 \times 1.5 = (5)^2 \times 1.5 = 25 \times 1.5 = 37.5\%$.
2 at 360 ppm CO2: $X = (1000/360)^2 \times 1.5 = (2.77)^2 \times 1.5 = 7.7 \times 1.5 = 11.6\%$
3 at 500 ppm CO2: $X = (1000/500)^2 \times 1.5 = (2)^2 \times 1.5 = 4 \times 1.5 = 6\%$.
4 at 1000 ppm CO2: $X = (1000/1000)^2 \times 1.5 = (1)^2 \times 1.5 = 1 \times 1.5 = 1.5\%$.

Example 1 indicates that an increase of 200 to 300 ppm results in a 37.5% increase in production. Example 4 illustrates that the effect of CO_2 dosing is very limited above 1000 ppm. To make it easier to use, the CO_2 rule has been calculated in increments of a hundred between 200 and 1400 ppm and is shown in table 2. However, the calculation of the effect of an arbitrary increase in CO_2 concentration, e.g. from 360 to 510 ppm, is not that simple with this general guideline.

Modifying general CO_2 guideline

Crops may react more or less strongly to CO_2 under specific conditions. This is illustrated in figure 6 with a fairly wide curve. Light is one of the influencing conditions. The effect of CO_2 is much greater during periods of high intensity light than during periods of low intensity light. If the condition of the crop is poor (as a result of disease or symptoms of flaws), CO_2 dosing will not be as effective. Sometimes other factors are involved, such as improving the setting for autumn peppers, less 'blind' shoots on roses or increased shoot development in cucumbers, resulting in more products due to a high CO_2 level. In general, healthy crops with sufficient leaves will respond very strongly to CO_2 in high intensity light, whereas diseased crops will have a weak response.
The general guideline does not take into account unusual conditions such as these. Fortunately, the CO_2 rule is easy to adjust, by changing the coefficient (1.5). This factor is decreased by for example up to 1.2 for poor (light) conditions and increased up to 1.8 for favourable (light) conditions. When the CO_2 rule is adjusted down [$X = (1000/CO_2)^2 \times 1.2$], the effect is 30% instead of 37.5% at 200 ppm and at 500 ppm 4.8% instead of 6% (per 100 ppm CO_2 increase). The CO_2 rule adjusted up [$X = (1000/CO_2)^2 \times 1.8$] calculated at 200 ppm the effect is 45% and at 500 ppm it is 7.2%. The calculated percentages are also shown in table 2. If there are no unusual circumstances the modification is kept to 1.2 and 1.8. If there is a forecast with unknown conditions, it is advisable to use the standard general guideline with the factor 1.5. Modifications are only appropriate if it is known that extraordinary conditions apply.



Translation: Relatieve produktie = Relative production, CO_2 concentratie = CO_2 concentration

Figure 6 CO_2 curve: relative production (in %) set against the CO_2 concentration (in ppm), where production at 340 ppm CO_2 is set at 100%. The wide CO_2 curve is compared against the CO_2 general guideline: $X = (1000 / CO_2)^2 \times 1.2$ and two modified forms of the CO_2 general guideline: (1) $X = (1000 / CO_2)^2 \times 1.5$ and (2) $X = (1000 / CO_2)^2 \times 1.8$.

CO_2 curve and CO_2 general guideline

Figure 6 shows the three calculated rules as well as the CO_2 curve. The standard guideline of 1.5 is slightly above the CO_2 curve. The CO_2 curve based on greenhouse experiments coincides with the general guideline for low light intensity conditions. That is correct as it is always difficult to maintain very high CO_2 levels during the summer and most CO_2 experiments were carried out during the winter. The results of later tests at PBG are in line with the standard CO_2 general guideline. Therefore, the CO_2 general guideline is a useful tool to approximate the average effect of CO_2 on production.

Table 2. Calculations using the CO_2 general guideline. Effect of a 100 ppm CO_2 increase on production with a specific CO_2 concentration, in % per 100 ppm CO_2. The middle column (bold) is the general CO_2 guideline, the other two columns show modifications to the rule.

ppm	$(1000/CO_2)^2$ x 1.2	**$(1000/CO_2)^2$ x 1.5**	$(1000/CO_2)^2$ x 1.8
200 – 300	30.0	**37.5**	45.0
300 – 400	13.3	**16.7**	20.0
400 – 500	7.5	**9.4**	11.3
500 – 600	4.8	**6.0**	7.2
600 – 700	3.3	**4.2**	5.0
700 – 800	2.4	**3.1**	3.7
800 – 900	1.9	**2.3**	2.8
900 – 1000	1.5	**1.9**	2.2
1000 – 1100	1.2	**1.5**	1.8
1100 – 1200	1.0	**1.2**	1.5
1200 – 1300	0.8	**1.0**	1.3
1300 – 1400	0.7	**0.9**	1.1
1400 – 1500	0.6	**0.8**	0.9
360 – 260	-17.6	**-22.2**	-26.6
360 – 460	9.3	**11.6**	13.9

2.5 INFLUENCE OF CO_2 ON ASSIMILATE DISTRIBUTION

Plant growth is due to the continual production of assimilates (sugars) and other building blocks. The production of assimilates is also referred to as the 'source'. Assimilates are used by growing plant parts: leaves, stems, roots, fruits. Each part that demands assimilates ('sink') attracts assimilates at a specific strength, the 'sink strength'. The strongest sink (the part with the greatest relative demand) receives the largest amount of assimilates. If the crop is growing successfully, the demand and supply (sink and source) of assimilates is balanced. Under constant conditions, a fixed proportion of the assimilates is sent to leaves, stems, roots and fruits. In other words, there is a specific 'distribution code' for assimilates.

Assimilate distribution

The balance between demand and supply and the assimilate distribution code may be affected by many different influences. CO_2 increases photosynthesis and therefore the supply of assimilates. The additional quantities of sugar can all be sent to the leaves or another part, or can be sent to different parts on the basis of a fixed distribution code. The distribution code is also influenced by temperature, light and plant density. Research has shown that the supply of assimilates does not affect distribution, but mainly influences the ratio of the forces with which the assimilates are attracted by the various parts. It was decided, therefore, to investigate the effect of CO_2 on these sink strengths. The influence of CO_2 on supply is clear, but the influence on demand is more difficult to assess. All fruits together form a sink. The strength of this sink depends on the number of viable gynoecia and fruits, and the stages they are at. In order to keep it simple we have assumed that the number of fruits mainly defines the sink strength of the collective fruits.

The influence of CO_2 dosing on the distribution of assimilates in tomatoes, cucumbers and peppers was studied. Plants were removed, measured and weighed for the various CO_2 experiments. Production was also closely monitored. The amount of 'dry matter' (assimilates) produced and how this was distributed across the various organs was defined. There appear to be distinct differences between different crops. We are purposely not including figures on assimilate distribution, as these figures are different for each crop. The distribution code depends on the season, cultivation conditions and cultivation method. The pattern also shifts as the crop progresses. Initially, all assimilates are sent to vegetative parts, the fruits are added later and during the production phase most of the sugars are sent to the fruits.

Cucumber

At high CO_2 concentrations, slightly more assimilates are sent to the fruits in cucumbers. This can be explained by the cultivation method. When the heads have been removed, the side shoots are left to flourish and pruning is kept to a minimum. With increased CO_2 levels, cucumber plants will grow more profusely and produce more side shoots. Each shoot has an end point (vegetative growth point) and each axil of the new shoot contains a number of blooms. More side shoots means that the plant has more young fruits, i.e. the sink strength of the fruits is much higher. This results in the fruits attracting a relatively large amount of assimilates. As a result, the extra assimilates created through CO_2 dosing will be sent to the fruits in higher proportions.

Peppers

A few years ago a CO_2 test with autumn peppers showed that a high CO_2 concentration resulted in significant increases in production but very moderate increases in vegetative growth. This implies that the distribution code was changed by the CO_2: a much greater proportion of the assimilates were sent to the fruits. The explanation lies in the fact that the setting was much better with a high CO_2 level than with a low CO_2 level, i.e. the sink strength of the collective fruits was much greater with high CO_2 than with low CO_2. The strong sink effect of the collective fruits resulted in strong fruit growth and inhibited leaf growth. The test was repeated in 1995 and 1996 with greenhouse peppers. Again a high CO_2 level (1000 and 1500 ppm) initially resulted in more assimilates being sent to the fruits, so that early production increased considerably but vegetative growth was inhibited.

With peppers, the internal competition between fruit growth and leaf growth is fierce. It is so strong that vegetative growth hardly improves at all with high CO_2 levels as opposed to low CO_2 levels. This is in contrast to cucumbers, in which both vegetative growth and fruit growth improved. In fact, only fruit production improved with peppers. Peppers react to CO_2 in such a positive way that during the winter and in spring the CO_2 concentration may exceed 1000 ppm under favourable conditions, providing the concentration of toxic gases (NO_x, ethylene) does not rise too much as a result.

Tomatoes

During tests on tomatoes in the summer, photosynthesis increased as a result of CO_2 dosing which in turn led to an increase in growth and production. However, the proportion of fruits in the dry matter weight was the same with high CO_2 and low CO_2. However, the fruits became heavier because of the additional CO_2. Again the explanation can be found in the cultivation method used for tomatoes. Tomatoes only have one surface level growth point, i.e. the head, as the other growth points (suckers) are removed.

Tomato plants have a specific number of clusters and specific number of gynoecia per cluster. During the summer, the setting is usually good and CO_2 dosing does not appear to improve it. This means that in tomatoes the number of fruits does not increase with CO_2, i.e. the sink strength of the fruits does not change with CO_2. There is no change in the strength ratios within the plant because the number of vegetative growth points does not change either. The distribution of assimilates is not influenced by CO_2 dosing.

Leaf thickness

These tests also investigated leaf thickness, which is defined by measuring the leaf surface and the dry weight. A leaf with a high weight per cm^2 or a small surface area per gram is a thick leaf. Large amounts of light and a high CO_2 concentration usually results in thicker leaves. However, it was noted with cucumbers that the leaves hardly thickened at all under the influence of CO_2, whereas with peppers and tomatoes thickening of the leaves was observed. The explanation lies in the fact that cucumbers can always send the additional assimilates to additional shoots with additional leaves and fruits. In tomatoes and peppers, the demand for assimilates did not increase in line with the supply of assimilates and so the surplus was stored in the leaves. This means that if tomato plants suffer from short leaves during the summer, the effect may be exacerbated by high CO_2 concentrations. This is because short leaves are the result of a surplus of assimilates. Therefore, it is advisable to reduce dosing if leaves are short.

Summary

In the research, CO_2 dosing on cucumbers and, in particular, peppers resulted in a more favourable distribution of dry matter (relatively more assimilates were sent to the fruits). This was caused by an increase in the number of fruits and consequent improved sink strength of the collective fruits. However, this was not the case in tomatoes.
Tomatoes and peppers grew thicker leaves as a result of additional assimilate production caused by CO_2 dosing. This was not the case in cucumber crops as the new shoots and fruits in this crop absorbed all the additional assimilates.

2.6 EFFECT OF CO_2 DOSING ON HORTICULTURAL CROPS

Research in the Netherlands and abroad has shown that CO_2 dosing under normal conditions always has a positive effect. The magnitude of the effect may differ depending on the crop and cultivation situation.

CO_2 and basic material

CO_2 dosing has a positive impact on cultivation from stock plants. The number and quality of the cuttings, and their fresh and dry weight increase. Excellent results have been achieved with Campanula isophylla, Pelargonium x zonale, Pelargonium x peltatum, Chrysanthemum x indicum, Fuchsia x hybrida and Saintpaulia. The cutting roots better and fewer cuttings are lost. In the case of rose cuttings, it appears that the leaves of the cutting are less prone to yellowing under the influence of CO_2 dosing and the percentage of successfully rooted cuttings increases by 25%. CO2 dosing for cuttings is more effective in summer than in winter, because of the increased light intensity. The growth of vegetable crops speeds up by approximately 10% if the plants are cultivated at 600 to 700 ppm instead of 350 ppm. The quality also improves, the plants have a higher dry matter content and leaves are thicker. The maximum target value for cultivation is 700 ppm.

CO_2 dosing for vegetable crops

The effects on the four major fruit vegetable crops are described in sections 2.5 (tomatoes, cucumber and peppers) and 2.3 (aubergines). CO_2 dosing also results in improved crop yields in all other vegetable crops. In lettuce and iceberg lettuce crops, an increase in CO_2 concentration to 800 -1000 ppm results in a rise in production. Higher CO_2 concentrations above this level do not lead to higher yields. In strawberries, an increase in CO_2 concentration also leads to improved production and better quality. If up to 1500 ppm CO_2 is dosed in the morning with the vents closed, the percentage of the 2nd type drops. In courgettes, development of the fruits improves so that more fruits can be harvested.

In general, CO_2 dosing has a very little or no effect on the quality of vegetable crops. This applies to appearance, shelf life and internal quality. In tomatoes, the results are contradictory. CO_2 does not affect the quality of cucumber, peppers, aubergines and various leaf crops. The positive results of CO_2 on vegetables are mainly improved crop growth and higher production levels.

CO_2 dosing for ornamental crops

In ornamental crops CO_2 dosing does not necessarily lead to increased numbers, but it often results in improved quality and shorter cultivation times. Quality is hard to define and depends on the type of plant. Better quality often results from higher stem weights or plant weights.

CO_2 dosing with cut flowers

In cut flowers, CO_2 dosing generally leads to more rapid growth, enhanced flowering, better stem and flower quality and, depending on the crop, earlier flowering. Flower quality refers to larger (heavier) blooms and more flowers per inflorescence. Botrytis and mildew are less likely to occur, because the plant is hardier.

Tests using lilies showed that withering of flower heads is reduced and the crop is greener and therefore looks better. In roses, Gerbera and Alstroemeria both production and quality improve. The quality of carnations improves and the plants flower earlier. In freesias both the yield and the quality are improved, the stems are heavier and the clusters develop better. The cultivation time of freesias is seven to ten days shorter when the temperature is increased slightly with CO_2 dosing. With high light intensity, a temperature of 18 to 20 °C is acceptable.

Dosing of CO_2 on amaryllis results in more and heavier leaves and an increase in bulb size when compared to not dosing. The bulb size continues to define the flowering results. Without dosing, the CO_2 concentration regularly drops below the outside value.

CO_2 dosing for pot and bedding plants

In green pot plants, CO_2 dosing mainly results in more rapid growth which leads to better quality plants with a more intense leaf colour. In addition, the cultivation time may be shortened by approximately two weeks. A number of crops, such as Ficus pumila and Hedera helix, remain more compact and more side shoots are produced, e.g. in Dieffenbachia, Ficus benjamina and Ficus pumila.

In flowering pot plants, CO_2 dosing also results in more rapid development and, as a result, flowering was accelerated by one to two weeks in most crops that were tested. The quality clearly improves, i.e. more compact growth, more side shoots and greener leaves.

The effects on bedding plants include faster development and flowering, more compact plants and improved quality. Development becomes more uniform, there are fewer losses when propagating and crops are less sensitive to fungal disease.

CO_2 dosing for CAM plants

CAM plants are found among succulent plants, such as cacti and succulents, e.g. Kalanchoe. A number of orchids such as phalaenopsis are also CAM plants. These are plants that, in their natural environment, absorb CO_2 during the night (see section 2.1). This would seem to imply that CO_2 dosing during the day would not be useful for these plants and it ought to be applied during the night. But it appears that, under favourable conditions, such as adequate water supply and moderate temperature, some types normally absorb and process CO_2 during the day. This applies to the Kalanchoe varieties 'Singapore' and 'Mistral', for example. Under the conditions prevalent in the Netherlands, with a cultivation temperature of 20 °C and sufficient humidity, CO_2 dosing during the night had very little impact. CO_2 dosing during the day in spring did result in an increase in fresh and dry weight, when compared to not dosing CO_2 during the day.

Phalaenopsis does not respond to CO_2 dosing during the day. The plant only starts to carefully open its stomata and absorb CO_2 a few hours before the onset of darkness when the stocks of malate have been depleted. The absorption of CO_2 is better with ideal humidity conditions.

PBG report no. 47 'Influence of CO_2 on the production and quality of pot plants and cut flowers' contains a detailed description of the effect of CO_2 on ornamental crops The report describes in detail a large number of ornamental crops and varieties.

Recommended values

The recommended value for vegetables is 700 ppm rising to 1000 ppm during the winter when there is sufficient radiation and CO_2 stocks. During the summer, the value is as high as economically viable.

The recommended values for CO_2 dosing for pot and bedding plants are between 600 and 900 ppm as a general rule. The recommended values for cut flowers tend to be further apart for the different crops. Table 3 shows the values for a number of important cut flowers.

Table 3. Recommended CO_2 concentration values for a number of important cut flowers

Crop	Recommended CO_2 value in ppm
Alstroemeria	700 - 900
Carnation	1000
Anthurium	600
Bouvardia	1000
Chrysanthemum	600 - 900
Cymbidium	600 - 700
Eustoma	600 - 900
Freesia	500 - 600
Gerbera	500 - 600
Gypsophila	700 - 1000
Lily	800 - 1000
Rose	- 900

Source: Dyk, D. Van and S. Seydel Planzen wecken mit CO_2 als 'lichtersatz', Zierplanzenbau 7 (1985): 316-319.

High CO_2 values can only be realised if vents are closed. When vents are open, it is advisable to maintain the outside concentration of 360

ppm at all times. Check that the CO_2 values do not increase too much if vents are closed causing the recommended values to be exceeded. Section 2.7 provides information on the damaging effects of CO_2 dosing.

2.7 DAMAGING EFFECTS OF CO_2 DOSING

Sometimes problems can occur during or as a consequence of CO_2 dosing. The CO_2 concentration in the greenhouse may rise too much. In addition, when flue gas CO_2 is used toxic gases such as ethylene and nitrogen oxides may be released into the greenhouse.

Damage caused by excess of CO_2

The greenhouse concentration may become very high, especially if there is no ventilation and the CO_2 source is located in the greenhouse itself. This particularly applies to hot air crops in winter. A defective measuring system could also lead to excessive concentrations in the greenhouse. Both vegetables and flowers are prone to damage.

The opening of the stomata decreases as the CO_2 concentration rises. This has been observed in many crops and applies to outside values in the range up to approx. 2000 ppm. This restricts evaporation and the plant can no longer cool down (sufficiently) and absorb water and nutrients. Damage consists of yellowing of the leaves followed by withering of the leaves.

Higher CO_2 concentrations, above 4000 to 10,000 ppm, completely disrupt the stomata's regulatory system. The stomata may open completely so that evaporation takes place too quickly and toxic substances can penetrate the leaves unhindered. The plant is damaged because evaporation and/or the concentration of toxic substances in the plant increase(s) too much. This could result in a reduction in growth, leaf chlorosis and necrosis or smaller leaves in the various crops. This reaction can be reversed, providing the exposure to excessive concentrations was limited to between one and a few days. Long term exposure to concentrations in excess of 10,000 ppm have an irreversible effect.

The weather plays an important role when damage occurs. Damage often occurs after a sudden transition from overcast to light conditions.

In 1995, setting problems occurred in peppers with doses from 1000 ppm using pure CO_2. With doses of 2500, 1500 and 1000 ppm the upper 50 cm of the pepper leaves became grey and later yellow. During that time the radiation also increased significantly. The leaf symptoms seemed to indicate a lack of boron, but with the striking difference that the leaf veins remained green. One year later, in 1996, the leaves remained green at comparable concentrations, but there were no severe weather transitions. In cucumbers, the leaves wither and leaf edges become yellow at concentrations far in excess of 1000 ppm. In aubergines, yellowing of the leaves starts to occur even at concentrations of approximately 750 ppm. This does not have any adverse effects on production when compared to 350 ppm. In tests over two consecutive years at 750 ppm CO_2, production was higher than at 350 ppm throughout the entire production period, even though there was considerable yellowing of the leaves. The cause of this yellowing is not completely clear. There is some indication that nutrients also play a part. In ornamental crops, leaf necrosis and inhibited growth also occur as a result of too much CO_2.

The upper CO_2 concentration limit depends on the type of crop and season. In nearly all cases, there is no damage at concentrations up to 1000 ppm.

Yellowing of the leaves in peppers as a result of high CO_2 concentrations

Lettuce damage due to SO_2 + NO_2

Damage due to other substances

When dosing CO_2, other gases may be released in the greenhouse. These include nitrogen oxides (NO and NO_2, referred to jointly as NO_x), ethylene (C_2H_4), carbon monoxide (CO) and sulphur dioxide (SO_2).

Ethylene, NO_x and SO_2 damage plants. Two types of damage can occur: acute and chronic. Acute damage is caused by brief, intense exposure. Usually, the damage is immediately obvious. Long term exposure to low concentrations can cause chronic damage. Usually this kind of damage is not immediately visible, but manifests itself in inhibited growth and reduced production. Table 4 shows the limit values for a number of substances.

Table 4. Plant sensitivity limits to toxic gases with different exposure times in parts per billion (ppb) and microgram per cubic metre ($10^{-6}g/m^3$).

Gas	Acute		Chronic	
	ppb	$10^{-6}g/m^3$	ppb	$10^{-6}g/m^3$
O_3	100	200	30	60
NO	1000	1250	250	313
NO_2	600	1150	100	192
SO_2	70	187	15	40
C_2H_4	50	58	8	9.3

Most substances have an accumulative effect. Therefore, damage thresholds cannot be added together. Under glass and with little ventilation, the NO concentration appears to increase more than the NO_2 concentration. Consequently, the damage threshold for NO is reached sooner than that for NO_2. The growth of various types of plants was significantly inhibited after three to six weeks exposure to mixtures of 30 ppb NO_2, O_3 and SO_2. Inhibited growth often occurs without there being any external symptoms.

Sensitivity to toxic gases is different for each type of plant and often for each variety. The level of sensitivity also depends on the opening of the stomata. If the stomata are opened wider, more toxic gas can penetrate the plant and, therefore, damage occurs at lower concentrations. When the greenhouse air is dry, this usually results in fewer problems as the stomata are closed further.

Sensitivity also decreases at a slightly higher CO_2 concentration, probably because the stomata close slightly as a result. Studies have shown that additional dosing with CO_2 could limit the damage caused by NO_x to a certain extent. However, the results of dosing pure CO_2 without NO_x were much better. The air temperature also has an impact on the damage. High air temperatures result in less damage than low temperatures. The presence of other substances such as ozone (O_3), can also exacerbate the damage. Ozone is highly toxic by itself, but the presence of ozone exacerbates the adverse affects of other types of air pollution.

NO_2 damage in tomatoes (photograph AB-DLO, Wageningen)

A few typical examples of damage in various crops

Ethylene

Ethylene or ethene is a plant hormone that stimulates ageing. It is damaging to crops even in small doses. Ethylene can cause the dropping of flower buds, flowers and leaves and/or growth stagnation in pot plants. Orchids are particularly sensitive to ethylene. Small concentrations result in flower discolouration, as occurs after pollination.

In freesias, ethylene results in delayed flowering, shorter shoots and stems and fewer flowers on the main cluster. In chrysanthemums, bud development is delayed and shooting may occur. In roses, an ethylene concentration of 0.5 ppb can result in rejection of the flower buds, short stems, yellowing of the leaves and the ejection of young leaves.

With small concentrations of ethylene, in the air lilies can be plagued by yellowing of the leaves, flower bud withering and bud drop. A number of other flower crops wilt early. When affected by ethylene, the flower buds of tomatoes and peppers remain closed and drop off more easily. Serious ethylene damage in vegetable crops manifests itself in yellowing of the leaves.

NO_x

The average NO_x level in the greenhouse is usually too low for acute effects.
Damage caused by NO_x is not usually obvious straight away. The difference only becomes noticeable when the crop is compared to a crop without NO_x. NO_x results in inhibited growth, and lost and delayed production.
It usually interacts with the CO_2 concentration. Higher CO_2 concentrations (up to approximately 1000 ppm) make plants slightly less sensitive to NO_x. However, the presence of NO_x always reduces the positive effect of the increased CO_2 concentration.

SO_2

Very little SO_2 is released by the combustion of natural gas. However, coal and oil release significant amounts. Even in low concentrations SO_2 has a damaging effect and results in chlorosis, leaf damage and inhibited growth.

CO

Small quantities of ethylene can be detected, but until recently this was very expensive. However, small concentrations of carbon monoxide (CO) can be measured easily. Ethylene and CO are both released during incomplete combustion. The measurement of CO in flue gases is a good indicator for incomplete combustion. As soon as the CO concentration exceeds 30 ppm the dosing of flue gases to the greenhouse must be stopped immediately. The flue gases must be sent out through the chimney. Carbon monoxide is not harmful to plants, but can be lethal in small doses in humans. Therefore, polluted flue gases must not be able to enter the boiler house or shed. While the CO remains high, all gas must be discharged via the chimney. The concentration must have been below the limit value for some time before dosing to the greenhouse can recommence.
The MAC value for CO is 25 ppm or 29 mg/m3 of air. This value applies to an eight hour working day. This means that personnel must not work/be present in areas where the CO concentration exceeds 25 ppm.
The development of affordable ethylene measurement systems has now progressed to the extent that these will have to be used in flue gas cleaning in the not too distant future. It is very likely that the use of both a CO meter and an ethylene meter in flue gases will become a requirement in future.

3. TECHNICAL ASPECTS OF CO_2 DOSING

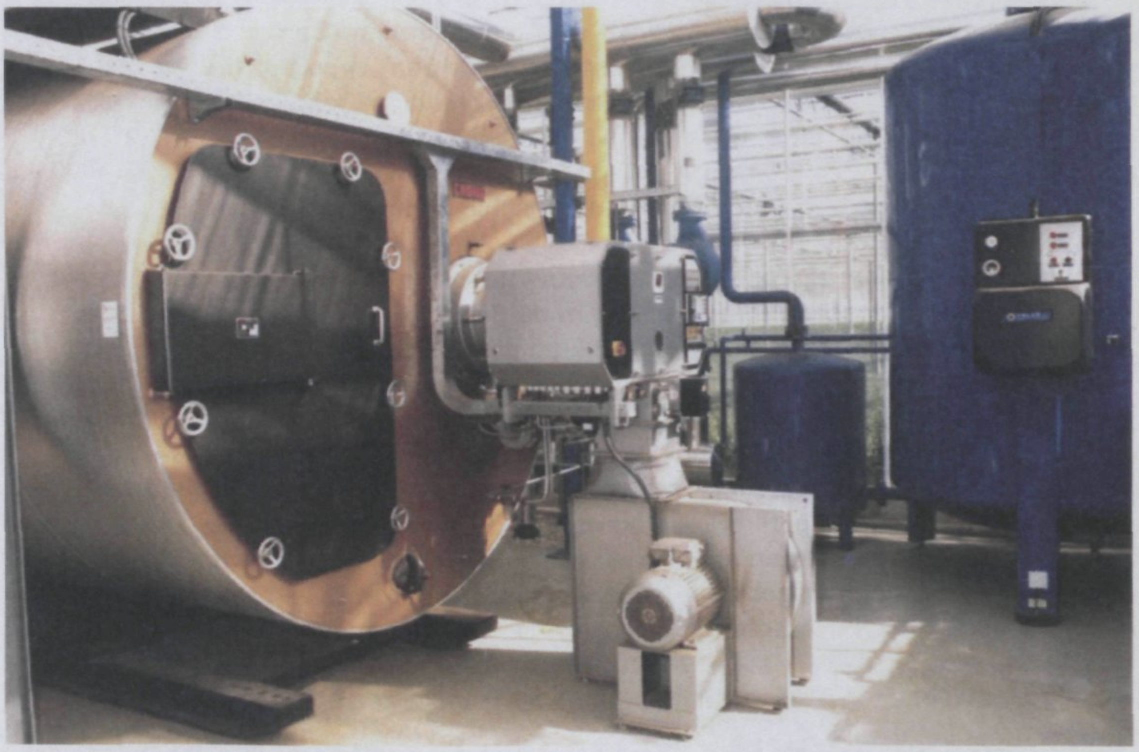
3.1 THE HEATING BOILER AS CO_2 SOURCE

Introduction

Gas fired central heating boilers have a dual function in greenhouse horticulture. Firstly, the heating system is used to heat the greenhouse Secondly, the boiler is used as a CO_2 source for CO_2 fertilisation of the crop. The combustion gases created during the combustion of natural gas are referred to as flue gases. The cooled combustion gases, either mixed or not mixed with outside air that are used for CO_2 fertilisation, are referred to as dosing gases. Dosing gases are distributed throughout the greenhouse via a dosing system and linked distribution system. The dosing value is the quantity of natural gas burned per ha per hour for CO_2 fertilisation.

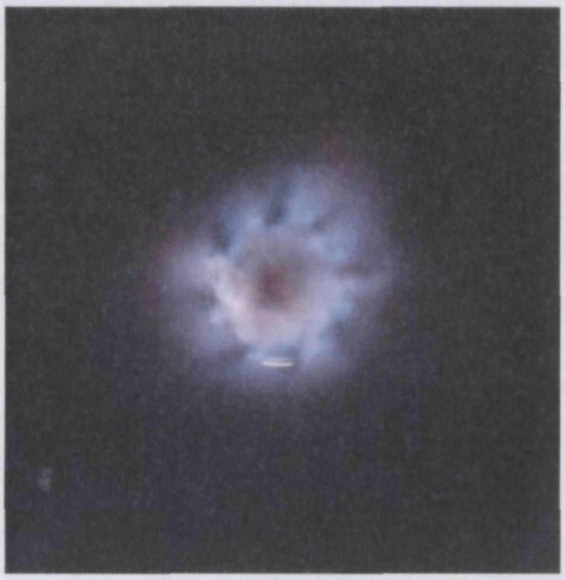
Burner

Gas burners are the most frequently used CO_2 producers for CO_2 dosing in greenhouse horticulture. The combustion of 1 m^3 of Dutch 'Slochteren' natural gas generates 1.78 kg CO_2. Conversely, the production of 1 kilo of CO_2 requires 1/1.78=0.56 m^3 natural gas. Providing natural gas burners comply with the statutory inspection requirements and are adjusted and maintained correctly, the combustion gases will contain only very small amounts of noxious gases. The combustion gases are suitable for use in CO_2 dosing straightaway.



Gasburner as producer of CO_2

Incomplete combustion

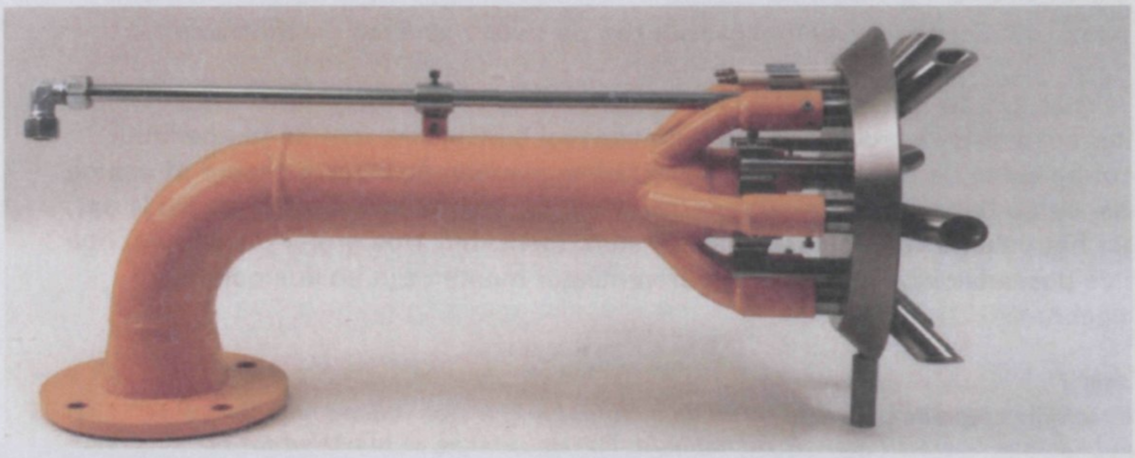


Complete combustion

Flue gases from oil burners are usually not suitable for CO_2 dosing. They contain too many noxious gases such as sulphur dioxide (SO_2).
To prevent the creation of noxious gases as a result of the incomplete combustion of natural gas, the latter is mixed with more air than theoretically necessary for complete combustion. This is referred to as air surplus. The air surplus is shown by an "air factor" (λ). A λ of 1.1 indicates an air surplus of 10%. The CO_2 content of the combustion gases is dependent on this air factor and is approximately 9% with a low flame (λ=1.3) and up to 10.5% with a high flame (λ=1.1) Table 3.1). If there is no air surplus (λ=1), but there is complete combustion, this is referred to as stoichiometric combustion.

In general, all gas burners used in horticulture are suitable for CO_2 dosing. The dosing value is between 30 m^3 and 150 m^3 natural gas per ha per hour. The control range on modern burners is so wide that complete combustion occurs and flue gases are suitable for CO_2 dosing in both the low (30 m^3) and the high burner position (150 m^3). A lock must be put on the burner in the lowest position at which it burns clean. This ensures that the burner can run above, but not below this setting during CO_2 dosing. The burner must not run below the locked position, as below this setting combustion is incomplete and noxious gases would be produced (see 3.6.). If the burner burns clean across the entire range there is no need to set a lock. Various control systems that provide the correct gas/air mixture are available on the market. These ensure that complete combustion occurs under all conditions. In this case, a specific oxygen surplus (3%) must always be available.

Low NOx burners
Even correctly adjusted burners produce NOx gases, a mixture of NO and NO_2 (see 3.6). NOx is toxic to plants and the environment. Improved burner designs have brought about a gradual decrease in NOx gas emissions. Traditional burners emitted 150-200 mg/m^3 flue gas, whereas the current low NOx gas burners produce between 60 and 100 mg NOx per m^3 flue gas. Some gas burners have a LOW NOx GAS INSPECTION certificate and produce even less than 60 mg/m^3. Burners in existing systems can be replaced by a LOW NOx burner without major technical changes ("retro fit").



Low NOx burner (retrofit)

Protection and maintenance
Dutch legislation requires that both the gas protection equipment in the gas manifold and the automatic burner unit/flame protection have an inspection certificate issued by GASTEC in Apeldoorn. A Royal Decree also requires that each gas burner system in excess of 660 kW is inspected before initial commissioning by the gas supply company: Gastec in Apeldoorn, or another suitably qualified body who holds a VISA-TECHNICIAN diploma. In addition, systems must be re-inspected every two years to ensure safety of the system over the long term.
To ensure correct and efficient combustion, the burner must be inspected and maintained at yearly intervals. Therefore, it is advisable to set up a maintenance contract or service certificate including a test report with a registered installation company. The test report must include the following information as a minimum:
- gas consumption in each burner position
- CO_2 percentage (O_2 percentage)
- CO percentage
- boiler capacity (kW)
- boiler output
- setting values of protection devices
- condition of gas burner system
- option for NOx values

CO_2 distribution system

Flue gases and dosing gases

Flue gases leaving the boiler are hot. The temperature varies between approximately 100°C with a low flame to approximately 200°C with a high flame. The amount of flue gas released per m^3 of combusted natural gas depends on the temperature and air factor. This relationship shown in Table 5.

Table 5. Amount of flue gas (m^3) released per m^3 combusted natural gas with different air factors (□ =1.0 to 1.6) and different flue gas temperatures (40 to 200°C). The second column shows the corresponding dew point and the third column the CO_2 content.

Air factor	Dew point temp.	CO_2 Content	Flue gas volume (m^3) relative to the flue gas temperature					
λ	°C	vol.%	40°C	60°C	100°C	140°C	180°C	200°C
1.0	58.6	11.7	10.9	11.6	13.0	14.4	15.8	16.5
1.1	56.9	10.6	11.9	12.7	14.2	15.7	17.3	18.0
1.2	55.2	9.7	12.5	13.3	14.9	16.5	18.1	18.9
1.3	53.7	8.9	13.6	14.5	16.3	18.0	19.8	20.6
1.4	52.4	8.2	15.0	16.0	17.9	19.8	21.8	22.7
1.6	49.8	7.1	17.0	18.1	20.2	22.4	24.6	25.6

Flue gases need to be cooled to below 60°C before they can be used as dosing gas. This is because the mostly synthetic dosing lines are not resistant to temperatures in excess of 60°C. Hot gases also damage the crop. Flue gases can be cooled in two ways.

1) Mixing in outside air.

The hot flue gases are mixed with outside air until the temperature drops below 60 °C. The amount of outside air mixed in depends on the flue gas and outside air temperatures (Table 6). The disadvantage of mixing in outside air is that the volume of the dosing gases increases considerably. Larger volumes require larger dosing lines and transport fans, which leads to a rise in power consumption.

Example 1:

Assume that the flue gas temperature is 200°C and the air factor 1.1. In this case, the flue gas volume per m^3 combusted natural gas is 18 m^3 (Table 3.1). To cool the flue gas to 60°C by mixing with (outside) air at 20°C, 63 m3 (outside) air is required per m3 flue gas. This produces 81 m^3 dosing gas (Table 3.2). At a dosing value of 80 m^3 natural gas per ha per hour, 80x81=6480 m^3 dosing gas must be blown into the greenhouse.

Table 6 Amount of (m^3) air of different temperatures (0, 10, 20°C) to be mixed in per m^3 combusted natural gas in order to cool flue gases of different temperatures (60 to 200°C) to 60°C. Air factor λ = 1,1.

Flue gas temp. in °C	m^3 fluegas per m^3 natural	Amount of (m^3) air required to cool the flue gas of 1 m^3 natural gas to 60°C			Produced quantity (m^3) dosing gas from 1 m^3 natural (rounded)		
		Air temperature			Air temperature natural gas		
		0°C	10°C	20°C	0°C	10°C	20°C
60	12.7	0	0	0	13	13	13
100	14.2	9.5	11.4	14.2	24	26	28
140	15.7	20.9	25.1	31.4	37	41	47
180	17.3	34.6	41.5	51.9	52	59	69
200	18.0	42.0	50.4	63.0	60	68	81

2) Use of a flue gas condenser.

A flue gas condenser is a heat exchanger that is installed behind the boiler. It extracts heat from the flue gases. The heat can then be utilised to heat the greenhouse. Depending on the type of condenser and how it is integrated into the heating system, a flue gas condenser can generate energy savings of approximately 15%. Heating companies should employ a flue gas condenser as standard to ensure maximum energy efficiency.

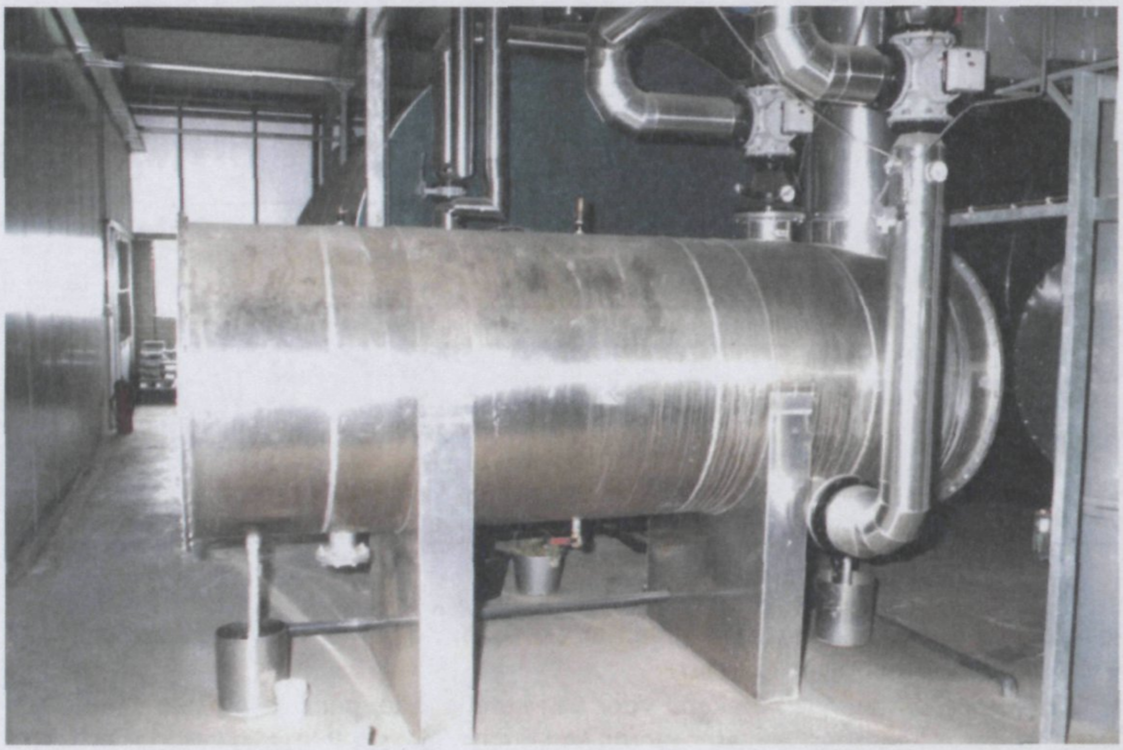
The condenser reduces the temperature and volume of the flue gases allowing them to be used as dosing gas (Table 3.2) straightaway. If the flue gas temperature drops below 58°C, the water vapour in the flue gas starts to condense (hence the name). This makes the dosing gas drier so that less moisture enters the dosing system and greenhouse air.

Example 2

The condenser reduces the flue gas temperature from 200°C to 60°C. The flue gas volume per m^3 natural gas decreases from 18 m^3 to 12.7 m^3 (air factor = 1.1). At a dosing value of 80 m^3/ha, 80x12.7=1016 m^3 dosing gas must be blown into the greenhouse. When outside air was used for cooling, this was 6480 m^3 (example 1). This means that a much smaller distribution system is required when a condenser is used.

The quantity of dosing gas drops even further at even lower flue gas temperatures. To ensure the successful distribution of dosing gases in the greenhouse additional air is mixed in, e.g. up to a minimum of 600-1000 m^3 dosing gas per hectare per hour. A valve system can be used to implement different mixing ratios between the flue gas and air to increase or decrease the amount of CO_2 in the dosing gas at a fixed dosing gas volume. This allows more or less CO_2 to be brought into the greenhouse to suit requirements.

If the CO_2 distribution system is calculated for a boiler without condenser, i.e. many m^3 dosing gas per m^3 natural gas, and a condenser is installed at a later date so that much less dosing gas per m^3 natural gas is produced, the distribution system will then be too large. The exact size of the distribution system must be recalculated and the system modified.



Flue gas condenser

Dosing value
To calculate the size of the required CO2 system, the required dose (dosing value) must be defined first. This depends on the required CO_2 concentration in the greenhouse and the ventilation rate. In practice, the dosing value, when there is no heat demand, for businesses without a heat buffer is usually 30-80 m^3 natural gas/ha/hour and for businesses with a heat buffer 80-150 m^3 natural gas/ha/hour.

Fan and dosing gas volume
The fan draws flue gases out of the chimney and forces them (mixed with outside air if necessary) as dosing gas into the greenhouse via a duct system. A resistance is sometimes installed in the chimney just above the point where gases are drawn in to ensure that the flue gases can be extracted. To ensure the most effective CO_2 distribution, the fan must have sufficient capacity to supply the required quantity of dosing gases per hectare (called the dosing gas volume) to the greenhouse. The dosing gas volume at maximum dosing defines the fan capacity and diameter of the ducts. This may coincide with the maximum load ('full load') of the burner.

Transport line and distribution lines
The transport line takes the dosing gases from the fan to the distribution line in the greenhouse. It is important to keep the pressure drop in the transport lines low to maintain sufficient pressure. The number of bends must be kept to a minimum and there must be no sharp bends. The maximum acceptable flow speed is 10 m/s. The duct diameter must be adequate. A PVC transport line with a reducing diameter of 400, 315, 250, 200, 160 and 125mm is usually applied for this purpose. The distribution line with the CO_2 hoses must then distribute the dosing gases evenly throughout the greenhouse.

To keep the pressure drop in the distribution line the flow speed must not exceed 10 m/s. The duct diameter can gradually decrease because the amount of dosing gases in the distribution line gradually decreases as well. Usually, the distribution line is made of PVC with a reducing diameter of 315, 250, 200, 160, 125 and 90 mm. To prevent burst or cracked pipes the walls must not be too thin. It is advisable, therefore, to use pipes with a class 51 wall thickness.

CO_2 hoses (plastic lay-flat ducts)
The CO_2 then flows, via the transport and distribution line, through a network of plastic lay-flat ducts. They represent the last stage of the distribution system. These are perforated plastic foil hoses coiled between the crops. The dosing gases enter the greenhouse through small perforations in the CO_2 hoses. The number of perforations in the hose defines the resistance the dosing gases are subjected to in the duct.

Distribution system for CO_2 with hoses pinched by stems or fruits because the pressure in the hoses is to low

The higher the number of perforations, the lower the resistance. The resistance creates pressure in the hoses, the hose pressure. To ensure the successful distribution of the dosing gases the pressure in the hoses must be between 50 and 70 mmwc (millimetre water column). At this pressure the CO_2 hoses cannot be pinched by stems or fruits allowing the condensed moisture to flow easily out of the hoses.
In order to achieve this pressure the number of perforations in the hoses must be geared to the amount of dosing gases. The number of perforations is indicated by the perforation distance. The perforation distance is the distance between the perforations in the hose in longitudinal direction. Four perforations with a diameter of 0.8 mm are made as standard (all the way around) per perforation distance.

Table 7 shows the required perforation distance with respect to the dosing gas volume. If the perforation diameter deviates from the standard 0.8 mm, the perforation distance needs to be adjusted as well!

Table 7. Required distance between two duct perforations in relation to the volume of dosing gases per hectare per hour (dosing gas volume)

Dosing gas volume (m^3/ha)	Hose distance	
	3.20 m	1.60 m
600	80 cm	160 cm
750	60 cm	120 cm
900	50 cm	100 cm
1200	40 cm	80 cm
1500	30 cm	60 cm
1800	25 cm	50 cm

Warning

In practice, some hoses are supplied with 1 mm perforations without an adjustment for the distance. These hoses create major problems. Because of the larger perforation diameter, the resistance in the ducts is much lower. This results in low hose pressure and uneven CO_2 distribution.

Because of the resistance in the CO_2 hoses the pressure at the start near the distribution line is higher than at the end of the hose. This means that more dosing gas is released at the start than at the end of the hose. To keep this release difference within acceptable values the pressure difference (pressure drop) must not exceed 20% of the pressure at the start of the hose. It is of the utmost importance that the hoses are not damaged in any way. Tears and holes - except for the dosing perforations - in the ducts will result in uneven CO_2 distribution.

Most CO_2 systems have hoses with a diameter of 41 mm spaced 3.20 m apart. In this case, the hoses must not exceed 40 m in length. Longer hoses can only be used if they are spaced 1.60 m apart or if the duct diameters are increased. Table 8 shows the maximum hose length in relation to the hose distance and hose diameter. Consult your installer for alternative hose distances.

Table 8. Maximum hose length in relation to hose diameter and hose distance

Hose diameter	Hose distance	
	1.60 m	3.20 m
41 mm	60 m	40 m
60 mm	120 m	75 m

Throttle plates

Even distribution of the dosing gases throughout the greenhouse is achieved when there is an even pressure throughout the hoses. The dosing gases that flow into the greenhouse at the end of the distribution line have a much greater distance to cover and meet with more resistance than the dosing gases that flow into the greenhouse at the start of the distribution line. In order to keep the hose pressure the same everywhere, each distribution line branch is fitted with a resistance in the form of a throttle plate. Throttle plates are small round plates with a perforation with a specific diameter. The ratio between the diameter of the perforation and the diameter of the branch defines the degree to which the pressure is throttled. The lower the ratio, the higher the degree of throttling. Concentration differences in the greenhouse occur if the throttle plates have been calculated incorrectly. It is important, therefore, to have this carried out by an expert. The same applies to calculating the rest of the CO_2 distribution system. Correctly calculated, installed and maintained systems will prevent major CO_2 differences and differences in production in the greenhouse.

Condensate discharge

Condensate is one of the main problems associated with CO_2 distribution systems. Condensate deposited in the transport and/or distribution line creates a strong resistance for the dosing gases. This results in the fan blowing fewer dosing gases into the greenhouse and poor distribution of the dosing gases.

Water problems in CO_2 systems can be prevented by observing the following guidelines:

- Fit condensate discharge points in the transport and distribution line.
- Always install the lines with a gradient towards the end.
- Prevent the lines from sagging.

Condensate can easily be discharged using a siphon trap. The siphon trap allows water to flow out of the lines without a drop in pressure. Dosing gases cannot escape via the siphon trap as it is always filled with water. Ensure that the siphon trap is long enough. Otherwise, the fan will blow the water out of the siphon trap thus allowing dosing gases to escape.

If the lines are installed with a gradient the water flows automatically to the condensate discharge points. Never install lines with a gradient towards the fan. The dosing gases and condensate would then flow in opposite directions causing undesirable resistances to be built up in the lines.

Underground lines must be dug in correctly to prevent any sagging of the lines. Sagging lines can act as a water lock.

For more detailed technical information refer to the handbook Greenhouse Horticulture Heating Manual, published in 1995 by Nutsbedrijf Westland N.V.

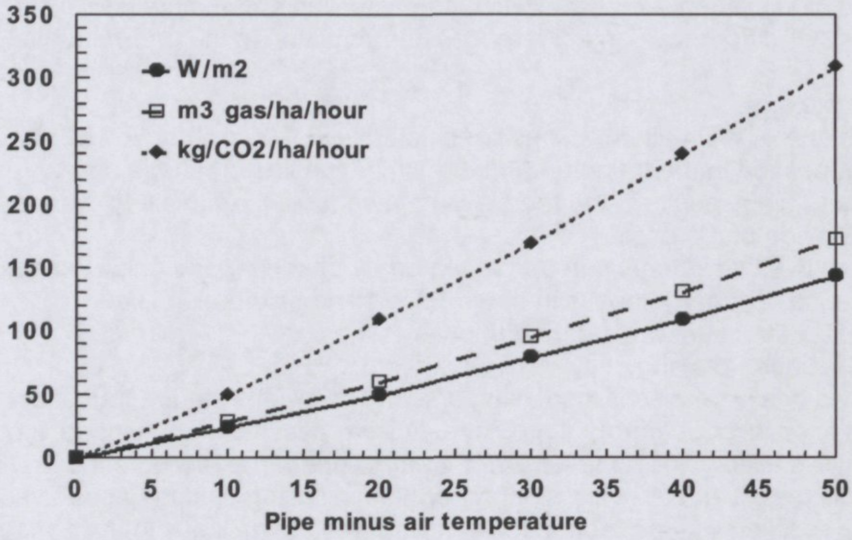
Heat surplus storage with CO_2 production

Introduction

CO_2 can be produced relatively cheaply within the business from natural gas combustion. The heat released during this process can be used to heat the greenhouse. If CO_2 is required, but there is no demand for heat, a heat surplus is created. This occurs in particular in spring and in summer, when the sun supplies sufficient energy to heat the greenhouse. As there is usually a heat demand during the night, an obvious solution is to store heat during the day for use during the night. A tank filled with water, a "heat storage tank" or (heat) buffer or buffer tank, is used for this purpose. If there is no heat storage facility or the facility is too small to store the entire heat surplus the heat has to be discharged. This can be done by using a maximum water temperature for CO_2, providing it is not harmful to the crops (Figure 7).

Heat can also be discharged via an "emergency cooler". In both cases, the heat is not used for a purpose, but is discharged and this means energy waste. This is an undesirable situation in terms of energy and the environment. Heat surplus should be stored in a heat storage tank. It is important, therefore, to provide a sufficiently large heat storage tank. With heating systems such as those for tomatoes and cucumbers, heat storage of 80-140 m^3 per hectare is ideal in business/economic terms (Table 17).

Figure 7. Ratio of temperature difference (°C) between pipe and air temperature with heat release (W) per m^2, gas consumption (m^3) per hectare per hour and produced quantity CO_2 (kg) per hectare per hour. This is based on 4 pipes (51mm) at a bay width of 3.20 m.



Heat storage tank" or (heat) buffer

Defining heat surplus

The computer will often indicate how many hours the burner has operated solely for CO_2 production. The number of hours combined with the burner position for CO_2 dosing will show the surplus heat that has been produced. The formula is as follows: natural gas consumption x H (= upper value natural gas) x η (=boiler efficiency at upper value).
The ventilated heat from a heat storage tank, that is too small, can be defined in the same way.

Heat demand

The stored heat is offset against the heat demand in the next period. It is desirable for ideal, energy efficient CO_2 dosing to start with an empty heat storage tank the next morning. Therefore, the heat demand during the night defines heat storage during the day. If more is stored during the day than can be offset during the night, the heat storage tank cannot be emptied. This means less dosing the next day, unless energy is wasted (discharge heat). This can lead to problems with flower crops that are blacked out, as the heat demand decreases sharply when screens are closed.
In spring, the nights are still cold enough to use up all the heat stored during the day. It is advisable, therefore, to base the size of the heat storage tank on this premise.

The gas meter can be used to get a good picture of the amount of heat that can be supplied to the greenhouse at night. Note the gas meter position when CO_2 dosing stops in the evening and starts again the following morning on a number of characteristic days during the summer (e.g. a very hot and a cool night). The difference is a measure for the heat used that could be supplied fully or partially by the heat storage tank.

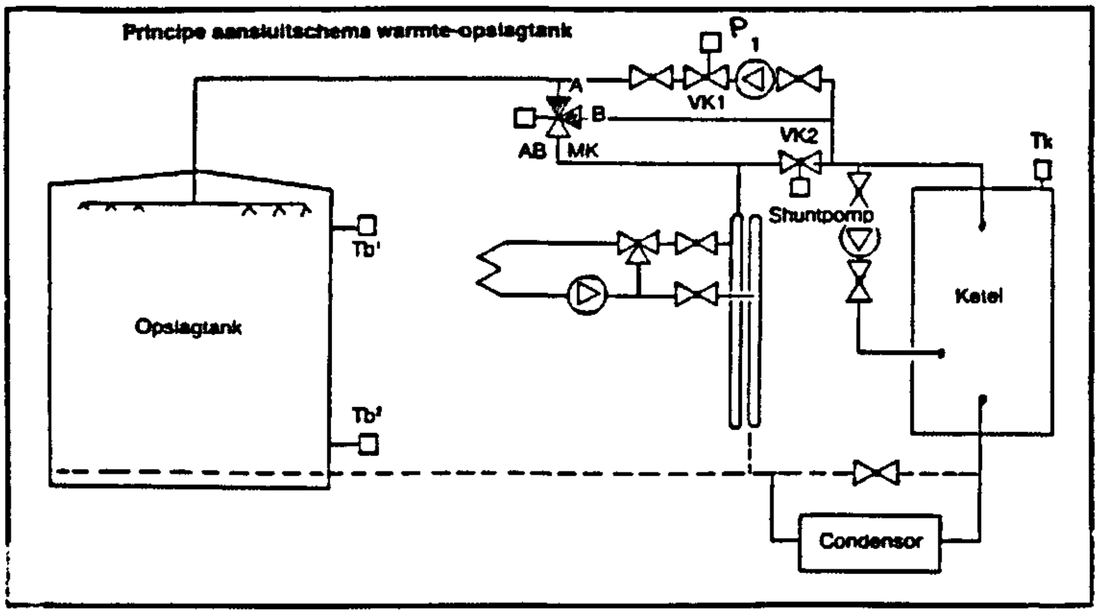
Relationship of heat storage capacity to maximum available quantity of CO_2

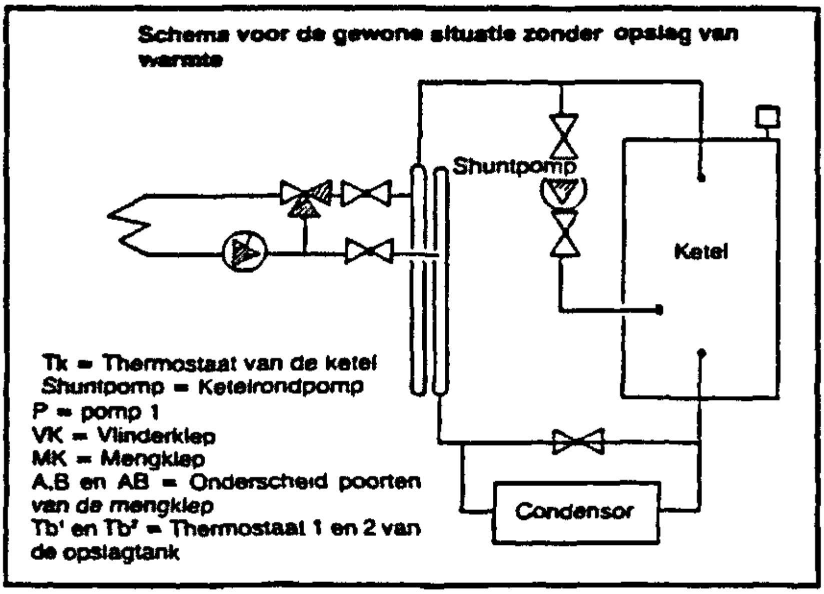
Assume:
The temperature of the heat storage tank increases by a maximum of 50 ^{0}C, e.g. from 45 ^{0}C to 95 ^{0}C. To increase the temperature of a 1 m^3 buffer by 50 ^{0}C, requires 7 m^3 natural gas and this will release 12.5 kg CO_2.

Calculation:
The combustion value of natural gas is 35.17 MJ/m^3.
The specific heat of water is (rounded) 4.2 Joule/gram/degree.
To increase the temperature of 1 gram water by 50 ^{0}C requires 50*4.2 = 210 Joules.
1m^3 natural gas supplies, with a boiler output of 85% (.85* 35,17) =29,89*10^6 Joules heat and 1.78 kg CO_2.
29.89*10^6 Joules can therefore be used to heat 29.89*10^6/210=142,333 gram= 142 kg water by 50 ^{0}C
To heat 1 m^3 (1000 kg) water in heat storage tank by 50 ^{0}C approximately 7 m^3 natural gas is required. This releases 7x1.78= 12.5 kg CO_2.
With a heat storage capacity of 80 to140 m^3/ha the figure per m^2 is: (80x12.5) to (140x12.5) = 1000 to 1750) kg. That is 100 to 175 g CO_2 per m^2.

General guideline:
Heat storage volume (m^3) multiplied by temperature increase (^{0}C) times 0.15 = required amount of natural gas (m^3)
(the factor 0.15 also incorporates the boiler efficiency and transport losses)
Chapter 5 describes the business aspects of a heat storage tank.

Schematic connection diagram of a heat storage tank
Figure 8 shows the principle of connecting a heat storage tank to the heating system. When heat from the buffer is used, it is extracted from the top of the tank. The temperature is highest at the top of the tank. Valve VK1 is closed and pump 1 has stopped. Three-way valve MK is opened to extract the water from the buffer (port A). Port B and two-way valve VK2 are closed. The hot water can now flow from the mixing valve to the distribution manifold through A-AB. If the temperature of the water from the buffer drops too much, the mixing valve can mix in hot water from the boiler via port B. Valve VK2 is still closed. When port B of mixing valve MK is fully open, two-way valve VK2 will open so that there is a full flow from the boiler to the manifold. The dimensions of mixing valve MK must be designed to ensure that the heat can be extracted from the tank as quickly as possible when it is required. Valve VK1 and pump 1 on the other hand only need to transport the heat generated when the burner is in low position to the heat storage tank.





Translation:
Principe aansluitschema warmte-opslagtank = Schematic connection diagram heat storage tank.
Schema voor de gewone situatie zonder opslag van warmte = diagram for a situation without heat storage tank.
Opslagtank = heat storage tank; ketel = boiler; shuntpomp = shuntpump; condensor = condensor

Figure 8 Schematic connection diagram with heat storage tank and diagram for a situation without heat storage tank.

Storage of flue gas CO_2

In winter, the boiler produces more CO_2 than the plant can use. In summer, not enough CO_2 is released by the boiler for maximum production. This raises the question of whether it is possible to store the surplus CO_2 produced in winter for use during the summer. This would also make sense in terms of the environment as a way to reduce CO_2 emissions.

During the mid eighties TU in Delft carried out research into the possibility of storing flue gas CO_2. However, the amount of flue gas required during the summer is such that it could not be stored without processing. The concentration of CO_2 needs to be increased from 9 to 10% in the flue gases to 90% for storage. In all the options investigated, purification, compression and storage costs are much higher than the costs involved in the normal method of running the heating system when there is a demand for CO_2. Even at a gas price of 40 cents per m^3, this method is still more profitable. If there is no heat demand, the gas price is significant when calculating the cost price of CO_2. The conclusion of the research was that it is only possible to make single-day storage profitable. In other words, heating during the night and storing flue gas CO_2 for dosing during the day. However, the cheapest storage method, where CO_2 is not stored under pressure, requires a volume of 800 m^3/ha. Night storage of CO_2 is the opposite of heat storage during the day in a buffer tank. However, a heat buffer is much smaller (100-120 m^3/ha). This represents a significant difference with respect to cost, space and blocking of light.

The overall conclusion was that the storage of flue gas CO_2 is technically possible, but impractical and too expensive over long periods.

Section 5 includes a calculation of the maximum cost of CO_2 storage if improved storage methods were to become available.

3.2 HOT AIR HEATERS AS CO_2 SOURCE

Introduction

With hot air heaters, the heat from combustion is released directly into the greenhouse air. A fan blows the greenhouse air past the combustion area and into the greenhouse. Hot air heaters are mounted in the growing areas that they heat. Therefore, they have to be resistant to greenhouse conditions. This includes direct sunlight, strong temperature and humidity fluctuations and crop protection agents.

They should be mounted to ensure that:

- The heat and CO_2 are evenly distributed.
- Plants are not adversely affected by excessive air speeds or excessive combustion gas temperatures or heat radiation.
- The equipment is not affected by spray or dripping water.

Two types of hot air heaters are used in horticulture, i.e. heaters without or with flue gas discharge (chimney). The first group includes suspended hot-air blowers and the second group the much larger, standing air heaters.

The equipment must comply with EU standards. From 1st January 1996 they must have a CE mark (European CE mark). GASTEC in Apeldoorn has been appointed by the Dutch government to carry out the relevant equipment inspections. In addition to the CE mark, the Netherlands also award a voluntary GASTEC QA (Quality approved) mark. The standards and requirements for GASTEC QA are continually revised and updated to suit the requirements of the market.

With the introduction of the GASTEC QA, the old GIVEG and GASKEUR marks have become void. Since 1st March 1996, these marks must no longer be applied to products.

Hot-air blowers

Hot-air blowers have an open combustion chamber. The combustion gases are blown by a fan into the area, in which the hot-air blower is suspended. The appliances used in horticulture are supplied with a maximum load of up to 130 kW and are sometimes also referred to as CO_2 burners. Hot-air blowers are designed to ensure that combustion is complete with a sufficient supply of oxygen and that very few harmful combustion gases are produced. This makes them suitable for use as a CO_2 source and means that they can be used in greenhouses where humans are present.

If combustion is incomplete the amount of harmful combustion gases (noxious gases), i.e. carbon monoxide (CO), ethylene (C_2H_4), nitrogen oxide (NO_x), increases considerably. To prevent problems associated with incomplete combustion, regular maintenance of the equipment and monitoring of the combustion gases for the presence of non-combusted hydrocarbons, is necessary. A maintenance contract with the manufacturer or installer is, therefore, highly recommended. This particularly applies if the CO_2 burner is also used to heat the greenhouse. With low outside temperatures, when the vents are closed and the equipment is operating for many hours at a time, the concentration of harmful gases can increase significantly. An adequate supply of oxygen to the burner is essential.

Hot-air blower

Oxygen supply

The combustion of natural gas uses oxygen from the greenhouse air and releases CO_2 into the greenhouse air. If the greenhouse is not ventilated, the oxygen content (normally approx. 20%) in the greenhouse air will drop and the CO_2 content will rise. A well designed appliance will still achieve complete fuel combustion with a slight drop in oxygen content, but this will not last for very long. Combustion will no longer be complete and ethylene and carbon monoxide will be released into the greenhouse. It is necessary, therefore, to ensure that there is a sufficient oxygen supply when using CO_2 burners. A number of options are available:

- Continuous minimum ventilation of the greenhouse.
- Use (outer wall) ventilation, which is switched on automatically when the CO_2 concentration increases too much.
- Outside air supply to the burner

A small axial fan sends oxygen-rich air from outside to the burner through a roof feed-through with rain cover and flexible hose. This system is most effective when the appliance is designed with the burner outside the body of the appliance. The outside air is then supplied directly to the burner. Then the burner operates in its own outside air environment, independently of the greenhouse air.

If gaps and joints in the greenhouse have become sealed by frost, extra care should be taken to ensure a sufficient air supply!

Low NO_x CO_2 burners (Low NOx hot-air blower)

A Low NO_x CO_2 burner is available in addition to conventional CO_2 burners. These burners have extremely low NO_x emissions due to a special burner design. Depending on the type, this is between 5 and 20 ppm (approx. 10-40 mg/m^3). As a result, these burners are more suitable for CO_2 dosing and are more environmentally friendly than more conventional burners. Conventional burners have NOx emissions of 70 -80 ppm (approx. 150 mg/m^3). Low NO_x burners usually have a >GASTEC QA mark. Low NO_x.

Standing air heaters

Standing air heaters are not suspended (as opposed to hot-air blowers). They are hot air heaters with a chimney that are mainly installed for heating purposes. These heaters were often used in the past for combination crops: tomatoes (during the summer) and lettuce (in winter). They are being used less and less as this combination crop is becoming less common. They are still used in small greenhouses and for some mildly heated vegetable and florist crops. The power of these appliances usually exceeds 300 kW. Combustion gases can be used for CO_2 dosing, providing a high quality, correctly adjusted and well maintained burner is used. A branch is inserted between the flue and the exhaust hood of the air heater for CO_2 dosing. A diverter valve in the flue discharges the flue gases via the flue or returns them (partially) to the air heater, where they are blown into the greenhouse and distributed with the air flow.

Standing air heater

3.3 DOSING WITH PURE CO_2

Introduction

Pure, industrially produced CO_2 is also used in horticulture and has the advantage of always being available in sufficient quantities. CO_2 is also a by-product of fertiliser production. When this crude gas has been compressed, cooled and purified, it becomes liquid CO_2. It does not contain undesirable noxious gases. The use of pure CO_2 does not generate heat. This is an advantage when there is little or no heat demand. The disadvantage of pure CO_2 lies in the fact that it is more expensive than flue gas CO_2.

Growers need the following equipment to dose pure CO_2:

- a storage tank for CO_2 supplied in liquid form;
- a CO_2 dosing system;
- a duct network to distribute CO_2 in gas form efficiently throughout the greenhouse;
- a climate control program for cost-effective dosing.

Storage and transport

Pure CO_2 is stored in liquid form under pressure in tanks, which are also referred to as cryogeen tanks. The storage system consists of a double walled tank. The intermediate space is filled with insulation material. The liquid CO_2 in the tank is at a temperature of approximately

-25 °C. Even with the insulation, some CO_2 may still evaporate. To ensure that the pressure does not become too high - at 20°C the pressure of liquid CO_2 is approximately 73 bar - some tanks are equipped with a cooling system. Other types merely vent the excess pressure.

Tanks are leased and maintained by the gas suppliers. It is important that tanks are well maintained to ensure successful operation. The supplier's extensive vehicle fleet (tanker trucks) guarantees a regular supply.

Storage tank for pure CO_2 (cryogeen tank)

CO_2 dosing techniques

There are various methods of turning liquid CO_2 into CO_2 gas.

1 - Liquid injection in the central CO_2 distribution system

In horticultural businesses that have a central CO_2 distribution system for flue gas CO_2, a special dosing unit is used to inject liquid CO_2 near to the central system fan. The air drawn in from outside or from the boiler house evaporates the liquid CO_2. If the CO_2 flue gas distribution system is working correctly, distribution of pure CO_2 will also be successful.

2 - Distribution via a special duct network

Liquid CO_2 is drawn through an electrically heated water bath via a coil tube. It requires 0.13 kW of energy to evaporate 1 kg of liquid CO_2 per hour into 0.552 m^3 CO_2 gas.
Sometimes, if this generates economic benefits for the grower, the gas supplier will install an air evaporator. The ambient air, that blows through and past the evaporator, supplies the necessary evaporation energy. A reducer lowers the high pressure to the desired operating pressure. A flow meter indicates how much CO_2 is dosed per time unit.

3 - Distribution via fans

CO_2 can also be dosed using air circulation fans. This method is preferable when duct networks on the ground (in plant beds) create an obstruction. This is a simple method, but it has limitations. Dosing with the vents open results in more CO_2 loss, because the gas is applied above the crop and therefore escapes more easily from the greenhouse.

Combi CO_2 gas dosing

With this method, several companies receive pure CO_2 from a shared tank. Gas meters register the consumption levels of each individual company. Economically this can be an attractive alternative. One large tank is cheaper than a number of small tanks.

The following is a list of the suppliers of pure CO_2 for horticulture that we are aware of:

AGA Gas BV
Distelweg 90 1031 HH
Postbus 37601 1030 BA
Amsterdam
Telephone 020-6345678
Fax 020-6341511

Hydrogas Holland BV
Maassluissedijk 103
Postbus 58 3130 AB
Vlaardingen
Telephone 010-4607484
Fax 010-4607419

Hoekloos NV
Havenstraat 1-3 3115 HC
Postbus 78 3100 AB
Schiedam
Telephone 010-4276699
Fax 010-4270500

Air Liquide BV
Witbogt 1 5652 AG
Postbus 7117 5605 JC
Eindhoven
Telephone 040-2503503

Messer Griesheim Nederland BV
Middenweg 17 4782 PM
Moerdijk
Telephone 0168-384390
Fax 0168-384395

3.4 HEAT/POWER SYSTEM AS CO_2 SOURCE

Introduction

Power stations convert primary energy (gas, oil, coal) into electricity and heat. In a conventional power station, the output is approximately 40%, in the latest, most up to date stations it is approximately 55%. The heat released, 60% and 45% respectively, is not usually used for a specific purpose. The heat is discharged into the environment via the cooling water or cooling tower and is wasted. An H/P system is a combination of a combustion motor, usually fired by natural gas, and a generator (type of dynamo). The natural gas is combusted in the gas motor and converted into heat (H) and power (P) = current. In fact, it is a kind of mini power station. The heat generated during this process is not wasted, however, it is used to heat the greenhouse. Both the power and the heat are used! When power is generated in a horticultural business via an H/P system instead of a power station, fuel savings of up to 29% can be achieved. This system also reduces CO_2 emissions by 29%.

Flue gas purification (FGP) necessary

The flue gases from the gas motor in the H/P system contain concentrations of toxic substances, including nitrogen compounds (NOx) and ethylene (C_2H_4), that are too high to be used for CO_2 dosing without purification. If the H/P does not have flue gas purification, the CO_2 required for CO_2 fertilisation is usually derived from the flue gases of the boiler available on site. This limits the number of operating hours of the H/P to approx. 4000 and achieves a heat coverage of up to 50%. Once the flue gases from the H/P are purified, they are suitable for CO_2 dosing. This creates a much more cost-effective situation in terms of energy. The number of operating hours can now be increased to approximately 5500 and the heat coverage to more than 70%. Therefore, flue gas purification for CO_2 dosing increases the number of operating hours for the H/P system and the targeted energy savings.

H/P + FGP from utility company

If the H/P system has been supplied by the utility company, it is advisable to get the utility company to install the flue gas purification system as well. The entire system is then in the hands of a single owner. This prevents legal and repair/maintenance problems that might occur if the utility company owns the H/P system and the grower owns the flue gas purification system. For example, the utility company might miss a peak moment because the grower's catalytic converter system is out of order. Or conversely, the grower's catalytic converter is damaged by excessive oil penetration from the gas motor.

H/P and FGP managed by the grower

H/P systems managed by the grower can be based on 'island' or 'parallel' operation. In the case of island operation the H/P is not connected to the mains electricity network, with parallel operation it is. In the latter case electricity can be supplied to the grid via a transformer.

CO_2 is also required when the HID lighting is active. When the H/P is active for lighting, the purified flue gases can be used simultaneously for CO_2 dosing. However, on days with sufficient sunlight, i.e. most of the summer months, there is a need for CO_2 but not for electricity for the HID lighting. With parallel connection to the mains electricity network the H/P + FGP can continue to operate. The CO_2 is sent to the greenhouse, the heat to the greenhouse or buffer and the electricity is supplied to the electricity distribution company. This is not possible with island operation. The H/P and FGP do not operate when there is no demand for electricity for the HID lighting. This limits the number of operating hours.

Comparison of H/P + FGP with CO_2 from the boiler

Heat and CO_2 production

The theory is simple. An H/P + FGP system supplies almost twice as much CO_2 as a boiler with the same amount of heat (Table 9). This surplus yield of CO_2 can be used to achieve a higher CO_2 concentration in the greenhouse and therefore higher production. The same CO_2 level as for the boiler can be maintained, but with 50% less heat production. Heat surpluses occur less often and less buffer capacity is required.

Table 9. Comparison of CO_2 production of heat/power system and a boiler with similar heat production

	Heat/power	Boiler
Heat	500 kW_{th}	500 kW_{th}
Electricity	350 kW_e	none
Gas consumption	110 m^3/h	60 m^3/h
CO_2	200 kg/h	110 kg/h

However, things are often more complicated in practice. Modulating burners can be set to a low burner position, where low CO_2 demand (start of the morning) is linked to minimum heat production.

Even if turned down to 50% partial load, an H/P + FGP might then produce too much CO_2 and supply more heat than the boiler. More than one H/P on a single site, where one or more H/Ps have FGP, would give more flexibility in this situation,
The H/P + FGP must also be tuned correctly to the CO_2 dosing program in the climate computer. Therefore, it is advisable to contact the computer supplier at an early stage.

Adjustment of the CO_2 dosing system on the grower's premises
When changing from boiler to H/P CO_2, the dosing system has to be adjusted to suit the new situation. The following aspects must be taken into account:

CO_2 content in the flue gases
The combustion of natural gas in a boiler usually occurs with a minimal air surplus, where the CO_2 content in the flue gases amounts to approx. 10% (table 3.1). With flue gases from the H/P, the CO_2 content is highly dependent on the type of gas motor. In order to comply with the legal standard for NOx emissions, most H/P gas motors installed since the end of the eighties are "poor mixture" motors. They operate using a generous air surplus (λ = 1.3-1.6). As a result, the CO_2 content is between 7.0 and 9.0 volume % (table 5).
Older motors often operate with no, or very little, air surplus. Consequently, the CO_2 content in the flue gases is high, up to 11.7 volume % (table 5).

Flue gas water vapour content
The water vapour content of the purified flue gases also differs for each system. Because of the high air surplus one m^3 natural gas from an H/P contains less water vapour than one m^3 from a boiler. Table 3.1 shows that the condensation point with a 60% air surplus (poor mixture gas motor, λ =1.6) is more than 7°C lower than with combustion in a boiler with a 10% air surplus (air factor =1.1). If there is insufficient cooling in the flue gas condenser of the H/P FGP system, large amounts of condensate could form in the CO_2 dosing system the greenhouse and have to be removed.

Dosing gas quantities
When dosing CO_2 using purified H/P flue gases, the gas volume flow will be considerably larger than when dosing with the boiler. This is because of the larger quantity of flue gas per m^3 combusted natural gas and the lower CO_2 content. This must be taken into account when installing or extending the duct system between the H/P system and CO_2 fan, when defining the size of the CO_2 fan and the design or modification of the CO_2 dosing system in the greenhouse.
When purified flue gases from a gas motor is used, the CO_2 content of the purified flue gases, the water content and dew point, the total flue gas quantity and quality must be taken into account.

Link with boiler flue gases
Even if the H/P has a flue gas purification system, it may be useful to have access to the flue gases from the boiler. For example, if the boiler is already running (in winter) or when more CO_2 is required than the H/P + FGP can supply or if the H/P is out of order due to a fault or for maintenance. The best link between boiler CO_2 and H/P CO_2 needs to be evaluated for each individual situation. When both flows are sent to the greenhouse via the same fan and dosing system, it must be possible to seal each individual gas flow via a valve with a limit switch. The fan must switch off automatically if the gas flow becomes polluted and must not reactivate until a signal has been received that the shut-off valve in the polluted gas flow has been fully closed.

3.5 CO_2 WITH CENTRALISED HEAT SUPPLY

Introduction
Large quantities of heat and CO_2 are released when electricity is generated. From an environmental point of view, it is important to put the residual heat and waste CO_2 to a useful purpose. The heat released when generating electricity can be used to heat greenhouses and for other purposes. The first business to apply this principle in the Netherlands was the Amercentrale in Brabant. As a result, the greenhouse horticulture area >Plukmade= near Made-Drimmelen came into being. Other electricity producers such as Elektriciteitsbedrijf Zuid-Holland (EZH) and GasEdon in Drente, followed suit with the development of horticultural projects. It soon became clear that the supply of CO_2 has a major impact on the extent of heating sales. If no CO_2 is supplied, growers use flue gas from their own boilers. The heat produced during this process reduces the potential sales of the power station. EZH has calculated that this could amount to up to approx. 40% of total heating sales so that the coverage rate would remain at approx. 60%. If the power station supplies CO_2 as well as heat the coverage rate could rise to more than 80%. CO_2 supplies therefore are in the forefront of considerations for each new and up and running residual heat project.

Plukmade greenhouse horticulture area in Noord-Brabant
The Plukmade greenhouse horticulture area is located near the municipality of Made-Drimmelen in Noord-Brabant. Initial development of the area started in 1985. It is the first large scale horticulture project in the Netherlands with centralised heat supplies. In 1997 it covered approximately 60 hectares distributed across 35 companies. In 1987 a facility for the supply of pure CO_2 was added. Growers in the area receive heat and pure CO_2 from the utility company PNEM. Heat comes from the nearby Amercentrale of N.V. Elektriciteit-Productiemaatschappij Zuid-Nederland (EPZ). The price of the pure CO_2 supplied is slightly lower than the usual price for pure CO_2. EPZ is currently investigating, in conjunction with PNEM, the possibility of supplying CO_2 originating from Amercentrale flue gases. This would mean that cheaper CO_2 could be supplied and waste CO_2 could be put to good use. Of course, the flue gases need to be purified to ensure that they are suitable for greenhouse horticulture. If this option proves feasible, it would mean that in principle large quantities of CO_2 would become available at a lower price than at present.
Other than the Plukmade polder, another 60 or so companies in Brabant with a total surface area of approx. 75 ha were connected to residual heat in 1997, including 30 ha near Asten.

RoCa project
The RoCa project started 10 years after the Plukmade project. The significance of CO_2 supplies played a part in its development right from the start. RoCa is an acronym of the place names Rotterdam and Capelle a/d IJssel. The Zuid-Holland electricity company (EZH) has the option of creating a large scale heat/power project in the greenhouse horticulture area around the localities of Bleiswijk, Berkel and Bergschenhoek, the "B-triangle". The current project provides heat for almost 270 ha. RoCa-3, the heat power station (HPS) in operation since 1st July 1996, supplies the lion's share of the heat required. 137 companies were connected in 1997. The contribution to national energy efficiency improvements of this single project amounts to 2%.
EZH has investigated various options to supply CO_2 in combination with heat. A study of the literature carried out by Comprimo showed that CO_2 extraction from the turbine flue gases was not financially feasible. The main reason for this was the low percentage of CO_2 (3.5%) in the flue gases. Purchasing pure CO_2 was also too expensive. EZH then developed the idea of burning natural gas in a separate boiler with the flue gas from the gas turbine as combustion air. This flue gas still contains approximately 14% oxygen because of the large amount of cooling air in the flue gas. Due to the combustion of natural gas in the "CO_2 boiler", the CO_2 content in the flue gas rises to approximately 10% and can then be piped to the horticultural businesses. EZH has submitted a patent application for this idea.

Environment

The combustion systems of both the gas turbine and the CO_2 boiler are among the most advanced high-tech systems currently available. As a result, the emission of air polluting substances per unit of fuel consumed is one of the lowest in the world. The objective is to comply with the requirements for the flue gases containing CO_2 imposed by the company's customers. This includes requirements for levels of nitrogen oxides, carbon monoxide and ethylene. The system includes measuring equipment to ensure immediate intervention if the acceptable value is exceeded. The main contribution to the environment, including CO_2 emissions in particular, relates to fuel savings due to the combined generation of electricity and heat. In the case of RoCa-3, these savings amount to approximately 55% of the fuel that would otherwise be burned in the grower's boiler.

Erica/Klazienaveen horticulture project

GasEdon Emmen (Gasunie and EDON) has built two H/P stations in Erica and Klazienaveen. They supply heat to almost 100 companies with a total surface area of approximately 145 ha. Savings in natural gas amount to approx. 30%, and CO_2 emissions are reduced. The intention is to supply pure CO_2 produced by the power station. The central pipeline required for this purpose is already in place.

New projects

The positive results from current residual heat projects have led to a number of new initiatives. 48 projects were submitted to the Ministry of Economic Affairs (EZ) and the Ministry for Housing, Regional Development and the Environment (VROM) in the spring of 1997. Preparations are underway for projects at Arnhem/Nijmegen (50 ha), Euro Delta in Westland/Botlek (500 ha), Schinkelpolder in Aalsmeer, Almere, Cromstrijen, Harmelen, Mijdrecht, Siberië (Limburg), Oude Camp and Eemsmond. The implementation of these projects will have a very positive impact on greenhouse horticulture energy efficiency and will significantly reduce CO_2 emissions. In 1997, the savings in primary energy amounted to 7% . During that same year, 11.5% of the energy consumed in greenhouse horticulture was supplied by third parties (LEI-1998).

Relocation and large-scale new build projects are definite candidates for the establishment of central energy centres. These central energy centres can supply heat, electricity and CO_2. With the eventual liberalisation of the energy market in Europe this type of centre could purchase its own natural gas and sell generated electricity to third parties. The flue gases are a cheap source of CO_2 for crops. Relatively high CO_2 concentrations maintained during the summer will increase production and improve quality. This results in a considerable rise in energy efficiency and makes a substantial contribution to reducing national CO_2 emissions.

3.6. AIR POLLUTION ASPECTS

The composition of flue gases

Introduction

The combustion gases used for CO_2 usually originate from a boiler fired with natural gas (central heating boiler, hot-air heater or CO_2 burner) or, following purification, from a gas motor (heat/power system). Natural gas is the safest fuel for this purpose. With complete combustion, the natural gas is converted into CO_2 and water vapour. In simplified form, this is expressed as the following formula:

$$1 \text{ mol C} + 2 \text{ mol } O_2 \rightarrow 1 \text{ mol } CO_2 + 2 \text{ mol } H_2O$$

In addition to CO_2 and water vapour, the combustion gases also contain other gases, some in very small concentrations. The flue gases are a mixture of the following gases:

- Ar = argon (inert gas which constitutes approx. 0.9 % of the outside air)
- CO = carbon monoxide (only with incomplete combustion)
- CO_2 = carbon dioxide (maximum 11.7 % with natural gas)
- C_2H_4 = ethene (ethylene), (only with incomplete combustion)
- H_2O = water (in vapour form)
- N_2 = nitrogen
- NO_x = nitrogen oxides (depending on the flame temperature)
- O_2 = oxygen (with oxygen surplus)
- SO_2 = sulphur dioxide (substantial amounts only with oil, with natural gas a minimal quantity originating from added artificial odour)

Table 10 shows the composition of flue gases measured in practical applications. Some of the data originates from manufacturers (also via FIGO) and some from the Gasunie. Sometimes the figures show a (very) wide distribution. This may be caused by differences in burners or motors, adjustment and maintenance.

Table 10. Flue gas composition based on practical measurements.

Flue gas component	**Gas boiler standard ($3\% O_2$)**	**Gas boiler low NOx**	**CO_2 hot-air heater standard**	CO_2 hot-air heater low NOx	H/P poor mixture, $\lambda=1.6$	**H/P with flue gas purifier**
CO_2 %	9-10.5	9-10.5	6-10	6-10	7-9.5	7-9.5
CO ppm	<1-50	0-5	60	10-20	5-2000	0.1-15 (1)
(C_2H_4) ppm	0.2-0.5	0-0.2	0.6	0.6	15-60	0.1-0.7 (2)
NOx ppm	60-85	20-40	50-60	<10	100-650	8-25 (3)

(1) Alarm is usually set at 10-15 ppm
(2) Alarm is usually set at 0.7 ppm
(3) Alarm is usually set at 30 ppm

If the combustion process is incomplete, nitrogen oxide (NO_x), ethylene (C_2H_4), ammonia (NH_3) and ozone (O_3) may occur in the greenhouse during CO_2 dosing in concentrations that are harmful to plants. The Institute for Research into Plant Disease (IPO-DLO) and the Research Station (PBG) have set up global standards for maximum chronic (long-term) concentrations (limit values) of flue gas components in greenhouse air that are harmful to plants (Table 11). These following parameters apply to these values: they are based on a situation in winter with closed vents, an air temperature of 20 °C and low photosynthesis (little light). Under these conditions, the crops are relatively tender and most susceptible to damage. The quoted limits are based on research carried out by IPO, PBG and data derived from the literature.

Table 11. Limit values for flue gas components in greenhouse air at 20°, the associated Maximum concentrations in flue gases with two air factors (λ =1 and 1.6) and the amount in grams per giga joule (10^9 Joule). One giga joule equals approximately 31.6 m^3 natural gas.

	Limit values in greenhouse air		**Maximum acceptable concentration in flue gases in parts per million (ppm)**		
Flue gas component	Micro(10^{-6}) gram per m^3	Parts per billion (ppb)	Air factor λ=1 CO_2=11.7%	Air factor λ=1.6 CO_2=7.0%	Grams per giga joule
NO	313	250	46	29	15.0
NO_2	192	100	19	12	9.2
C_2H_4	9.3	8	1.4	0.9	0.44
NH_3 *	150	200	41	26	7.3
O_3 *	60	30	1.3	0.8	0.66

* May be released during flue gas purification, depending on the purification process

These undesirable flue gas components, also referred to as noxious gases, enter the greenhouse together with the dosing gases during the dosing process. The higher the CO_2 concentration, the more noxious gases will enter the greenhouse and the sooner limit values will be reached. It is obvious that if flue gases are cleaner, the likelihood of the limit value being exceeded at high dosing values will be smaller. With a correctly adjusted and maintained burner and a CO_2 concentration up to 1000-1200 ppm, the system will remain outside the problem zone. LOW NOX burners will be more reliable than a traditional burner and is, therefore, the recommended option.

Carbon dioxide (CO_2)

Although CO_2 is not noxious as such, very high concentrations can lead to problems caused by a lack of oxygen. To prevent this, work areas, including greenhouses, are subject to a Maximum Acceptable Concentration (MAC value) of 5000 ppm (9000 mg/m^3).

Carbon monoxide (CO)

Carbon monoxide (CO) is generated during incomplete combustion. This could be due to several causes:
- air excess or shortage;
- incorrect gas/air mixture;
- excessive burner control range;
- too much gas.

CO in combustion gases results in reduced efficiency, because substances that are still flammable have not been combusted. The gas is colourless and odourless and extremely toxic (lethal) for humans (carbon monoxide poisoning!). Therefore, CO_2 dosing must be stopped immediately in the event of incomplete combustion. CO sensors are available to detect CO. Depending on the location of the CO sensor in the flue gas flow, the alarm limit will be set at 30 (undiluted flue gases) or 15 (flue gases diluted with air). Above these values, dosing is stopped and the flue gas is exhausted via the chimney. The MAC value for CO in work areas during an 8-9 hour working day amounts to 25 ppm or 29 mg/m^3 air. If the CO detector is operating correctly, this concentration will never be reached. If the burner is operating correctly, the CO content in the flue gases will be well below the hazardous zone.

Ethylene (C_2H_4)

Ethylene (Ethene) is generated at the same time as carbon monoxide (CO) as a result of incomplete combustion. This gas is very toxic to plants. The maximum acceptable value in greenhouse air is: 0.008 ppm = 8 ppb (8 cm^3 op1000 m^3 air!). CO_2 dosing with flue gases containing ethylene has disastrous consequences. Direct detection of ethylene is still quite expensive. Even though there is no fixed ratio between CO and C_2H_4, C_2H_4 is usually detected indirectly with a CO sensor. This is because, when ethylene is generated due to incomplete combustion, CO will be generated at the same time and this is easy and relatively cheap to detect (see 3.6.2, Monitoring equipment for flue gases).

Damaged leaves of endive by NO_2

Nitrogen oxide (NO_x)

Air contains 78.1% nitrogen gas (N_2) and 20.9 % oxygen gas (O_2). High combustion temperatures generate nitrogen oxides, NO and NO_2, jointly referred to as NO_x.
The NO : NO_2 ratio can vary and rise to approx. 9 : 1. Lower combustion temperatures generate fewer NO_x emissions, but increase the chances of incomplete combustion and CO and C_2H_4 being produced.

NOx is damaging to crops and the environment (acid rain!) and therefore must be limited where possible. The government has issued regulations with respect to NO_x emissions that all gas burners have to comply with (see 3.6.2).
NO is subject to a MAC value of 25 ppm (=30mg/m^3) and NO_2 to a value of 2 ppm (= 4 mg/m^3)

Sensitivity limits
The plant sensitivity limits to noxious gases are indicated in Table 2.7.1. This does not imply that there will be no negative effects on production below the limits quoted in this table. Production losses of a few percentage points are not very noticeable and are difficult to prove. Nonetheless, they can run into tens of thousands of Guilders per ha, hence the need to minimise noxious gas emissions as much as possible.

Other flue gas components

Sulphur dioxide (SO_2), only with oil
Horticulture mainly uses gas burners. Usually, they are designed to operate with primary gas and light fuel oil in an emergency. Fuel oil contains impurities such as sulphur that generate sulphur dioxide (SO_2) following combustion. Flue gases that are polluted with these products must not be used for CO_2 dosing under any circumstances. When switching to oil, the valve to the CO_2 exhaust line in the boiler chimney must be closed and the CO_2 fan must be switched off.

Oxygen (O_2)
Air contains 20.9% volume of oxygen. Oxygen is needed for combustion and is supplied to the burner by the fan. Complete combustion requires approximately 8.4 m^3 air per m^3 natural gas. 1 m^3 cold air (of for example 10°C) contains more oxygen than 1 m^3 hot air (e.g. of 25°C). If the burner is adjusted very precisely during the winter it will lack oxygen in summer, resulting in incomplete combustion. To ensure a sufficient oxygen supply during the summer, the gas burner must not be set to a CO_2 percentage of 11% (air factor less than 1.1) during the winter.

Water vapour (H_2O)
With complete combustion, approximately 1400 g water vapour is produced per m^3 natural gas. Downstream of the flue gas condenser, this drops to approx. 350 g. At a dosing value of 50 m^3 per ha per hour, 17,500 g (50x350) vapour is released into the greenhouse air. A greenhouse with an average height of 5 m contains 50,000 m^3 air per ha. For each m^3 greenhouse air, 0.35 grams (17,500/50,000) of water vapour is then added per hour. In practice, this is even less because of the condensation in ducts and dosing hoses. Greenhouse air at 20°C with a relative humidity of 80% contains 11.9 g water vapour per m^3. That is more than a thirty-fold increase. A mature tomato crop evaporates between 100 and 500 g per m^2 during the day in April. In a 5 m high greenhouse, this corresponds to 20 to 100 g per m^3 greenhouse air. Earlier in the season, evaporation rates are lower but they can nearly double in the summer. The rate of evaporation is the same in other mature vegetable and florist crops. The crop introduces many times more vapour into the air than CO_2 dosing. Therefore, CO_2 dosing has hardly any effect on humidity. Occasionally, localised differences may be observed.
For example, if a plant located a few centimetres from a dosing perforation is treated directly with warm moist dosing gas, condensation may occur on the crop in that particular location.

Flue gas purification

Introduction
Flue gases from natural gas produced by a correctly adjusted and maintained boiler can be used for CO_2 dosing without further processing. This is not possible with flue gases from a Heat/Power system. Exhaust gases from the H/P gas motor contain many more toxic substances than the flue gases from a boiler. This is because the combustion process is totally different. H/P flue gases need to be purified in order to meet standards set for safe dosing.

Flue gas requirements
Section 2.7 includes the standards for acceptable concentrations of noxious gases in crop greenhouses, "the sensitivity limits". These standards have been converted to acceptable concentrations in flue gases used for CO_2 dosing. The calculations take into account the following:

- CO_2 set point in the greenhouse (ppm)
- a ventilation rate of 0.5 times the greenhouse volume per hour
- damage thresholds
- photosynthesis on a winter's day
- poor mixture gas motor ($\lambda = 1.55$) or rich mixture motor ($\lambda = 1$)

These calculations are based on winter conditions, when the crops are most sensitive. The results of the calculations are shown in table 11. If the flue gases from gas motors are to be used safely for CO_2 fertilisation up to a level of 800 ppm CO_2 in the greenhouse, the flue gases must not exceed the stated concentrations.
The following must be borne in mind when using these values: the damage thresholds apply to each individual component. This means that the maximum acceptable concentration of NO ($15\ g.GJ^{-1}$) and NO_2 ($9.2\ g.GJ^{-1}$) must not be added together to get $24.2\ g.GJ^{-1}$ NO_x. These concentrations must be applied as individual values.

Emissions from H/P gas motors

Requirements
NO_x emissions from gas motors are subject to specific requirements in the Netherlands. Since January 1994, the legal requirement for new gas motor systems is 140 g/GJ x r/30 where r is the electrical output of the gas motor. Therefore, higher NO_x emissions per GJ are acceptable with a higher output. Since 1987, a limit value of 800 g/GJ x r/30 has applied to older motors, and since 1st August 1990 270 g/GJ x r/30 (Table 12d).

Market availability
Various brands and types of poor mixture motors (air factor $\lambda = 1.55$ or above) that meet the 140 g/GJ x r/30 NO_x emission requirement are now available on the market. Some manufacturers guarantee 100 g/GJ or even 70 g/GJ, but that is still three to four times too high for direct CO_2 dosing. Some motors have achieved even lower values. However, this is at the expense of a large proportion of the electrical output and with considerably higher concentrations of other hazardous substances, such as carbon monoxide (CO), ethylene (C_2H_4) and other non-combusted hydrocarbons (CxHy).
This leads to the conclusion that the gases from gas motors first need to be purified in order to be used as CO_2 fertiliser in greenhouse horticulture.

Flue gas purification systems

Although there are dozens of flue gas purification processes and methods, only a few qualify for use in greenhouse horticulture . The following is a brief description of systems suitable for horticultural applications.

SCR + oxidation catalytic converter (ureum catalytic converter)

Until 1998, only one system was used for practical applications: ureum injection with a selective catalytic converter reduction (SCR) catalytic converter followed by an oxidation catalytic converter. In the meantime, dozens of companies have acquired experience in using this system. It works as follows: an ureum solution is injected into the hot flue gases causing the ureum to split into NH_3 (ammonia) and CO_2. In the SCR section, selective catalyst reduction generates a reaction between NH_3 and NO_x , producing water vapour (H_2O) and harmless nitrogen gas (N_2). Finally, carbon monoxide (CO) and ethylene (C_2H_4) are converted into CO_2 and H_2O in the oxidation section.

Several systems are based on this principle. The difference lies in the design and the catalytic converter. As there is still insufficient experience of practical use of some systems, it is too soon to indicate the advantages and/or disadvantages of particular systems. One thing is clear, the purity of the purified flue gases is considerably higher in all systems than in boiler flue gases. No quantitative data is available (as yet) on the possible favourable effects on crops.

Three-way catalytic converters

In three-way catalytic converters, which are often used in cars as well, three hazardous components, i.e. NO_x, CO and C_xH_x (non-combusted hydrocarbons, including ethylene) are converted into N_2, CO_2 and H_20. This system is suitable for stoichiometric motors with an air factor λ of 1 (11.7 % CO_2), in other words, no air surplus. The system is very sensitive and needs to be adjusted within very narrow limits (air/gas ratio), as otherwise certain components are inadequately converted and air pollution may still occur. The advantage of a ureum catalytic converter is that no other agents need to be added. Three-way catalytic converters are also much more compact than ureum catalytic converters.
GASTEC has developed a system with flue gas recirculation based on this principle, so that the system can also be used for poor mixture motors (air factor λ 1.55). Measurements taken at test sites have shown that the purified flue gases comply with the set quality requirements. On gas motors where very little or no air surplus is used (usually older motors), flue gas purification can be achieved with a ureum system by adding extra air or using a three-way catalytic converter. A three-way catalytic converter can also be used on motors with a low air surplus by replacing the air surplus with recirculated flue gases. This type of system has been used for demonstration purposes by a grower since 1996. These flue gases also have a CO_2 content of 11.7 vol.-%.

Membrane gas absorption

The TNO Institute of Environmental Science in Apeldoorn has developed a new system that allows pure CO_2 to be produced from flue gases. The system was still being tested at the time this brochure was written. The membrane gas absorption system will enable power stations and factories to supply pure CO_2 as by-product. The system is also suitable for H/P systems used in greenhouse horticulture. According to TNO, the system will be able to supply pure CO_2 for greenhouse horticulture at an attractive price.

Bacteriological purification

Paques (Balk, Fr.) is cooperating with Hoogovens, NUOM, Gasunie, Zantingh and the Van Hall Institute (Leeuwarden) on the development of a biological purifier for flue gases. The biological purification process uses bacteria. The process operates at a temperature of 50°C. Again the system is in two stages. The first stage removes the non-combusted hydrocarbons (oxidation stage), the second stage removes the NOx. The second stage uses special bacterial strains to remove the NOx gases biologically. This represents an alternative to ureum injection. The second stage is currently being tested by two horticultural businesses in Friesland. A test project for the first (oxidation) stage using biological processes was planned for 1998.

Monitoring equipment for flue gases

The dosing of purified flue gases in the greenhouse requires the use of analysis equipment. Various devices are available to measure CO (in use for some time), NO_x and C_2H_4. Two measurement systems are currently (October 1998) available to measure very low quantities of ethylene.

1) A system based on a gas chromatograph, the 'COditheen', is a C_2H_4 (Ethene) analyser from Hanwel in Hengelo).
2) A system based on chemoluminicence, the Ethylene-NOx analyser, developed by Gastec (Apeldoorn) and marketed by Envico in Zoeterwoude. This system measures both C_2H_4 and NOx.

Crop damage insurance

If the flue gas purification system is not operating correctly and insufficient protection measures have been installed, the crop may be damaged by flue gases with an excessively high ethylene content. It is important to clarify in advance who is responsible for any damage. The associated risk is usually entirely the grower's responsibility in systems managed by the grower and utility company systems. The grower will be responsible for checking that the purified flue gases comply with the required specification and that the analysis equipment is operating correctly. Insurance cover can be obtained for damage caused by a faulty flue gas purification system. The premium will be discounted if a monitoring device is used.

Legal emissions requirements

Introduction

In order to limit the emission of toxic substances from boilers, gas turbines, gas turbine installations and piston engines, two decrees were included in the Environmental Protection Act in the Netherlands. Up until 1st March 1993, these were incorporated in the Air Pollution Act and the Nuisance Act. The Environmental protection decree on emission requirements for heating systems A (BEES A) and, likewise, BEES B were changed on 23rd April 1998. BEES A applies to power stations, the chemical industry and refineries. The other categories, including greenhouse horticulture, are covered by BEES B. Boilers with a thermal output of 900 kW or more as the lower value are covered by BEES B. Boilers up to 900 kW are covered by the Heating Appliance Act. Gas motors, including those used in heat/power systems are always covered by BEES B. The responsibility for implementation lies with the local authority, the executive task with an environmental service or official.

Changes in requirements

To achieve the policy objectives with respect to reducing emissions of nitrogen oxides (NOx) and sulphur dioxide (SO_2) from heating systems, the Ministry for Housing, Regional Development and the Environment (VROM) will update BEES A and B in line with developments in technology as far as possible. The changes to BEES dated 23rd April 1998 are mainly related to reducing NOx emissions. BEES B now also applies to systems between 900 kW and 2.5 MW. The requirements for this category of boilers apply from 1st January 1999. Where the same areas are controlled in BEES B as in BEES A, the emission requirements will be the same.

Local implications of the requirements

The Environmental Protection Act states that the authorised body is entitled to include more stringent measures in the licence than those prescribed by BEES. The 'band width' is applied to set more stringent requirements. More detailed requirements can only be imposed if this is required by local conditions.

New requirements

These should not pose a problem for boilers in horticulture. However, burners with a NOx emission requirement of 60 mg/m^3 are more expensive than those with a requirement of 100 mg/m^3. It is possible to convert existing burners. In this case, the >old= burner head is replaced by a new type that combines complete combustion with a lower average flame temperature halving NO_x emissions.

Mandatory measurements

Emission measurements are mandatory not only for new heating systems, but also for existing heating systems, which are subject to emission requirements in accordance with the above decrees. Before the emission requirement comes into force the system needs to be checked to verify whether the system needs to be modified to meet the requirement.
The method of measuring emissions is defined in the 'Measurement method regulations for heating system emission requirements', Environmental Protection Act B'.

Boiler systems

The concentration of nitrogen oxides in the exhaust gases of a boiler system must be defined using individual or continuous measurement. Individual measurements must be carried out at the latest twelve months after the emission requirement on the heating system came into force.

Piston motors (including natural gas motors)

In the case of piston motors, the NOx emissions must be defined using an individual measurement.
In the case of gas turbines, gas turbine systems and piston motors, the individual measurement must initially be carried out twelve months at the latest after the emission requirement came into force and must be repeated every three years thereafter.

Measurement methods

The 'Measurement method regulations for emission requirements on heating systems B' includes specific instructions for individual measurements on how to comply with mandatory measurement requirements in BEES.

Product inspections

Measurements on new and existing systems can be avoided if the product has been awarded an inspection certificate. Until recently, GASTEC NV awarded the 'Gas Inspection Cleaner Combustion' certificate to burners up to 660 kW, larger burners only received the 'Gas Inspection' certificate. Following changes in the use of inspection certificates for larger burners, particularly as a result of European certification with the CE mark, the name of the emission inspection certificate has been changed to GASTEC QA Low NO_x.

For further information on GASTEC QA product inspection contact the Certification Department of GASTEC NV (Centre for Gas Technology) in Apeldoorn, telephone 055 - 5393393.

Individual measurements

If individual measurements are required for a licence or acceptance test, the measurements can be carried out by GASTEC NV. In this case, contact the Meetdienst Zakelijke Markt (Business Measurement Department), telephone 055-5393573

Current requirements

The following tables 12a, b, c and d are a summary of the emission requirements from 23rd April 1998.

Table 12a Emission requirements for systems that received a licence on or after 23rd April 1998 or systems including a burner that was replaced on or after this date.

Heating system	Requirement	Note
New gas turbine	65 g/GJ	Can be tightened to 45 g/GJ. No output factor
New gas fired boilers	70 mg/m^3	
Oil fired boilers and furnaces	120 mg/m^3	
Gas fired boilers up to 10 MW with burner replacement	70 mg/m^3	

Tabel 12b NO_x emission requirements for a natural gas fired boiler system < 7.5 MW, in which water or steam is heated at a pressure < 1 Mpa, without air preheating.

	NO_x emission requirement (at 3% O_2)	Mandatory measurements
Systems with licence between 1-8-90 and 15-10-92	175 mg/ m^3	Individual measurement within 12 months of date of licence.*
Systems with licence on or after 15-10-92	100 mg/ m^3	Individual measurement within 4 weeks of date of licence.*
* If the burner is installed with inspection certificate, no individual measurement is required.		

Table 12c NOx emission requirements for other natural gas fired boiler systems, where the burner was not replaced.

	NO_x emission requirement (at 3% O_2)	Mandatory measurements
Systems with licence between 1/8/90 and 15/10/92	200 mg/ m^3	Individual measurement within 12 months of date of licence.
Systems with licence on or after 15-10-92	100 mg/ m^3	Individual measurement within 4 weeks of date of licence.

Tabel 12d NO_x emission requirements for piston motors with power > 50 kW.

Gas motors	NO_x emission requirement	Mandatory measurements
Licence awarded before 29/5/87	500 g/GJ from 1/1/2000.	
Licence awarded between 29/5/87 and 1/8/90 covered by BEES B	800 g/GJ * output/30 from 1/1/2000	
Licence awarded between 1/8/90 and 1/1/94	270 g/GJ x 1/30 of the motor output	Individual measurement within 12 months of date of licence.**
Licence awarded on or after 1/1/94	140 g/GJ x 1/30 of the motor output	Individual measurement within 12 months of date of licence.**
Diesel motors	400 g/GJ x 1/30 of the motor output	Individual measurement within 12 months of date of licence.**
** Individual measurement must be repeated every 3 years.		

4. CO_2 MEASUREMENT AND CONTROL

4.1 CO_2 MEASUREMENT AND MAINTENANCE METER

Different types of CO_2 meters are used to measure and control the CO_2 concentration in the greenhouse. Most types have a range between 0 and 3000 ppm, are based on the same principle and have the same overall limitations with respect to accuracy.

CO_2 concentration measurement
Reliability of the CO_2 measurement is very important. This is defined by the accuracy and readability of the meter. CO_2 meters in use at the moment are up to 1% accurate. This means a deviation of 30 ppm on a scale of 3000 ppm.
In practice, meter deviations are often higher up to more than 100 ppm. If the meter measures too high, the dosage is too low and this affects production. If the meter indicates a lower concentration than the actual concentration, dosing activates too often. This is expensive, particularly if the heat produced cannot be utilised.
During the summer, there is little heat demand and the vents are open. At this time of the year, the purpose of monitoring is to prevent the CO_2 concentration from becoming too low. Usually, the concentration is around the outside value. At 350 ppm, a 1% inaccuracy will have major consequences. With full sun (700 W/m^2), a concentration difference of 30 ppm represents a difference in photosynthesis of 4 to 5%. In fact, meters currently in use are not suitable for control during the summer. This must be taken into account. First of all, the deviation must be limited as much as possible by calibrating regularly using the correct calibration gas.

CO_2 measuring point in the greenhouse

Secondly, the CO_2 unit must run regularly between 10.00 and 16.00 on sunny days, even continuously if this fits in with the heat demand. In the summer, it is better to set a required flow rather than dosing on the basis of greenhouse concentration. Sections 4.3 to 4.5 describe this subject in further detail.

In the winter, the system monitors for CO_2 concentrations that are too high. A small measurement deviation is not a problem. Whether dosing is stopped at 800 or 850 ppm does not affect the plants. Nor is cost an issue, as more than sufficient flue gases are produced by the heating.

Position of the meter and sampling points

Two aspects are important for CO_2 measurement: the actual meter and the sampling point. The CO_2 meter can be suspended in various locations, providing the sampling points are suspended correctly in relation to the meter. The meter must not be positioned in the sun, but in a well ventilated area with a constant temperature.

CO_2 must be measured in each compartment, as compartments are controlled individually. One sampling point per compartment is sufficient.

The choice of sampling position is important as there are always concentration differences in a compartment. The sampling point should be located between the crops in the centre of the compartment. Most of the photosynthesis occurs at the top of the crop. With tall vegetable crops, the best location for the sampling point is at the top of the crop: approximately one third of the crop height below the top of the plant. With many florist crops, a similar height or just above the top leaf is the best position. The sampling point must be at least one metre from the hoses, to prevent air from being drawn in directly from the hoses.

For effective control, the sampling time must not exceed three minutes. With closed vents and a dosing speed of 100 m3 natural gas per ha per hour, the concentration in the greenhouse will rise by approximately 100 ppm during that time. If the sampling time is longer, this problem can be solved by fitting an extra pump in the suction line or by suspending the CO_2 meter closer to the sampling point. Reducing the suction line, so that the sampling point is nearer to the boiler housing, is not an advisable solution. Practical measurements have shown that the CO_2 concentration often exceeds the compartment average in this area. If measurements were taken in this area, the CO_2 unit would activate rarely resulting in a negative impact on production.

Other important points

Horizontal and vertical differences in CO_2 concentration in the greenhouse must be prevented where possible. High humidity in the air supply can affect measurements. This can also cause condensation in the meter. To prevent condensation in the suction line, it must not run past cold structural parts. Condensate from the suction line is collected in the steam trap. If crop protection agents are used, the supply of air drawn in from the greenhouse must temporarily be interrupted, as this would pollute the dust filter. If sulphur evaporators are used during the night, it is advisable to stop CO_2 measurements for the same reason. CO_2 should not be dosed when it is dark anyway.

Several measuring points

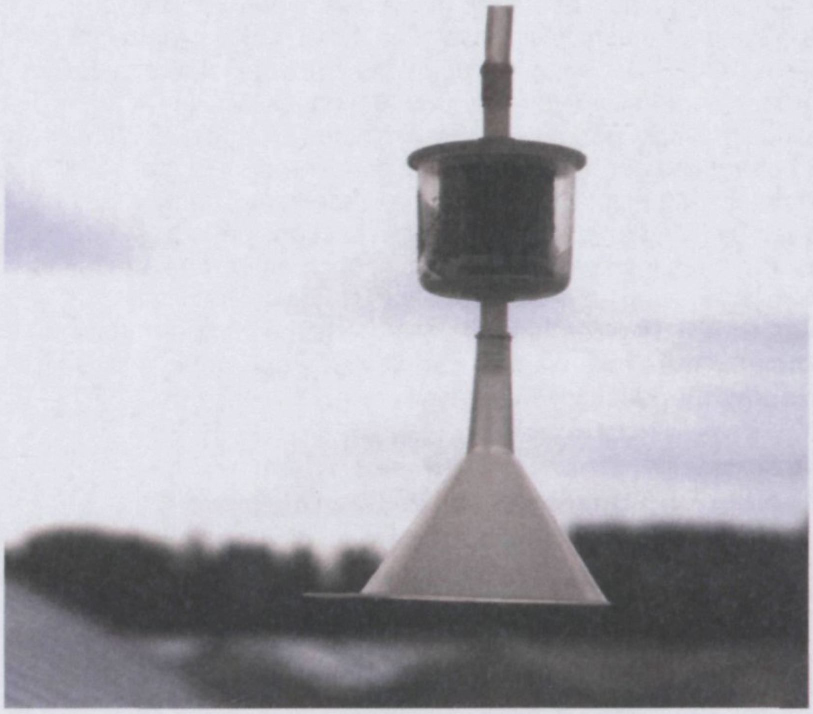
One CO_2 meter can be used to take measurements in several compartments. Multiplexers, or converters, used for this purpose are available on the market. They are fitted with valves that switch between sampling points. The simple types have two-way valves. Once switched over, fresh air needs to be drawn in before measurements are taken. With four or more measuring points the cycle time becomes too long. For example, if each measurement takes three minutes each compartment is measured only once every twelve minutes. Consequently, the dosing is switched on or off once every twelve minutes. Ten minutes between measurements in the compartment is just about acceptable, but the maximum interval for optimum control is four minutes.

If more than three compartments are linked to one meter, it is advisable to use a multiplexer with three-way valves. It has an extra pump, which continually draws in air from all compartments. Once switched over, measurements can be taken immediately.

Again a maximum number of compartments for each multiplexer applies, i.e. as many as can be measured within four minutes.

Outside air measurement

Outside air is often included as an additional measurement. Sometimes, the outside value may explain a deviating CO_2 concentration in the greenhouse. It can also be used to roughly estimate CO_2 loss. This depends on the concentration difference between inside and outside and the ventilation in the greenhouse. The outside air must be measured in a suitable location, i.e. on the measuring tower at least three metres above the ridge of the greenhouse. The measuring tower must stand at a distance of at least 10 bays (32 m) from the outer wall of the greenhouse and away from the shed and boiler house. Water must not be drawn into the line when it rains. This can be prevented by installing a cover made from a funnel or similar item.

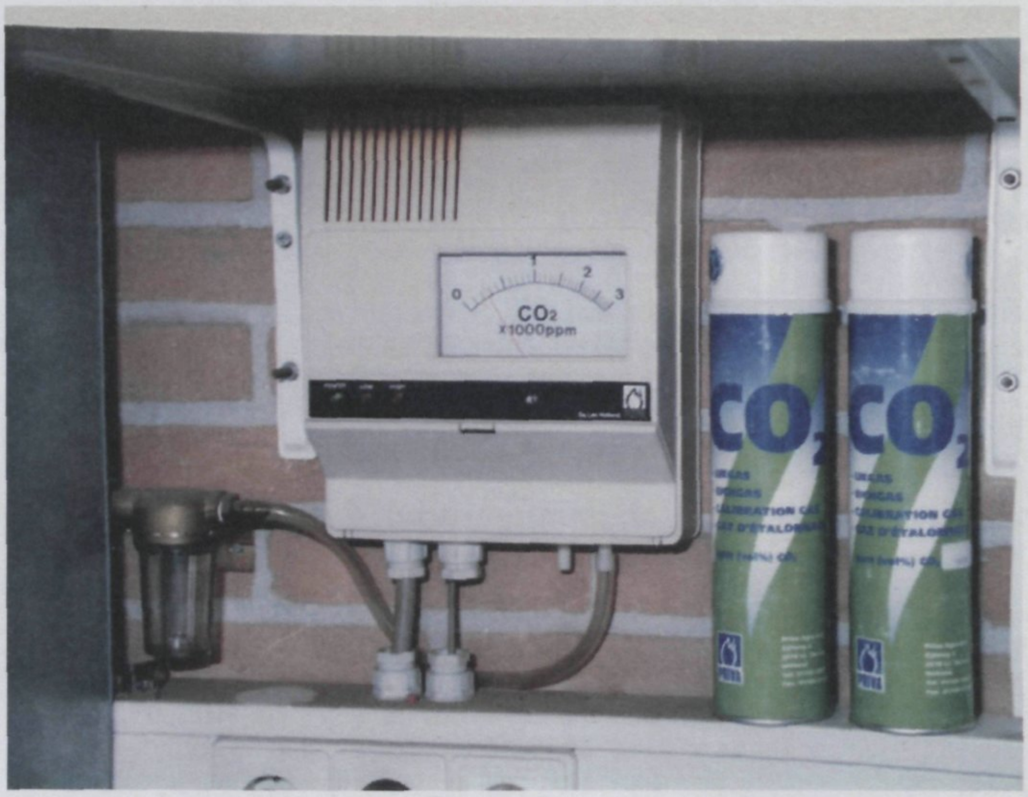


Measuring of the CO_2 concentration in the outside air

Meter calibration and maintenance

The meter must be calibrated once every three months. One calibration must be at the start of the summer and one halfway through the summer using the summer concentration. The calibration procedure for the equipment must be followed. Zero calibration is carried out first using a CO_2 free gas (zero gas) or a zero cartridge (container with carbonated lime that absorbs all CO_2 from the air). This is followed by pressure calibration using a gas concentration relevant to the control. This is 1000 ppm in the winter and 350 to 400 ppm in the summer. Outside air is definitely not suitable for use as calibration gas. To illustrate this figure 4.1.1 shows how the outside concentration changes on a day picked at random. Calibration is improved if the calibration gas is continually drawn in during calibration rather than just filling the measuring chamber with calibration gas. The calibration may deviate under the influence of air pressure and temperature.

The gas is adjusted as standard to a pressure of 1013 mbar and a temperature of 20°C. The deviation amounts to -1% for every three degrees increase in temperature and +1% for every percentage point increase in pressure. If there are extremes on the barometer of 940 or 1050 mbar pressure, the measurement will deviate up to -7 and +4% respectively. This should be taken into account during calibration. Carry out calibration at a pressure of approx. 1013 mbar where possible. When calibrating, check that both the meter and the climate computer indicate the correct values . After all, this data is used for control purposes. When the mains supply is switched off, the indicator must point to zero. If not, the indicator position must be corrected. Use the set screw on the measuring scale to do so. The set screw should only be adjusted when the meter is switched off.



CO_2 meter with calibration gas cartridges

Regularly check and empty the steam trap, if necessary. The filter at the sampling point in the greenhouse must be cleaned or replaced at least once every six months. To clean the filter immerse it in paraffin for a while, rinse it and blow air through it. The entire measuring system must be checked at least once a year. The dust filter in the meter must be replaced and the suction line checked for leakage. To do so, connect a zero cartridge at the sampling point. After a while, the measurement must drop towards 0 ppm. If not, connect the zero cartridge directly to the meter. If the measurement on the meter does move towards zero, the suction line is leaking. Replace the suction line. If the meter does not move towards zero, it needs to be readjusted and a new zero measurement from the sampling point must be carried out.

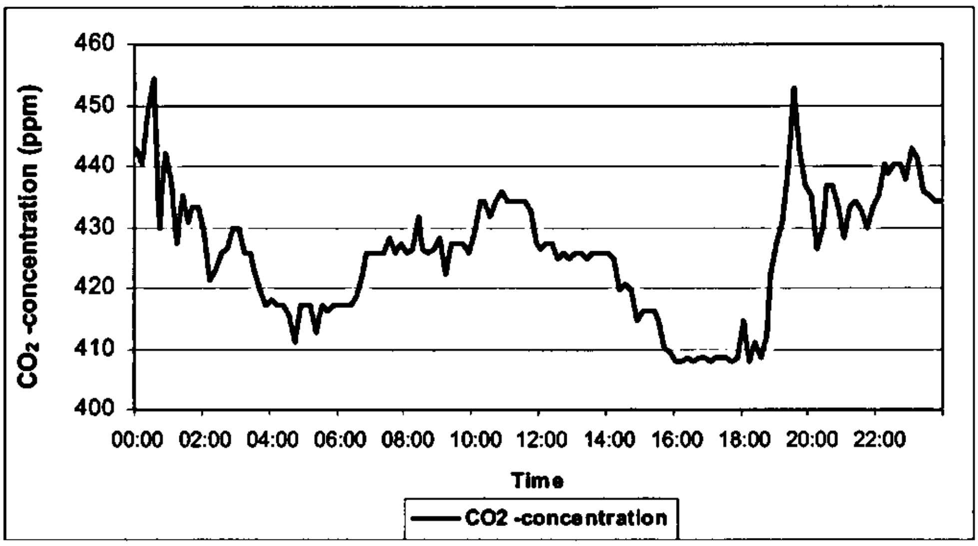


Figure 9 Progress of CO_2 outside value on 25th March 1997, measured at PBG in Naaldwijk

Logging

As mentioned above, CO_2 meters currently in use are not accurate enough for correct dosing during the summer. Improvements will have to be made to these meters in the future. Comparing actual CO_2 contents with those of colleagues does not make sense as long as the measurement is inaccurate.

4.2 HORIZONTAL AND VERTICAL CO_2 DISTRIBUTION

It is important to make maximum use of the available CO_2. Distribution is an important aspect in this process. To ensure successful horizontal distribution the fan, main line and perforation distance on the hoses must be coordinated. This needs to be calculated by an expert. If successful, the pressure in the hoses will be the same in all hoses. Practical measurements on site showed that the pressure distribution in the hoses deviates by more than 20% in many businesses. Both the horizontal and the vertical distribution need to be correct. Research at the test station and practical applications have shown that the height at which the CO_2 hoses are positioned has an impact on the successful use of CO_2.

Photosynthesis varies in the vertical plane

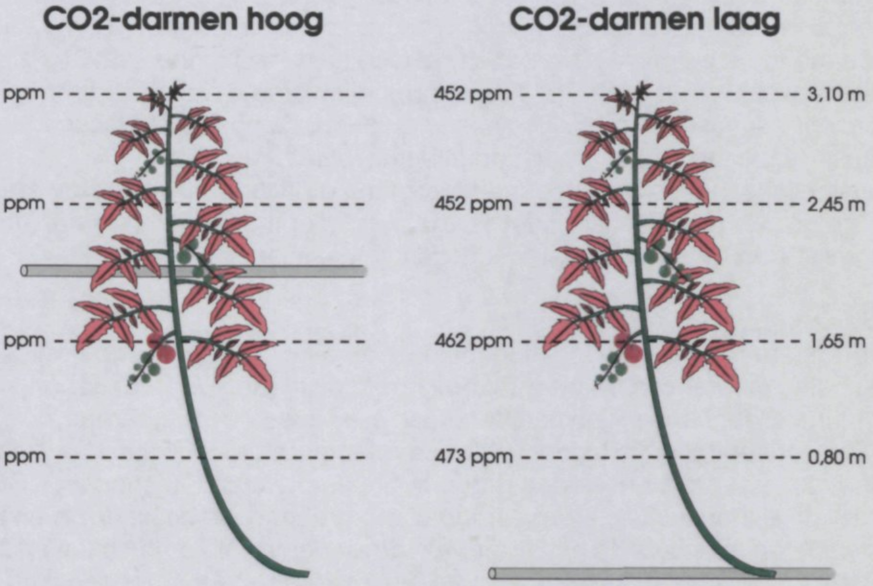
Most of the photosynthesis takes place in the upper section of the crop. This is where most of the sunlight is absorbed by the leaf. An increase in CO_2 concentration here will be the most profitable option.

Measurements have shown that, during dosing, the CO_2 concentration around a freely suspended dosing hose is 20 to 25 ppm higher than the average concentration in the greenhouse. If the hoses are suspended where the greatest amount of photosynthesis takes place, higher yields will be obtained with the same CO_2 dose. Model calculations have shown that, if the hoses are suspended at the most favourable location in relation to the hoses on the ground, approximately 1.5% extra photosynthesis occurs in a healthy crop during the summer. During the spring and autumn the figure is 1%.

CO_2 flows out of the hoses at a concentration of 5 to 10%. This concentration drops very rapidly. Contrary to popular belief, the CO_2 does not all drop to the ground. The CO_2 gas from the hoses seeks to achieve an even distribution in the air and this has more impact than the fact that CO_2 is heavier than air. Figure 10 clearly shows that the concentration is the same above and below the hoses.

Figure 10 Vertical CO_2 distrubution if hoses are on the ground or between the crops

Translation: CO2 darmen hoog = CO2 hoses positioned high
CO2 darmen laag = CO2 hoses positioned low



Measuring CO_2 pressure in the hoses

Height depends on crop

The ideal height for the dosing hoses depends on the crop density. For example, peppers are a dense crop. The leaf index (number of m^2 of leaf per m^2 soil) can easily reach 6 to 7. Light interception, and consequently photosynthesis, hardly increases at all with a leaf index above 3 The top of a dense crop intercepts the most light. With peppers, the hoses are best suspended 0.5 m below the top. The same applies to aubergines and cucumbers, which are also dense crops. Tomato is an open crop. The number of m^2 of leaf per m^2 soil fluctuates around 2 during the summer. This means that CO_2 is utilised to the same extent everywhere between the leaves. In this case, the hoses can be lowered to 75 cm below the top. The outflow concentration is very high. The hoses must not be positioned close to the top of the plant because of the risk of the growth point being 'burnt'.

In many businesses, hoses are suspended from the growth tube when they are lifted off the ground. If the growth tube is suspended at the bottom of the crop, this is not ideal for photosynthesis. Part of the potential production gain is lost.

Horizontal CO_2 displacement

The dosing system pressure distribution must be as even as possible to prevent major horizontal dosing differences. Even with the correct distribution concentration, differences can occur in the greenhouse. These differences are caused by temperature differences or the wind. The concentration is highest where the temperature is highest and vice versa. This is due to the fact that hot air rises and draws in the ambient air enriched with CO_2 from the bottom of the greenhouse. The air at the top of the greenhouse cools down and loses CO_2 through exchanges with outside air, and drops down again with a much lower CO_2 concentration. Occasionally, the temperature differences between hot and cold areas may reach 2°C or more resulting in concentration differences of up to 100 ppm. This effect occurs near the hoses in between the crop and on the ground, but it is stronger near the hoses on the ground.

Wind has a major impact on air flows and temperature differences. Wind creates pressure differences in the greenhouse, causing the air to circulate in the same direction as the wind at the top and in the opposite direction to the wind at the bottom of the greenhouse. This air flow at the bottom of the greenhouse has a high CO_2 concentration. This is why the CO_2 concentration is highest near the outer wall on the wind side. At the opposite outer wall the air drops from the top to the bottom of the greenhouse. This has a low concentration after exchanges with outside air. The effect increases as the wind speed increases. Because of air flows, dosing on the ground usually results in concentration differences twice the size of those when dosing between the crop.

One or two hoses

If hoses are on the ground, it makes no difference for distribution whether one or two hoses are used per roof (3.20 m). There is always an air flow on the ground, therefore CO_2 mixes rapidly especially in the case of open crops such as tomatoes. This is less so with dense crops such as peppers, but there is also no difference between one or two hoses per 3.20 m in the upper part of the crop. However, it may be necessary to lay two hoses on the ground per 3.20 m to achieve large dosing capacities. This provides a better pressure distribution than attempting to dose large amounts with few hoses.

The idea, often quoted, that CO_2 always has to pass the plants before escaping through the vents when dosing hoses are on the ground, is incorrect. As the CO_2 can easily move in a horizontal direction, part will rise via the path and part with the air flow towards the outer walls. This reduces the amount of CO_2 eventually reaching the leaves and does not promote even distribution in the greenhouse.

Horizontal displacement is much smaller if hoses are suspended between the crops. The leaves create resistance. Tests showed a concentration difference of 30 ppm measured between a row with a suspended hose and a row without hose. Successful distribution requires two hoses per 3.20 m roof.

Problems

It makes sense to suspend the hoses between the crops, but there are some problems associated with this method. It is advisable not to hang the hoses too high to begin with, because they intercept the light. If the hoses are suspended above the crop they will intercept 1 to 1.5% of the light. The interception of light is much smaller with hoses positioned among the crops (" 0.3%). This means that the hoses need to be lifted during cultivation, so they need a flexible connection to the main line.

The problem is different with high wire crops caused by lowering of the plants. Leaves and fruits can easily hang down across the hoses. Hoses can get kinks in them or they could even become detached from the suspension hooks. It is important to check this. When laying the line and hoses also check where the plants are growing. High hoses may present an obstruction. This can be solved by routing the lines differently or having the CO_2 main line in a low position and then raising it via an S-bend pipe. The plants can then run behind the bend.

Botrytis

Some tomato growers seem to think that raising the hoses causes botrytis. Botrytis is a weakness parasite. Infection starts as small blemishes. Spores germinate easily with high humidity. The flue gases emanating from the hoses are saturated with moisture and mix with the surrounding air very rapidly. Measurements have shown that the high humidity can no longer be detected 20 cm from the outflow opening. An increase in botrytis attacks is possible if the hoses are suspended from the growth tube where the leaves are picked and also if the hoses are suspended close to the stems. There is a risk of the hot, moist air condensing on the stems next to the perforations on the side the hoses. If the hoses are suspended at some distance from the stems, with the perforations pointing downwards, the condensate will end up between the crops. In this case, problems with dosing related botrytis are unlikely.

Hose type

Condensation in the dosing system, due to the fact that the flue gases are saturated with water vapour, can be a major problem. If the temperature of the flue gases in the dosing system drops from 40 to 30°C for example, 20 g condensate will be created per m3 of flue gas. With a dose of 25 m3 natural gas per ha per hour approximately 350 m3 flue gas will pass through the system. This includes 7 kg condensate. If the water is not discharged properly the system will get blocked. If the dosing hoses are suspended between the crops, water can easily accumulate in a bend between two suspension hooks. The weight will cause the hose to bend even more and it stays full of water. This problem can be solved by ensuring that the coiled hoses are tensioned correctly and the perforations are underneath. In fact, this can only be achieved with hoses specifically designed to be suspended. This type of hose is more rigid and therefore stays taut and, when suspended from a flap, the dosing perforations will automatically point downwards. Research has shown that the hoses remain taut if they are tensioned and tied to a chain on the growth tube, or a stand, at the end. It is definitely not advisable to use, and perforate, standard hoses for the water to flow out. In this case, the required pressure distribution will not be attained. This is foolish economy.

4.3 CO_2 DOSING WITH THE VENTS OPEN

There is a constant supply and discharge of CO_2 in the greenhouse. It flows into the greenhouse via the hoses. It simultaneously enters the plants via the stomata and escapes outside via the vents. The concentration around the leaves is particularly important as it determines the absorption by the leaves and therefore the amount of photosynthesis. The higher the concentration around the plant, the more the plant can absorb and the higher the increase in photosynthesis. If the CO_2 concentration drops during the day photosynthesis will also reduce, the plant is 'hungry' because the CO_2 supply is insufficient. Concentrations below the outside value have an adverse effect on production.

Photosynthesis increases as the light intensity increases. This is why the plant uses more CO_2 on sunny days than on overcast days. On sunny days, the vents are open because the greenhouse heats up due to high radiation. The rate of ventilation also increases as a result. If the CO_2 concentration in the greenhouse is the same as the outside concentration, no CO_2 is lost when the vents are opened. If the greenhouse concentration is below the outside concentration, CO_2 is supplied from outside. If the CO_2 concentration in the greenhouse exceeds the outside concentration, CO_2 will escape when the vents are opened. This is referred to as ventilation loss. The figures 11 and 12 illustrate the correlation between venting and ventilation loss.

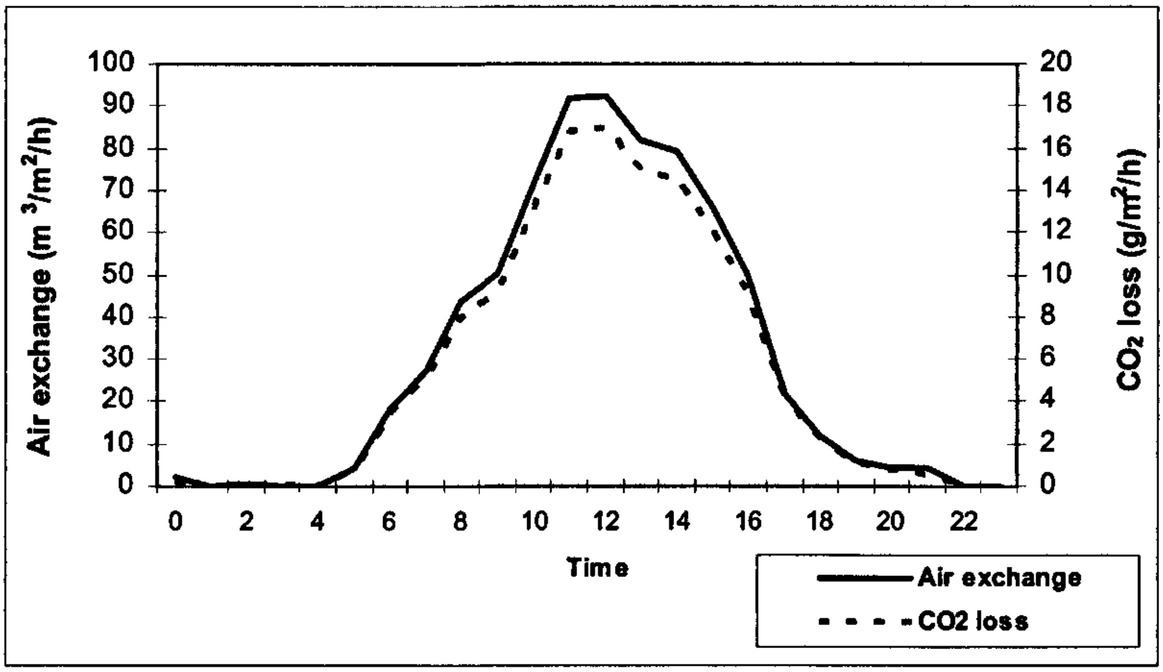


Figure 11 CO_2 loss and air exhange on a sunny day

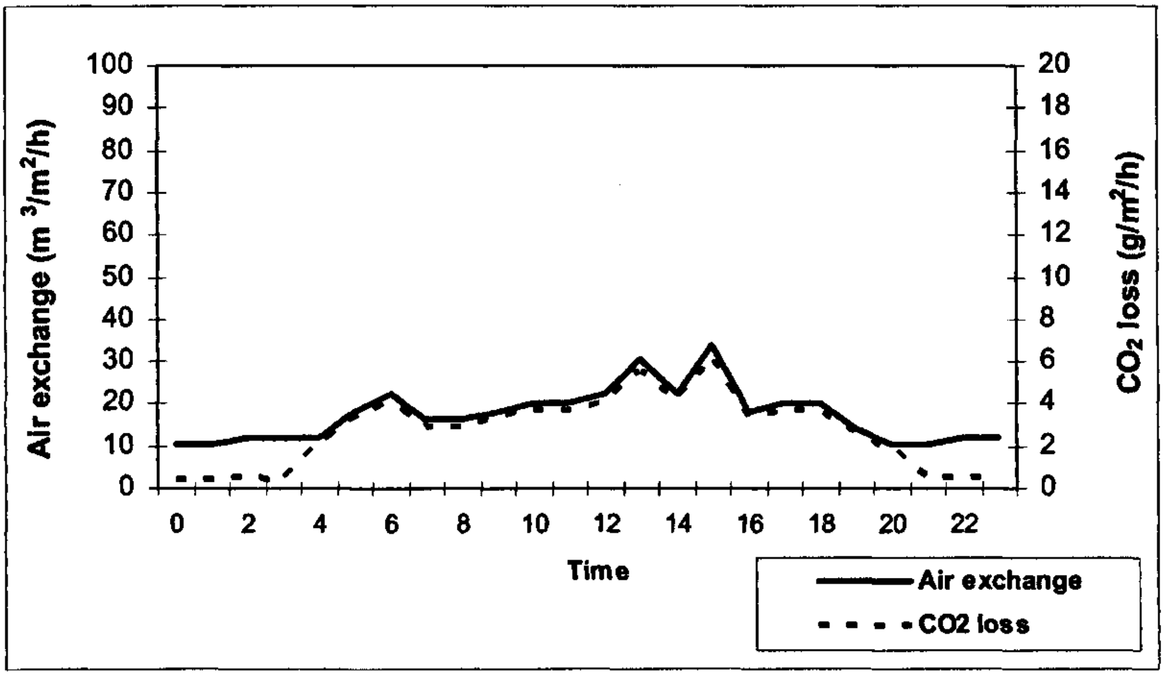


Figure 12 CO_2 loss and air exhange on an overcast day

Ventilation loss

The CO_2 loss from ventilation is proportional to the difference in concentration between greenhouse and outside air. This implies that if the concentration difference doubles, the ventilation loss also increases twofold.

The above is illustrated by the following example. Assume that the outside air contains 350 ppm CO_2 and a 4 m high greenhouse 400 ppm. The difference is 50 ppm. A ventilation rate of 50 generates a ventilation loss of 18 g/ m^2/hr. A ventilation rate of 50 is a realistic value, with an average wind speed and the vents on the lee side fully open. An increase in greenhouse concentration from 400 to 450 ppm increases the difference with the outside air by 100 ppm. The ventilation loss is now 36 g/ m^2/hr.

How much CO_2 should be dosed?

The amount of CO_2 that needs to be dosed is equal to the CO_2 ventilation loss plus the CO_2 absorption by the crop. Crop absorption is also defined by radiation and cannot be calculated without using a computer. Experiments have demonstrated that, with a CO_2 concentration of 450 ppm and 400 W/m^2 radiation, a fully grown fruit vegetable crop has a CO_2 absorption of approximately 4 g/m^2/h and 6 g/ m^2/h at 800 W/ m^2. Table 13 indicates the CO_2 absorption of cucumbers. In woody ornamental crops, the photosynthesis is usually slightly lower.

On sunny days with the vents wide open, the ventilation loss is so great that CO_2 absorption by the plant does need not be calculated accurately to decimal places when defining the amount of CO_2.

Table 13. CO_2 absorption in a fully grown cucumber crop with different CO_2 concentrations and light intensities

Light intensity w/ m^2	CO_2 concentration ppm	CO_2 absorption g/ m^2/hr
0	340	-0.23
20	200	0.11
20	340	0.20
20	1000	0.32
100	200	1.14
100	340	1.59
100	1000	2.31
400	200	3.00
400	340	4.49
400	1000	7.82

The CO_2 loss from Venlo greenhouses can be calculated using the following formula:

CO_2 ventilation loss = ventilation rate x average greenhouse height x CO_2 difference x 0.0018.

This formula only applies to a Venlo greenhouse with the vents not fully open.

The 0.0018 is used to convert ppm to grams of CO_2.

The CO_2 difference is the difference between the inside and outside concentration in ppm.

The greenhouse height is in metres.

The ventilation rate is the number of times the air volume in the greenhouse is replaced per hour and is roughly based on the following formula:

$V = 0.09 \times W \times (R+L)$.

V is the ventilation rate, W the wind speed in metres per second, R the vent opening percentage and L the amount of leakage from the greenhouse. In a modern Venlo greenhouse L is approximately 0.3 air replacements per hour. Older greenhouses may have an L of 2 or more.

Example calculation
In spring, with 500 W/m^2 radiation and a wind speed of 5 m/s, the vents on the lee side will be 50% open. The CO_2 concentration in the greenhouse is 450 ppm. The outside concentration is 350 ppm. The greenhouse is 4 m high (average). The crop absorption is 6 g/ m^2/hr.
The ventilation rate is $0.09 \times W \times (R+L) = 0.09 \times 5 \times (50+0.5) = 22.7$. To obtain the air replacement per m^2 greenhouse surface area, this figure needs to be multiplied by the average greenhouse height. The ventilation speed is $22.7 \times 4 = 91$ m/hr. The difference in CO_2 concentration between the greenhouse and outside air is 100 ppm. This leads to a CO_2 ventilation loss of $91 \times 100 \times 0.0018 = 16.4$ g/ m^2/hr.
The total amount of CO_2 that needs to be dosed to maintain the CO_2 concentration in the greenhouse is $16.4 + 6= 22.4$ g/ m^2/hr. This requires a burner position of 125 m^3/ha/hr.

Increasing the concentration is most effective during period of high radiation. The disadvantage is that the vents are usually also open, so that part of the dosed CO_2 escapes. This raises the question of how useful it is to dose large amounts of CO_2 in the summer. It is difficult to evaluate when CO_2 dosing becomes unprofitable.

It is always useful to at least maintain the outside air concentration (approx. 350 ppm) when radiation exceeds 100 W/ m^2.
Chapter 5 provides further details on the costs and profitability of CO_2 dosing. A useful guideline is that on sunny days with a healthy crop, at least 25 to 30 m^3 gas needs to be dosed per ha per hour between 10.00 and 15.00.

4.4 CONTROL OF THE CO_2 CONCENTRATION

The ideal CO_2 concentration to aim for in the greenhouse depends to a large extent on the availability of CO_2 and the climate inside and outside the greenhouse. Correct CO_2 adjustment is only possible if measurement and control of compartments is on an individual basis. Many business do not currently use this method. In this case, all compartments are controlled on the basis of the measured value of a single compartment, or an average value for all compartments. This can result in high or low CO_2 concentrations in a single or several compartments.
In most businesses, the CO_2 meter is connected to the climate computer. Sometimes, the CO_2 meter is used for direct control, although the available options are limited. Depending on the measured value and set maximum values, these meter/controllers can switch the CO_2 dosing on or off. A good climate computer is the best method of control. The influence of various factors, such as heat demand, vent position, wind speed, radiation etc., on CO_2 control can be set in the computer. The setting options and names may differ depending on the manufacturer.

Global overview of CO_2 settings in the climate computer

CO_2 availability

When the greenhouse is heated free flue gas CO_2 becomes available. The dose can be adjusted to what is considered useful for the crop. This maximum CO_2 concentration is entered in the high CO_2 setting. With overcast weather during the winter, it does not make sense to dose more than 600 ppm. With low light intensity, photosynthesis hardly increases above this concentration whereas the risk of air pollution does increase. If the weather is sunny during the winter, the concentration can be increased to 800 to 1000 ppm using the'radiation range' setting. In summer, the concentration for **high** CO_2 can be set to 1000 ppm.

Limited CO_2 is available during the summer and efficient control is very important than. The heat demand drops as the radiation increases. The vents also open further so that ventilation loss increases. The CO_2 demand is high during high radiation. It is now necessary to estimate how much CO_2 should be dosed. The concentration at which CO_2 dosing starts, even if there is no heat demand, can be entered in the **low** CO_2 setting. Depending on the vent position and/or wind speed (vent range and wind influence settings) the required concentration is reduced to a **minimum CO_2 concentration**. This is the minimum concentration to be used, providing the heat generated during this process can be discharged. If necessary, CO_2 dosing can be switched off above a specific vent limit. To allow dosing, the burner on the CH system is set to the **minimum** position and the boiler temperature is (initially) raised. Once the maximum boiler temperature has been reached, the heat is sent to the heat buffer or, if this is not available, to the greenhouse. When discharging to the greenhouse (heat elimination) it is possible to set the maximum acceptable rise in water temperature and/or the greenhouse temperature at which CO_2 dosing stops . The limit value varies for each crop, as some crops are sensitive to high greenhouse temperatures.

Estimating CO_2 absorption and loss

Photosynthesis is higher with more radiation. In this case, CO_2 dosing will have more effect. The 'radiation range' setting takes this into account. It indicates the radiation range within which the required CO_2 concentration rises. Both the ventilation and CO_2 loss increase as the radiation increases. The extent of the loss depends on the concentration difference between the air inside and outside the greenhouse, the vent opening and the wind speed. Doubling the concentration difference between inside and outside results in twice the ventilation loss. Doubling the vent position results in almost twice the ventilation.

Using the 'vent range' and 'wind influence' settings, the CO_2 concentration can be reduced to a **minimum CO_2 concentration** in order to limit ventilation loss.

The eventual required CO_2 concentration is determined by the positive influence of radiation and the negative influence of ventilation. The cost of CO_2 and the expected product yield are the most important factors when specifying the settings for these influences.

Global overview of the CO_2 setting options on the climate computer. The names may be different for different makes:

High CO_2:	Required maximum CO_2 concentration with heat demand (free flue gas CO_2)
Low CO_2:	Required CO_2 concentration in the absence of a heat demand and with the vents closed. This value is reduced to minimum CO_2

Minimum CO_2: Required CO_2 concentration applicable above a specific vent position.

Increase in water temperature/air temperature: The maximum increase in water or air temperature with heat elimination for the purpose of CO_2 dosing

Radiation threshold value: Radiation level above which CO_2 can be dosed (with a radiation level in excess of 15 W/m_2 outside the greenhouse CO_2 is absorbed by the crop).

Radiation range: Radiation range within which the required CO_2 concentration rises by a specific value.

Vent range: Vent position range within which the required CO_2 concentration drops.

Wind influence: Speed at which the desired CO_2 concentration drops with increasing wind speed. Some manufacturers use this as influence on the vent range.

4.5 CO_2 DOSING IN THE ABSENCE OF A DIRECT HEAT DEMAND

No heat demand

To dose flue gas CO_2 when there is no heat demand, the boiler temperature is first raised. When the maximum boiler temperature has been reached the heat needs to be discharged. The heat can either be eliminated or used to fill a heat buffer. The heat can be eliminated by raising the water temperature in the greenhouse and venting the extra heat or by using an emergency cooler. However, heat elimination is not a favourable option. Filling a heat buffer is the best solution from an environmental, horticultural and economic point of view.
Sunny weather requires a burner position of 25 to 30 m^3/ha/h in order to supplement crop absorption and maintain the outside value in the greenhouse. This equates with a water temperature of 30°C and an air temperature of 25°C. A higher concentration requires considerably more gas. In addition to the amount absorbed by the crop the CO_2 ventilation loss must also be compensated for. To reach a density of 400 ppm in summer with wide open vents, 150 kg flue gas per ha per hour or a burner position of 80 m^3 gas/ha/h is required. To reach a density of 450 ppm requires a burner position of approximately 125 m^3/ha/h. To discharge the resultant heat without a buffer, with an air temperature of 25°C, a minimum water temperature of 50 or 65°C respectively needs to be maintained. However, high water temperatures in the greenhouse can lead to undesirable side effects in the crop. In that case, CO_2 concentrations of 400 or 450 ppm require a heat buffer or pure CO_2. The major advantage of pure CO_2 is that no heat is released. It is important, however, to set the required greenhouse concentration correctly for cost reasons. Excess CO_2 dosing can be very expensive. The inaccuracy of CO_2 meters presents a problem in this respect. Therefore, it is better to dose on the basis of flow rather than measured concentration.

Use of a heat buffer

Heat buffers are used to separate the use of heat and CO_2. Without a buffer, the burner switches off when the boiler has reached its maximum temperature and the production of CO_2 stops. When heat is stored in a buffer, the burner remains switched on for longer. When a buffer is used, extra CO_2 is provided during the day that would otherwise be lost during the night when the greenhouse is heated. The way the buffer is filled has direct consequences for the availability of CO_2 during the day. An appropriate buffer filling strategy is required to make the most effective use of CO_2 dosing. Special computer programs to control buffer filling are now available, but improved use of buffers is possible even without these programs.

Filling based on a straight line

The simplest strategy distributes the CO_2 evenly throughout the day. This is often controlled by setting a limit on the buffer temperature, which increases throughout the day on the basis of a straight line. Carbon dioxide is dosed as long as there is a CO_2 demand and the buffer temperature is below the limit. This means that an even amount of CO_2 is available throughout the day. However, with this strategy the additional CO_2 is not utilised to maximum effect. This is because the same amount of CO_2 is available at any time during the day, whereas the additional CO_2 demand varies throughout the day.

Using the most effective hours

Section 2.2 describes how the effect of CO_2 varies during the day. In the morning and the evening, additional CO_2 has less effect than at midday and during the early afternoon. It is advisable to dose CO_2, and therefore to heat the boiler, mainly during the most effective hours of the day. This means that the buffer filling method needs to be adjusted.

Often, heat can still be sent to the greenhouse early in the morning. It is best to keep the pipes hot during the initial hours after sunrise to prevent condensation on the crops. Start filling the buffer as late as possible. At 11.00 am the buffer must be no more than a quarter full, preferably less.

At midday the CO_2 concentration in the greenhouse must not drop below the outside value. In order to achieve, this the buffer can be filled by at least another half during this period. After this period, the buffer will be at least three quarters full.

The ventilation is often most active at the end of the afternoon when the greenhouse has heated up due to radiation. More CO_2 than in the morning with comparable radiation is often required in order to maintain the CO_2 concentration level . The rest of the buffer can now be filled. Later in the evening the amount of radiation drops considerably. Plants cannot use CO_2 to the same extent and dosing is less important. The buffer must be emptied during the night. If the buffer also needs to be used to run the H/P without flue gas purification, the same strategy can be applied to the part of the buffer that is used for the boiler.

Optimal use

The next step is to integrate factors related to the crop and the outside climate when defining the required CO_2 concentration at any time during the day. When outside conditions change, adjustments are immediately made in the greenhouse. Individual computer programs are available for this purpose. For example, Carbonaut uses crop reactions and outside conditions to control the greenhouse climate. The local weather forecast is used to define the ideal CO_2 distribution throughout the day. This local weather forecast has been developed specifically for greenhouse horticulture.

The forecast focuses on the precise location of the horticultural business and is retrieved automatically via a modem at the start of the day. Weather data is used to calculate the greenhouse climate and then to prepare a greenhouse heat balance for the entire day. The heat balance provides the expected ventilation progress throughout the day. During the day, the optimum target CO_2 value for the conditions applicable at the time is continually defined and any CO_2 shortage is taken into account. This allows a correction to be made for any errors in the weather forecast.
The optimum target CO_2 value is not used directly by the control, but is converted into a required increase in buffer temperature. The burner position is adjusted in order to increase in buffer temperature and, as a result, the correct amount of CO_2 is sent to the greenhouse in order to achieve the optimum CO_2 value. Only the required buffer temperature for the end of the day needs to be set, the control ensures that it is reached. Graphs show how the CO_2 is used making it clear at all times why the computer has taken a specific decision.

4.6 CO_2 OPTIMISATION

The influence of CO_2 on growth is extremely important. The optimum dose can be calculated on the basis of photosynthesis models. To use these, correct logging climate and crop data is essential. Photosynthesis, and consequently CO_2 absorption, can be calculated quite accurately using the radiation, air temperature, CO_2 concentration and leaf index of the crop. The optimum CO_2 concentration is defined by its cost and benefits. The cost is made up of the CO_2 price, the amount necessary to maintain the required concentration and the additional harvesting and sorting activities. The yield depends on the actual surplus production and the auction price.
Each day, and each hour in the day, is different. The climate inside and outside the greenhouse changes constantly with a similar effect on cost and benefits. When it is sunny, a higher CO_2 concentration has a major impact on photosynthesis, but equally CO_2 loss is high because of high ventilation. The effect of a rise in concentration on both photosynthesis and ventilation loss is small on an overcast day in June. So, what is the optimum concentration? The use of an optimisation model is indispensable to ensure this can be calculated correctly. This section briefly explains the basic concepts that are important for optimisation and what the optimisation model is used for. It also shows some of the results.

Efficiency

The efficiency of dosing is the ratio between CO_2 absorption and CO_2 dosing. The efficiency of dosing depends on the CO_2 absorption and ventilation loss. CO_2 absorption mainly depends on the leaf quantity and radiation, as described in chapter 2. The ventilation loss is mainly defined by the difference in concentration between inside and outside and the ventilation rate, also defined by radiation (see section 4.3).
Efficiency drops if a higher concentration is used. In fact, CO_2 loss caused by ventilation increases in line with the concentration difference between inside and outside, whereas CO_2 absorption by the crop does not increase in line with the concentration increase.

Differences between crops

The figures in table 14 and figure 13 can be applied to various crops, as a healthy leaf has the same CO_2 absorption per leaf surface area unit in cucumbers, tomatoes or peppers. There may be differences in CO_2 absorption between crops, as some crops have more leaves than others. If the leaf surface area is more than 3 m2 leaf per m2 soil (leaf index = 3), CO_2 absorption will hardly increase at all. With a leaf index below 2, CO_2 absorption drops quite dramatically. This has a two-fold negative effect on CO_2 efficiency. Less CO_2 is absorbed by the plants and there is less evaporation due to the small leaf surface area. There is less cooling in the greenhouse by evaporation and, as a result, the vents open wider and more CO_2 escapes from the greenhouse.

In tomatoes, the leaf surface is often around the critical value of 2 in summer. A mature cucumber plant has a leaf surface of 3. Aubergines and peppers both have a leaf index that varies between 3.5 and 6 in summer. In peppers in particular the leaf surface area can be very extensive.

Climate control represents another major difference between crops. Aubergines, for example, will tolerate much higher temperatures during the day than most other plants. This means that less CO_2 is lost through ventilation. With cool cultivation crops, such as courgettes and freesias, more CO_2 is lost because of increased ventilation, and frequently less flue gas CO_2 is available anyway.

Production increase and yield

To find out the yield of an increase in CO_2 absorption it needs to be converted into production data. This is done as follows:

The plant produces approximately 1/2 gram of dry matter per gram of CO_2 absorbed. In cucumbers, tomatoes and aubergines, 70% of this dry matter is sent to the fruits. In peppers, it is slightly less approximately 65%. Large production differences between crops are mainly caused by the dry matter content of the fruits. Cucumber contains 3 to 3.5% dry matter, tomato 5.5 to 6%, aubergine 7 to 7.5% and red peppers 8.5%. When it is converted, one gram of absorbed CO_2 produces 11 g cucumber, 6 g tomato, 5 g aubergine or 4 g red pepper. This production rate must be multiplied by the price the grower hopes to obtain for the product. The same calculation can be applied to ornamental crops, such as roses. Depending on the cultivation system, 70 to 80% dry matter is used for the bloom stems in roses. A harvested stem contains 25% dry matter. This means that one gram of absorbed CO_2 supplies 1.4 to 1.6 g to the stems. The surplus price for longer and/or thicker stems has to cover the cost of the CO_2.

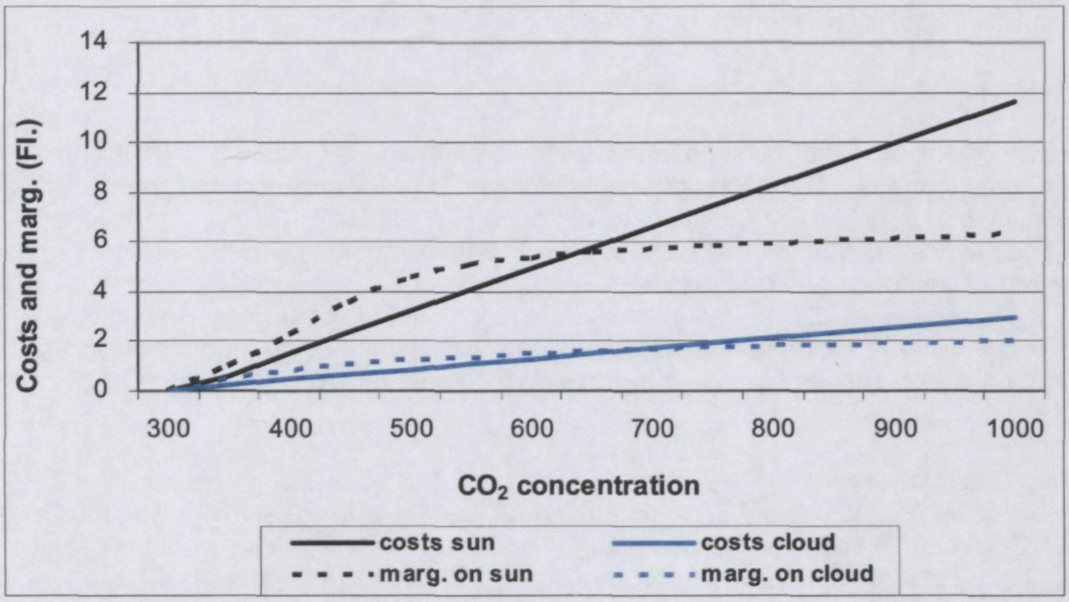


Figure 13 CO_2 optimisation on an overcast and a sunny day in June

The role of the computer

The computer uses various models to constantly balance costs and benefits. Using the radiation and crop size, the computer estimates the current photosynthesis on the basis of a photosynthesis model. This is then used to calculate production. A greenhouse model is also used to calculate ventilation or the costs of dosing. The CO_2 concentration to give maximum profit can be defined by balancing these models against one another. Figure 13 shows an example of a optimisation control on a sunny and a cloudy day. This is based on dosing with pure CO_2. In the example, the optimum concentration crosspoint of the lines is virtually the same on both days, but there is a difference in CO_2 consumption.

The optimisation program can be used virtually straightaway. To use it for practical applications, it is important to define the correct ventilation loss, as underestimates or overestimates would result in the calculation of excessively high or low concentrations. A more accurate formula for calculating the ventilation with wide open vents was developed in 1998.

Example

Table 14 shows the calculations for two days in June, a sunny day and an overcast day. The nights are still quite cold, so the buffer is filled during the day and the heating comes on briefly in the morning. A heat buffer of 100 m3 per ha has sufficient storage capacity to dose approximately 125 g per m2 during the day. The model has been used to calculate that, together with the CO_2 released during heating on the sunny day, a concentration between 400 and 450 ppm (dose of 128 - 198 g per m2) can be achieved. The CO_2 concentration is now topped up using pure CO_2 dosing from 450 to 500 ppm. On a sunny day, this provides 5 g of additional CO_2 per m_2, but 66 g more is lost via the vents. The required quantity of CO_2 rises from 198 to 269 g, that is 71 g supplementary pure CO_2. Efficiency drops from 33% at 450 ppm to 26% at 500 ppm. The additional 5 g CO_2 results in 20 g red pepper for example. The dose may be profitable if the 20 g pepper yields more than the 71 g CO_2 costs, i.e. the price of a kg of peppers must be more than 3.5 times the price of a kg CO_2.

On an overcast day, the results are different. In this case, an increase from 450 to 500 ppm costs 32 g extra and only yields 1 g per m2 extra CO_2 absorption. There is not sufficient light to produce more. 86 or 118 g CO_2 respectively is required. The yield drops from 24 to 19%. The yield is lower during overcast weather, but less CO_2 is required. When converted, 4 g additional pepper is produced. In this case, the peppers need to yield 8 times the cost of the CO_2. However, this calculation is for pure CO_2. On an overcast day, it is highly likely that sufficient (free) CO_2 is released during heating in which case this calculation does not apply. It can be concluded that the main focus should be on sunny days. This is where significant production increases can be achieved. During a high radiation day, even with considerable ventilation, high doses can be justified providing the crops are healthy.

Table 14 CO_2 absorption and loss with different concentrations on a sunny and an overcast day in June. The figures have been calculated on the basis of a scientific model.

CO_2 dose	SUNNY DAY (radiation sum 2960 J per cm2)			OVERCAST DAY (radiation sum 890 J per cm2)		
	CO_2 absorption (gram per m2)	ventilation loss (gram per m2)	efficiency (%)	CO2 absorption (gram per m2)	ventilation loss (gram per m2)	efficiency (%)
none	50	-46.5	*	17	-17	*
350 ppm	56	0	100	19	0	100
400 ppm	61	67	48	20	34	37
450 ppm	65	133	33	21	65	24
500 ppm	70	199	26	22	96	19
550 ppm	72	265	21	23	127	15
750 ppm	75	530	12	24	251	9

5. MANAGEMENT ASPECTS

This chapter describes the business economics of CO_2 dosing. Cucumbers and tomatoes are used as example crops for illustration purposes. It is impossible to include calculations for every type of crop in this brochure, but this chapter is still useful for other types of crops. In fact, the calculation methods apply to all greenhouse crops. Only specific crop characteristics, such as the required amount of gas for heating and the product price, are different for each crop. Use this chapter to evaluate what your crop requirements are, either individually, within your field trip group or together with your instructor.

Heat buffer
Section 5.1 compares the use of a heat buffer with other CO_2 supply methods, section 5.2 calculates the size of the heat buffer and section 5.3 calculates the levels up to which supplementary dosing is profitable.

Pure CO_2
Section 5.1 compares the use of pure CO_2 with other CO_2 supply methods and section 5.3 calculates the levels up to which supplementary dosing is profitable.

Flue gas CO_2
Section 5.1 compares flue gas CO_2 with other CO_2 supply types, section 5.3 calculates the levels up to which supplementary dosing is profitable. The above also covers the effect of a rise in the gas price.

Heat power
Section 5.4 covers the competitive aspect between H/P and CO_2 supply if the heat power flue gases are not purified. Section 5.5 then describes the financial options for flue gas purification when using heat power.

Storage of glue gas CO_2
Section 5.6 focuses on the financial options associated with the storage of flue gas CO_2.

Central heating supply
Section 5.7 deals with the financial aspects of CO_2 when central heating facilities are used.

1 Dfl. = 100 ct = € 0,45

5.1 HEAT BUFFER MUCH BETTER THAN SUPPLEMENTARY DOSING

Chapter 2 describes how an increase in the CO_2 content in the greenhouse leads to increased production and, especially in floristry crops, to quality improvements. The best way to implement an increase in CO_2 content from a business economics point of view is explained on the basis of two example crops. The situations are based on the use of a heat buffer, as opposed to supplementary dosing with pure CO_2 or dosing with CO_2 from the boiler. The size of the buffer and the CO_2 content up to which supplementary dosing can be used, are described in the following two sections.

Comparing various situations

The examples are based on tomato and cucumber crops. The initial situation is a crop where CO_2 is dosed only when the heating is on. These businesses consume 52 and 59 m3 of natural gas per m2 respectively. Of the flue gases released during this process 29 and 31 kg of CO_2 per m2 respectively are used for dosing. This produces 43 kg of tomatoes and 60 kg of cucumbers with a revenue of Dfl. 55.00 and Dfl. 63.50 per m2 (1995 price levels).

Calculations for three situations are shown:

In the first situation, supplementary CO_2 is dosed in this business when the CO_2 content is below 400 ppm. This is calculated for flue gas CO_2 and pure CO_2. In the second situation, a heat buffer of 100 m3 per ha is used. The heat buffer is filled during the spring and only the heat required to keep the greenhouse warm is taken from the buffer each night. The buffer is refilled the next day.

In the third situation, supplementary CO_2 is dosed when the CO_2 content is below 400 ppm, but there is no heat demand and the buffer is full.

CO_2 content

Figure 14 shows the progress of the average CO_2 content throughout the day between weeks 10 and 42. It shows the initial situation and the situation with a 100 m3 per ha heat buffer. Because of the supplementary CO_2 generated by the use of the buffer, the maximum CO_2 content can be achieved for three weeks longer at the beginning of April. Following that, the difference in CO_2 content between using and not using a buffer drops from 450 ppm in week 15 to approximately 50 ppm in week 24. During the summer the average CO_2 content with a heat buffer is approximately 40 ppm higher than without a heat buffer. After week 33 the difference between using and not using a heat buffer increases again. The greatest impact of the heat buffer on the CO_2 content is between the beginning of April and the middle of June, and the effect also increases during the autumn.

Without a heat buffer, the greenhouse does not attain 350 ppm on average during the day between the beginning of May and the end of August. With a heat buffer, this only occurs in June. From the middle of April until the end of September, the CO_2 content without a heat buffer is below 400 ppm on average during the day. Without a heat buffer, additional heat is required throughout this entire period in order to attain a CO_2 content of 400 ppm in the greenhouse. With a heat buffer, this is from June to the end of September.

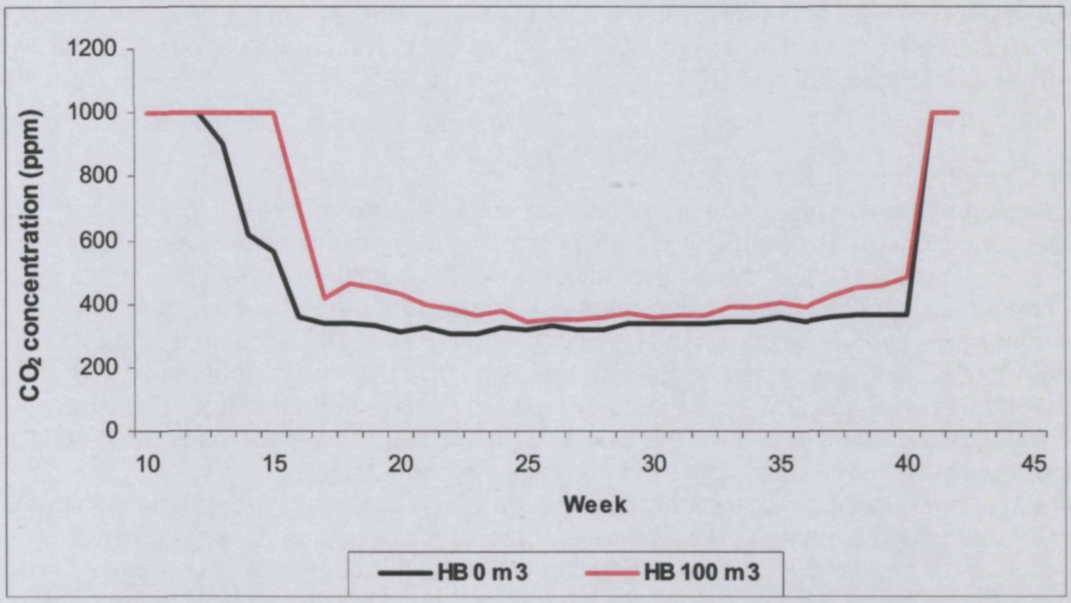


Figure 14 Average CO_2 content during the day with tomatoes, if all available CO_2 is dosed and the heat buffer is only used to heat the greenhouse during the night.

Production

Table 15 shows that without a heat buffer but with supplementary dosing up to 400 ppm, 3.4 kg of tomatoes and 7.3 kg of cucumbers per m2 additional production can be achieved. The use of a 100 m3 per ha heat buffer results in a production increase of 8 kg of tomatoes and 16.7 kg of cucumbers per m2. This increase in production is mainly caused by the large increase in the average CO_2 content during the spring. If, when using this buffer, supplementary dosing is applied up to 400 ppm, the increase in production will rise by 1 kg to 9 and 17.5 kg per m2 respectively.

Gas and CO_2 consumption

To maintain the CO_2 content in the greenhouse at a minimum level of 400 ppm, additional gas needs to be consumed or pure CO_2 used. Table 5.1.1 illustrates both situations. The differences in gas consumption between supplementary dosing up to 400 ppm with and without a heat buffer are not that pronounced, as even with a heat buffer the average CO_2 content in the greenhouse is below 400 ppm over a prolonged period. In this case, the heat buffer only saves 1.4 m3 gas with tomatoes and 2.1 m3 with cucumbers.
If the heat buffer is solely used for heat required during the night for tomatoes, a production surplus of 8kg is realised with 1.4 m3 additional gas. This is more than 5.7 kg tomatoes per additional m3 natural gas. For cucumbers, the figure is 16.7 kg per m3 additional natural gas. Supplementary dosing up to 400 ppm with flue gas CO_2 without a heat buffer generates a production surplus of 3.4 kg, but costs 10.2 m3 additional natural gas, which is approximately 0.3 kg of tomatoes per extra m3 natural gas. For cucumbers, it is 0.9 kg per m3 additional natural gas. Supplementary dosing up to 400 ppm when using a heat buffer generates a production surplus of just over 1 kg of tomatoes and almost 3 kg of cucumbers per additional m3 natural gas. The additional cubic metres natural gas are always compared to the reference crop 43 kg tomatoes/m2 with 52 m3 gas/m2, or 60 kg cucumbers with 59 m3 gas. Therefore, the use of a heat buffer appears to be highly energy efficient. Supplementary dosing considerably reduces the energy efficiency of the buffer.

If pure CO_2 is used instead of flue gas CO_2, the use of a heat buffer results in a difference of 5 to 6 kg pure CO_2 to achieve the required 400 ppm. It is clear that the use of pure CO_2 is more energy-efficient than flue gas CO_2.

Costs and benefits

Both supplementary dosing up to 400 ppm and the use of heat storage result in a clear increase in production. This corresponds to an increase in revenue. Table 15 calculates whether this is sufficient to cover the additional costs. As the additional production is mainly generated during the summer months, the prices are lower than the annual average. The average increase in revenue is set out over a period of ten years. The additional costs associated with gas, CO_2, sales and harvesting are also included. The cost of the heat buffer has also been taken into account. If all the above extra costs are deducted from the additional revenue the result is 'profit'. The calculations are based on a gas price of 25 cents per m3 and a pure CO_2 price of 25 cents per kg, excluding tanker hire.

The best results are obtained with the heat buffer only, which generates a profit of more than Dfl. 3.- for tomatoes and almost Dfl. 12.- for cucumbers. Supplementary dosing up to 400 ppm results in lower profits. Supplementary dosing without a heat buffer has a negative result with tomatoes and a positive result with cucumbers, but it is still well behind the heat buffer result.

When comparing the use of flue gas CO_2 with the use of pure CO_2, only cucumbers generate positive results with pure CO_2, but they are significantly lower than those for flue gas CO_2. The effect on 'profits' if both the gas and the CO_2 price rise to 30 cents, is shown in the bottom line of the table. The heat buffer results hardly drop with these higher prices. With supplementary dosing, the profit margin drops after an increase in the price of gas and CO_2. Supplementary dosing with pure CO_2 alongside the use of a buffer generates negative results in tomatoes.

Conclusion

A heat buffer is the best way to increase the CO_2 content in the greenhouse. This method is also least affected by an increase in the gas or CO_2 price. Supplementary dosing up to 400 ppm using flue gas CO_2 or pure CO_2 combined with the use of a buffer does not provide additional benefits in view of the deterioration in results and the additional use of natural gas or CO_2.

Table 15 Results of the three different methods used to increase the CO_2 content. Comparisons are made with a crop where only CO_2 released by the heating during the day is dosed. Average prices of the years 1995-1997. The profit is averaged over ten years and is given for a gas price of 25 and 30 cents

Tabel 15a Tomatoes: production 43 kg/m^2, revenue Dfl. 55.-/m^2, gas consumption 52 m^3/m^2, gas price 25 ct/m^3, CO_2 price 25 ct/kg)

Heat buffer m3/ha	0	0	100	100	100
Minimum CO_2 content	400	400	none	400	400
Supplementary CO_2 source	CH boiler	pure	none	CH boiler	pure
Additional production kg/m^2	3.4	3.4	8.0	9.0	9.0
Additional gas consumption m^3/m^2	10.2	0.0	1.4	8.8	1.4
Additional CO2 consumption kg/m^2	0.0	18.4	0.0	0.0	13.4
Additional revenue Dfl./m^2	4.40	4.40	10.40	11.70	11.70
Additional gas cost Dfl./m^2	2.60		0.40	2.20	0.40
Additional CO_2 cost Dfl./m^2		4.60			3.40
Additional sales and labour cost Dfl./m^2	1.70	1.70	4.00	4.50	4.50
Heat buffer cost Dfl./m^2			1.50	1.50	1.50
profit Dfl./m^2 (25 ct)	0.60	-1.30	6.00	5.00	3.60
profit Dfl./m^2 (30 ct)	0.10	-2.20	5.90	4.50	2.80

Tabel 15b Cucumbers: production 60 kg/m^2, revenue/m^2, gas consumption 59 m^3/m^2, gas price 25 ct/m^3, CO_2 price 25 ct/kg

Heat buffer m3/ha	0	0	100	100	100
Minimum CO_2 content	400	400	none	400	400
Supplementary CO_2 source	CH boiler	pure	none	CH boiler	pure
Additional production kg/m^2	7.3	7.3	16.7	17.5	17.5
Additional gas consumption m^3/m^2	8.4	0.0	1.0	6.3	1.0
Additional CO_2 consumption kg/m^2	0.0	15.1	0.0	0.0	9.5
Additional revenue Dfl./m^2	7.30	7.30	16.70	17.50	17.50
Additional gas cost Dfl./m^2	2.10		0.30	1.60	0.30
Additional CO_2 cost Dfl./m^2		3.80			2.40
Additional sales and labour cost Dfl./m^2	2.30	2.30	5.20	5.40	5.40
Heat buffer cost Dfl./m^2			1.50	1.50	1.50
profit= Dfl./m^2 (25 ct)	3.70	2.10	11.70	10.90	9.90
profit= Dfl./m^2 (30 ct)	3.20	1.30	11.60	10.60	9.40

5.2 HOW BIG SHOULD THE HEAT BUFFER BE?

The calculations in section 5.1 show that, in terms of business economics and energy consumption, the use of a heat buffer is preferable to supplementary dosing up to 400 ppm using the boiler or pure CO_2. This section describes the ideal buffer capacities with respect to business economics.

When a heat buffer is used, the maximum increase in CO_2 content is achieved during the spring and autumn. During these periods, the greenhouse heat requirement is fairly high at night and often lower during the day due to radiation from the sun. As a result, the average CO_2 content in the greenhouse will drop during the day if dosing is only used when there is a heat demand. To gain maximum benefit from the buffer during spring and autumn nights, it is advisable to choose a buffer capacity to suit requirements for that particular period. Crops with a high night temperature can use larger buffer capacities than crops with a low night temperature. The energy savings with a heat buffer can only be realised if the heat stored during the day can be used overnight. Selecting a buffer capacity to suit the heat requirement during spring nights means that the buffer will be too large during the summer. Storing more than the heat requirement for the coming night during the summer results in a shift in heat elimination or reduces the amount that can be filled the following day.

Comparing situations
Again tomato and cucumber crops are used as an example. The basic crops are identical to those in 5.1, crops where CO_2 is only dosed when the heating is on. These basic crops consume 52 and 59 m^3 of natural gas per m^2 respectively. From the flue gases released during this process, 29 and 31 kg CO_2 per m^2 respectively are dosed. This produces 43 kg of tomatoes or 60 kg of cucumbers with a revenue of Dfl. 55.- and Dfl. 63.50 per m^2.
Nine heat buffers of varying sizes - 20, 40, 60, 80, 100, 120, 140, 160 and 200 m^3 per ha - are compared. These heat buffers are filled during the day in spring and only the heat required to keep the greenhouse warm is taken from the buffer each night. The buffer is refilled the following day, preferably at midday.

Production
Table 16 shows that the use of heat buffers, as opposed to only dosing when there is a heat demand, results in a large increase in production. With a capacity of 60 m^3 per ha, this produces more than 6.5 kg of tomatoes or 13 kg of cucumbers per m^2. If the storage capacity is doubled to 120 m^3 per ha, the extra production increase is only 1.7 kg of tomatoes or 4 kg of cucumbers per m^2. The greatest increase in production is obtained with a relatively small heat buffer.

Additional gas
A small amount of heat is lost during storage. This means that a small amount of additional gas is required. The additional gas consumption varies between 0.2 and 3 m^3 gas with tomatoes and 0.2 to 2.4 m^3 gas with cucumbers.

Costs and benefits
Heat storage has an effect not only on production but also on cost. To understand the profit options associated with heat storage, the average additional revenue and costs of the various buffer capacities have been calculated over a period of ten years. They are shown in the table under profit. When the additional costs are deducted from the additional revenue the profit as a result of heat storage is shown. The highest profit is achieved with a storage capacity of 120-140 m^3 per ha. With tomatoes, the benefit is Dfl. 3.- per m^2 and with cucumbers almost Dfl. 12.- per m^2. The results from the 80 and

100 m^3 per ha buffers are not far behind. A heat buffer between 80 and 140 m^3 per ha will yield the best results from a business economics point of view.

The last line in the table shows to what extent the choice of buffer capacity depends on the gas price. The table is based on a gas price of 25 ct per m^3. The last line shows the figures for a gas price of 30 ct per m^3. Higher gas prices hardly seem to affect the optimum buffer size. This was to be expected in view of the small additional gas consumption.

Conclusions

- *Choose a heat buffer capacity to suit heat requirements during spring nights.*
- *Increased heat requirements during the spring justify a larger heat buffer and, if heat requirements are lower, a smaller heat buffer should be used.*
- *In the case of heating regimes such as those for tomatoes and cucumbers, the ideal, most cost-effective buffer capacity lies between 80 and 140 m^3 per ha .*

Table 16 Surplus production, additional costs and yields from nine different heat buffer capacities in relation to a standard crop where only CO_2, released by the heating during the day, is dosed. Average prices of the years 1995-1997. The profit is a ten year average.

Table 16a Tomatoes: production 44 kg/m^2, revenue Dfl. 55.-/m^2, gas consumption 52 m^3/m^2
1 Dfl. = € 0,45

Heat buffer m^3/ha	20	40	60	80	100	120	140	160	200
Additional production kg/m^2	3.0	5.1	6.6	7.5	8.0	8.3	8.5	8.7	8.9
Additional gas consumption m^3/m^2	0.2	0.5	0.8	1.1	1.4	1.7	2.1	2.4	3.1
Additional revenue Dfl./m^2	3.90	6.60	8.60	9.80	10.40	10.80	11.10	11.30	11.60
Additional gas cost Dfl./m^2	0.05	0.10	0.20	0.30	0.40	0.40	0.50	0.60	0.80
Additional sales and labour cost Dfl./m^2	1.50	2.60	3.30	3.70	4.00	4.20	4.30	4.40	4.50
Heat buffer cost Dfl./m^2	0.90	1.00	1.10	1.20	1.50	1.60	1.80	1.90	2.20
profit= Dfl./m^2 gas 25 ct	2.00	3.80	5.10	5.80	6.00	6.00	5.90	5.90	5.60
profit= Dfl./m^2 gas 30 ct	1.90	3.80	5.00	5.70	5.90	5.90	5.80	5.80	5.50

Table 16b Cucumbers: production 60 kg/m^2, revenue Dfl. 63.50/m^2, gas consumption 59 m^3/m^2

Heat buffer m^3/ha	20	40	60	80	100	120	140	160	200
Additional production kg/m^2	6.5	10.7	13.3	15.4	16.7	17.3	17.9	18.5	19.2
Additional gas consumption m^3/m^2	0.2	0.4	0.6	0.8	1.0	1.3	1.6	1.8	2.4
Additional revenue Dfl./m^2	6.50	10.70	13.30	15.40	16.70	17.30	17.90	18.50	19.20
Additional gas cost Dfl./m^2	0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.45	0.60
Additional sales and labour costs Dfl./m^2	2.00	3.30	4.10	4.80	5.20	5.40	5.60	5.90	6.10
Heat buffer cost Dfl./m ^{2}	1.10	1.20	1.50	1.60	1.80	1.90	2.20		
profit Dfl./m^2 gas 25 ct	4.20	5.80	9.30	10.90	11.70	11.90	12.20	12.40	12.50
profit Dfl./m^2 gas 30 ct	4.20	7.40	9.30	10.90	11.60	11.90	12.10	12.30	12.40

5.3 IS SUPPLEMENTARY DOSING PROFITABLE?

Section 5.1 uses a few situations to illustrate that using a heat buffer produces better results in terms of business economics than supplementary CO_2 dosing up to 400 ppm with flue gas or pure CO_2. In 5.2 the ideal buffer size was 80 to 140 m^3 per ha. This section uses the same business examples to illustrate why supplementary dosing to 350 ppm produces the highest improvement in business results, with or without a heat buffer.

Comparing situations

The examples are again based on tomato and cucumber crops. These basic crops consume 52 and 59 m^3 of natural gas per m^2 respectively. 29 and 31 kg CO_2 per m^2 of the flue gases are used for dosing purposes. CO_2 is dosed only when the heating is on. This produces 44 kg of tomatoes or 60 kg of cucumbers with a revenue of Dfl. 55.- and Dfl. 63.50 per m^2 respectively. Calculations for three practical situations are shown:

In the first situation supplementary CO_2 is dosed at the above business up to 350, 400, 450, 500, 550, 600, 650 or 700 ppm. The calculations apply to flue gas CO_2 and pure CO_2.

In the second situation, a heat buffer of 60, 80, 100, 120 or 140 m^3 per ha is used. The heat buffers are filled during the spring and only the heat required to keep the greenhouse warm is taken from the buffer each night.

In the third situation, supplementary CO_2 is dosed when the heat buffer is full at times when the CO_2 content is lower than 350, 400, 450, 500, 550, 600, 650 or 700 ppm.

Production

Table 17 shows the additional production for all the above situations. Production continues to increase if the heat buffer increases and a higher minimum CO_2 content is maintained. The combination of a 140 m^3 per ha heat buffer with supplementary dosing to 650 ppm results in additional production of 12 kg of tomatoes and 20 kg of cucumbers per m^2. It is also clear that additional production generated by progressing to a larger buffer or higher CO_2 content becomes increasingly smaller. A minimum CO_2 content of 400 ppm instead of 350 ppm, without the use of a buffer, produces 2 kg additional tomatoes (3.4 - 1.4), whereas an increase from 600 to 650 ppm produces only an additional 1.1 kg of tomatoes (10.2 - 9.1). With cucumbers, this figure is 2.8 and 2.4 kg extra respectively. This is the principle of decreasing returns where each extra kg requires more input. The same effect can be observed when a larger heat buffer is used.

The production results are comparable if either a buffer or supplementary dosing are used individually. The additional production of 8 kg of tomatoes with a 100 m^3 per ha heat buffer is the same as the additional production generated with supplementary dosing to 550 ppm, and the extra 16.7 kg cucumbers with a 100 m^3 per ha buffer is the same as with dosing to 650 ppm.

Gas and CO_2 consumption

Supplementary CO_2 can be derived from flue gas CO_2 or pure CO_2. Both options are included in the calculations. Table 18 shows the additional gas consumption for additional flue gas CO_2. The additional gas consumption as a result of heat loss during storage for the various buffer capacities is shown in column none. The amount of gas required to achieve the desired CO_2 dosing is added in the following columns. The use of heat storage leads to a reduction in additional gas consumption for supplementary dosing. As the heat requirement during the night, in particular during the summer months, is not high enough to utilise all the extra heat, the differences in terms of

additional gas consumption without a heat buffer are fairly constant. The extra heat released can be stored, but does not produce additional savings.
Supplementary dosing with flue gas CO_2 to 700 ppm, even with the use of a heat buffer, doubles the gas consumption in relation to the basic crop, in both tomatoes and cucumbers. About 20% additional gas is required to maintain 400 ppm with tomatoes and about 12% with cucumbers. This has an adverse effect on energy savings. The question also remains whether all this extra heat can be discharged during the summer.
When a heat buffer is used, supplementary CO_2 dosing with pure CO_2 instead of flue gas CO_2 only results in additional gas consumption due to storage losses.

Table 19 shows the amount of pure CO_2 required for supplementary dosing. The heat buffer ensures that less supplementary pure CO_2 is required to maintain a desired minimum CO_2 content. Without a heat buffer, each 50 ppm above 350 ppm costs about 14 kg CO_2 per m2 extra. A heat buffer of 120 m3 per ha reduces these costs to a 11 to 12 kg per 50 ppm increase. When compared to a no heat buffer situation, a heat buffer of 120 m3 saves approximately 5 kg pure CO_2 per m2 per annum at a minimum level of 400 ppm. At a minimum of 650 ppm, the difference is 18 kg CO_2 per m2.

Table 17 Production increase with six different buffer sizes (m3/ha) in combination with nine dosing levels relative to the basic crop. Reference year 1995. Unit: kg/m2 per annum

Tabel 17a <u>Tomatoes</u>: basic production 44.0 kg/m^2 without extra CO_2.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	1.4	3.4	5.1	6.6	8.0	9.1	10.2	11.0
60	6.6	7.0	7.9	8.7	9.4	10.0	10.6	11.1	11.6
80	7.5	7.8	8.5	9.2	9.8	10.4	10.9	11.3	11.8
100	8.0	8.3	9.0	9.6	10.2	10.7	11.2	11.6	12.0
120	8.3	8.5	9.2	9.8	10.4	10.9	11.4	11.8	12.2
140	8.5	8.8	9.5	10.1	10.6	11.2	11.6	12.0	12.0

Table 17b <u>Cucumbers</u>: basic production 60.3 kg/m^2 without extra CO_2.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	4.5	7.3	9.7	11.7	13.5	15.1	16.5	17.7
60	13.3	14.2	15.2	16.0	16.7	17.4	18.0	18.5	19.1
80	15.4	15.9	16.5	17.1	17.7	18.1	18.5	19.0	19.4
100	16.7	17.0	17.5	18.0	18.4	18.8	19.1	19.4	19.7
120	17.3	17.6	18.0	18.5	18.9	19.2	19.5	19.8	20.1
140	17.9	18.1	18.6	19.0	19.3	19.6	19.9	20.2	20.4

Table 18 Additional gas consumption with six different heat buffer capacities in combination with nine different dosing systems relative to the basic crop. Reference year 1995. Unit: m^3 natural gas/m^2 per annum.

Table 18a Tomato: basic gas consumption: 52.2 m^3, only for heating.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	1.8	10.2	18.0	25.8	33.6	41.3	49.1	56.9
60	0.8	1.6	8.7	15.2	21.7	28.1	34.6	41.4	48.3
80	1.1	1.7	8.7	15.0	21.2	27.5	33.9	40.3	46.9
100	1.4	2.0	8.8	15.1	21.3	27.6	33.8	40.2	46.5
120	1.7	2.3	9.1	15.4	21.5	27.9	34.1	40.5	46.8
140	2.1	2.6	9.5	15.9	22.1	28.4	34.6	40.9	47.3

Table 18b Cucumbers: basic gas consumption: 59.1 m^3, only for heating.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	2.1	8.4	16.2	23.9	31.7	39.5	47.2	55.1
60	0.6	1.3	6.6	13.4	20.1	27.0	34.0	40.9	48.0
80	0.8	1.3	6.4	13.0	19.5	26.1	32.9	39.6	46.4
100	1.0	1.4	6.3	12.8	19.2	25.7	32.4	38.8	45.4
120	1.3	1.6	6.6	13.0	19.4	25.9	32.5	38.9	45.5
140	1.6	1.8	6.7	13.1	19.4	25.9	32.4	38.8	45.3

Table 19 Required amount of pure CO_2 (kg) with six different heat buffer capacities in combination with nine different dosing systems compared to the standard crop (no supplementary CO_2). Reference year 1995. Unit: kg CO_2/m^2 per annum

Table 19a Tomatoes: basic CO_2 consumption 29 kg, from heating only.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	3.3	18.4	32.4	46.4	60.4	74.4	88.4	102.4
60	0.0	1.5	14.3	25.9	37.6	49.2	60.9	73.0	85.5
80	0.0	1.2	13.7	25.0	36.2	47.6	59.0	70.6	82.5
100	0.0	1.1	13.4	24.6	35.8	47.1	58.4	69.8	81.2
120	0.0	1.0	13.4	24.6	35.6	47.1	58.4	69.8	81.1
140	0.0	1.0	13.4	24.8	36.0	47.3	58.5	69.9	81.3

Table 19b Cucumber: Basic CO_2 consumption 31 kg from heating only.

	CO_2 dosing level (ppm)								
Heat buffer m^3/ha	none	350	400	450	500	550	600	650	700
0	0.0	3.8	15.1	29.1	43.1	57.1	71.0	85.0	99.2
60	0.0	1.3	10.8	23.0	35.2	47.6	60.0	72.6	85.3
80	0.0	0.9	10.1	21.9	33.7	45.6	57.7	69.9	82.1
100	0.0	0.7	9.5	21.2	32.8	44.5	56.4	68.1	79.9
120	0.0	0.5	9.5	21.0	32.7	44.3	56.1	67.7	79.6
140	0.0	0.4	9.2	20.6	32.1	43.8	55.4	67.0	78.7

Costs and benefits
A larger buffer or higher minimum CO_2 content always leads to increased production and a rise in revenue. However, costs of labour, sales, gas or CO_2, and possibly the heat buffer, are also higher. These extra costs need to be compensated for by additional revenue. The profit associated with the various additional CO_2 sources has been calculated relative to dosing only CO_2 released from heat production during the day. To do so the average extra costs and revenues over a period of ten years, and the difference between extra revenue and extra cost, the profit, have been listed. The figures are shown in tables 20 and 21. The figures for flue gas CO_2 are shown in table 20. Without a heat buffer, supplementary dosing to 400 ppm results in a loss of Dfl. 0.50 per m^2 in tomatoes, with a gas price of 25 ct per m^3. At a gas price of 30 ct, the loss even increases to Dfl. 1.00. With cucumbers, the result is positive:. Dfl. 3.70 and 3.20 extra per m^2. The combination of a heat buffer and supplementary dosing to 350 ppm generates the highest profit in cucumbers. With tomatoes, the best results are generated if only a heat buffer is used. Supplementary dosing to 350 ppm has more or less the same result. Increased supplementary dosing is expensive. Because of the small amount of extra gas required for supplementary dosing to 350 ppm with a heat buffer, an increase in the gas price will hardly affect this optimum value.

Table 21 is based on the use of pure CO_2 at 25 ct per kg. Without a heat buffer, the result of supplementary dosing with pure CO_2 soon becomes negative. The best results are obtained with both tomatoes and cucumbers with supplementary dosing to 350 ppm. Increasing this amount to 400 ppm with tomatoes and 500 ppm with cucumbers
no longer produces positive results. If the CO_2 price rises to 30 ct per kg, supplementary dosing to 400 ppm only has a positive effect for cucumbers.

The use of a heat buffer immediately produces better results. As with the use of flue gas CO_2, the combination of a buffer and supplementary dosing to 350 ppm where necessary, is the best option. Again, the CO_2 price has minimal impact on the optimum value.

The optimum results when using flue gas CO_2 and pure CO_2 combined with a heat buffer are pretty close together. In terms of saving energy, pure CO_2 is preferable to flue gas CO_2 for supplementary dosing . As the price of pure CO_2 is largely determined by the annual off take, the use of a shared CO_2 tank is advisable. Consumption of 1 kg per m^2 per annum is not enough to negotiate a low price.

Table 20 Increase profit from supplementary dosing with flue gas CO_2 with six different heat buffer capacities in combination with nine different dosing levels. Unit: Dfl./m^2.
1 Dfl. = € 0.45. Average prices of the years 1995-1997. Profit calculated over a period of ten years.

Table 20a Tomatoes: production 44 kg/m^2, revenue Dfl. 61.60/m^2, gas consumption 52 m^3/m^2

Natural gas 25 ct/m^3

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0	0.00	0.90	0.60	0.30	-0.30	-1.00	-1.90	-2.90	-4.10
60	5.10	5.20	4.30	3.40	2.30	1.20	0.20	-1.10	-2.40
80	5.80	5.90	4.80	3.80	2.80	1.70	0.60	-0.70	-2.00
100	6.00	6.10	5.00	3.90	2.90	1.80	0.60	-0.60	-1.90
120	6.00	6.10	5.00	3.90	2.90	1.70	0.60	-0.70	-1.90
140	5.90	6.10	5.00	3.90	2.80	1.70	0.50	-0.70	-2.40

Natural gas 30 ct/m3

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
00.00	0.80	0.10	-0.70	-1.60	-2.70	-4.10	-5.40	-7.10	
60	5.00	5.10	3.80	2.60	1.20	-0.20	-1.60	-3.30	-4.90
80	5.70	5.80	4.30	3.00	1.70	0.30	-1.20	-2.80	-4.40
100	5.90	6.00	4.50	3.20	1.80	0.30	-1.10	-2.70	-4.30
120	5.90	5.90	4.50	3.10	1.80	0.30	-1.20	-2.80	-4.30
140	5.80	6.00	4.50	3.10	1.60	0.30	-1.30	-2.90	-4.80

Table 20b Cucumbers: production 60 kg/m^2, revenue Dfl. 63.50/m^2, gas consumption 59 m^3/m^2

Natural gas 25 ct/m^3

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0 0.00	3.10	3.70	3.60	3.10	2.60	1.80	0.90	-0.20	
60 9.30	9.90	9.30	8.20	7.00	5.80	4.50	3.00	1.70	
8010.90	11.20	10.30	9.10	7.90	6.50	5.10	3.70	2.30	
100	11.70	11.80	10.90	9.60	8.30	6.90	5.40	4.00	2.50
120	11.90	12.10	11.10	9.80	8.50	7.00	5.60	4.10	2.70
140	12.20	12.30	11.40	10.10	8.60	7.20	5.80	4.30	2.80

Natural gas 30 ct/m3

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0 0.00	3.00	3.20	2.70	1.90	0.90	-0.20	-1.50	-3.00	
60 9.30	9.80	9.00	7.50	5.90	4.40	2.70	0.90	-0.80	
8010.90	11.10	10.00	8.40	6.80	5.10	3.40	1.60	-0.20	
100	11.60	11.70	10.60	9.00	7.30	5.60	3.80	2.00	0.20
120	11.90	12.00	10.80	9.20	7.50	5.70	3.90	2.10	0.30
140	12.10	12.20	11.10	9.40	7.60	5.90	4.10	2.30	0.40

Table 21 Increase profit from supplementary dosing with pure CO_2 with six different heat buffer capacities in combination with nine different dosing levels.

Unit: Dfl./m^2. 1 Dfl. = € 0.45. Average prices of the years 1995-1997. Profit calculated over a period of ten years.

Table 21a Tomatoes: production 44 kg/m^2, revenue Dfl.61.60/m^2, gas consumption 52 m^3/m^2

Natural gas 25 ct/m^3, CO_2 price 25 ct/kg

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
00.00	0.50	-1.30	-3.20	-5.20	-7.30	-9.80	-12.20	-14.90	
605.10	5.10	2.70	0.60	-1.60	-3.90	-6.30	-8.80	-11.50	
805.80	5.80	3.30	1.20	-1.00	-3.30	-5.70	-8.20	-10.70	
100	6.00	6.00	3.30	1.40	-1.00	-3.20	-5.50	-8.00	-10.50
120	6.00	5.90	3.50	1.30	-0.90	-3.20	-5.60	-8.00	-10.50
140	5.90	6.00	3.60	1.30	-1.00	-3.30	-5.70	-8.10	-11.00

Natural gas 30 ct/m^3, CO_2 price 30 ct/kg

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0	0.00	0.40	-2.20	-4.80	-7.50	-10.40	-13.50	-16.60	-20.00
60	5.00	5.00	2.00	-0.70	-3.60	-6.40	- 9.40	-12.50	-15.80
80	5.70	5.70	2.60	-0.10	-2.90	-5.70	- 8.70	-11.80	-14.90
100	5.90	5.80	2.80	0.10	-2.70	-5.60	- 8.50	-11.60	-14.60
120	5.90	5.80	2.80	0.00	-2.70	-5.70	- 8.60	-11.60	-14.60
140	5.80	5.80	2.80	0.00	-2.90	-5.70	- 8.70	-11.70	-15.10

Table 21b Cucumbers: production 60 kg/m^2, revenue Dfl. 63.50/m^2, gas consumption 59 m^3/m^2

Natural gas 25 ct/m^3, CO_2 price 25 ct/kg

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0	0.00	2.70	2.10	0.50	-1.40	-3.50	-5.70	-8.00	-10.60
60	9.30	9.80	8.20	5.80	3.30	0.70	-1.90	-4.60	-7.30
80	10.90	11.10	9.30	6.80	4.30	1.70	-1.00	-3.70	-6.40
100	11.70	11.70	9.90	7.40	4.80	2.20	-0.50	-3.20	-5.90
120	11.90	12.00	10.10	7.60	5.00	2.30	-0.40	-3.00	-5.70
140	12.20	12.20	10.40	7.90	5.30	2.60	-0.10	-2.80	-5.50

Natural gas 30 ct/m^3, CO_2 price 30 ct/kg

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
0	0.00	2.50	1.30	-1.00	-3.60	-6.30	-9.20	-12.30	-15.60
60	9.30	9.70	7.60	4.60	1.50	-1.70	-4.90	-8.30	-11.60
80	10.90	11.00	8.70	5.60	2.60	-0.70	-4.00	-7.20	-10.60
100	11.60	11.60	9.40	6.30	3.10	-0.10	-3.40	-6.70	-10.00
120	11.90	11.90	9.50	6.50	3.30	0.10	-3.20	-6.50	-9.80
140	12.10	12.10	9.90	6.80	3.60	0.30	-2.90	-6.20	-9.50

Effect of product price

Table 22 looks at the effect of price on additional production. It is particularly noticeable that the optimum does not alter at the chosen prices. At a price level between Dfl.1.00 and 1.20 for the additional kilograms of tomatoes it stays at supplementary dosing up to a maximum 350 ppm. At a price level of Dfl.0.90 to/including 1.10 for the extra kilograms of cucumbers the optimum is between 350 and 400 ppm. Due to the low prices, the results soon drop and a greater number of dosing levels becomes unprofitable. The use of a heat buffer produces the best results at all price levels, however.

Conclusions

- *The best results are produced by using a heat buffer in combination with supplementary dosing to 350 ppm. Both flue gas and pure CO_2 can be used for this purpose.*
- *In terms of saving energy, pure CO_2 is preferable, providing a favourable purchase price can be negotiated.*
- *If purchasing a heat buffer is not an option, supplementary dosing to 350 ppm is just about still profitable when using both pure and flue gas CO_2.*
- *When using a heat buffer, increases in the gas or pure CO_2 price only have a minor effect on the results.*
- *The results of supplementary CO_2 dosing drop sharply with an increase in the gas or CO_2 price.*
- *A drop in product prices results in a lower supplementary dosing profit. However, the use of heat buffers remains profitable.*

Table 22 Effect of product price on increased business results through supplementary dosing with flue gas CO_2, with and without heat buffers in combination with nine different dosing systems. Comparisons are made with a crop where only CO_2 released by the heating during the day is dosed. Unit: Dfl./m^2, 1 Dfl. = € 0.45

Table 22a Tomatoes: production 44 kg/m^2, revenue Dfl. 61.60/m^2, gas consumption 52 m^3/m^2

Natural gas 25 ct/m^3

Heat buffer m^3/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
	Dfl. 1.00 per kg								
0	0.00	0.40	-0.50	-1.40	-2.50	-3.60	-4.90	-6.20	-7.70
100	3.30	3.40	2.00	0.80	-0.40	-1.80	-3.10	-4.50	-5.80
	Dfl. 1.10 per kg								
0	0.00	0.60	-0.10	-0.90	-1.70	-2.70	-3.90	-5.10	-6.50
100	4.20	4.30	3.00	1.80	0.70	-0.60	-1.80	-3.20	-4.50
	Dfl. 1.20 per kg								
0	0.00	0.70	0.30	-0.30	-1.00	-1.80	-2.90	-4.00	-5.30
100	5.10	5.20	4.00	2.90	1.80	0.60	-0.60	-1.90	-3.20

Table 22b Cucumbers: production 60 kg/m², revenue Dfl. 63.50/m², gas consumption 59 m³/m²

Natural gas 25 ct/m³

Heat buffer m³/ha	CO_2 dosing level (ppm)								
	none	350	400	450	500	550	600	650	700
	Dfl. 0.90/kg								
0	0.00	2.60	2.90	2.50	1.90	1.10	0.20	-0.90	-2.10
100	9.80	9.90	9.00	7.70	6.30	4.90	3.30	1.90	0.40
	Dfl.1.00/kg								
0	0.00	3.10	3.70	3.60	3.10	2.60	1.80	0.90	-0.20
100	11.70	11.80	10.90	9.60	8.30	6.90	5.40	4.00	2.50
	Dfl.1.10 per kg								
0	0.00	3.60	4.50	4.60	4.40	4.00	3.50	2.70	1.80
100	13.50	13.70	12.80	11.60	10.30	9.00	7.50	6.10	4.70

5.4 CO_2 AND HEAT MANAGEMENT

Businesses are increasingly using heat power systems (HP) to heat their greenhouses. Flue gases from HPs are not pure enough to be used for CO_2 dosing. If no flue gas purifier is available, the flue gases from the heating boiler are used.
The use of an HP without flue gas purification for heating purposes has a negative impact on the amount of available CO_2. If using an HP instead of, or in combination with, a boiler, it is always necessary to check that sufficient CO_2 will be available. The following example describes the effect of an HP on CO_2 management.

Gas consumption share for CO_2 dosing

Most businesses use flue gases from the boiler to dose CO_2. Without heat storage facilities, only the flue gases released by the heating during the day are available for CO_2 dosing. CO_2 dosing can be used to a greater extent when heat storage is used. The heat released is used for heating at night. The bars in figures 15, 16 and 17 show the heat requirement per m² per week for tomato crops. The bottom part of the block shows the consumption in m³ gas during the day, the upper part during the night. The lines in figure 15 also show the share of gas used for CO_2 purposes.
In winter, the CO_2 requirement is low because there is little ventilation. However, the heat requirement is high and therefore only a small proportion of the flue gases are used for CO_2 dosing. Between weeks 48 and 8 less than half of the amount of gas required for heating purposes during the day is needed to fulfill the CO_2 requirement. No gas consumption is required for heating during the night.
Between weeks 13 and 40, all the CO_2 released when heating the greenhouse during the day is used for dosing. This amount is not enough for optimum crop growth, more CO_2 is required! When a heat buffer is used, more CO_2 can be produced and the heat released during this process can be stored and used at night. Figure 15 also shows how much gas can be used during the day for supplementary CO_2 production with a 100 m3 per ha heat buffer. This is based on the assumption that the heat released during supplementary CO_2 production does not exceed the expected heat demand for the night. No heat is eliminated.

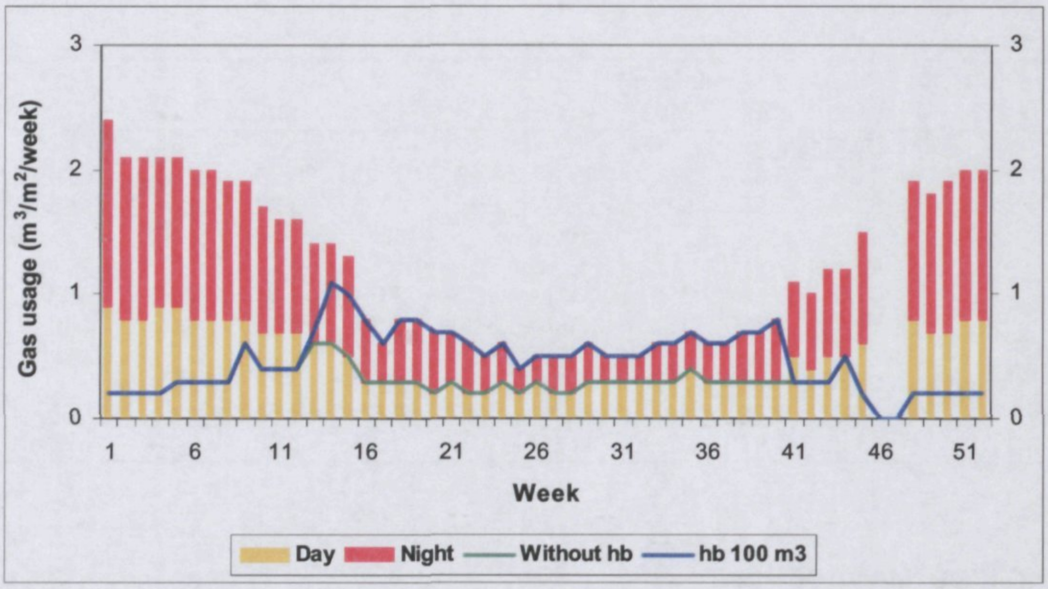
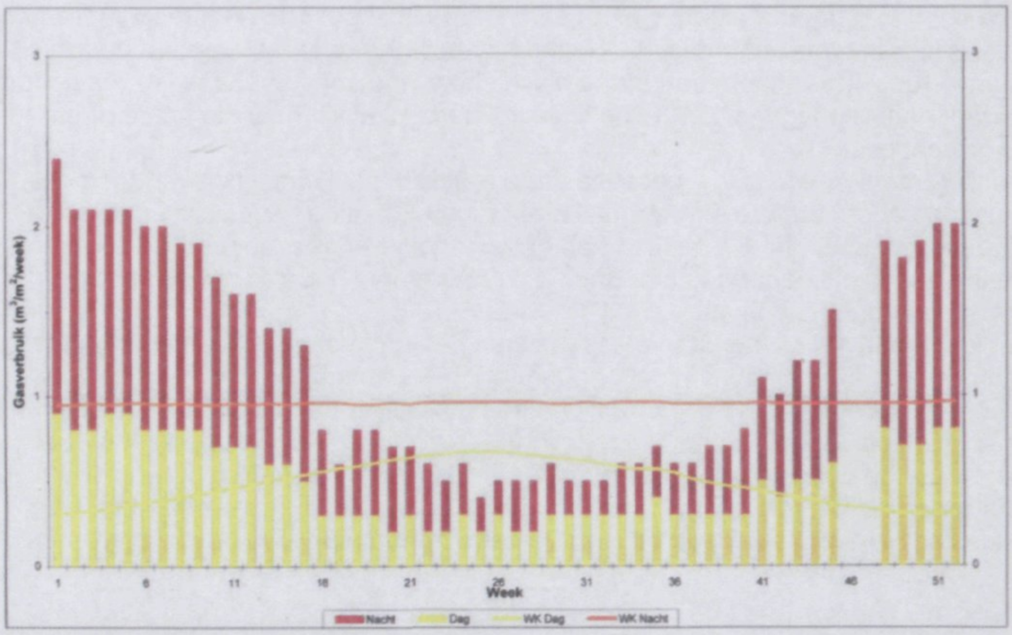


Figure 15 Gas consumption distribution without and with a heat buffer for a tomato crop (night time gas, day time gas, of which gas for CO_2 dosing). Gas unit: m^3/m^2/week.

Heat share of the HP

Figure 16 shows what share of the heat requirement for this tomato crop is supplied by the HP when it is operating continually. The HP has an electrical capacity of 300 kW and thermal capacity of 500 kW per ha. The thermal capacity is similar to that of a boiler of 430,000 kCal per hour. The HP does not supply sufficient heat between weeks 42 and 14, so that the boiler needs to provide additional heat. The rest of the year, the HP supplies more heat than necessary. If the HP only operates when there is a heat requirement, it will regularly be inactive.



Translation: gasverbruik = gas usage; nacht = night; dag = day.

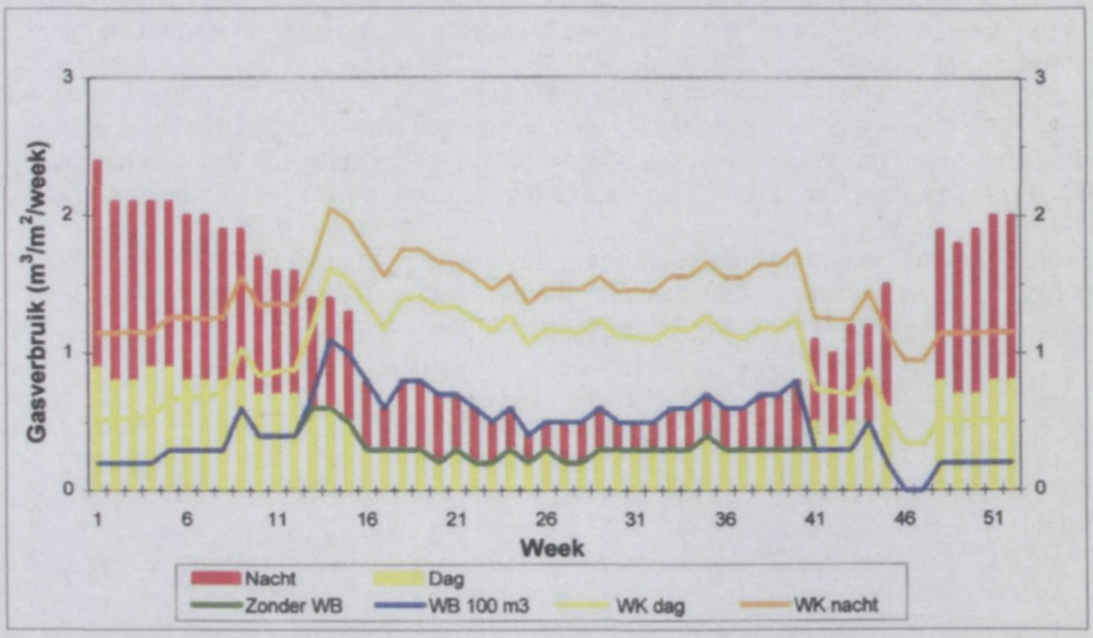
Figure 16 HP share in the total heat requirement of a tomato crop. (night time gas, day time gas and heat share by 300 kWel and 500 kWth HP). Unit: m^3 gas/m^2/week.

HP or CO_2 production

It is important to check when the use of the HP conflicts with the production of CO_2 by the boiler. Figure 17 is a combination of figures 15 and 16. The lines in 17 indicate how much gas is required for CO_2 dosing and how much heat is released when the HP is used. When compared to the heat requirement (bars) it becomes clear how much of the heat can be utilised. Between weeks 48 and 13, the gas consumption for heating purposes drops during the day from 0.8 to 0.6 m^3 gas per m^2 per week. The share for CO_2 dosing during this period increases from 0.2 m^3 to more than 0.6 m^3. Heat production by the HP between weeks 48 and 13 rises from approx. 0.3 to 0.5 m^3 per m^2 per week. The point at which the heat produced by the HP and the heat released during CO_2 production together exceed the heat requirement during the day is around week 9. This means that the HP can run without problems for CO_2 supply between weeks 48 and 8. Between weeks 13 and 41, all available flue gases are required for CO_2 dosing during the day. The use of an HP during this period immediately lowers the amount of CO_2 available from flue gases. This has a direct impact on production. If the HP is running and the boiler is used for CO_2 production, a heat surplus will be generated. Between weeks 9 and 41 a decision has to be made on whether to run the HP and supplement the desired amount of CO_2 in a different way, or to opt for the production of CO_2 via a boiler and switch off the HP.

The storage of surplus heat in a buffer offers a few weeks of respite, but even this will soon lead to heat surplus problems. If the HP is used at night during the summer, the stored heat cannot be used as the HP is already supplying enough heat. This means that no supplementary CO_2 can be produced the next day without heat elimination. Even if a heat buffer is used, the same choice will have to be made for summer nights, i.e. whether to produce supplementary CO_2 during the day and not to use a HP during the night or to use the HP at night and supplement CO_2 in a different way.

If the HP is selected, extra costs will be incurred to replace the CO_2 that would otherwise be produced by the boiler. These costs will have to be paid back from the extra savings resulting from the use of the HP.



Translation: gasverbruik = gas usage; nacht = night; dag = day.

Figure 17 Gas consumption distribution for heat, buffer, HP and CO_2 dosing. (night time gas, day time gas, gas share for CO_2 dosing and heat share by 300 kWel and 500 kWth HP). Unit: m^3 gas/m^2/week

Conclusion

- *The use of a heat buffer extends the option to dose CO_2 during the day.*
- *The use of an HP without flue gases suitable for dosing soon competes with CO_2 production by the boiler during the summer.*
- *With tomato crops, the HP has to be switched off during the day between weeks 8 and 45 because of the requirements for a CO_2 supply.*
- *The use of a heat buffer for CO_2 production further reduces the number of effective operating hours for the HP for heat production.*

5.5 HOW MUCH SHOULD FLUE GAS PURIFICATION COST WITH A HP?

Section 5.4 explains why it is necessary to choose between heat and CO_2 production via the boiler or heat production via an HP system and the use of CO_2 from another source during the summer. A suitable alternative is now available based on the purification of flue gases from the HP. With flue gas purification the HP can now be used throughout the year for CO_2 dosing without any problems. This section calculates the acceptable annual costs for flue gas purification with an HP for a number of crops.

Benefits of flue gas purification

With flue gas purification, the HP can be used without problems throughout the year for CO_2 supplies, it even supplies additional CO_2. With a boiler most of the energy in natural gas is converted into heat. Depending on the boiler and the use of a condenser the output is between 90 and 105% lower value. The heat output from the HP is between 50 and 55%. More natural gas than with the boiler is needed to produce the same amount of heat with an HP. Because of the increased gas consumption, more CO_2 is available for dosing after purification of the flue gases.

Table 23 shows the effect on gas consumption and CO_2 with an HP with a thermal capacity of 500 kW per hectare for various crops. Column 1 shows the additional gas consumption relative to heating with the boiler if the HP always operates with a heat demand. Column 2 shows how much is used during the day.

Not all the extra CO_2 released after flue gas purification is required for CO_2 dosing. In winter, the demand for CO_2 is low and enough CO_2 is available anyway because the boiler is operating for heating purposes. Columns 3 and 4 indicate how many m3 gas can be utilised for CO_2 dosing; column 3 is based on no heat buffer and column 4 on a 100 m^3 per ha heat buffer.

In columns 5 and 6, the amount of extra natural gas that can be used for dosing is converted into extra kg CO_2. An HP uses more gas to fill the heat buffer. As a result, more CO_2 is available with an HP with a heat buffer than when filling with the boiler.

Table 23 Additional gas consumption (m^3/m^2 per annum) and additional CO_2 production (kg CO_2/m^2/annum) when using a 500 kW/ha HP system as the basic heating system, supplemented with heat from the CH boiler, compared to the same heat production by the CH boiler. Calculations are based on a situation without and a situation with a 100 m^3/ha heat buffer.

Unit	Gas consumption for heating		Gas consumption for CO_2 dosing		Gas consumption for extra CO_2 dosing	
	24 hr period	during day	without buffer	with buffer 100 m3	without buffer	with buffer 100 m3
column number	1	2	3	4	5	6
Tomatoes	36.9	16.0	8.0	10.8	14.5	19.4
Peppers	33.4	13.7	6.5	9.8	11.8	17.6
Cucumbers	38.2	17.2	9.6	10.8	17.3	19.4
Cultivation vegetable plants	35.1	14.2	5.5	9.7	10.0	17.4
Roses	33.5	13.8	6.1	9.8	11.0	17.6
Chrysanthemums	35.8	15.9	7.7	10.6	13.8	19.1
Orchids	33.9	13.8	5.6	10.3	10.2	18.6
Pot plants	26.0	6.4	2.6	7.4	4.7	13.3
Other floristry crops	43.3	30.5	3.4	6.1	6.0	11.0

Spending range

The main objective of flue gas purification is to replace the CO_2 released without using the HP during heat production by the boiler. The HP uses more gas in excess of this quantity and therefore more CO_2 is available. To calculate the acceptable maximum additional costs per annum, it is necessary to calculate whether, and how, the same amount of supplementary CO_2 can be obtained. This supplementary quantity of CO_2 can be produced by the boiler, in combination with the use of a heat buffer if necessary, or by using pure CO_2. The extra annual costs of the cheapest way to obtain this amount of CO_2 is the maximum acceptable amount to be spent on flue gas purification. Flue gas CO_2 costs the same per kg as one m^3 of natural gas divided by 1.8. With a gas price of 25 ct this amounts to 13.9 ct per kg, whereas pure CO_2 is between 20 and 30 ct per kg (1997 price level). This makes flue gas CO_2 the cheapest option.

To calculate the spending range of flue gas purification the supplementary produced CO_2 is valued at 13.9 ct. Table 24 shows the maximum annual costs for various crops. These are calculated for businesses without a heat buffer and with a 100 m^3 per hectare heat buffer. The increase in production from supplementary CO_2 is not taken into account in the calculation of the maximum annual cost of flue gas purification. This is because this increase in production is achieved with all other supplementary CO_2 supply methods so that it need not be included in the comparison.

Conclusions

- *The spending range for flue gas purification depends on the heat requirement in the summer. The higher the heat requirement and associated gas consumption during the summer, the higher the spending range.*
- *The use of a heat buffer results in a wider spending range during the night because of the utilisation of the heat requirement.*
- *On average Dfl. 15,000 per hectare can be spent on flue gas purification per annum without a heat buffer and Dfl. 23,500 with a heat buffer. This needs to pay for the associated investment and running costs.*

Table 24 Maximum annual cost for the purification of flue gases from heat power systems on the basis of the costs for the production of additional CO_2 using the boiler, with a gas price of 23 ct per m^3.

Unit:	Annual costs in Dfl./ha	
	Without heatbuffer	With 100 m3 heatbuffer
Tomatoes	20,100	26,900
Peppers	16,400	24,500
Cucumbers	24,000	26,900
Cultivation of vegetable plants	13,900	24,200
Roses	15,300	24,500
Chrysanthemums	19,200	26,600
Orchids	14,100	25,800
Pot plants	6,600	18,500
Other floristry crops	8,400	15,300
Average	15,300	23,700
Average with and without heat buffer	18.600	

5.6 HOW MUCH SHOULD CO_2 STORAGE FROM FLUE GASES COST?

Greenhouse horticulture businesses consume on average 45 m^3/m^2 of natural gas per annum to heat their greenhouses. This produces more than 80 kg CO_2 per m^2. CO_2 production does not coincide with CO_2 demand. The question is often asked of whether it is possible to store excess CO_2 during the winter for use later when there is a shortage of CO_2. This section calculates how much CO_2 needs to be stored to maintain a minimum concentration of 340, 400 or 450 ppm throughout the year. This is followed by a calculation of the maximum CO_2 storage cost per annum.

Available CO_2

The available amount of CO_2 depends entirely on the crop's heat requirement. The higher the gas consumption the higher the amount of available CO_2. With fruit vegetables between 80 and 110 kg CO_2 per m^2 is available per annum. With ornamental crops this is between 50 and 90 kg per m^2 per annum overall. 25 to 50% of this CO_2 is released during the day. Approximately 75% of the CO_2 is made available during the winter and the rest between May and September.

The amount of CO_2 that can be stored depends on the minimum CO_2 content used. When a CO_2 content of minimum 340 ppm is used, an average of 58 kg CO_2 per m^2 per annum is not used and is therefore available for storage. With 400 ppm, 52 kg CO_2 per m^2 per annum is left over and with 450 ppm only 50 kg CO_2 per m^2 per annum.

More CO_2 is available with crops with a high heat requirement and the CO_2 content is higher than with crops with a low heat requirement. With a low temperature requirement the CO_2 content is often below 340 ppm and more supplementary CO_2 is required. If, with a heat demand during the day, all available CO_2 is dosed to a maximum of 1,000 ppm and with an insufficient heat demand to a minimum of 340 ppm, an average of 28 kg CO_2 per m^2 per annum will be dosed. In order to maintain a minimum CO_2 content of 400 ppm, an average of 44 kg CO_2 per m^2 per annum is required, for 450 ppm the amount is 58 kg CO_2 per m^2. A CO_2 requirement does not always coincide with the production of heat and CO_2, so that supplementary dosing is required.

Supplementary CO_2 dosing

The amount of supplementary CO_2 required to maintain a minimum CO_2 content of 340, 400 or 450 ppm during the day, also depends on the amount of CO_2 made available during heating and the amount escaping via the ventilation. The higher the gas consumption for heating purposes, the higher the available amount of CO_2 and the lower the need for supplementary CO_2. This applies in particular during the summer. Table 25 shows the requirement for supplementary CO_2 for various crops with three minimum CO_2 content levels. In order to maintain a minimum of 340 ppm throughout the year about 4 of the above mentioned 28 kg per m^2 supplementary CO_2 is required, for 400 ppm on average 20 of the 44 kg supplementary CO_2 is required. At 450 ppm 34 of the 58 kg supplementary CO_2 is required. With crops with a low heat requirement, such as summer flowers and many pot plants, this amount of CO_2 is not available from the flue gases on an annual basis.

Table 25 Amount of supplementary CO_2 required each year to maintain a minimum CO_2 level in excess of the amount of CO_2 made available by heating during the day. If lower than the requirement, the available quantity is shown in brackets. Unit: kg CO_2/m^2 per annum.

Crop	CO_2 shortage, and/or to be supplemented from CO_2 storage		
	340 ppm	400 ppm	450 ppm
Tomatoes	2.7	18.4	32.4
Peppers	4.9	21.1	35.1
Cucumbers	1.3	15.1	29.0
Cultivation vegetable plants	5.1	22.1	36.4
Average vegetables	**3.5**	**19.2**	**33.2**
Roses	5.3	21.6	35.7
Chrysanthemums	3.4	19.3	33.3
Orchids	5.2	22.1	36.3
Average cut flowers	**4.6**	**21**	**35.1**

Storage capacity

A storage tank is required to store CO_2 throughout the year. The size of the tank is defined by the difference between the available CO_2 and the CO_2 demand. As spring approaches the CO_2 requirement frequently exceeds the CO_2 supply. Initially, this can be compensated for by storing the CO_2 produced the night before. However, as summer approaches the total amount of CO_2 available each 24 hour period will no longer be sufficient. Access to a CO_2 stock is necessary. The size of the CO_2 stock is determined by adding together the shortages accrued during the day throughout the entire summer. The largest sum of these shortages determines the storage capacity. Table 26 shows the size of the required storage capacity for CO_2 from flue gas in order to have sufficient

CO_2 to maintain the desired minimum CO_2 content. For 340 ppm the average is 7 ton per hectare, for 400 ppm 80 tonnes for vegetables and approximately 100 tonnes for ornamental crops. The required capacity for 450 ppm varies from 200 tonnes for vegetables to more than 225 tonnes for cut flowers.

This relates solely to the storage of separated CO_2. It is possible to store flue gases to save on the cost of separating CO_2. The CO_2 concentration in flue gases never exceeds 11.7%. Storing the necessary flue gases means that ten times the amount of storage capacity for CO_2 is required.

Table 26 Required storage capacity to separate CO_2 from the heating flue gases for CO_2 supply during the day with 340, 400 and 450 ppm as minimum CO_2 content.
Unit: tonnes CO_2/ha

Crop	Capacity -storage 340 ppm	400 ppm	450 ppm
Tomatoes	7	70	190
Peppers	7	95	220
Cucumbers	3	40	140
Cultivation vegetable plants	7	120	245
Average vegetables	**6**	**81**	**199**
Roses	7	95	220
Chrysanthemums	7	90	210
Orchids	7	120	255
Average cut flowers	**7**	**102**	**228**

Spending range

The objective of storing CO_2 from flue gases is to store the available CO_2 for use when insufficient CO_2 is available to maintain the desired CO_2 content. Alternatively, supplementary flue gas CO_2 can be produced or pure CO_2 dosed when insufficient CO_2 is available. The annual flue gas storage cost must not exceed the cheapest alternative. With the current price ratios between pure and flue gas CO_2, the production of extra CO_2 using a boiler is the cheapest option. The spending range is calculated by multiplying the required or, if it is less, the available CO_2 quantity by the price of flue gas CO_2, i.e. 13.9 ct per kg. Table 27 includes the maximum annual costs, calculated on the basis of this method, for the various crops and CO_2 contents. The investment and running costs are paid for from these amounts.

The maximum acceptable spending range to maintain a minimum CO_2 content of 340 ppm is Dfl. 5,000 per hectare per annum for vegetables and Dfl. 6,333 for flowers. To maintain a minimum of 400 ppm between Dfl. 25,000 and Dfl. 30,000 per hectare per annum is required, to maintain 450 ppm this just over Dfl. 46,000 per hectare per annum. If the annual interest, depreciation, maintenance, insurance and running costs are on average 20% of the investment amount, approximately Dfl. 28,000, 137,500 and 230,000 respectively can be spent on storage and possible separation of CO_2 from flue gas.

Table 27 Spending range for separating and storing CO_2 flue gases from natural gas fired CH boilers on the basis of 1.8 kg CO_2 per m^3 natural gas and a natural gas price of 25 ct/m^3. Unit: Dfl./ha

Crop	Maximum annul cost CO_2 separation and storage 340 ppm	 400 ppm	 450 ppm
Tomatoes	4,000	25,500	45,000
Peppers	7,000	29,500	49,000
Cucumbers	2,000	21,000	40,500
Cultivation vegetable plants	7,000	30,500	50,500
Average vegetables	**5,000**	**26,625**	**46,250**
Roses	7,500	30,000	49,500
Chrysanthemums	4,500	27,000	46,500
Orchids	7,000	30,500	50,500
Average cut flowers	**6,333**	**29,000**	**48,800**

Conclusions

- *When greenhouses are heated with natural gas burners sufficient CO_2 is usually released to maintain a minimum content between 350 and 450 ppm. However, the demand for CO_2 often does not coincide with the production of CO_2 and therefore large amounts of CO_2 are not utilised.*
- *With most crops the storage of unused CO_2 for use at times of insufficient CO_2, it is possible to maintain a minimum content between 350 and 450 ppm.*
- *The maximum annual cost for separating and storing CO_2 from flue gases depends on the desired CO_2 content and the amount of CO_2 that needs to be stored.*
- *The maximum acceptable annual costs vary between an average of Dfl. 5,500 per ha to maintain a minimum CO_2 content of 340 ppm and Dfl. 46,000 with a minimum of 450 ppm.*
- *This requires an average of 7 tonnes CO_2 storage capacity per ha at 340 ppm and more than 200 tonnes at 450 ppm. The storage capacity for flue gas is 70 and 2000 tonnes respectively.*

5.7 REGIONAL HEAT AND CO_2 MANAGEMENT

In addition to individually installed heat power (HP) systems, an increasing number of areas are using "regional heat", heat supplied by an outside supplier. This is usually heat generated during the production of electricity. Typical examples include the Plukmadesepolder with heat from the Amer power station, the B-Triangle with heat and CO_2 from the ROCA power station and two 50 MegaWatt power stations in Erica and Klazinaveen that supply heat to the outlying area. The use of regional heat for greenhouse heating contributes to improved fuel utilisation for electricity production. Regional heat is cheaper than heat produced individually by businesses. If CO_2 is not supplied at the same time, the use of regional heat can have disadvantages. As not all the heat is produced locally by the business, the CO_2 that would otherwise be released during heating with the boiler, is not available. The CO_2 content in the greenhouse becomes lower than it would be if regional heat were not used. This also has an impact on production.
This section describes the consequences for the CO_2 supply if heating comes from regional heat, supplemented by heat from the on-site boiler and **no** CO_2 is supplied together with the regional heat.

Gas consumption share for CO_2 dosing

Most businesses use flue gases from the boiler to dose CO_2. Without heat storage, these are just the flue gases released when heating during the day. With heat storage this can be supplemented by additional flue gas CO_2, the heat from which is used during the night following storage. As shown in section 5.4 on the HP, sufficient CO_2 is available during the winter. Between weeks 48 and 8 less than half of the amount of gas required for heating purposes during the day is needed to fulfill the CO_2 requirement. No CO_2 is needed for heating during the night. Between weeks 13 and 40 all the CO_2 released when heating the greenhouse during the day is used for dosing. With a 100 m^3 per ha heat buffer most of the CO_2 released during the day is used during the same period. The stored heat is used during the night.

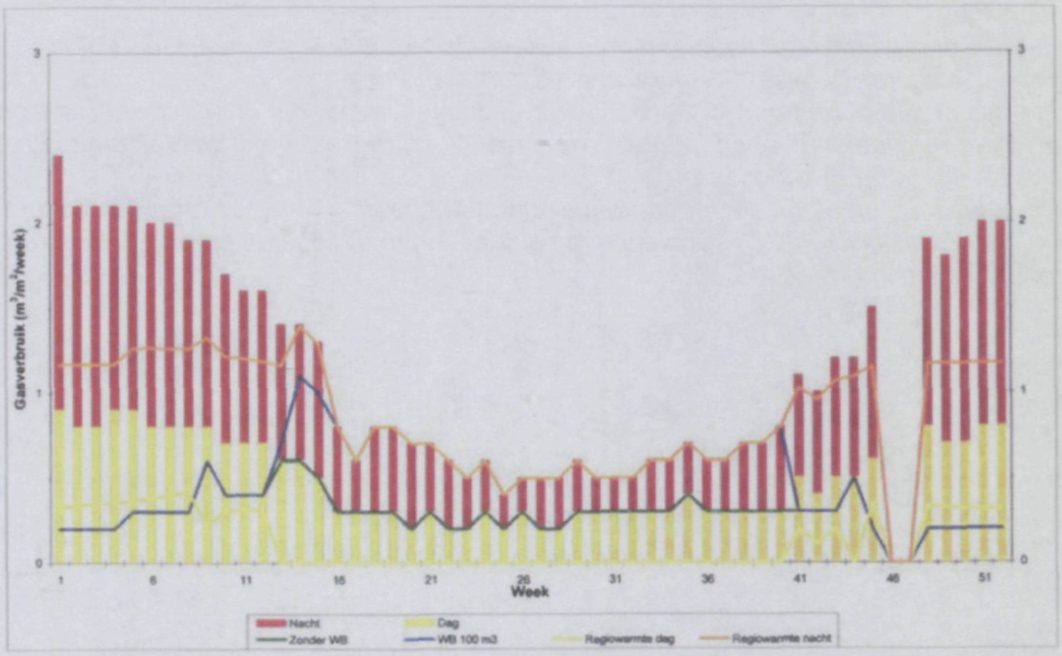
Table 28 shows how much CO_2 is made available each year, as a result of natural gas combustion to heat the greenhouse for various crops. Columns 2 and 3 show the share made available during the day and at night respectively. Columns 5, 6 and 7 indicate how much CO_2 is being dosed if a maximum of 1000 ppm and a minimum of 340, 400 and 450 ppm respectively is maintained.

Heat share of regional heat

Figure 18 shows what share of the heating requirement of the same tomato crop is supplied by regional heat if it acts as the primary heat source. The regional heat is calculated with a thermal capacity of 500 kW per ha. The thermal capacity is similar to that of a boiler of 430,000 kCal per hour. Regional heat does not supply sufficient heat between weeks 42 and 14, therefore the boiler needs to provide additional heat. The rest of the year, regional heat supplies more heat than necessary. This means that regional heat is partly, or even completely, unused during specific parts of the day.

Table 28 Overview of the amount of available CO_2 from natural gas for the heating, CO_2 requirement for dosing between maximum 1,000 ppm and, with insufficient CO_2, refilling to minimum 340, 400 or 450 ppm. Unit: kg CO_2/m^2/annum)

Crop	CO_2 available			CO_2 utilised		
	day	night	sum	340	400	450
Tomatoes	44	61	106	30	45	59
Peppers	38	43	80	28	44	58
Cucumbers	48	62	110	31	45	59
Vegetable plants	45	74	119	28	45	59
Roses	29	41	70	29	45	59
Chrysanthemums	34	59	93	30	45	59
Orchids	36	50	86	28	45	59
Other floristry	22	26	48	26	43	57
Pot plants	12	38	49	23	41	55
Average	**34**	**50**	**85**	**28**	**44**	**58**



Translation: gasverbruik = gas usage; nacht = night; dag = day; regiowarmte = regional heat.

Figure 18 Distribution tomato crop gas consumption figures (night time gas, day time gas) and share of regional heat with a capacity of 500 kWth). Unit: m^3 gas/m^3/week.

Regional heat or CO_2 production

As with heat power the regional heat can be used between weeks 48 and 8 without any problem for the CO_2 supply. Around week 8 regional heat will start to clash with CO_2 production. Between weeks 13 and 41 all flue gases are used for CO_2 dosing. The use of regional heat during the day will then reduce the amount of CO_2 available. This has a direct impact on production. To prevent this effect when regional heat is used, pure CO_2 needs to be dosed or the on-site boiler must be operated simultaneously for the production of CO_2. The latter case, there is a heat surplus. If the heat surplus is stored in the buffer, no or less regional heat can be used during the night. If regional heat is used during the night as well, the buffer will not be emptied and cannot be refilled the next day. In this case, no supplementary CO_2 can be produced without heat elimination.

With tomatoes 19 kg CO_2 per m^2 is utilised throughout the summer without a heat buffer from flue gases released when heating the greenhouse with the boiler and 30 kg CO_2 with a 100 m^3 per ha heat buffer. When using regional heat, the amount of CO_2 needs to be supplemented to prevent production loss. It is necessary to decide, therefore, whether to continue to use regional heat and dose sufficient supplementary CO_2, or to use the boiler instead of regional heat during the summer. The above 19 and 30 kg CO_2 relate to a gas consumption of 10 and 16 m^3 respectively. If regional heat qualifies for a 10% discount and the gas price is 20 ct, the amount of replacement CO_2 must not cost more than 20 to 32 ct.

In fact, a contract for the supply of heat by third parties without the necessary CO_2 arrangements represents a backwards step in terms of self sufficiency.

Conclusion

- *The use of regional heat soon competes with CO_2 production via the boiler. With tomato crops this occurs between weeks 8 and 45 during the day.*
- *The use of a heat buffer for CO_2 production reduces the number of effective utilisation hours for regional heat even further. Extensive use of regional heat without supplementary CO_2 results in production loss.*
- *When drawing up plans and/or contracts for central heating supplies for a horticultural area, the possibility of CO_2 supplies or a contribution to the cost of pure CO_2 for example, should be incorporated.*

Glossary

respiration	Exchange of CO_2 and O_2. Sugars are oxidised (respirated) with absorption of O_2 and release of CO_2, and the stored energy is released again.
assimilation	Conversion of CO_2 into sugars. Storage of energy (from light) in sugars while absorbing CO_2 and releasing O_2.
gross photosynthesis	Actual binding of light energy in organic substances (sugars).
upper value (u.v.)	See pages below.
toxic gases	Toxic gases created during incomplete combustion.
CO_2 compensation point	CO_2 concentration at which the same amount of CO_2 is absorbed and released.
dew point	Temperature at which the water vapour in the flue gas starts to condensate. Approximately 59°C.
dissimilation	Respiration, breaking down of sugars.
dosing gas	Flue gas mixed/not mixed with outside air that is used to increase the CO_2 concentration in the greenhouse.
dosing value	The quantity of natural gas (m^3), burned per hectare per hour to increase the CO_2 concentration in the greenhouse.
photorespiration	Light-dependent O_2 absorption and CO_2 production.
photosynthesis	Binding of light energy in organic substances (sugars), in which process CO_2 is used.
light compensation point	Light intensity at which the same amount of CO_2 is absorbed and released.
air surplus	See pages below.
air factor(λ)	See pages below.
net photosynthesis	Gross photosynthesis minus photorespiration.
net assimilation	Net photosynthesis.
lower value (l.v.)	See pages below.
ppm	Parts per million, 1 ppm = 1 part gas per million parts air = 1 ml/m^3.
ppb	Parts per billion, 1 ppb = one thousandth of one ppm.

respiration	Breathing.
"retro-fit"	Replacement of existing burner with low NO_x burner.
flue gas	Combustion gas from the boiler. Is discharged via the chimney or used (partially) for CO_2 dosing.
stoichiometric combustion	Combustion where there is precisely the right quantity of air for complete combustion of the fuel.
ventilation multiple	Number of times the greenhouse air is refreshed per hour.
ventilation loss	Amount of carbon dioxide that escapes as a result of ventilation.
hymidity deficit	Difference in water vapour content between saturated air (in the leaf) and the (surrounding) non-saturated air.
heat/power (H/P)	Device, usually a gas motor with a current generator that produces both heat and a current (power).
swan neck	Siphon. A U-shaped tube with water connected to the main CO_2 line, through which water from the main line, but not CO_2, can flow.

Air surplus and air factor (λ)
The air surplus is the additional air percentage required above the theoretical 100% in order to achieve complete combustion.
The air factor (λ) is the stated 100% plus the air surplus, divided by the theoretically required quantity.
Example: in theory 8.41 m^3 of air is required for the complete combustion of 1 m^3 natural gas. If the burner uses 9.25 m^3 the air factor(λ) is: 9.25/8.41 = 1.1. In this case, the air surplus is (9.25-8.41)/8.41 = 10%.

Upper value (u.v.) = Gross Caloric Value (GCV)
The amount of heat released during the complete combustion of a quantity of dry (natural) gas with oxygen, if the combustion gases are cooled back down to the start values and the water generated during combustion is in the liquid phase after cooling (the u.v. for our natural gas is: 35.17 MJ/ m^3, or 8400 kcal/ m^3).

Lower value (l.v.) = Net Caloric Value (NCV)
The amount of heat released during the complete combustion of a quantity of dry (natural) gas with oxygen, if the combustion gases are cooled back down to the start values and the water generated remains in the gas phase (not condensed). (the l.w. for our natural gas is: 31.65 MJ/ m^3, or 7560 kcal/ m^3).

The difference between the upper and lower value is the evaporation heat of the water produced during combustion.

Literature

Greenhouse Horticulture Heating Manual. (published by: Nutsbedrijf Westland N.V. en Misset publishers bv)

PBG Report 47 Influence of CO_2 on the production and quality of pot plants and cut flowers

CO_2 and greenhouse problems. NRLO report no. 88/15, 1988

Energy in greenhouse horticulture in the Netherlands: sector and business developments up to 1997; N.J.A van der Velden; R. Bakker en A.P. Verhaegh, Den Haag October 1998. LEI-DLO Periodic Reports 39-96 63. page

Nederhoff E.M. 1994. Effects of CO_2 concentration on photosynthesis, transpiration and production of greenhouse fruit vegetable crops. Thesis.

Greenhouse Crop Technology, Greenhouse Horticulture Energy Management. M. Dumont, HAS Den Bosch, November 1997

Polytechnic Notebook, Koninklijke PBNA bv