



Title: Carbon Dioxide In Greenhouses

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Introduction

The benefits of carbon dioxide supplementation on plant growth and production within the greenhouse environment have been well understood for many years.

Carbon dioxide (CO₂) is an essential component of photosynthesis (also called carbon assimilation). Photosynthesis is a chemical process that uses light energy to convert CO₂ and water into sugars in green plants. These sugars are then used for growth within the plant, through respiration. The difference between the rate of photosynthesis and the rate of respiration is the basis for dry-matter accumulation (growth) in the plant. In greenhouse production the aim of all growers is to increase dry-matter content and economically optimize crop yield. CO₂ increases productivity through improved plant growth and vigour. Some ways in which productivity is increased by CO₂ include earlier flowering, higher fruit yields, reduced bud abortion in roses, improved stem strength and flower size. Growers should regard CO₂ as a nutrient.

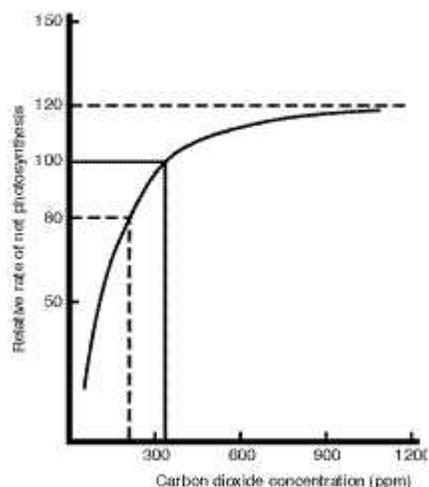
For the majority of greenhouse crops, net photosynthesis increases as CO₂ levels increase from 340–1,000 ppm (parts per million). Most crops show that for any given level of photosynthetically active radiation (PAR), increasing the CO₂ level to 1,000 ppm will increase the photosynthesis by about 50% over ambient CO₂ levels. For some crops the economics may not warrant supplementing to 1,000 ppm CO₂ at low light levels. For others such as tulips, and Easter lilies, no response has been observed.

Carbon dioxide enters into the plant through the stomatal openings by the process of diffusion. Stomata are specialized cells located mainly on the underside of the leaves in the epidermal layer. The cells open and close allowing gas exchange to occur. The concentration of CO₂ outside the leaf strongly influences the rate of CO₂ uptake by the plant. The higher the CO₂ concentration outside the leaf, the greater the uptake of CO₂ by the plant. Light levels, leaf and ambient air temperatures, relative humidity, water stress and the CO₂ and oxygen (O₂) concentration in the air and the leaf, are many of the key factors that determine the opening and closing of the stomata.

Ambient CO₂ level in outside air is about 340 ppm by volume. All plants grow well at this level but as CO₂ levels

are raised by 1,000 ppm photosynthesis increases proportionately resulting in more sugars and carbohydrates available for plant growth. Any actively growing crop in a tightly clad greenhouse with little or no ventilation can readily reduce the CO₂ level during the day to as low as 200 ppm. The decrease in photosynthesis when CO₂ level drops from 340 ppm to 200 ppm is similar to the increase when the CO₂ levels are raised from 340 to about 1,300 ppm (Figure 1). As a rule of thumb, a drop in carbon dioxide levels below ambient has a stronger effect than supplementation above ambient.

Figure 1. The effect of carbon dioxide on net photosynthesis.



During particular times of the year in new greenhouses, and especially in double-glazed structures that have reduced air exchange rates, the carbon dioxide levels can easily drop below 340 ppm which has a significant negative effect on the crop. Ventilation during the day can raise the CO₂ levels closer to ambient but never back to ambient levels of 340 ppm. Supplementation of CO₂ is seen as the only method to overcome this deficiency and increasing the level above 340 ppm is beneficial for most crops. The level to which the CO₂ concentration should be raised depends on the crop, light intensity, temperature, ventilation, stage of the crop growth and the economics of the crop. For most crops the saturation point will be reached at about 1,000–1,300 ppm under ideal circumstances. A lower level (800–1,000 ppm) is recommended for raising seedlings (tomatoes, cucumbers and peppers) as well as for lettuce production. Even lower levels (500–800 ppm) are recommended for African violets and some Gerbera varieties. Increased CO₂ levels will shorten the growing period (5%–10%), improve crop quality and yield, as well as, increase leaf size and leaf thickness. The increase in yield of tomato, cucumber and pepper crops is a result of increased numbers and faster flowering per plant.

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Sources Of Carbon Dioxide

Carbon dioxide can be obtained by burning carbon-based fuels such as natural gas, propane, and kerosene, or directly from tanks of pure CO₂. Each source has potential advantages and disadvantages. When natural gas, propane or kerosene is burned, not only CO₂ is produced, but also heat is generated that can supplement the normal heating system. However, incomplete combustion or contaminated fuels may cause plant damage. Most sources of natural gas and propane have sufficiently low levels of impurities, but notify your supplier of your intention to use the fuel for CO₂ supplementation. Sulphur levels in the fuel should not exceed 0.02% by weight. Combustion of fuels also generates moisture. For natural gas it is estimated that about 1.4 kg of water vapour is generated for each m³ of gas burned. For propane the amount of moisture generated per kg of CO₂ is slightly less than it is for natural gas.

Natural gas, propane and liquid fuels are burned in specialized CO₂ generators located throughout the greenhouse. (Plate 1). The size of the unit (BTU's produced) and the degree of horizontal airflow in the greenhouse determine the number and the location of these units. The most important feature of a burner should be that it burns the fuel completely. Some manufacturers make burners in which either natural gas or propane can be used, as well as units with adjustable outputs. A potential disadvantage of this system is that the heat generated by these units may have a localized effect on temperature and disease incidence (i.e. powdery mildew and Botrytis), particularly in tall growing crops.

Alternatively, a portion of the flue gas from natural gas boilers connected to hot water heating systems can be directed into the greenhouse as a means of supplementing CO₂ to the crop. The boiler must be equipped with a flue gas condenser specifically designed for this purpose. (Plate 2)

Plate 1. Carbon dioxide generator.**Plate 2.** Hot water boiler with flue gas condenser.

Note: not all boilers, particularly older boilers, are designed for this task. Natural gas boilers must burn cleanly, generating low or no nitrogen oxides (NOx) or ethylene. Contact your boiler manufacturer before proceeding. All equipment must be CSA approved or equivalent.

This allows for safe flue gas introduction into the greenhouse. The flue gases are extracted where the boiler connects to the stack. These units are designed to reduce the temperature and moisture impact on the greenhouse environment, and have monitoring systems that safe guard against flue gas introduction when the carbon monoxide (CO) level is higher than a set level (usually 6–10 ppm). The system is designed with a small capacity ventilator with low suction resulting in a fixed volume of the flue gases. A second ventilator is used to mix the flue gases with the greenhouse air and then the mixture is introduced throughout the greenhouse. This system provides the flexibility to introduce the CO₂ low within the crop and allowing it to rise through the crop before exiting the vents. The delivery system must be designed to ensure even distribution throughout the greenhouse ([Plates 3 & 4](#)). In order to increase efficiency and to provide CO₂ during the day when there is no requirement for heat, a hot water heating system equipped with an insulated hot water storage tank is used. The size of the tank may vary from 30–130 m³/ha of greenhouse. The heat generated by the boiler during the day is stored in the tank and is used at night as required ([Plate 5](#)). Summer CO₂ supplementation using flue gas can be achieved as long as the stored heat is used during the night. In some cases during the summer months the stored heat is not required as the outside night temperature remains higher than 22°C. In this situation CO₂ application is limited.

Plate 3a. CO₂ condenser and blower.**Plates 3b.** Flue gas CO₂ distribution pipes.



Plates 3c. Flue gas CO₂ distribution pipes.



Plates 3d. Flue gas distribution in greenhouse.



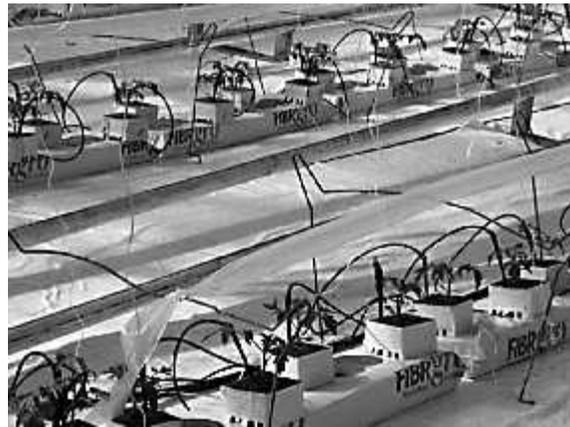
Plates 3e. Flue gas distribution in greenhouse.



Plate 4. Flue gas CO₂ distribution in greenhouse through clear polyethylene tubes.



Plate 5. Hot water tank to store heat when supplementing with flue gas CO₂.



Plates 6a. Liquid CO₂ tanks.



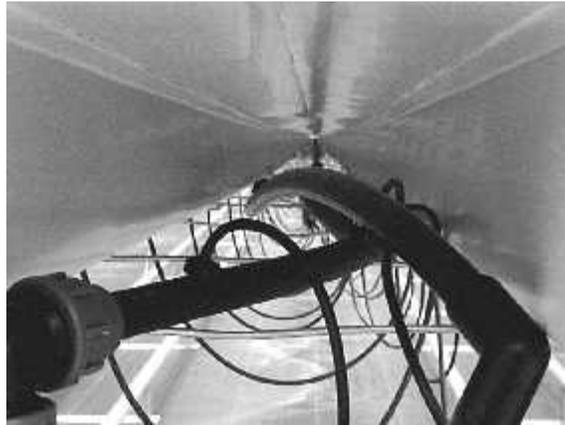
Plates 6b. Liquid CO₂ tanks.



Plate 7. Liquid CO₂ vaporizer.



Plate 8. Liquid CO₂ distribution pipes located below raised trough system.



Liquid carbon dioxide has become popular for many growers even though it is usually more expensive. The main advantages of using liquid CO₂ include purity of product, no concerns about crop damage, nor heat or moisture production, better control of CO₂ levels and the flexibility to introduce the CO₂ within the plant canopy at any time. Pure CO₂ is delivered in bulk by truck to the greenhouse. Special storage tanks rented from the supplier are required at every site ([Plate 6](#)). The compressed CO₂ is in a liquid state and must be vaporised through vaporiser units ([Plate 7](#)). The distribution system for liquid CO₂ in the greenhouse is simpler to design and install. Most growers use 18 mm black flexible polyvinyl chloride (PVC) tubing with holes punched at an appropriate spacing ([Plate 8](#)). For a small operation the CO₂ may be supplied in cylinders.

When growers still growing in soil incorporate or surface apply animal manure or other organic materials, such as straw, levels of CO₂ in the greenhouse will be increased during the breakdown process. The amount of CO₂ produced depends on the stability of the mulch and the activity of the microorganisms, which convert the organic material into CO₂. Production of CO₂ from rotting manure will only be significant for about one month following incorporation. In some cases organic growing media such as coconut coir will increase the CO₂ level in the greenhouse to 1,200 ppm during the night. This is usually not a problem, as the levels will drop quite rapidly at daylight.

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Supplementation Levels For Carbon Dioxide

Today, most growers monitor and control the greenhouse environment with sensors linked to a central computer to allow integration of the different environmental factors. A carbon dioxide controller, usually an infrared gas analyser (IRGA) is used to monitor and maintain the minimum and maximum CO₂ level in the greenhouse. Usually a single IRGA is used per operation. Multiple readings within individual compartments or from different zones can be obtained by using a scanner or a multiplexer. The IRGA unit can be stand-alone or, as in most cases, connected to the environment control computer. In the latter case the environment control computer is used to control the CO₂ level, through integration with light levels, stage of ventilation, and wind speed. Infra red gas analysers require routine calibration to insure accurate measurement of the CO₂ levels.

Rates of carbon dioxide supplementation are dependent on the crop response and economics. Flower and vegetable growers may take somewhat different approaches. In general, carbon dioxide supplementation of 1,000 ppm during the day when vents are closed is recommended. At 10% vent opening the CO₂ supplementation can be shut off or reduced to 400–600 ppm. In order to improve economic efficiency, CO₂ levels can be set depending on light levels. The following is a recommended strategy for vegetable growers. On sunny days when the vents are closed, supplement with 1,000 ppm CO₂ while on cloudy days when the light level is below 40 watts/m² supplement with only 400 ppm CO₂. However most flower growers will supplement with 1,000 ppm regardless of light levels. The environment computer can be set to adjust the CO₂ level depending on the light measured but once the vents open beyond 10% or the second stage of exhaust fans becomes operational, the focus is to maintain a CO₂ level in the crop canopy at 400 ppm.

To provide a guideline for CO₂ addition, a theoretical calculation is given below for a glass house of 100 m², with a growing crop, on a day with average light intensity. In this calculation, a level of 1,000 ppm CO₂ will be supplemented to maintain 1,300 ppm during the day. Normally CO₂ supplementation is not required at night as no photosynthesis occurs. Actually, the CO₂ concentration will tend to build up naturally as a result of plant respiration. Therefore, it is not uncommon to find elevated levels (500–600 ppm) early in the morning. Growers using

high-pressure sodium lighting during the night should maintain at least 400 ppm of CO₂.

A typical greenhouse with a 2.4 m gutter has an approximate air volume of 400 m³/100 m² floor area. To increase the level from 300–1,300 ppm requires the addition of 1,000 ppm or 0.1% CO₂. This requires 0.40 m³ or 0.75 kg of CO₂ per 100 m² of greenhouse floor space. Add this amount before sunrise because photosynthetic activity is usually the greatest early in the day. After a level of 1,300 ppm is achieved, it must be maintained.

Carbon dioxide levels are reduced in a greenhouse by natural air exchange and photosynthesis.

(a) Natural air exchange

Leaks in the greenhouse allow a continuous infiltration of outside air, which contains only 340 ppm CO₂. An average value for infiltration in a glass house would be one air change per hour. To compensate for this dilution, approximately 0.37 kg CO₂/100 m² must be added to maintain the desired level of 1,300 ppm CO₂.

Note that a correction should be made for gutter height and/or width of greenhouse. A wide span greenhouse has more air volume than a narrow span given the same gutter height. For houses with double glazing (double polyethylene or acrylic) an air exchange of $\frac{1}{4}$ – $\frac{1}{3}$ of 1 greenhouse air volume is expected. For greenhouses with forced ventilation, a lower CO₂ level is usually maintained if fans are in operation, and as a result the rate of supplementation will be different.

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(b) Photosynthesis

Plants during photosynthesis use carbon dioxide. Rate of consumption varies with crop, light intensity, temperature, stage of crop development and nutrient level. An average consumption level is estimated to be between 0.12–0.24 kg/hr/100 m². The higher rate reflects the typical usage for sunny days and a fully-grown crop.

When the 2 factors are combined, it is estimated that about 0.50–0.60 kg of CO₂/hr/100 m² must be added in a 'standard' glass greenhouse to maintain 1,300 ppm. For double-polyethylene houses supplementation is 0.25–0.35 kg of CO₂/hr/100 m². For glass houses, supplementation is primarily used to offset the dilution due to air infiltration, while for double-poly houses the amount of CO₂ required is about equal for the natural air exchange and photosynthesis. Make adjustments in supplementation if lower levels are to be maintained.

Table 1, Potential Yearly CO₂ Use on a Monthly Basis, shows the theoretical amount of CO₂ used for a vegetable crop being supplemented at 3 different rates based on sunshine hours.

Table 1. Potential Yearly CO₂ Use on a Monthly Basis (based on sunshine hours at Harrow, Ontario)

Month	Number Hours Applied	Rate Applied (kg/ha/hr)		
		45	65	90
Jan	82	3690	5330	7380
Feb	100	4500	6500	9000
Mar	127	5715	8255	11430
Apr	168	7560	10920	15120
May	234	10530	15210	21060
Jun	253	11385	16445	22770
Jul	283	12735	18395	25470
Aug	252	11340	16380	22680
Sep	187	8415	12155	16830
Oct	157	7065	10205	14130
Nov	89	4005	5785	8010
Dec	67.1	3019.5	4361.5	6039

Total (kg)	89959.5	129941.5	179919
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Burner Capacity Required

For calculating the capacity of the burners, only natural gas and propane are considered as these fuels are most commonly used in the industry. Growers who do not have a CO₂ gas analyser or environmental computer need to properly size their burners. This is especially true of bedding plant growers with freestanding hoop houses. Table 2, Capacity of burner to maintain 1,300 ppm of CO₂ under assumed conditions, lists the burner capacity based on the compensation rates stated above.

At the recommended levels ([Table 2](#)) it can be calculated that the relative humidity will increase by about 3%–6% when using natural gas provided the greenhouse temperature is not affected from the heat generated by the CO₂ burners. Typically, when the temperature is raised by 1°C there is no effect on the relative humidity.

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When To Supplement With Carbon Dioxide

Since photosynthesis normally occurs only during daylight hours, CO₂ addition is not required at night. However, supplementation is recommended during cloudy, dull days to compensate for the lower rate of photosynthesis. Because photosynthesis increases with high light levels, the optimal CO₂ concentration becomes higher. Start supplementation approximately 1 hr before sunrise and shut the system off 1 hr before sunset. However, CO₂ supplementation is highly recommended when supplemental high-pressure sodium (HPS) lighting is used at night to insure adequate levels.

Although the optimal CO₂ level increases with increasing light levels, it is often wasteful, depending on wind speed, to attempt to maintain a rate of 1,000 ppm supplementation when vents are more than 10%–15% open or the full complement of exhaust fans are operational. Growers should however, aim to maintain ambient levels within the crop canopy. The increased air circulation enhances the rate of diffusion by reducing the boundary layer around the leaf surface.

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The Costs Of Adding Carbon Dioxide

The cost of generation and distribution as well as the cost of the fuel are the key factors that must be considered. Table 3, Cost comparison of various sources of CO₂ (kg/ha), indicates the cost of supplying CO₂ from the various sources for a 12-hour day. Most large operations, especially those using flue gas CO₂ may use double the amount indicated per day. Equipment cost must also be added to the equation (Table 4, Equipment Costs for 4 Hectare (10 acre) Operation).

Table 2. Capacity of burner¹ to maintain 1,300 ppm of CO₂ under assumed conditions.

	Natural Gas		Propane	
	kW/1,000 m ²	m ³ /1,000 m ² /hr	kW/1,000 m ²	L/1,000 m ² /hr
Glass house	30–36	2.8–3.4	20–24	2.8–3.4
Plastic house	15–18	1.4–1.7	10–12	1.4–1.7

¹ kW kilowatt = 3420 BTU/hr

The foregoing calculations are based on continuous operation of the burner.

Table 3. Cost comparison of various sources of CO₂ (Kg/Ha)*

	# hrs	CO ₂ rate	Amount of	\$Cost/unit	CO ₂ Cost/hr	Total cost/day
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		kg/ha/hr	Product Req			
Liquid CO₂	12	50	50.0 kg	0.11 kg	\$5.50	\$66.00
	12	50	50.0 kg	0.15 kg	\$7.50	\$90.00
	12	50	50.0 kg	0.2 kg	\$10.00	\$120.00
Natural Gas	12	50	27.8 m ³	0.1 m ³	\$2.78	\$33.33
	12	50	27.8 m ³	0.15 m ³	\$4.17	\$50.00
	12	50	27.8 m ³	0.3 m ³	\$8.33	\$100.00
Propane	12	50	27.8 L	0.2 L	\$5.56	\$66.67
	12	50	27.8 L	0.25 L	\$6.94	\$83.33
	12	50	27.8 L	0.3 L	\$8.33	\$100.00

* Does not include equipment costs

Table 4 : Equipment Costs for 4 Hectare (10 acre) Operation

Liquid CO₂			
Tank Rental			\$6,000
CO₂ Distribution			
1,000 ft	90	50	\$4,500
Total			\$10,500*
Flue Gas CO₂			
Condenser			\$30,000
Blower			\$20,000
Distribution			\$15,000
plastic tube 65 mm			
1,000 ft	150	100	\$15,000
Total			\$80,000
Burner CO₂			
Units Required			
20		2,500	\$50,000
Total			\$50,000

*this is an annual cost

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Distribution Of Carbon Dioxide In The Greenhouse

It is important to have an adequate distribution system. The distribution of CO₂ depends mainly on air movement within the greenhouse(s), as CO₂ does not travel very far through diffusion. For instance, when a single source of CO₂ is used for a large surface area or several connecting greenhouses, a distribution system must be installed. This system must be designed to evenly distribute the CO₂ in the greenhouse especially when flue gas CO₂ or liquid CO₂ is used. Air circulation using horizontal airflow fans or fan-jet system provides uniform distribution by moving large volumes of air within the greenhouse when top vents are closed or exhaust fans are not operational. Today, growers supplementing with liquid CO₂ or flue gas CO₂ have a central header with small individual tubes (with evenly spaced holes) placed low in the crop canopy or in the case of bench crops, under the bench. The potential for low CO₂ levels inside a dense crop canopy (chrysanthemums) makes it beneficial to supplement within the canopy. Air movement around the plants will also improve the CO₂ uptake because the boundary layer around the individual leaf

is lessened bringing the CO₂ molecules closer to the leaf.

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Plant Damage As A Result Of CO₂ Supplementation

Do not allow excessive CO₂ levels in greenhouses. Levels of 5,000 ppm can cause dizziness or lack of co-ordination to humans. Higher than recommended levels can cause necrosis of old tomato and cucumber leaves. African violet leaves become very hard and brittle, show a very dark greenish-grey colour and often malformed flower petals, which do not fully expand. A similar symptom with freesia flowers has been observed where the CO₂ burner was used to provide the majority of the heat requirements of the greenhouse, and thereby generating excessive amounts of CO₂. Except in emergencies, do not use CO₂ burners as the prime heating system.

Since sulphur dioxide can cause acute necrosis (0.2 ppm in the air), the sulphur content of the fuels should be less than 0.02%. Heating fuels such as No. 2 oil and bunker C (# 6 Oil) are not suitable for CO₂ supplementation.

Ethylene at 0.05 ppm and propylene at higher levels can cause premature senescence on tomato and cucumber plants, induce sleepiness in carnations, create flower shatter of geraniums, promote excessive side shoot development, prevent normal flower initiation, and flower bud abortion in chrysanthemums and poinsettia. Ethylene is often produced as a result of incomplete combustion, while propylene is usually associated with the use of propane. Leaky propane supply lines have created serious financial damage to growers in the past. Carbon monoxide (CO), which usually does not create any problems by itself, is often used as the indicator for incomplete combustion. Levels exceeding 50 ppm CO in the flue gases are an indication of the presence of ethylene at levels capable of causing crop damage.

Burners with a high flame temperature can cause the formation of nitrous oxides (NO_x and NO₂). Excessive amounts of nitrous oxide can cause diminished growth or even necrosis. Boilers equipped with low NO_x burners must be used for flue gas utilisation as a CO₂ source.

A low level of both SO₂ and NO_x in combination can cause greater phytotoxicity damage or be more detrimental to the plants than a high level of either. Excessive and prolonged use of CO₂ (especially in tomatoes) results in the plants not responding well to the supplemental CO₂. Interruption of the CO₂ application for a few days results in an improved response.

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Cultural Practices To Improve Productivity

Depending on the crop, the increased growth rate related to CO₂ application may require the nutrient solution to be applied at a higher electrical conductivity (EC). As well, the increased CO₂ levels can result in partial closure of the stomata reducing transpiration and increasing leaf conductance in some crops. This decrease in transpiration reduces calcium (Ca) and boron (B) uptake, which may affect tomato fruit quality. Increased applications of these nutrients, within reason, will adequately compensate the decreased uptake.

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Notes:

- 1 kg of CO₂ is equivalent to 570 L of CO₂
- 1 m³ of natural gas provides about (1.8 Kg) 1,000 L of CO₂ when combusted and 1.4 L of water
- 1 m³ of natural gas = 0.75 L of kerosene = 1.0 L of propane for an equivalent amount of CO₂ produced

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