COVERED CROPS

Greenhouse energy efficiency

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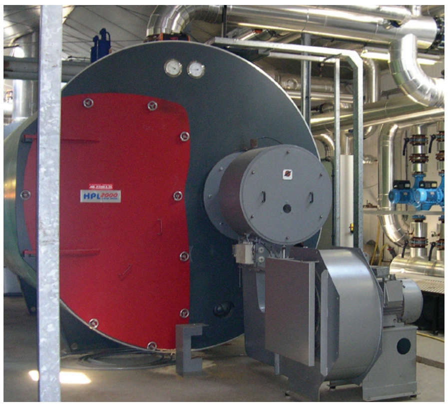
Vegetables NEW ZEALAND Inc





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Source: Tomatoes New Zealand

CHAPTER 1
Energy for greenhouse climate control

Now in 2022, energy prices in New Zealand are skyrocketing and are expected to rise further. Carbon emission charges will rise steadily. The availability and price of natural gas is uncertain, even for the coming winter.

The government's directive for decarbonisation means that greenhouse operators must reduce and ultimately end the emission of carbon (in fact carbon dioxide, CO_2). So the use of fossil fuels must stop. This causes unprecedented challenges for the New Zealand greenhouse industry. Several other countries, including in Europe, face a similar situation.

For a long time, the goal was to improve the energy efficiency, which is the yield per unit of energy, but now the goal is an absolute reduction in energy use. The targets leave little time for a gradual energy transition. Drastic and fast action is required. If you keep doing what you are doing, you keep getting the same result.

This e-book is about advances in greenhouse climate control that have been developed or are being trialled in glasshouses in the Netherlands. Dutch growers have been working on energy transition for over a decade.

Decarbonisation

Fossil fuels contain carbon; when burned, they produce carbon dioxide gas. It is ironic that increasing the CO_2 concentration in the atmosphere is 'bad' because it contributes to climate change, whereas increasing the CO_2 concentration in a greenhouse is 'good' as it stimulates plant growth. It is doubly ironic that CO_2 in the atmosphere is called a greenhouse gas, simply because it acts as a blanket that traps heat, like a greenhouse does. The reality is that CO_2 is a costly liability if you emit it, and a precious commodity if you need it.

So the New Zealand economy is on a path to phase out fossil fuels, and move to renewable energy sources, aka green or sustainable energy. Over time, greenhouse horticulture will become (nearly) fossil-free or zero-carbon.

Energy for climate control

Greenhouses require energy for several purposes: (1) controlling temperature, humidity and CO_2; (2) powering vents, motors, fans, pumps, etc; and (3) running the sorting machine, cool stores, vehicles, etc. Although all categories are important, our focus will be on heating, venting and CO_2 enrichment and other elements of greenhouse climate control.

There is a wide spectrum of situations:

- climate zones, with cold winters in the South versus mild in the North
- greenhouse types, from uncontrolled tunnel houses to state-of-the-art glasshouses
- seasons: in winter, fuel is used most for heating, in summer more for CO_2 enrichment
- crops: for instance lettuce and cucumber have different climate requirements.

The focus will be on greenhouses that have advanced control technology and are willing to invest further in new technology to tackle new challenges.

Greenhouse climate factors

Greenhouse climate control is not simply heating for temperature, but it involves light, lighting, air temperature, plant temperature, absolute and relative humidity, dewpoint, CO_2, air movement and more. Tools to manipulate the climate include heating, venting, screening, irrigating, fogging/misting, fans, CO_2 enrichment and in some cases lighting. One action can affect many factors, for instance, closing a screen affects the light level, air and leaf temperature, air humidity and air movement.

Dynamics

A greenhouse is a dynamic environment. Weather and solar radiation change all the time, especially on a partly cloudy day. Controllers act swiftly, but it takes some time for changes to take effect, e.g. changing a pipe temperature. Also, the plants are impacted by the greenhouse climate, and vice-versa, the climate is influenced by the plants.

Active plants bring a lot of water vapour into the air, thereby increasing the air humidity and lowering the temperature. This is clear in summer: an empty greenhouse is very hot and dry, while a planted greenhouse is relatively cool and pleasant. Understanding the dynamics and interactions is necessary for improving greenhouse climate control.

Short-term and long-term effects

Plants respond to their environment with various speeds. For instance, if the sun comes out, the stomata (leaf pores) will open immediately, creating a sudden increase in water loss (transpiration) and CO_2 uptake (photosynthesis). In contrast, there are slow processes, such as growth, stretching, leaf appearance, developing leaf area and leaf thickness, formation of flowers and fruit set. Plant growth and shape are the result of the average climate conditions over a period of time, while any extreme conditions in that period can have a strong (negative) effect.

Optimal growing conditions

A greenhouse with a good computer and advanced control can create the optimal growing environment. That costs energy, and the challenge is to use the energy wisely. But what are optimal growing conditions? The ideas have changed, as the understanding of greenhouse physics and plant physiology has developed a lot in recent years. Energy demand can be reduced by installing good equipment and using it properly. It is also about choosing optimal settings in the greenhouse control computer. Later we will introduce 'The New Way of Growing', also known as 'Growing By Plant Empowerment' (GPE).

Figure 1A. Optimal climate control creates balance.

CHAPTER 2

Greenhouse climate physics

Greenhouses have been used for centuries for protecting plants from the elements, as well as overwintering subtropical plants, bringing harvest forward, producing out of season and out of normal climate zones.

Over time, greenhouses developed into efficient production facilities where growing conditions are optimized. Temperature, humidity, CO_2, light/shade, air movement and root-zone conditions can be controlled by heating, venting, screening, fans, fogging/misting and more. This chapter outlines some physical principles that are the background of energy-wise climate control in greenhouses to be discussed in later sections.

Solar radiation

Solar radiation, or sun rays, provide the light and warmth that are vital for plant growth. Nearly 50% of solar energy is visible light aka shortwave radiation. Light is what we can see, and what plants use for photosynthesis and growth. Therefore light is also called PAR, which is short for Photosynthetic Active Radiation. The other nearly 50% of the solar radiation is heat, aka longwave radiation or Infra-Red (IR). We can't see heat radiation, but we feel it. A small fraction of the solar radiation is Ultra-violet (UV). This is largely invisible, but is dangerous for our eyes and skin.

The solar spectrum in Figure 2A shows the relative intensity against the wavelength in nanometers (nm). Visible light aka PAR, shown as the colours of the rainbow, has a wavelength of 350-700 nm. Infra-Red or heat radiation, shown as red, has wavelengths above 700 nm. The small amount of Ultra-violet, shown as purple, has a wavelength under 350 nm.

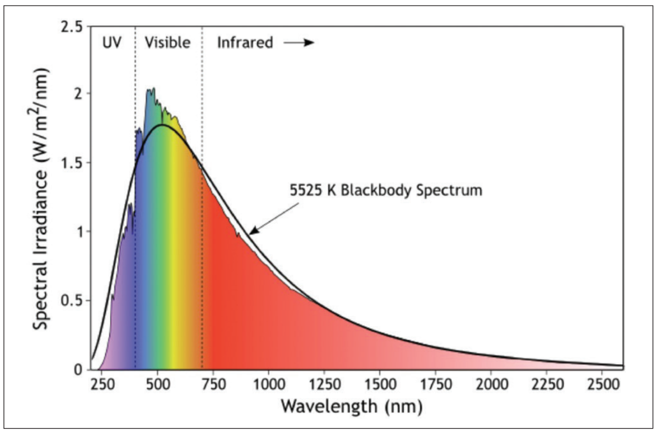


Figure 2A. Solar radiation is 50% light and 50% warmth.

Measuring radiation

Worldwide, it is common practice to measure solar radiation with a pyranometer or solarimeter. This gives a measurement of the total energy in the solar radiation, which includes light + heat + UV. This is a very important measurement for irrigation management and for climate control. For instance the radiation sum over a day is used to determine the setpoints for temperature, as will be discussed in Chapter 5.

For reliable measurements, a pyranometer is positioned outside, is not shaded and is kept clean. How much radiation reaches the plants inside depends on the greenhouse cover: glass or plastic, old or new, no screen or closed screen, etc. It is often assumed that a certain fraction (e.g. 70%) of the radiation enters the greenhouse and reaches the plants. But it differs a lot between greenhouses, so it is much better to measure it for a particular greenhouse.

Figure 2B. A pyranometer (solarimeter).

Measuring light

Measuring light is a complicated thing. Some climate control systems are fitted with a cheap lux meter that measures light in lumen and lux. This type of meters is meant for photography, and can lead to totally wrong decisions in greenhouse climate control. It is better to assume that light is 50% of the reading of the solarimeter, or even better, to use a proper light meter.

Light should be measured with a PAR meter (PAR = Photosynthetic Active Radiation). Some PAR meters measure the amount of energy in light expressed in Watts per square meter (W/m^2). Their measurement is about 50% of a pyranometer measurement, as light makes up half of the solar radiation energy.

In glasshouses with lighting (which is quite common overseas), light inside the glasshouse is measured with a so-called PPFD sensor, or a Photosynthetic Photon Flux Density sensor. This measures photons instead of energy. A Photon or Quantum is an extremely small amount of light. A PPFD meter measures in micromol photons per square meter per second ($\mu mol/m^2/s$). As lighting is rare in New Zealand, PPFD sensors are hardly used here.

Transmission

Because plants need light, we cover greenhouses with a translucent material such as glass or clear plastic, e.g. polyethylene, polycarbonate, etc. Glass and clear plastics transmit light very well (transmit = let go through). In contrast, the transmission of heat (longwave radiation) through glass is very poor, and through most plastics it is low to moderate. UV radiation is considerably blocked by most materials. Rafters and other construction elements block off a small part of **all** incoming sun rays. It is important that the roof allows plenty of light to come into the greenhouse, while partly blocking heat from coming in. The transmission of light and heat can be altered by using special covering material or coatings or screens. The proper use of screens has great potential benefits for optimizing the climate and energy use.

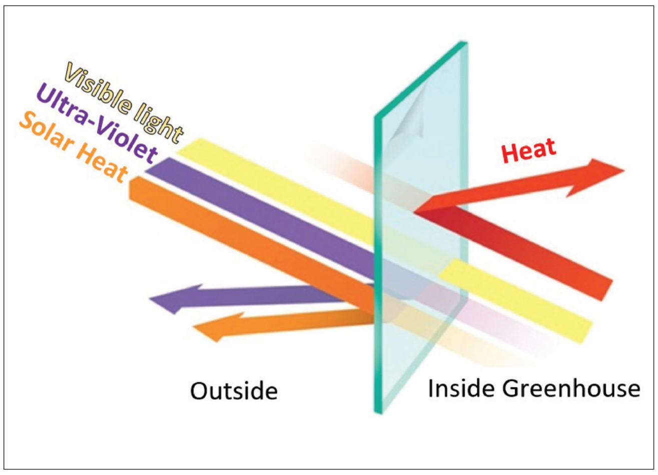


Figure 2C. Glass lets light through, but blocks heat.

Heat trapping

Solar radiation warms up a greenhouse. The first trick is that a glasshouse lets in much more light than a building. The second trick is that a good part of the incoming **light** (shortwave radiation) turns into **heat** (longwave radiation). The third trick is that glass blocks longwave radiation (heat) from going out. On top of that, warm air cannot easily escape through the roof, unless there are leaks or open vents. This all means that a greenhouse roof acts as a blanket that traps the heat. The heat trapping ability of a greenhouse is most obvious on a sunny winter's day: with vents closed, even without heating, it is much warmer inside than outside. The heat trapping is not perfect though. In cold winter conditions, a good energy screen is needed as an extra blanket.

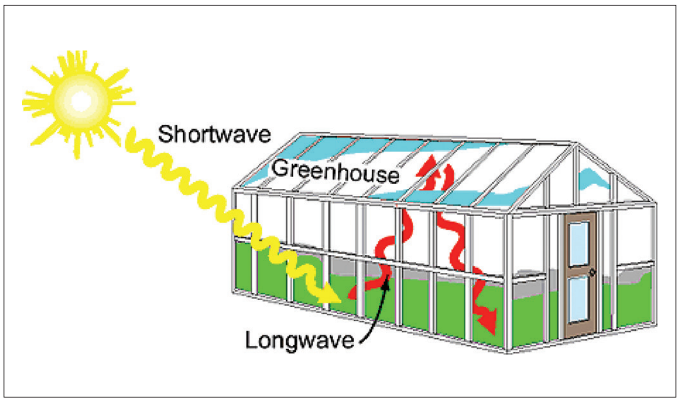


Figure 2D. Light (shortwave) enters the greenhouse and is turned into heat (longwave), which cannot escape.
Source: agron-www.agron.iastate.edu

Radiation and convection

Radiative energy is longwave radiation (heat) coming from the sun, as discussed above. Also the warmth beaming from a hot surface such as a radiator or heating pipes is radiative energy. **Convective energy** is warmth in a mass of warm water or warm air. For instance, hot air blown out by an electric fan heater is convection. Heating pipes in a greenhouse produce both radiative and convective energy. The latter is because an air mass warms up when it comes in contact with hot heating pipes.

One other form of heat radiation occurs in winter when the plants are in a heated greenhouse, but there is the cold roof and cold winter sky above the plant heads. The plant heads then lose heat by radiation and become quite cold in winter. A screen significantly reduces the heat emission and thus keeps plant heads warm.

Latent heat

Latent energy is the energy that is present in water vapour in the air. Note that water vapour is a gas and is invisible, whereas fog or mist consists of small water droplets that are visible.

To understand why water vapour is energy, think about boiling water in a kettle inside a small space. After some time and using a lot of energy (electricity or gas), the water will be completely evaporated. The kettle used a lot of energy for the evaporation, indicating that water vapour is very energy-rich.

Plants in a greenhouse evaporate a lot of water. The energy for the evaporation (or transpiration) comes from the sun; if there is no sun, the energy comes from the heating system. In mild weather, not much energy is needed for maintaining the temperature, so 80% or more of the energy received is for the transpiration.

If the kettle boils water in a small room (or glasshouse), we will see water dripping from the windows and walls. Condensation happens when more moisture is added to already saturated air, and the place where it happens is where humid air touches a colder surface. Condensation releases energy.

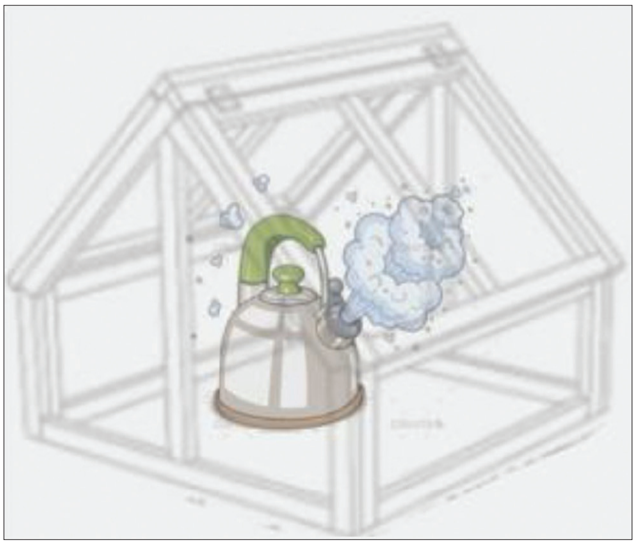


Figure 2E. Air can only contain a certain amount of water vapour. Once air is saturated (100% relative humidity) any more water added will turn into condensation (dew).

CHAPTER 3

New Way of Growing and Plant Empowerment

Here we introduce a new innovative approach of greenhouse climate control, which aims to grow in an energy efficient way, while achieving optimum production.

In fact several new approaches have emerged, with names such as semi-closed greenhouses, HNT 'Het Nieuw Telen' (in Dutch), meaning 'The New Way of Growing', Next Generation Greenhouse Cultivation, Growing by Plant Empowerment (GPE), and more. Here we will use GPE as an abbreviation that also includes the other approaches.

Drastic changes

Innovative climate control started in the Netherlands around 2010, when the Dutch greenhouse industry was compelled to save more energy. Until then, the energy **efficiency** had improved over several decades, but the energy **consumption per m^2** had not declined enough. It was decided that drastic measures were needed, because 'if you keep doing what you are doing, you keep getting the same result'.

Several research teams developed new methods of climate control, with overlap between each approach. Growers who adopt the new methods get markedly better energy efficiency, yield and fruit quality.

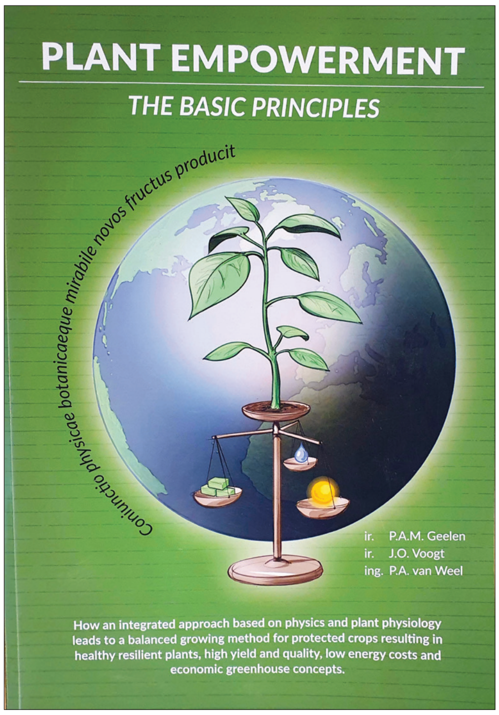


Figure 3A. Growing by Plant Empowerment (GPE) book. *Source: plantempowerment.com*

The new methods require investments in new technology and investment in time for learning a new method. It is complex: for instance, GPE is described in a 300-page book **(www.plantempowerment.com).**

The New Way of Growing and GPE

First of all, the ideas behind GPE are useful for all greenhouse operators, not only for those with a high-tech glasshouse. GPE does not aim to optimize conditions such as temperature, but to optimize **plant processes**, such as nett photosynthesis, transpiration, growth and development. GPE calculates six balances: for water, for energy and for CO_2, both in the plants and in the greenhouse. Overall, plants are kept in balance by maintaining a temperature that suits the light level, in fact by maintaining a stable Radiation-Temperature Ratio.

Some key elements of GPE are: (1) uniform climate, (2) smart humidity control, (3) optimal use of energy screen(s), (4) reducing heat emission, (5) maintaining air movement. Elements of GPE will feature throughout the chapters.

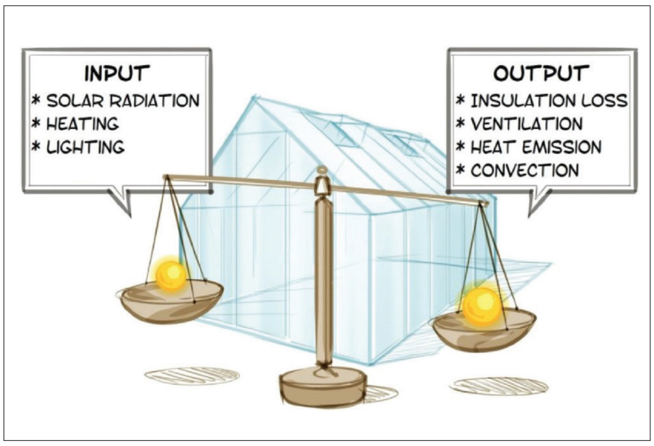


Figure 3B. GPE calculates the greenhouse energy balance.

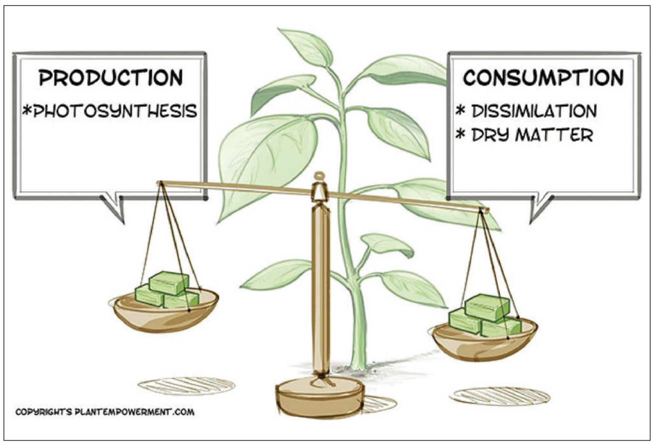


Figure 3C. GPE also calculates the plant's CO2 balance.
Source: plantempowerment.com

Investments

A complete change to an innovative method of growing requires serious investments. It is worthwhile mostly for energy-intense glasshouses that produce high value crops. Some investments can best be done when a glasshouse is newly built, while others can be retro-fitted. The possible investments include mechanical ventilation (possibly with Air Handling Units, or otherwise additional fans), a climate screen, an extra temperature/humidity measurement above the screen, sensor for plant temperature, and some new software.

This comes on top of the normal sensors for temperature, humidity and CO_2 in the plant zone, and the normal weather sensors outside. Another requirement is the grower's commitment and time for understanding the underlying physics and plant physiology.

Figure 3D. Climate is measured at three heights.
Source: plantempowerment.com

Figure 3E. A thermo-sensor monitors the plant temperature.
Source: Hoogendoorn.nl

Energy screen keeps plant heads warmer

An important tool in GPE is the energy or climate screen. GPE uses the screen more and differently than a conventional control regime. A screen not only reduces the amount of energy needed but also keeps the plant heads warm as it reduces the emission of long-wave radiation (heat radiation) from the plants to the cold greenhouse roof. It also creates a more even climate.

This has several positive effects:

- less condensation (and guttation) on the plant heads, so less fungal diseases
- more transpiration from the plant heads, so more water and calcium go through the plant heads; hence less calcium-related problems such as blossom-end rot (see Fig. 8E)
- higher development rate, meaning that the plant heads produce more new leaves and flowers (or trusses) per week (see page 12).

Proper use of an energy screen is good for the plant balance (vegetative versus generative), plant health and fruit quality, including reduced blossom-end rot.

Figure 3F. A screen blocks heat loss from the plant heads.

Traditional humidity control

The energy consumption in a greenhouse depends a lot on how the humidity is controlled. Quite often, more energy is used for dehumidification than for maintaining the temperature, especially in milder weather conditions. Traditionally, high humidity is prevented by minimum pipe temperature or minimum ventilation. This leads to concurrent heating and venting, which releases energy-rich air. Moreover, that practice increases the transpiration, which **increases** the humidity. This is a vicious circle that costs a lot of energy. If there is a screen, the risk of high humidity is a reason for not using it. Growers would use the screen a lot more, and thus use far less energy, if they were able to prevent high humidity under a screen.

Innovative humidity control

GPE (and HNT etc.) does not use minimum pipe, minimum vent opening and does not work with the Relative Humidity, but rather uses Absolute Humidity and Dewpoint. Ventilation is sometimes done by first opening the wind side vents and then the leeside of the roof vents. Fans are used to create a more even climate and help prevent condensation on the plants. Often mechanical ventilation is used instead of natural ventilation by vents. If there is a screen, fans can pull cold dry air from above the screen into the plant zone. The ultimate is the use of Air Handling Units (AHU's) which then leads to a semi-closed greenhouse. Dehumidification will be discussed in detail in chapters 7 to 10.

Mechanical ventilation and AHU's

GPE is especially used by growers who have a semi-closed glasshouse with mechanical (forced) ventilation. Large ventilation systems suck in (or blow in) drier air from outside to replace the moist inside air. If so-called Air Handling Units (AHU's) are installed, they can mix outside air with greenhouse air in variable ratio. The AHU's can be fitted with devices for air treatment, either heating, cooling, dehumidifying, or humidifying. The air can be blown in overhead or via large air ducts. There are many different systems, from simple to advanced. More on this later (page 31-34).

Figure 3G. A 'screen fan' controls the air exchange between the warm plant zone and the cold top. *Source: Hinova.nl*

Screens again

GPE uses screens a lot more than the traditional control methods do. If the screen material is translucent, it can be used during daylight hours too, although in winter it is always a trade-off between energy saving and light loss. If high humidity is a problem, the screen can be closed just 80 or 90% during the day. The energy saving is not as much as it could be, but the advantage of the warmer plant heads remains.

There are also special screen fans that are fitted within the gaps of energy screens. They move cooler drier air from above the screen to the plant zone. This is an effective way of dehumidification, as will be discussed later (page 30).

Figure 3H. Some innovative technology can only be installed when building new, while others can be retro-fitted.

CHAPTER 4
Temperature effects on plants

Reducing the energy use in a greenhouse cultivation is not only a matter of 'hardware' such as a thermal screen, but also of smart control. After all, every degree higher temperature costs energy (in wintery situations).

The aim is reducing the energy input while achieving the best possible production and quality. This is a fine art. If a grower understands the many effects that temperature has on plants, they can choose better temperature setpoints and settings and so improve the energy efficiency. A too high or too low setpoint costs money, one way or another.

Temperature

Temperature control in a greenhouse is a key factor for heating costs and for plant growth and (fruit) production. In this chapter, we examine the effects of temperature on plant processes like development, photosynthesis, respiration, assimilate transport, vegetative/generative balance and fruit ripening. The best temperature strategy is maintaining a good balance between average temperature and prevailing light level (or light sum). The next chapter will give specific numbers on that.

The 24-hour average temperature

Most temperature strategies have temperature settings for daytime, pre-night and night, with some 'ramping'. There is also the average temperature over a full day and night, or the **24-hour average temperature.** This is calculated by the computer from the number of hours at a certain temperature. For instance, the temperature can be 19.5°C for 10 hours during the day, then 16°C for 4 hours in the evening; and 17.5°C for 7 hours at night. In between there will be some 'ramping' from one to the other temperature level. The computer can calculate that the average temperature over 24 hours is 18.2°C.

Rate of plant development

In all plants, the 24-hour average temperature has a strong effect on the rate of development, which is the speed of appearance of new leaves and flowers (or trusses in tomatoes). For instance, tomato plants that grow at an average temperature of 17°C get 2.5 new leaves and 0.8 new trusses per week. The same tomato plants growing at 23°C throw out 3.5 leaves and 1.2 trusses each week. This is a 50% faster development rate.

If the 24-hour average temperature is too low, the plants don't create enough flowers/trusses, so will have poor production later. Plants whose average temperature is too high over 24-hours, create too many young leaves and flowers/trusses. So the 24-hour average temperature not only affects the development rate, but also the balance between vegetative and generative development.

Figure 4A. Development rate is how fast new flowers appear.

Source and sink

After development follows growth. For growth, it is important to have a balance between sugar production by photosynthesis in leaves (called 'source') and sugar consumption in growing plant parts (called 'sink'). The grower strives to keep the plants balanced, in this case meaning with right source/sink balance. This is foremost controlled by temperature in relation to light. Sugar production is stimulated by more light, while sugar consumption is stimulated by higher temperature. This means at low average light level, the average temperature must be relatively low, while at higher average light level, the temperature must be higher. More about that in the next chapter.

Photosynthesis and respiration

Photosynthesis is uptake of CO_2 by the leaves to produce assimilates (sugars), which are the building blocks for new plant tissue. Photosynthesis is driven by light, so it happens only during the day, or when artificial lighting is on.

There is gross and nett photosynthesis; the difference between them is respiration. Respiration is the breakdown of sugars inside the plant to provide energy to keep the plant going. Respiration continues day and night, irrespective of light. In short: gross photosynthesis is the initial production of sugars; respiration then 'burns' a part of the newly formed sugars; nett photosynthesis is then the balance of gross photosynthesis minus respiration. We are interested in nett photosynthesis, as that tells us the amount of assimilates (sugars) available for growth, after the respiration has taken its toll. Photosynthesis generally means nett photosynthesis.

Nett photosynthesis

Nett photosynthesis depends on light, temperature, CO_2 and more. Figure 4B shows that nett photosynthesis drops sharply at very high temperatures, say above 30 or 32°C. This is due to increasing respiration. Temperature has little influence on the nett photosynthesis if the CO_2 level is low or moderate (say up to 600 ppm), as shown by the blue and green line. This is the most common CO_2 level. At a very high CO_2 level (1000 ppm), increasing the temperature is better for the nett photosynthesis (red line).

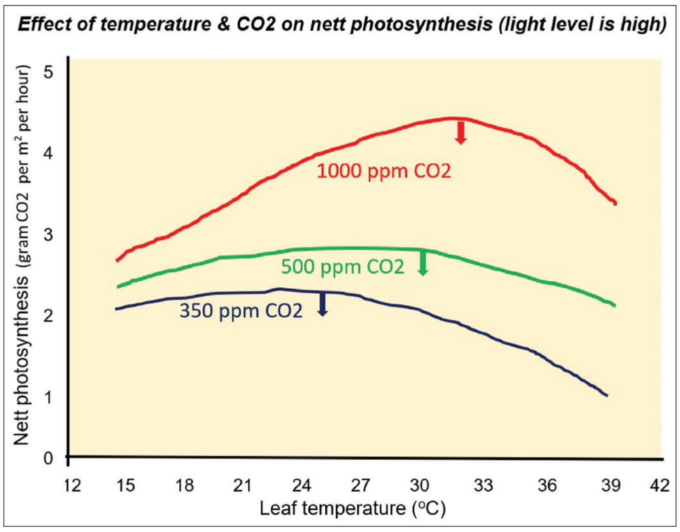


Figure 4B. Increasing temperature is good only at high CO_2.

Assimilate transport

An important factor to consider for selecting a temperature is the light level. We will show that at a higher light level, it is better to have a higher temperature. On a sunny day, the leaves produce large amounts of assimilates (sugars). These must be exported out of the leaves quickly, so the leaves don't get saturated. Warmth is essential for speedy transport. In sunny weather the sun provides the necessary warmth.

At night the grower can set a temperature level. After a very sunny day, the assimilate export must continue until well into the night. Therefore the night temperature must be set higher after a light day than after a dark day. If the night temperature is too low, assimilates are not transported out of the leaves, but instead are converted into starch and stored locally in the leaf cells. A trained eye can see if the leaves of a tomato plant are filled with starch in the morning: they are thick, firm and slightly purple. In contrast, after a dull day with a low light sum, the night temperature must be set accordingly lower, to avoid too many assimilates being burned up.

Vegetative/generative balance

The rate of plant development is the speed at which new leaves and new flowers/trusses appear on a plant. This speed is much higher at higher temperature (see above).

The new organs then need assimilates (sugars) to grow. Assimilates are transported out of mature leaves towards the various plant parts: growing point, young leaves, stems, roots and generative organs (flowers, trusses, fruit). The warmest plant parts attract the most assimilates and grow the fastest. If there are many flowers, and if they attract a lot of assimilates, the plant becomes very generative and potentially very productive. This can only work if there are enough mature leaves to produce the necessary sugars for the new fruit. If relatively more assimilates go to the leaves, the plant becomes more vegetative. The vegetative/generative balance is very important and should be kept stable. The temperature, in relation to light sum, plays an important role in this.

Fruit ripening

Higher temperatures strongly stimulate fruit growth and fruit ripening. If the fruits are warmer than the leaves (e.g. due to sunshine or heating pipes) they attract more assimilates than the leaves, so they grow faster. High temperature also makes them ripen faster. This shortens the fruit growth duration, and leads to faster picking, which reduces the fruit load on the plants. In contrast, low temperature makes fruits hang on the plants longer. Cucumber fruits hanging on the plant for too long may lose some of their shelf life.

Figure 4C. Fast picking is good for unloading the plant and also for the shelf life of cucumbers.

Conclusion

Temperature has many effects on plants, even more than described above. Research and practice have proven that the best strategy is to strive for a balance between the 24-hour average temperature in the greenhouse and the average light level (or light sum or radiation level or sum) over that day. In the next chapter we will look at the so-called Radiation-Temperature Ratio and give some clear guidelines for average temperature. In the chapter after that, we will distinguish between day and night temperature, as they have quite different effects. Finally, we will look at temperature control in relation to energy use.

CHAPTER 5
Radiation-temperature ratio

The key to a productive cultivation is a good balance: between leaves and fruit, between source and sink, and between average temperature and average light level.

Light determines how much sugars are produced (the source), while the temperature determines how much sugars are burnt and how the remaining sugars are distributed to the growing plant parts (the sinks). As discussed in the previous chapter, light and temperature affect many processes, including plant development rate, vegetative/generative balance, plant shape, ripening speed, and overall yield.

In this chapter we look in detail at the so-called Radiation–Temperature Ratio (RTR). The company Letsgrow in the Netherlands developed an online RTR tool that is used in 'The New Way of Growing' (HNT) and in 'Growing by Plant Empowerment' (GPE). The Radiation–Temperature Ratio is applied a lot for tomatoes and capsicums, and it is relevant for many other crops too.

The 24-hour average temperature

The previous chapter discussed the '24-hour average temperature'. Imagine two lots of tomato plants both getting the same 24-hour average temperature of 19°C. One lot gets 22°C in the daytime and 16°C at night (day/night of 22/16°C). The other lot gets the opposite temperature regime: 16°C in the daytime and 22°C at night. Because both lots get the same 24-hour average temperature, they had the same development rate and therefore the same number of leaves and flowers (see page 12). However, the plants will have a totally different appearance. Those at 16/22°C day/night will be worn out due to a high respiration rate at night due to the higher temperature. The other lot will be vigorous.

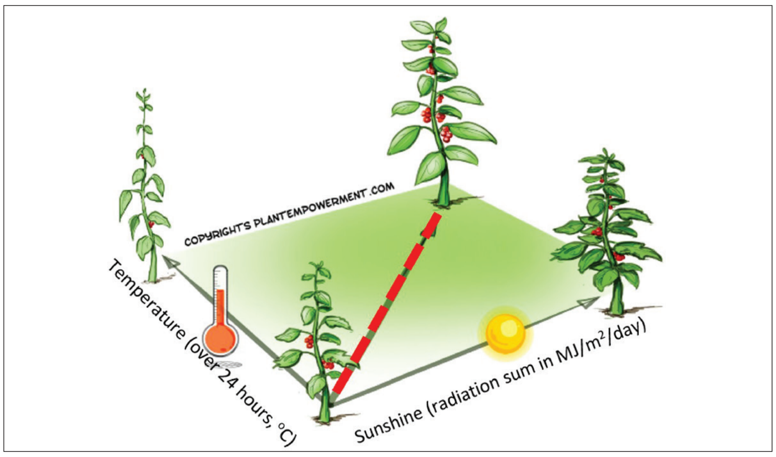


Figure 5A. Radiation-temperature ratio shapes the plant.
Source: plantempowerment.com

Higher temperature after lighter day

The day temperature and night temperature should be higher on a sunny day than on a dull day. This is because more assimilates are made during a sunny day, and they all need to be processed, which happens in the day and evening. Most control programs can add a light-dependent increase to the heating temperature and/or the ventilation temperature. The grower must choose these light-dependent settings.

First, we will discuss how to quantify the light sum or radiation sum.

Radiation measurements

Light or sunshine can be a good guide for the temperature settings: more light requires a higher temperature. It has been found that the daily sum of **solar radiation** measured outside is a good guideline. Radiation is easy to measure with a solarimeter aka pyranometer (page 5). To find the radiation sum, the radiation is multiplied by the duration in seconds. The pyranometer readings are in Watts per m^2 (W/m^2), which is exactly the same as Joule per second per m^2 (J/s/m^2). When multiplied by seconds, the outcome is a radiation sum in Joule per m^2 (J/m^2). For instance, 300 W/m^2 (= 300 J/s/m^2) for an hour (= 3600 seconds) gives a radiation sum of 1,080,000 Joule/m^2 in that hour. To avoid large numbers, we add 'Mega' and drop 6 zeros. This gives 1.08 MegaJoule per m^2 (MJ/m^2) in that hour. Accumulated over a whole day the radiation sum can reach 30 MJ/m^2/day.

Another way to avoid big numbers is by giving the radiation sum per cm^2 instead of m^2. Then 'Mega' is not needed. So 30 MJ/m^2/day equals 3000 J/cm^2/day. The graph in this chapter shows both units along the horizontal axis because both are commonly used by different computer systems.

Radiation–Temperature Ratio (RTR) graph

On a dull day, tomato plants prefer a low 24-hour average temperature, while on a sunny summer day they thrive at a high temperature. It is interesting to look at the relation between the 24-hour average temperature and the daily radiation sum in a so-called Radiation-Temperature-Ratio graph or RTR graph. The computer holds all the recorded measurements to make this graph, or the data can be recorded in a spreadsheet or in an online system such as **https://www.Letsgrow.com** (although only accessible for subscribers). In the Netherlands, growers do this analysis in a group to learn 'the new way of growing' (HNT).

The RTR graph on this page shows the radiation sum on the horizontal axis, and the average 24-hour temperature on the vertical axis. Each dot represents one day. Ideally all dots would sit close to the red line, as that is a constant RTR ratio. But in reality the red dots are dancing around the red line. The grey arrows point at two days that had the same radiation sum (about 11.5 MJ/m^2/day), but a different average temperature (18.5 and 22.6°C). This large difference demonstrates that the control strategy was not consistent.

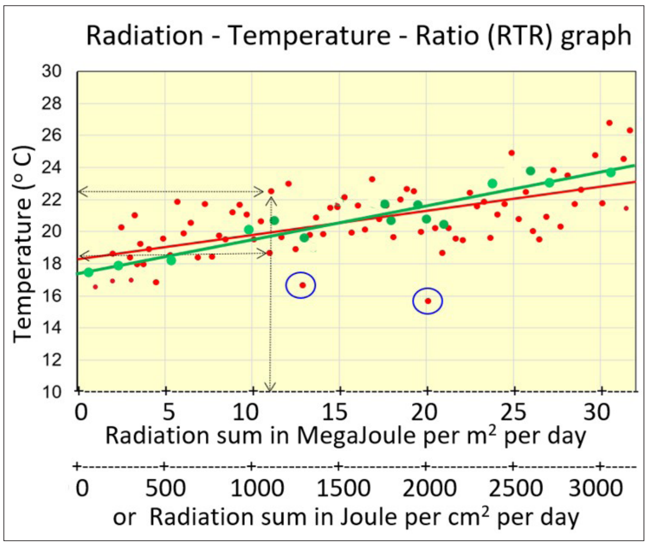


Figure 5B. Each dot represents one day, with measured average temperature plotted against the daily radiation sum.

Setpoints

To find out why the dots are so spread out, we first check if the data was correct. The two blue circles in the graph mark two data points that are obviously wrong. They can be completely removed. Secondly, we check if either the day or the night temperature was odd. Thirdly, was the deviation most likely due to faulty data for heating or for 'cooling' (venting, screening, fogging, use of fans, etc) or due to humidity control?

Based on the RTR-graph, the grower can adjust the settings in the climate control computer. The new data from then on can be put in the same graph, but as a separate dataset, and in another colour, e.g. green. A line is drawn through the green dots. It is good that the green dots sit closer to the green RTR line, indicating a consistent temperature–radiation balance. So the changes in the settings were indeed an improvement.

RTR line

The red line in the graph is fitted through the points. It has a certain slope and a certain formula: the average temperature equals 18.3 degrees + 1.5 degree for every 1000 J/cm^2/day. So at a radiation sum of 3000 J/cm^2/day, the line goes through 22.8°C. In a formula: 18.3 + (1.5 x 3) = 22.8.

This formula tells something about the temperature strategy that was followed in a particular greenhouse. The line depends on the light transmission of the greenhouse roof, and also on the setting chosen by the grower. This RTR formula is not a general recipe, but rather a method to analyse what is happening.

Slope of the RTR line

The line shown in Figure 1 is not necessarily the optimal balance, not even for this greenhouse. The grower may decide to aim for a different RTR next year. Generally, a steeper line indicates a warmer environment, leading to longer (perhaps lankier) and more generative plants. A flatter line (less steep) indicates a lower average temperature, leading to lusher more vegetative plants, as shown in Figure 2. The art of growing is to strike and keep the right plant balance. The right radiation-temperature-ratio helps with that.

Figure 5C. High temperature with low light causes stretching.

Figure 5D. Cool temperture with good light gives lush plants.

Figure 5E. A good temperature-light ratio gives balance.

Figure 5F. Go with the natural conditions, not against them.

CHAPTER 6
Greenhouse temperature day and night

We continue the discussion about temperature control, in particular the effects of day and night temperature.

Day temperature

Day-time temperature has a strong effect on cell division and stretching. Plant stems stretch most in the morning, and this is stimulated by a high temperature. In an experiment with reversed day and night temperature (similar to the trial described on page 14), two lots of tomato plants got the same 24-hour average temperature, and thus developed the same number of leaves. However, the plants at high day temperature grew much faster, became more than twice as tall and had 18% larger leaf area than those grown at high night temperature.

Also, higher day temperature and higher 24-hour average temperature have a generative effect. Also, higher temperature causes faster wear and tear of the leaves.

We saw in Figure 4B that at normal CO_2 levels, there is little effect of the temperature on the nett photosynthesis (the sugar production minus sugar breakdown). Only if the CO_2 concentration is very high, it is beneficial for the nett photosynthesis to maintain a higher day temperature.

Day temperature control

On overcast days in winter or shoulder seasons, heating is often needed to maintain the required temperature (also to keep up the temperature when the greenhouse is vented for humidity control). In sunny weather, the art is to utilise the free energy from the sun. If it gets too warm, one option is to get rid of it by venting. But advanced glasshouses employ active cooling and ideally put the heat into underground storage. Alternatively, a somewhat higher day temperature can be accepted and compensated for by a lower night temperature, to maintain the required 24-hour average temperature. The use of a (translucent) screen will add a new dimension to temperature control. Screens will be discussed in a later chapter.

Night temperature

Respiration (burning of sugars) continues day and night. Lower temperature at night is good, as it reduces the respiration and thus leaves more sugars available for growth. In contrast, higher temperature in the pre-night is good for transport and processing of assimilates that were formed during the day. Especially after a sunny day, a lot of sugars are waiting for processing, and a (moderately) high temperature in the pre-night will speed that up. These two requirements seem conflicting, but it sorts itself out, because after a sunny day there is plenty of sugar, so losing a bit through respiration does not matter. The RTR graph (Radiation-Temperature Ratio, see previous chapter) shows that the average 24-hour temperature must be higher when the radiation sum is higher. So that naturally works out well.

Too high night temperature will burn assimilates unnecessarily. Too low night temperature creates starch accumulation, making the leaves less efficient the next day. With a suitable night temperature, the plants gain a lot of useable biomass after a sunny day and look fresh the next morning. The plant heads will indicate whether the generative/vegetative balance is adequate. The use of a screen adds options to temperature control at night.

Dif

Dif is the difference between day and night temperature, e.g. a day temperature of 22°C with a night of 17°C gives a dif of 5°C. Not everybody uses dif, but it can be handy.
Dif should vary between the seasons and even between days. Higher dif makes plants more generative, and also more stretched. For some ornamental plants, dif can be set negative, meaning that the day temperature is lower than the night temperature. This keeps those plants short and compact.

Temperature with young seedlings

Young seedlings must grow fast to occupy the ground and catch the available light. Important processes are leaf development, which depends on the 24-hour average temperature, and stretching, which depends on the day temperature. In an experiment, tomato seedlings were grown at either 18 or 21°C average 24-hour temperature. The plants at 21°C clearly grew many more leaves, due to a higher rate of leaf appearance, but the leaves stayed smaller. Net photosynthesis was similar, but the available sugars were shared over more leaves. The total leaf area in both temperature regimes was practically the same. Temperature strongly affects the shape of young seedlings.

Temperature in the production phase

The experiment with either 18 or 21°C 24-hour average temperature continued into the productive stage. At the higher temperature, the tomato plants pumped more energy into their trusses and thus became more generative. This is because a higher temperature has a positive effect on: (1) rate of appearance of new trusses, (2) sugar transport to fruit and (3) fruit growth and ripening. It took 56 days from fruit set to harvest at 18°C, and only 46 days at 21°C.

The higher temperature resulted in more fruit, but smaller fruit, as they had to share the available sugars. Fruit weight can be increased by lowering the 24-hour average temperature.

In addition, the higher 24-hour average temperature wears the plants out faster. In the experiment, leaf picking was needed earlier at 21°C than at 18°C. Hence the leaf area got 25% smaller, so 25% less sugars were available for fruit growth. In this situation, the production was considerably lower at the higher 24-hour average temperature.

Figure 6A. A heat buffer for day-to-night heat storage.

Figure 6B. ‘Heat and cold storage’ in the aquifer for seasonal heat storage

CHAPTER 7

Air humidity in a nutshell

Air humidity is very complicated. For one, humidity is entangled with temperature. Secondly, there are many different measurements and units for air humidity. This chapter is about understanding humidity and converting from one unit to another.

It can be done with software that is available on the internet (e.g. **http://gpe.letsgrow.com/psychro**) and by checking out tables such as the one on page 21. Note that throughout these chapters, moisture means the same as water vapour, and condensation means the same as dew.

Water content and temperature

When working with measurements and units of air humidity, the air temperature is very important. Therefore the table is set up with four sections for four temperature levels (0, 10, 20 and 30°C). **It shows that warmer air can hold a lot more moisture than colder air.** This can be seen by comparing the four sections, especially in the top row (where RH is 100%): air of 0°C can hold 4.8 g/m^3 (it is then saturated, aka RH is 100 %). In contrast, air of 30°C can hold 30.5 g/m^3 (and is then saturated, aka RH is 100 %). Air holds about six times more moisture at 30°C than at 0°C.

Ways of measuring air humidity

Air humidity can be expressed in many different ways, each with its own units. The main measures of humidity follow here.

Relative Humidity (RH in %) indicates how much water vapour is contained in the air, as a percentage of the maximum amount the air can hold at the given temperature. Air can only hold a certain amount of moisture; it can hold more moisture at a higher temperature. Air containing the maximum amount it can hold at a given temperature, is called saturated, and has a Relative Humidity (RH) of 100%.

Absolute Humidity (AH, in g/m^3 or g/kg) is the water content, or the amount of water vapour in the air expressed as gram water vapour per m^3 air. Alternatively it can be expressed as gram water vapour per kilogram of dry air, and is then also known as **Specific Humidity (SH in g/kg)**.

Dewpoint (DP in degrees Celsius) is a measure of air humidity that tells us at which temperature condensation will occur. The dew point of air is always below or at the air temperature, never higher. If a surface (e.g. the glass roof) has a temperature equal to the dewpoint of the air (and thus colder than the air temperature) or lower, condensation will occur on that surface.

Humidity Deficit is the amount of water vapour that is missing from the air compared to when the air would be saturated with water vapour. Higher deficit means lower humidity, or drier air, and means a stronger suction on the plants to evaporate water.

Vapour Pressure Deficit (VPD in kilopascal, kPa) is also the amount of water vapour that is missing compared to when the air would be saturated with water vapour, but now expressed in units of pressure. Again, a higher deficit means lower humidity, or drier air.

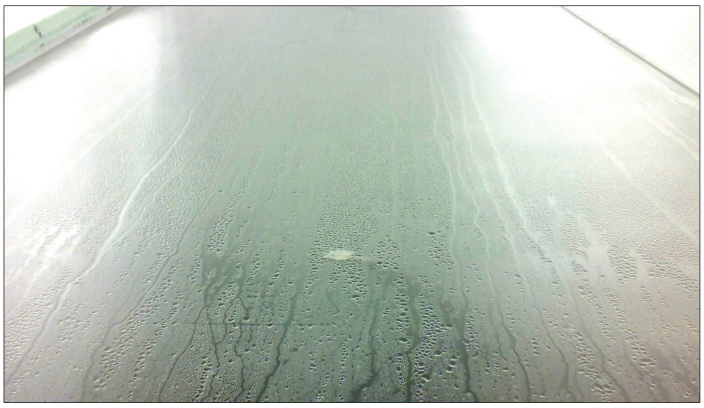


Figure 7A. Condensation on glass reduces the air humidity.

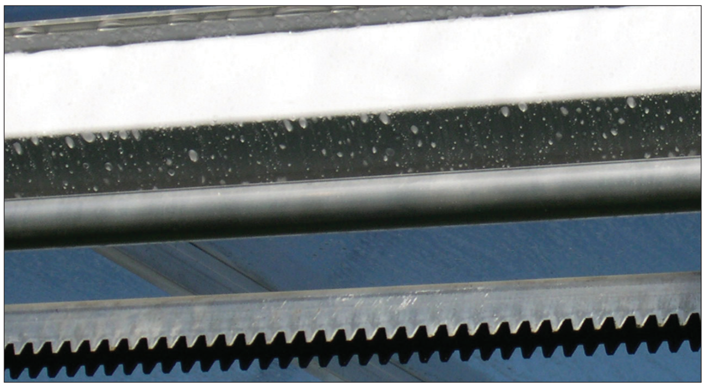


Figure 7B. Condensation on a gutter can be collected.

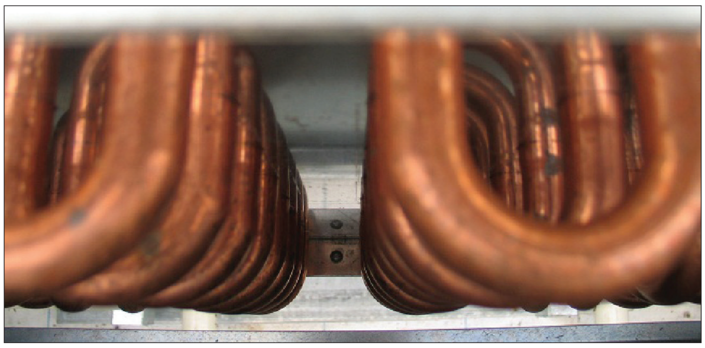


Figure 7C. A cold coil removes water vapour from the air.

Figure 7D. Condensation on plants should be prevented.

RH	0 °C				10 °C				20 °C				30 °C			
	AH	SH	VPD	DP	AH	SH	VPD	DP	AH	SH	VPD	DP	AH	SH	VPD	DP
%	g/m^3	g/kg	kPa	°C	g/m^3	g/kg	kPa	°C	g/m^3	g/kg	kPa	°C	g/m^3	g/kg	kPa	°C
100	4.8	3.8	0.00	0.0	9.4	7.6	0.00	10.0	17.4	14.5	0.00	20.0	30.5	26.5	0.00	30.0
95	4.6	3.6	0.03	-0.7	8.9	7.2	0.06	9.2	16.5	13.7	0.12	19.2	28.9	25.1	0.21	29.1
90	4.4	3.4	0.06	-1.4	8.5	6.8	0.12	8.4	15.6	13.0	0.23	18.3	27.4	23.8	0.42	28.2
85	4.1	3.2	0.09	-2.2	8.0	6.4	0.18	7.6	14.7	12.3	0.35	17.4	25.9	22.4	0.64	27.2
80	3.9	3.0	0.12	-3.0	7.5	6.1	0.25	6.7	13.9	11.6	0.47	16.4	24.3	21.1	0.85	26.2
75	3.6	2.8	0.15	-3.9	7.1	5.7	0.31	5.8	13.0	10.8	0.59	15.4	22.8	19.8	1.06	25.1
70	3.4	2.7	0.18	-4.8	6.6	5.3	0.37	4.8	12.1	10.1	0.70	14.4	21.3	18.4	1.27	23.9
60	2.9	2.3	0.24	-6.8	5.6	4.5	0.49	2.6	10.4	8.7	0.94	12.0	18.3	15.8	1.70	21.4
50	2.4	1.9	0.31	-9.2	4.7	3.8	0.61	0.1	8.7	7.2	1.17	9.3	15.2	13.1	2.12	18.4
40	1.9	1.5	0.36	-12.0	3.8	3.0	0.74	-2.9	6.9	5.8	1.41	6.0	12.2	10.5	2.55	14.9
30	1.5	1.1	0.43	-15.5	2.8	2.3	0.86	-6.7	5.2	4.3	1.64	1.9	9.1	7.9	2.97	10.5

AH = absolute humidity, SH = specific humidity, VPD = vapour pressure deficit, DP = dewpoint

Figure 7E. Table with relative humidity in the first column. Other humidity units are shown for four temperature levels.

Examples to understand humidity

Below are some examples with numbers taken from the table.

Example 1. Relative Humidity (RH): at 20°C, air with 100% RH has an absolute humidity (AH) of 17.4 gram/m^3. At the same temperature, air with 80% RH has an AH of 13.9 gram/m^3 (13.9 is 80% of 17.4), while air of 30 % RH has an AH of 5.2 gram/m^3 (5.2 is 30% of 17.4).

Example 2. At 10°C (in the second section of the table), fresh outside air with a RH of 90% has an AH of 8.5 gram/m^3 and SH of 6.8 g/kg. If this air enters the greenhouse and is warmed up from 10 to 20°C, the AH in this air mass remains the same (8.5 g/m^3 or 6.8 g/kg). But as it warms up, the RH now becomes 46%. So if cold air from outside comes inside, and is warmed up, the relative humidity drops. Because the fresh air mixes with wet warm greenhouse air, we don't see a dramatic drop in RH, just a modest reduction.

Example 3. Condensation occurs if the temperature of a surface is equal to or lower than the dewpoint of the air. Note that 'dewpoint' in °C is a measure of air humidity! A Relative Humidity (RH) of 100% means that the dewpoint is exactly the same as the air temperature. This can be seen in the top rows of the four sections, at 0, 10, 20 and 30°C. For example, at 10°C and RH of 100 %, the dewpoint is 10°C, and the AH is 9.4 gram/m^3.

Example 4. At 20°C and RH of 90%, the AH is 15.6 gram/m^3, and the dewpoint is 18.3°C. If this batch of air touches a surface of 18.3°C, dew will form. The glass roof is probably below 18.3°C, so condensation will form there. It can easily happen that the plants in some places in the greenhouse are 2 degrees colder than the air temperature, so they are 18°C. This is below the dewpoint, and the RH is 100% in these places. So the plants in this cold spot will get wet from condensation.

CHAPTER 8
Reasons for dehumidification

Removing excess water vapour, or dehumidification, accounts for a considerable portion of the energy use in a greenhouse, especially in mild climates or mild conditions.

So it is worthwhile finding out if dehumidification can be achieved with less energy. It starts with the notion that **every percent lower relative humidity** in the humidity setpoint costs energy (we are talking winter conditions here). The question is how high the humidity is allowed to be without being a risk factor. This chapter is about the risk of condensation and fungal infections, and a bit about the effect of humidity on transpiration and nutrient uptake.

Aim of humidity control

The aim of humidity control is to grow a healthy crop without wasting energy. In summer conditions, the aim is to prevent **too low** humidity and the risk of drought stress, but that is not relevant for energy saving. In winter and in overcast conditions, it is about preventing **too high** humidity, for two reasons: avoiding fungal diseases and secondly maintaining sufficient nutrient uptake.

There are some other (smaller) effects too, for instance the air humidity affects leaf stretching, plant shape, susceptibility for diseases and pollination in fruit crops.

Preventing fungal diseases

Spores of fungal diseases such as grey mould (Botrytis) hang around in a greenhouse waiting for the right conditions. The right condition is a thin layer of water or dew on a plant, which stimulates the fungal spores to germinate. Germinating spores produce hyphae (threads) that grow on the plant surface where the spore has landed, e.g. a leaf, flower, fruit or stem.

If the plant stays wet for several hours, the hyphae have enough time to penetrate the plant, for instance via leaf pores (see Figure 8B) or via wounds on the stem.

Once the hyphae are inside the plant, they are not dependent on humidity or dew anymore. From then on, the plant is infected, and the fungus will do its destructive work. If the plant dries up before the hyphae enter the plant, the hyphae will wilt, shrivel and die.

Thus, fungal diseases can be prevented by limiting the period that plants are wet. If condensation does happen, the greenhouse control must dry the plants within a couple of hours, so the spores don't get enough time to cause infection.

Condensation and dewpoint

Condensation or dew forms when humid air meets a cold surface that has a temperature below the dewpoint of the air. Dewpoint is a measure of air humidity but is expressed in degrees Celsius, as discussed in the previous chapter.

Condensation is inevitable if the Relative Humidity (RH) is 100%. The air temperature then equals the dewpoint. Condensation is very likely to occur if the RH is in the high nineties, and it is possible to occur if the RH is in the eighties or even seventies. It depends on the temperature of the coldest places in the greenhouse.

A cold surface is for instance the glass roof, but it can also be a cold plant part, and that is the problem. Plant heads and leaves can be cold due to heat emission, meaning that heat radiates from the plant heads to the cold roof (page 6). Whole plants can be cold if they are in a cold spot in the greenhouse. Fruits can be cold early in the morning, when the greenhouse is warming up from the night temperature to the daytime temperature. Fruits take longer to warm up because they have a bigger mass than leaves.

Plants can also be wet due to fogging or spraying. Fogging is normally done when it is warm and dry, so not in wintery conditions that are relevant for energy saving. Spraying must be done when the plants have a chance to dry.

Cold spots in the greenhouse

Most greenhouses have several places where the temperature is a bit lower than in other places, due to inadequate heating, a broken venting motor, or because that place lies lower. In such 'cold spots' the absolute humidity (AH) is the same as elsewhere, but the Relative Humidity (RH) is much higher than in other places. See example 4 in the previous chapter. If the RH in cold spots hits 100%, in other words, if the temperature gets as low as the dewpoint, condensation will occur.

It can be useful to perform a series of accurate temperature measurements to determine the temperature distribution in the greenhouse. If it is uneven, the best remedy is to address the cause, e.g. adjust the lay-out of the heating pipes, or repair a damaged ventilation motor, etc.

Safe humidity level

Many conventional computers work with relative humidity (RH) and aim to keep that far below 100%. The more uneven the temperature is, the higher the risk that condensation occurs **somewhere** and the bigger the safety margin needs to be. For example, if the setpoint is 75% RH to avoid 100% RH, the safety margin is 25%. This results in a very high energy bill.

In contrast, if the cold spots are fixed and the temperature is nice and even, the RH setpoint does not have to be as low. In theory the RH setpoint can be 95%, but it is more realistic to aim for 85 - 90%. Obviously, this requires a lot less energy than the target of 75% RH.

New innovative control methods such as GPE work with the dewpoint, and use precise methods to prevent condensation.

Figure 8A. Traditional way of measuring temperature differences in a greenhouse: beerbottles placed in selected locations, filled with water (to capture average temperature). The temperature in all bottles is measured quickly with a 'fast' thermometer, or with multiple equal thermometers. The pattern will vary depending on heating, venting and more. Measuring without sunshine is best.

Transpiration and nutrient uptake

The second reason for dehumidification in winter is to improve the uptake of plant nutrients.

When the humidity is very high (in cold conditions), plants cannot evaporate enough water, and therefore don't take up a lot of water. Therefore the delivery of nutrients to the leaves is very low too. This can lead to nutrient deficiencies, in particular calcium related problems. This can be a problem in winter especially when an energy screen is closed for many hours over many days.

In sunny weather, the transpiration is largely driven by radiation from the sun, while other factors are relatively unimportant. But when there is little or no sunshine, other climate factors do have an impact, for instance air movement, radiation from heating pipes, venting, and artificial lighting if present. Growers can use those factors to 'activate' the plants, and thus ensure sufficient nutrient uptake.

Humidity deficit

Several modern computer programs use the humidity deficit or vapour pressure deficit in relation to transpiration. Both measures determine how much water vapour can be added to the air before it is saturated. In contrast, relative humidity (RH) is not helpful in this respect, because it depends on the temperature.

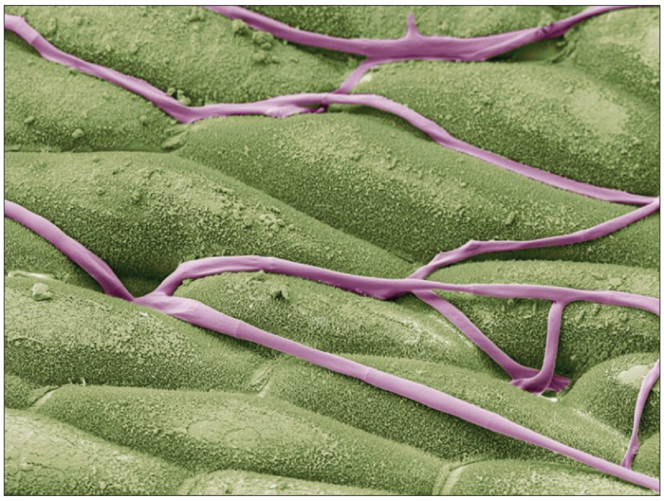


Figure 8B. Hyphae (threads) from a fungus grow into the pores of a leaf. *Source: syngentaturf.co.uk*

Figure 8C. Botrytis affects many plant species.

Figure 8D. Botrytis can affect all plant parts.

Figure 8E. Blossom-end rot is related to water balance.

Hortimax weather station. Source: ridder.com/weather-stations/

CHAPTER 9

Humidity control

Dehumidifying costs energy, no matter how it is done.

The traditional way of keeping the humidity low is by applying concurrent venting and heating.

Control devices

Dehumidification requires adequate control devices, such as heating, vents and/or mechanical ventilation, optionally fans and screens. Another pre-requisite is a good greenhouse climate control computer. Basically, the grower chooses the desired humidity level and sets the relevant settings in the computer. But what is a desirable humidity level? This depends on several factors.

Venting & heating

In a heated greenhouse in wintery conditions, the humidity (absolute and relative) is higher inside than outside. If it is too high, venting and/or heating are applied for dehumidification.

One method is having a minimum vent opening. This lets warm humid air escape and gets colder drier air in from outside. When it becomes too cold, the computer cranks up the heating pipes. The other way is having a minimum pipe temperature, but this is no longer recommended because it uses energy all the time. Minimum pipe temperature warms up the air, so that the RH declines. The vents must be slightly open, to let the warm humid air escape and to prevent the temperature being too high. Both methods of dehumidification are concurrent heating and venting.

Dehumidification boosts transpiration

Minimum pipe temperature, or in fact any method of reducing the air humidity, stimulates the transpiration. Sometimes this is desirable, for instance in dull and still weather conditions, especially if the dull weather lasts for several days. However, at other moments the transpiration may be adequate and does not need a boost. The fact that dehumidification stimulates the plant transpiration is then not desirable, because adding more water vapour to the air is exactly the opposite of reducing the air humidity. So there is a need for smarter control, that determines whether the transpiration needs to be stimulated or not. This will be discussed in the following chapters.

Screens and high humidity

A climate screen is a powerful tool to save energy when it is cold and also to improve the growing conditions in winter and summer.

A well-known problem is the accumulation of water vapour under the screen. Fortunately, many of the modern screen materials let water vapour pass through the screen, so that at least some of the moisture travels to the top compartment above the screen, where it condenses against the cold glass.

If that is not enough, the screen is opened on a crack of between 1-5%. The GPE and HNT methods, however, open the **vents** above the screen on a crack. This takes away a part of the energy saving, but still keeps the plant heads warm.

Improved humidity control

One step towards better humidity control is to measure the plant temperature and use software that calculates the risk of condensation on the plants, based on measured plant temperature and dewpoint (dewpoint is a measure of air humidity, see page 20). The climate control computer uses this information to take action to prevent plant wetness. The dehumidification is then more targeted and uses less energy than the normal control of humidity, by minimum pipe, minimum vent opening or aiming for a low Relative Humidity.

When condensation on the plants is imminent, the usual actions can be taken, such as opening the vents a crack. When a screen is used, the screen can be gapped, or the vents above the screen can be opened on a crack.

A good improvement is to use fans to create air movement, which either prevents condensation or helps to dry the plants quicker. Even better, is using fans to force air from outside (or from above the screen if there is one) into the plant zone. The ultimate solution is to bring fairly large volumes of dried air into the greenhouse, ideally under the plants. Fans and screens will be discussed in chapters 11 and 13.

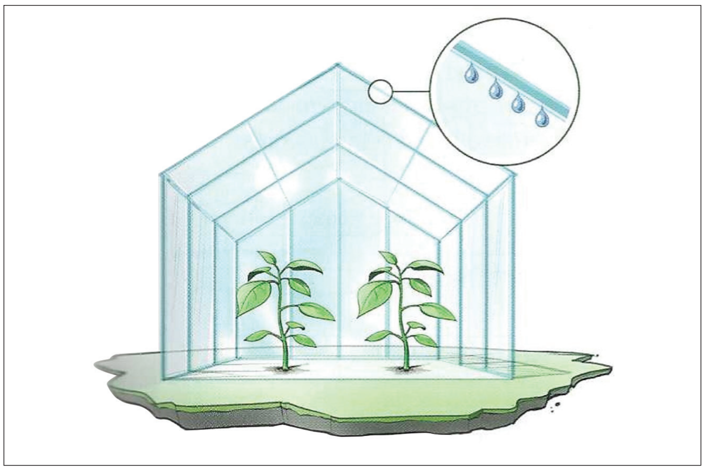


Figure 9A. Water vapour condenses against the cold roof. *Source: plantempowerment.com*

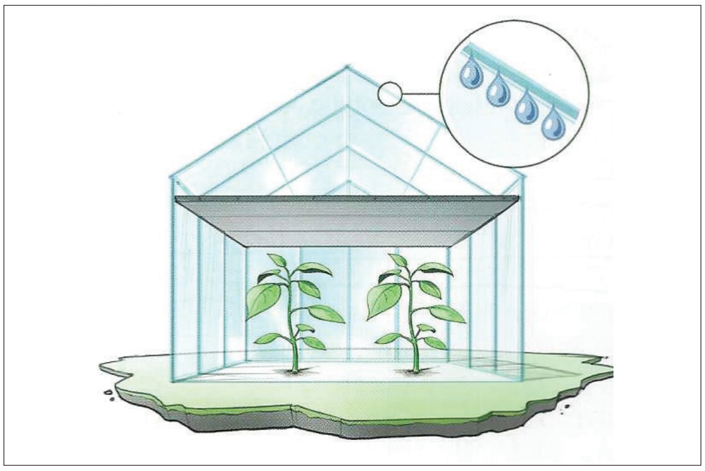


Figure 9B. A glass roof above a closed screen is extra cold, leading to heavier condensation. *Source: plantempowerment.com*

Figure 9C. Fans are the tradional way to keep plants dry.

CHAPTER 10

Innovative humidity control

As already mentioned, growers in Europe and elsewhere are using new innovative climate control methods, such semi-closed greenhouse systems, GPE ('Growing by Plant Empowerment'), HNT (in Dutch 'Het Nieuwe Telen', meaning 'The New Way of Growing'), and more (see Chapter 3).

Technology

As noted in Chapter 3, the full implementation of GPE requires large investments, of which several are only viable for newly built greenhouses. The new technology can include: an energy/climate screen, fans, mechanical ventilation or even Air Handling Units, an extra measuring box, a sensor for plant temperature, new software, as well as commitment and time.

Some ideas of GPE, such as about humidity control, may be worthwhile for all greenhouse operators, also without high-tech glasshouse. Note that 'moisture' means the same as 'water vapour'.

The New Way of Growing and GPE

Humidity control according to GPE and HNT features two separate actions: (1) preventing condensation and fungal diseases by controlling the dewpoint (= air humidity, see page 20). And (2) stimulating plant transpiration. This two-pronged approach gives a much better humidity control than just avoiding 100% Relative Humidity. Therefore it saves energy. The full version of HNT and GPE make use of mechanical ventilation for dehumidification, and screens for better climate control. Without such technology, the GPE approach can still be useful, but certain parts cannot be achieved.

Moisture balance

The New Way of Growing and GPE calculate the moisture balance. It uses measurements of the temperature and air humidity at three levels: two are in the plant zone and one is above the screen. The base load is the water vapour in the outside air, that comes into the greenhouse. On top of that comes moisture that is being added by plant transpiration. Deducted is the water vapour that disappears through ventilation and condensation. These various moisture flows are calculated, from which the water balance is determined. The moisture balance can then be controlled with the aim of avoiding condensation on the plants and maintaining sufficient transpiration. This control is done by the computer that steers the heating, venting or mechanical ventilation, screens, fans, etc.

Steering on dewpoint

To prevent condensation, the climate control computer works with the dewpoint (DP) and the leaf temperature (LT). DP is a measure of air humidity, expressed in degrees Celsius (°C). See the example in Chapter 7 for a description. The dewpoint tells us how cold the glass roof or a plant part must be to get wet from condensation. If the leaf temperature is below the dewpoint (both measured in °C), the leaf acts as a cold body where condensation occurs. To prevent condensation, the dewpoint (humidity in °C) of the air must be kept a bit below the leaf temperature, or the leaf temperature above the dewpoint. A method to prevent plant wetness is keeping the plants warm by closing a screen (a translucent screen during the day).

Steering the transpiration rate

Transpiration control is traditionally aimed at maintaining a certain RH, or more recently at maintaining a certain moisture deficit (either humidity deficit, HD or vapour pressure deficit, VPD). The innovative climate control systems are aimed directly at maintaining a certain plant transpiration. Therefore the computer calculates the water balance. If the calculated transpiration is not at the desired rate, the computer adjusts the devices (heating, vents, etc). This is very direct, and therefore it saves energy.

Transpiration calculation

The calculation of transpiration is briefly outlined here. When mechanical ventilation is used, such as extractor fans or Air Handling Units, the rate of air exchange is known exactly. It is then simple to calculate how much moisture is removed from the greenhouse air to the outside, and from this to determine the transpiration rate. To change the transpiration rate, the devices are adjusted.

Irrespective of the type of ventilation system, if the difference in AH between inside and outside is larger, less air exchange is needed to remove a certain amount of water vapour and to keep the transpiration going. Then far less energy is required.

Figure 10A. A sensor measures the temperature of some leaves and fruit. This data is used in calcualations of the energy and water balances. *Source: hoogendoorn.nl*

CHAPTER 11

Fans in innovative climate control

Electric fans (e.g. Vortex fans) have been used for decades in NZ greenhouses for creating air movement, keeping plants dry and maintaining an even temperature and humidity. Nowadays, fans are an important tool in energy saving and decarbonisation.

Fans vary from humble air fans to advanced Air Treatment Corridors that are part of semi-closed greenhouses. Fans for mechanical ventilation are a core part of new approaches such as HNT (The New Way of Growing) and GPE (Growing by Plant Empowerment). Mechanical ventilation using (green) electricity is a step towards 'electrification' of greenhouse climate control.

Fan functionality

Fans of various shapes and sizes are used, with different functionalities, for instance:

1. fans stirring the greenhouse air
2. fans drawing in outside air
3. fans creating vertical air movement
4. fans moving air through the screen
5. fans mixing two air flows
6. fans as part of Air Handling Units (AHU's) or an Air Treatment Corridor

Benefits of air movement

- Fans create air movement that drives moisture away from the plants and up against the cold greenhouse roof, where the water vapour condenses. Condensation dries the air, which is better for plant health.
- Drier air is cheaper to heat.
- Air movement improves the uniformity of the greenhouse climate. It smooths out 'cold spots' where plants would get damp, and moulds would flourish. (The best remedy would be to fix the cause of an uneven temperature, for instance to adjust the heating lay-out).

- Using air movement instead of ventilation keeps the valuable CO_2 inside the greenhouse.
- Fans stimulate the transpiration and thereby improve the nutrient uptake and nutrient transport from the roots to the shoots. This is important in dull overcast conditions, especially under a closed screen.

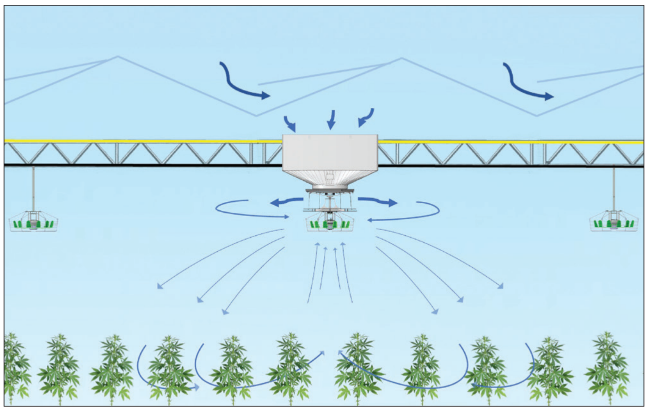


Figure 11A. A VentilationJet spreads fresh cool (drier) air from above the screen to the plant zone. *Source: Hinova.nl*

Heating and venting

Other methods of generating air movement in winter conditions include the use of minimum pipe temperature, minimum ventilation opening and gapping the energy screen. These practices cost energy and cause carbon emission. Calculations prove that using fans is more energy-wise and more economic than combined heating and venting. Using fans is a form of 'electrification' of greenhouse climate control, which fits in with decarbonisation plans.

Horizontal and vertical fans

Horizontal fans are nothing new for NZ growers. The configuration of the fans is important, but not discussed here. Horizontal fans may also be used for spreading plant protection products (LVM method).

Vertical fans create air movement from the top to the bottom in the plant, and smooth out temperature differences between the plant head and lower leaves. This is used especially in greenhouses with lighting (overseas), because the lamps produce a lot of heat above the plants.

Figure 11B. An AirMix system. *Source: vanderendegroep.nl*

Screen fans

Screen fan systems are a special form of vertical fan, designed to draw air from above a closed screen. This is a good way to dehumidify: the air above the screen is dry, because it is cold up there, and cold air cannot hold much moisture. Moisture is removed as it condenses against the cold glass. The vertical fan inlet is very thin and pokes up between two screens without creating a gap.

Obviously, the cold air that come in must be warmed by the heating pipes. Fortunately, dry air is easy to warm up. The exact temperature and humidity depend on the type of screen, how tight it closes, and whether the roof vents are fully closed or on a crack. Strong screen fans create an overpressure under the screen, which requires the installation of some pressure release openings (valves) in the greenhouse wall.

Figure 11C. A Hinova screen fan inhales air from above the screens. *Source: Hinova.nl*

Special screen fan systems

A special screen fan system allows mixing two air streams: cold dry air from above the screen and warm humid air from under the screen. One example is the Hinova VentilationJet System. The vertical air inlet is very narrow so there's no gap between the two screens. A connected fan in this system spreads the air vertically into the greenhouse under the screen. Another example is the AirMix, which throws the air out horizontally. It has a controllable valve for mixing two air flows. In principle, air is taken from both below and above the screen, and then mixed. But it is possible to take greenhouse air only and use the fan as a simple horizontal fan.

Fans drawing outside air

Fans that draw in fresh air from outside are an important element of humidity control in semi-closed glasshouses and other modern greenhouses. Cold outside air has a very low **absolute** humidity (the **relatively** humidity can be high, but that is irrelevant). The fresh air must be warmed up to the required temperature level, but it takes far less energy to warm up dry air than to warm up humid air. If the temperature is raised by a built-in electric heating block, it is a further step towards 'electrification' of greenhouse climate control.

Air Treatment Units and Corridors

Air Handling Units (AHU's) or Air Treatment Units (ATU's) consist of a strong axial fan, optionally with built-in technology for heating, cooling, humidifying and/or dehumidifying. Sometimes AHU's are placed in a long corridor where indoor and outdoor air is mixed and treated, before being blown into the greenhouse.

AHU's are the core of semi-closed greenhouses that have been built world-wide in a wide range of climate zones. Different suppliers offer different designs, and often build custom-made designs. The production results are impressive, especially in harsh climates. More about AHU's in the next chapter.

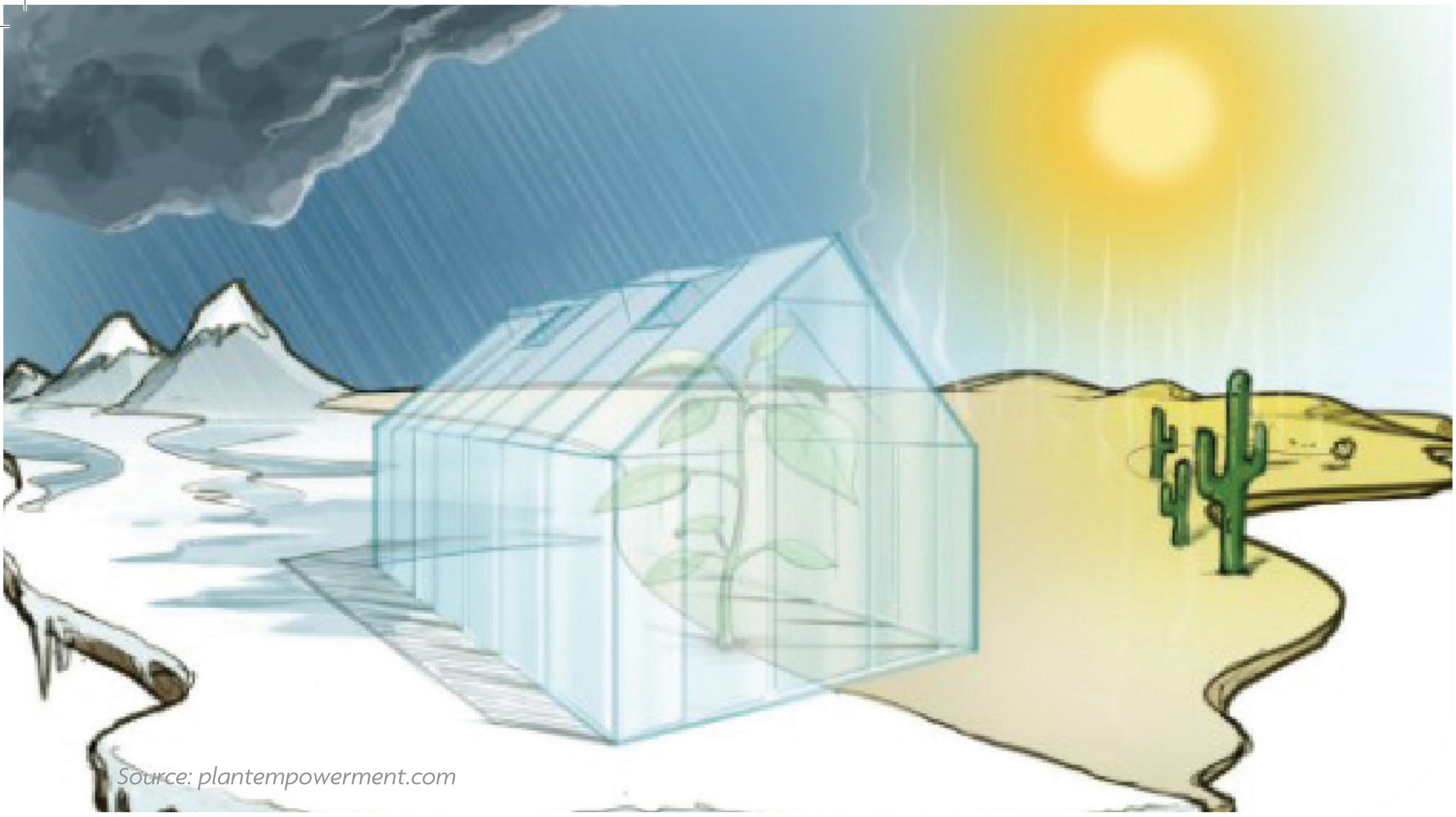
Figure 11D. One of the many types of Air Handlig Units (AHU's) outside a greenhouse.

Figure 11E. A treatment chamber or corridor, where greenhouse air and outside air are mixed. *Source: reinders-corporation.com/enerdes*

Fan outlet

Fans in a greenhouse can blow the air directly into the greenhouse space, or into large, perforated air ducts (sleeves / tubes / hoses) that spread the air evenly over a much larger area. The air ducts are often used under hanging gullies.

Figure 11F. Air ducts (sleeves / hoses / tubes) spread treated air throughout the greenhouse.



CHAPTER 12

Semi-closed glasshouses with mechanical ventilation

New Zealand's decarbonisation plan forces growers to move to alternative climate control methods and/ or alternative fuels.

One possible solution for new-builds is a semi-closed greenhouse with mechanical ventilation, combined with a form of heat supply and/or heat storage. Mechanical ventilation uses Air Handling Units (AHU's) that blow dried air into the greenhouse or into long plastic air ducts (tubes / sleeves / hoses) positioned under the suspended gullies. This system will be powered by sustainable electricity. Some features are discussed below.

Figure 12A. A semi-closed greenhouse with AHU's.

Electricity

Electrification of greenhouse climate control can only be sustainable if the electricity is generated in a sustainable way, e.g. by hydro, wind or solar. For decades, a large proportion of NZ's power was generated by hydro stations, so electricity was largely sustainable. But when water levels in the hydro lakes are low, and when demand exceeds supply, the shortfall is often filled by other power stations fired by fossil fuels. Running a large-scale greenhouse on unsustainable electricity does not help the decarbonisation goal.

It is desirable that power is generated close to where it is needed, perhaps even on site. But currently there is little support for growers to generate sustainable power. When green power and proper infrastructure is available at a reasonable price, electrification of greenhouse control can become a viable option.

Semi-closed glasshouses

Over more than a decade, many semi-closed greenhouses have been built in Europe and elsewhere in the world. There are several manufacturers and many variations of semi-closed systems. Some have shown astonishing results, especially in regions with extreme climates.

Semi-closed greenhouses usually have 50 to 80% less roof vent opening than standard greenhouses, and instead have mechanical ventilation from Air Handling Units (AHU's).

The ventilation rate varies widely, some systems can only do 5 m^3 air exchange per m^2 per hour, others can do up to 80. The warmer the climate and the lower the natural ventilation, the heavier the forced ventilation must be.

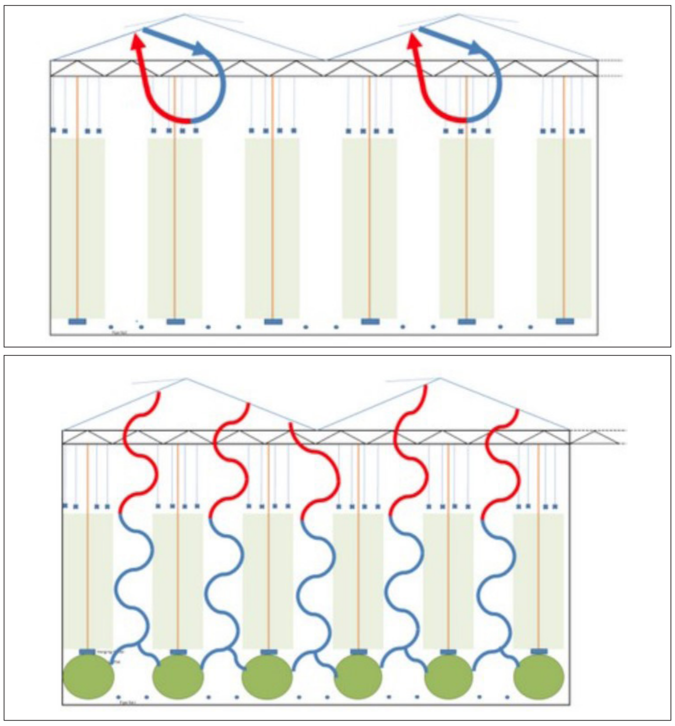


Figure 12B. Cooling by conventional venting (top), versus by AHU's (bottom). *Source: glasshouse-consultancy.com*

Air Handling Units (AHU's)

An AHU or ATU (Air Treatment Unit) in its basic form is an axial fan unit. Other devices can be added, such as a heating coil, cooling coil, pad-and-fan cooling (adiabatic cooling), energy recovery, condensation recovery, CO_2 injection and fogging. The AHU then becomes a much bigger unit.

The AHU's can be installed on the outside against the greenhouse wall, or in an enclosed 2-meter-wide and 3-meter-high corridor over the entire length of the glasshouse.

In the AHU itself or in the corridor, the greenhouse air is mixed with fresh air from outside. The ratio of inside air and outside air can be varied by a computer-controlled valve. The mixed air can be heated, dried, cooled, etc, depending on the technology in the AHU's and what is needed in the prevailing conditions. The treated air is then blown into the greenhouse, often via perforated air ducts.

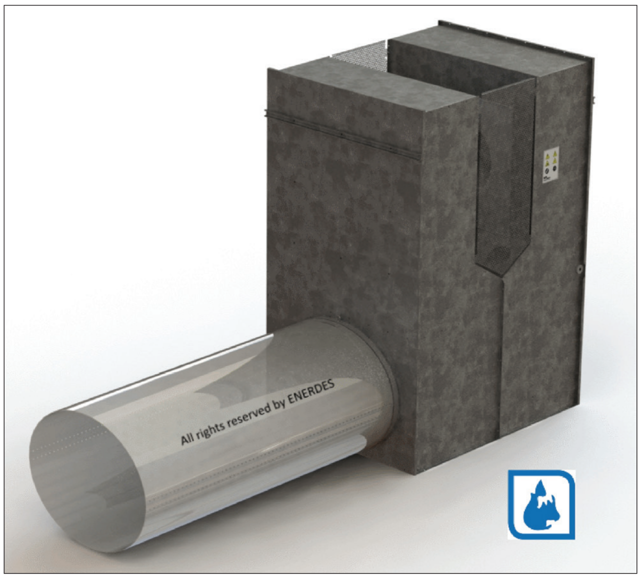


Figure 12C. A 'bare' Air Handling Unit. *Source: reinders-corporation.com/enerdes*

Figure 12D. One of the many types of AHU's.

Air ducts / hoses / tubes / sleeves

The air ducts are mostly made of polyethylene and come in various diameters (0.3 - 1 meter) and lengths. They can be single layer or tube-in-tube, and there are different perforation options. The hose must stay pressurised over its entire length while the fans can run at variable speed. The fans are often designed to run at 30 - 70% of full capacity, and 50% on average. Over the years, many different features have been trialled.

Figure 12E. An AHU with an air duct.

Some numbers

It is a skilful art to properly design the forced ventilation systems regarding electrical capacity, fan speeds and air duct characteristics. The tubes can be spaced out for example at 2 meters. A 100 meter long tube then serves 200 m^2. An example of a small system is one with 60 meter long tubes, serving 120 m^2. Each tube is connected to a 350 Watt axial fan. Each fan can move about 6,000 m^3 of air per hour, which is 50 m^3/m^2/hour. Assuming the fans run at 50%, the electricity capacity is only 1.5 Watt per m^2 (350 x 0.5 x (1/120). The annual power use can be estimated at 13 kiloWattHour per m^2 per year (1.5 * 365 * 24 * 0.001 kWh). This is equivalent to about 1.5 m^3 gas/m^2/year, but it does not include heating.

A large system is for instance one with very long tubes of 140 meter (covering 280 m^2) with a very strong axial fan of 2.6 or even 3.5 kiloWatt. Each fan can move 18,000 - 22,000 m^3 per hour, or 64 - 79 m^3/m^2/hour. If a fan runs at 50%, it uses 4.6 - 6.3 Watt per m^2. Over a whole year at 50% on average, the power use would be 41 - 55 kWh/m^2/year. This is equivalent to about 5m^3 natural gas per m^2 per year.

*(With thanks to Frank Van Rooijen, **www.reinders-corporation.com/enerdes**)*

Advantages

The advantage of a semi-closed greenhouse is better controllability, saving energy, keeping CO_2 inside. Fewer ventilation windows mean less maintenance and wear & tear and also less light loss and reduced insect ingress.

Some advantages of mechanical ventilation over natural ventilation are:

- better controllability
- better temperature and humidity distribution
- less condensation and less fungal infection
- able to run safely at a higher humidity setpoint, thus saving energy
- keeping CO_2 inside, so higher level at the same CO_2 injection rate

Also, the forced ventilation can be used to improve the transpiration, because by removing moisture from the air, the plants will respond by increasing the transpiration. In greenhouses with a thermal screen, forced ventilation prevents moisture build-up under the screen. Hence there is no need for a gap in the screen for humidity control, which saves energy.

Heating

The AHU's do not necessarily heat the greenhouse, as heating requires an energy source. AHU's can contain a heating coil. This can be heated by green electricity if that is available and affordable, or by a form of stored heat, reject heat, geothermal heat. That often requires a heat exchanger or even a heat pump running on electricity. It is quite common in the Netherlands that heat is collected from the greenhouse in summer and stored underground for use in winter.

When using air ducts (tubes / hoses / sleeves), it is important to know that the warm air in tubes cools down much faster than hot water cools down in a heating pipe. It works best if the incoming fresh air is heated to just above the temperature of the greenhouse air and not much higher.

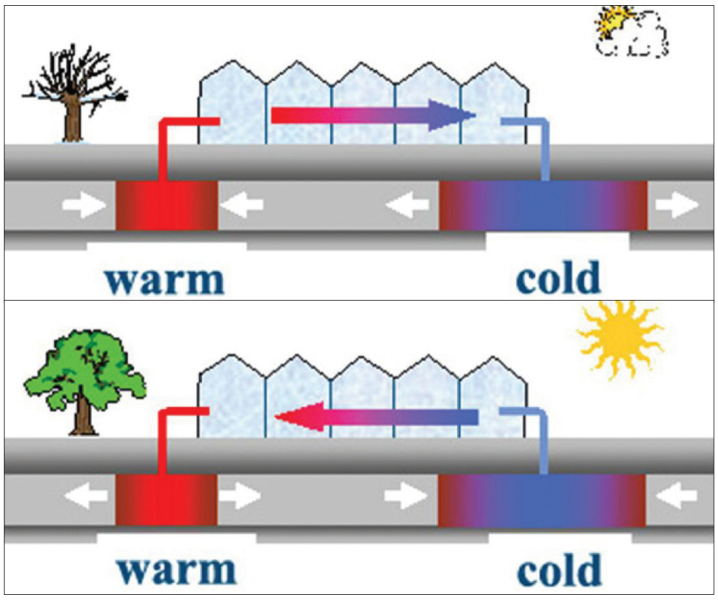


Figure 12F. 'Heat and cold storage'. Warmth is stored in the aquifer in summer and used in winter.

CHAPTER 13

Climate screens for energy saving and more

Retractable screens are a key tool for glasshouse climate control in many parts of the world.

The first screens were developed for energy saving during the energy crisis in the 1970s. Now there are many types of screen materials, designed either for energy saving, shading, light diffusion, blackout or insect control. Some screens can serve several purposes.

Earn-back

The earn-back time of an investment in energy saving depends on many factors, for instance: How cold is it? How many cold nights (or days) in a year? Is enough heat available on a cold night? How much damage is caused by not meeting the target temperature? Obviously, screens that are purely meant for energy saving are only useful when it is cold.

But the modern translucent screens can be used for other purposes too, such as improving the growing conditions, even in the summer. The economics are different for each situation but are not discussed here.

Screens for different purposes

Retractable energy screens were first introduced some 40 years ago by Ludvig Svensson in Sweden. Today Svensson and other manufactures produce over 100 types of climate screen materials, with different combinations of energy saving (up to 80%) and light transmission (from 0 to 80%). At the end we outline these percentages for some screen types.

Modern screen materials have some other (optional) characteristics too: high translucency, anti-condense, letting water vapour through, fire-resistant, and folding up into a small compact bundle.

Screen materials from Svensson. The first number is % light reduction, the second is % energy saving

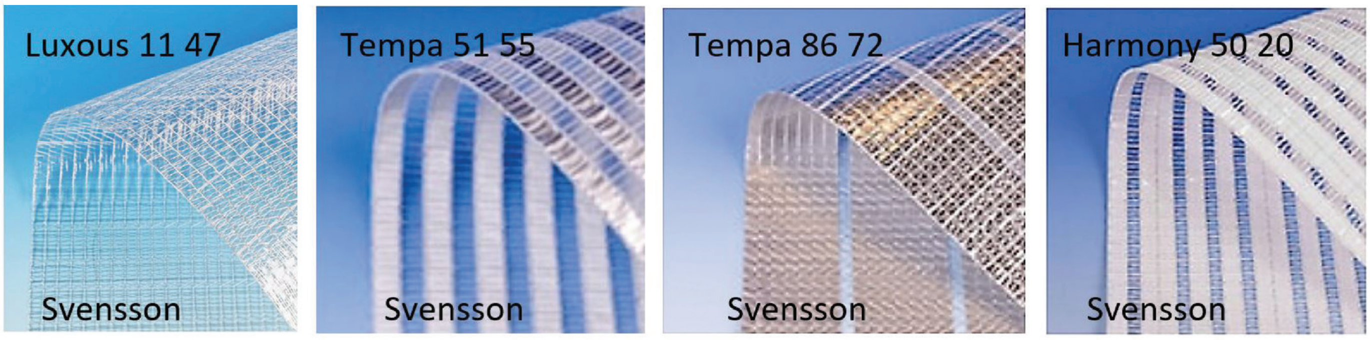


Figure 13A. Examples from four groups of screen materials for climate control. *Source: /www.ludvigsvensson.com/*

Screen materials

The Svenssons screen materials are divided into six groups:

1. Energy saving combined with maximum light transmission (named Luxous)
2. Energy saving in winter especially at night, and light reduction in summer (Tempa)
3. Light diffusion (Harmony)
4. Light restriction and total blackout (Obscura)
5. Ultimate solar protection (Solaro)
6. Insect control while allowing ventilation (Xsect)

Energy saving

A screen saves energy in cold conditions in three ways. It separates the warm air in the plant zone from the cold air in the top zone (reducing convection). It prevents the air in the plant zone from flowing along the cold roof (reducing conduction). Thirdly, it blocks the heat emission from the plant (reducing heat radiation), which results in warmer plant heads and a string of positive effects.

Warmer plant heads

Without an energy saving screen, plants radiate their warmth to the cold glass roof and to the very cold sky. This heat emission results in cold plant heads. Screens clearly keep the plants warmer. One effect is that warm plants attract less condensation (dew) and stay drier. Hence they get far less mould and fungal infections, and need less spraying. Warmer plant heads have a higher transpiration, and the internal water flow supplies nutrients like calcium to the plant heads.

Also, as the growing point at the top of the plant stays warmer, the development rate increases, meaning that the growing point throws out more new leaves and flowers (or trusses) per week, than if there was no screen (see page 12). This latter effect is not always noticed but can mean a lot for the plant balance.

Humidity problems in the past

Energy screens were notorious for creating problems with high humidity, condensation, water dripping and light loss due to wetness. Many growers left the screens partly open for most of the night, to let moisture escape to the top compartment. This obviously considerably reduced the energy saving results. With old-fashioned screens, large droplets formed underneath that created a rain shower on the plants, especially when the screen opened.

Nowadays the problems of high humidity are largely overcome. The Svensson climate screens are designed to let moisture go through, so that it disappears to the top compartment. Here it condenses or escapes through the vents that are opened on a crack. Woven screens are warmer on the underside and therefore attract less condensation. The anti-condensation attribute means that water forms a film rather than large droplets.

The most effective remedy against high humidity under a screen is the use of fans that extract cold dry air from above the screen and spread that out in the plant zone (see page 30). This controlled way of gapping is extremely effective.

Figure 13B. Two separately controlled screens in cucumber.
Source: /www.ludvigsvensson.com/

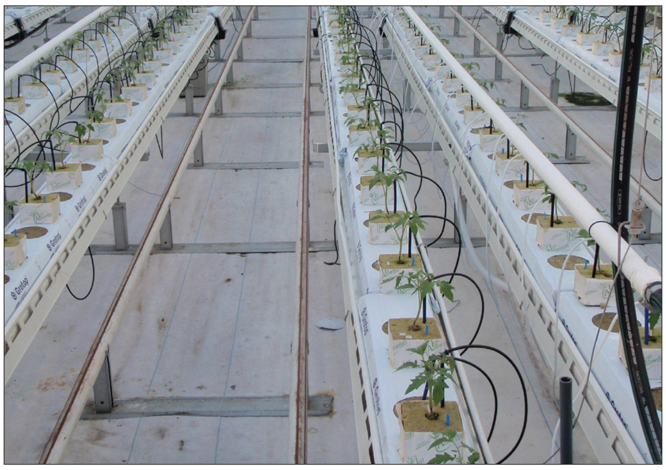


Figure 13C. A screen creates a mild climate for young plants.
Source: /www.ludvigsvensson.com/

Controlling the screen opening and closing

The New Way of Growing (HNT) and Growing by Plant Empowerment (GPE) have demonstrated the benefits of using the climate screen a lot more than done traditionally. This has become common practice now. Translucent screens are often closed some hours before sunset to lock in the heat of the day. The next morning they open somewhat later than what was normal.

The timing of opening and closing is often based on air humidity (increasingly absolute humidity compared inside and outside), temperature (inside and out) and radiation or light. The computer program considers the trade-off between energy saving and light loss. So if it is cold outside, the screen can open later in the morning when the solar radiation reaches 250 Watt/m^2 (measured outside with a pyranometer).

The early morning hours are the coldest hours of the day. It is also the time when the temperature must be raised from the night level to the day level. If the screen was opened at that time (as was done traditionally) the heating would also have to warm up the cold air that falls down from the compartment above the screen. This would create an enormous peak in heat demand. This would require a much higher heating capacity.

If the screen is closed during daylight, the plants are evaporating, and the humidity will build up even more than at night. The remedy is to open the screens on a wide gap, not just on a tiny crack as done traditionally. The benefit of warmer plant heads remains, while excess moisture easily streams to the top compartment.

Young plants under a screen

A special situation occurs when plants are planted in winter during cold or even frosty weather. Cold air has a very low moisture content (low absolute humidity). Young plants do not bring much moisture into the air, so the humidity (absolute and relative humidity) in the greenhouse stays low. This causes stress on the young plants. Screens help to increase the humidity and make the conditions milder. In this situation (which is different from the situation with large plants) the increase in air humidity under a screen is desirable. Of course the screen must be translucent if it is to be used during the day.

Figure 13D. Climate screens can be a year-round control.
Source: /www.ludvigsvensson.com/

Benefits in summer

Using a translucent screen during the day in summer has many potential benefits, if done in the right way. Here are some advantages in a nutshell: reducing plant temperature and plant stress; avoiding sunburn and other damage; preventing wilting; making the radiation more diffuse thus increasing the photosynthesis; reducing peak water uptake; improving the working conditions. Again, it is very important to install a screen that is suitable for the key purposes, either energy saving in winter or improving the conditions in summer, or both.

In colder countries, growers now install two screens. Both screens can be closed for energy saving on cold winter nights. A translucent screen can be used on a winter's day for energy saving, and on a summer's day for shading.

Energy saving and light transmission percentages

Below is a brief description of three types of screen materials made by Svensson (source: **www.ludvigsvensson.com/en/climate-screens/**).

Screen materials from the TEMPA group are extremely good for energy saving (52 - 72% when closed) and offer a range of light transmissions (5-50% light transmission, aka 50 - 95% light reduction). They are made of alternating aluminium and polyester 4-mm wide strips, ranging from 1/3 aluminium to full aluminium. Tempa screens are perfect for energy saving at night, but those with poor light transmission are not suitable for energy saving in the daytime. Some Tempa screens can be used on summer days for tempering the incoming solar radiation.

Screens from the LUXUOUS group save up to 47% energy when closed and have a very high light transmission (ca 80%). Made of translucent polyester strips, they are suitable for energy saving during the daytime, and can be used for softening the sunshine in summer. When retracted, they pack very tightly, to minimize the shade.

Screens from the HARMONY group also give up to 47% energy saving, and block 30-40% of the light. They are primarily meant for scattering the sun light, as scattered or diffuse light is better for plants than harsh direct light.

Figure 13E. This shade screens is specially designed for this wide-span glasshouse.

Figure 13F. The mechanism for screen movement.

CHAPTER 14

CO_2 enrichment in changing times

The greenhouse industry does not just emit CO_2, like other industries do, but also utilises CO_2 to stimulate plant growth and production. CO_2 is often obtained from burning natural gas, because the flue gases are clean and very suitable to be fed (with caution) to the plants.

Due to the call for decarbonisation, aka reduction of the use of fossil fuel, growers are seeking non-fossil energy solutions. Then questions pop up about CO_2, for instance: how much production is missed without CO_2 enrichment, what is the actual benefit of CO_2, how much CO_2 is needed, what alternative CO_2 sources exist, what CO_2 price is justifiable. There are no simple answers. This chapter touches on some of these topics and gives some estimates of CO_2 amounts needed.

Figure 14A. A lay-flat duct for CO_2 distribution.

Ambient CO_2 concentration

CO_2 is a natural component of air. Currently the concentration is about 0.0415 % or 415 millilitres per m^3 of air, which is usually expressed as 415 ppm (ppm = parts per million). In 1950 it was ca 315 ppm. So it has risen 100 ppm, or about one-third in only 70 years. The rise is largely due to human industrial activity.

CO_2 from natural gas

Flue gas from combustion of natural gas is high in CO_2 and virtually free of impurities (if the burner is working properly). What is not ideal is that heat and CO_2 are produced at the same time but required at different times. A heat buffer can partly resolve this problem. Then natural gas is burned during the day for CO_2, with the heat stored in the buffer and released the following night. This is now common practice, also in New Zealand, in large and medium-size greenhouse operations.

Just some figures: 'standard' minimum supply rate is considered 50 kg per hectare per hour (50 kg/ha/hour = 5 g/m^2/hour). This requires the boiler to burn about 25 m^3 of natural gas per ha per hour, or nearly 1 GJ/ha/hour. The real injection rate is often 4 to 6 times this standard amount and can be more at times. The burner must be fully adjustable and controlled, so that it produces what is needed at that moment.

Alternative fuels for CO_2

For decades, the search has been on for alternative CO_2 sources, because many growers (e.g. on the South Island) had no access to natural gas. Several fuels are suitable to be burned for CO_2 enrichment, including propane, butane, premium kerosene (paraffin), low-sulphur natural gas, low-sulphur oil, and (with caution) also LPG. Most large-scale greenhouses in the North Island use natural gas. Of course, all fuels will be charged with increasing carbon emission costs.

Not suitable for CO_2 enrichment are the flue gases of coal, wood-products and heavy oil, as they contain dangerous compounds that cause severe damage to plants (and possibly humans too). Wood-based fuels don't have a consistent composition, so it is hard to maintain the right fuel-to-air ratio.

HotLimeLabs system

There is a promising development by the NZ company HotLimeLabs, where waste wood is first 'gasified' and then the gas is burned. The CO_2 that is produced is temporarily absorbed in lime pellets and can be released when needed. The system is being develop and tested here in NZ.

Figure 14B. HotLime Labs is an innovative CO_2 solution.

Pure/liquid CO_2

Overseas, a very important CO_2 source is the exhaust gas from heavy industries. After passing an expensive purification process, it can be nearly 100% CO_2 gas. It must be of horticultural quality, which is different from medical or food quality. The most important feature is that it must be free of ethene aka ethylene, and very low in sulphur-containing compounds, and in NO_x (NO and NO_2). It can be delivered by road trucks. In several regions in the Netherlands, there is a huge CO_2 network in place that distribute the CO_2 to greenhouses via gas pipes.

CO_2-uptake / photosynthesis

Plants exposed to (sun)light take up CO_2 gas and transform that into sugars and ultimately new plant tissue. This is photosynthesis or CO_2 assimilation. Every 1 kilogram of CO_2 absorbed by a plant gives around 10 kilograms of new plant material. In mature tomato plants, about 80% of this (or 8 kg) ends up in fruit, and the remaining 20% makes up the leaves, stems and roots. Note that this is % of CO_2 taken up, not % of CO_2 injected in the greenhouse.

Photosynthesis requires light, so CO_2 enrichment at night is pointless (unless with lighting). In darkness, plants emit CO_2 due to respiration (burning of sugars). This causes the CO_2 concentration to rise overnight to above-ambient levels (say to 500 ppm) if the vents are closed.

CO_2 depletion

In cold winter days, when there is no ventilation, the natural CO_2 influx is very low. If it is sunny, the CO_2 is being consumed and not replenished. This can lead to a drop in CO_2, even below the outside concentration. This is called CO_2-depletion. See Figure 14C. The low CO_2 level hampers the CO_2 uptake. If CO_2 is injected during CO_2 depletion, the CO_2 level will rise and so will the CO_2 uptake. As long as the CO_2 level inside is lower than outside, there is no CO_2 loss to the outside. So all CO_2 injected will end up in the plants (100% utilisation).

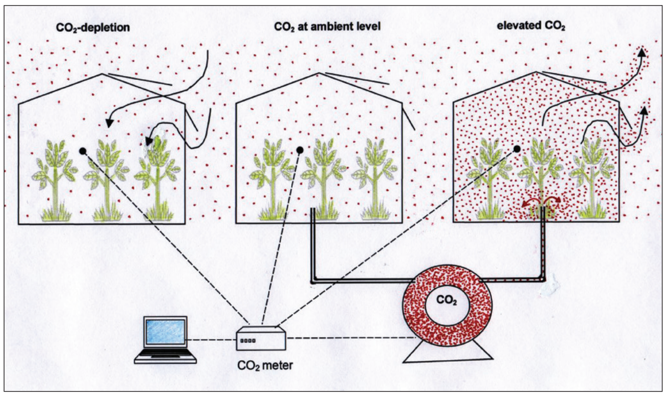


Figure 14C. Left: CO_2 depletion, venting brings CO_2 in. Right: elevated CO_2, ventilation means CO_2 loss.

'CO_2 curve'

CO_2 enrichment stimulates plant growth, resulting in bigger leaves, branches, flowers, fruit, and thus higher yield. Figure 14D shows 'the CO_2 curve', depicting the relative production versus the CO_2 concentration. The CO_2 curve has a wide band, because it is based on many experiments with a range of crops. The data was collected when the ambient level was 340 ppm, and the graph is adjusted for the current ambient level of 415 pm.

At a very low CO_2 level (say 200 ppm), photosynthesis and plant growth are nearly zero. The first 100 ppm increase in CO_2 gives the greatest increase in photosynthesis; the next 100 ppm gives a very good increase; and gradually the effect of more CO_2 levels off. Beyond about 1100 ppm, there is almost no further effect of more CO_2, and the line goes horizontal.

It is important that the effect of CO_2 is proportional to the time that a certain concentration was given. For instance, if CO_2 enrichment to 600 ppm is given only for 4 hours in the morning out of 12 hours daylight, the expected effect will be one-third of what the graph shows, namely one-third of ca 18%, or 6%.

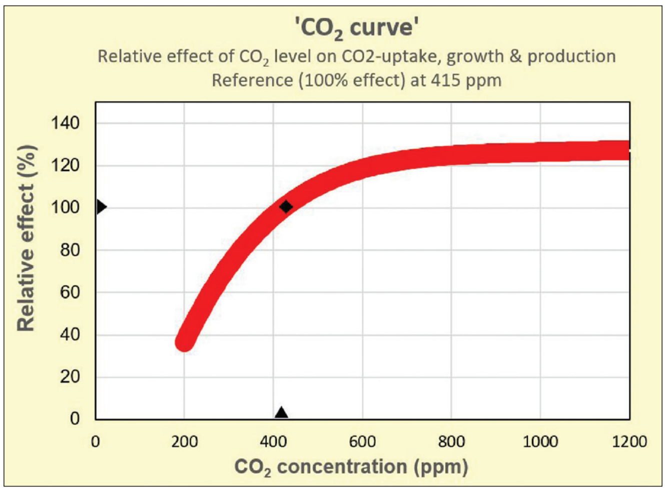


Figure 14D. CO_2 curve showing the effect of CO_2 on growth.

Optimum CO_2 level

The maximum effect of CO_2 may be reached at say 1100 ppm (or sometimes higher), but it is better to aim for a moderate level (say 600-700 ppm). Some reasons are: a high CO_2 level means that a relatively large portion of CO_2 gas is lost by ventilation, which is very uneconomical. At a high CO_2 concentration there is more risk that harmful gases (that can be accidentally part of the CO_2 gas) reach a dangerous level. Moreover, a higher CO_2 concentration means that the stomata (pores in the leaves) close a bit further.

Only in some conditions can it be economical to increase the CO_2 concentration to a very high level of 1000 ppm: healthy producing plants, good growing conditions (light), a low ventilation rate, cheap CO_2, and favourable produce prices. In other situations, it is probably safe to have a modest target level, and reap the greatest benefit, while keeping the costs down.

Control

There are several ways to control CO_2 enrichment. It can be based on time: CO_2 enrichment is on only in the morning; or based on vent opening: CO_2 enrichment is on only when vents are open 15% or less. The standard way was aiming for a certain level (say 900 ppm) when ventilation is low, and reducing the CO_2 target with increasing ventilation or increasing air exchange rate.

Another way is to work with the CO_2 injection rate. The CO_2 injection can be maximised depending on the conditions. It can be fixed, permanently, at say 150 kg/ha/hour injection and a CO_2 level of 800 ppm. The concentration will vary depending on the ventilation and other conditions.

In innovative control such as HNT and GPE, the idea is to align the CO_2 level with the light level, and so achieve the highest 'Light Use Efficiency'. GPE uses a rule of thumb that the CO_2 level in ppm must be at least the same as the radiation level in W/m^2 measured outside. That is achievable in a semi-closed glasshouse when the greenhouse air is recirculated but a very high CO_2 level is impractical in greenhouses with natural ventilation.

Changing times

A big question is how much CO_2 is needed. For figures about CO_2 use, we first look at CO_2 use the Netherlands in the past (and present). The future is uncertain due to extravagant energy prices and uncertainty about natural gas. Many growers used the flue gas from burning natural gas and employed a heat buffer for day-to-night heat storage. They could apply CO_2 quite generously, assuming the heat was used at night. Many other growers were using CO_2 that was (and is) easily available via a CO_2 network. This piped CO_2, a by-product of petrochemical industries, was very cheap. The low CO_2 price allowed growers to use CO_2 generously.

However, these CO_2 enrichment practices have been the topic of discussion and research in the last 10-15 years in the Netherlands. Where flue gas CO_2 was used, the CO_2 enrichment sometimes accounted for a measurable part of the energy consumption, as CO_2 enrichment was only partly covered by heat demand.

Some figures

Initially in the 1980's, a standard minimum injection rate was 5 gram/m^2/hour (50 kg/ha/hour), but after the 1990's it became fairly standard to inject 20 gram/m^2/hour (200 kg/ha/h) or more. For annual CO_2 consumption, 60 to 70 kg/m^2/year (600-700 ton/ha/year) became quite common.

In 2011, an experiment was done with tomatoes to determine the effect of a 50% reduction in CO_2 enrichment (WUR, de Gelder et al, 2012). The energy requirement for heating could already be reduced by employing the New Way of Growing, GPE, etc., and was estimated at 750 MJ/m^2/year (in The Netherlands that is 24 m^3 gas/m^2/year). But the annual energy requirement was higher due to CO_2 enrichment. For comparison: standard energy use was at least 1200 MJ/m^2/year, but mostly far more.

In the experiment, one compartment was controlled in the standard way, with a maximum CO_2 injection rate of 22 g/m^2/h (220 kg/ha/h) and a maximum CO_2 concentration of 1200 ppm.

Another compartment received limited CO_2 enrichment, also with a maximum concentration of 1200 ppm. The injection rate was restricted to 7.5 g/m^2/h (75 kg/ha/h), plus optionally an extra 2.5 g/m^2/h liquid CO_2. The annual consumption of the extra CO_2 was limited to 5.5 kg/m^2/year. It was controlled by a CO_2 optimisation program, which dedicated the CO_2 to the lightest hours. Peak use was in the middle of summer.

The results of this experiment showed that the CO_2 injection was indeed halved, from 46 to 23 kg/m^2/year. Interestingly, generally the CO_2 concentration was not very different between the compartments, especially on sunny days. The difference in tomato production was only 1 kg, from 66 to 65 kg/m^2/year.

Nowadays, the New Way of Growing and GPE make use of optimisation programs that weigh up the photosynthesis (which is highest in the lightest hours) versus the CO_2 losses (which depends on air exchange rate). It then depends very much on what form of cooling is used: natural venting or mechanical ventilation with air recycling.

Figure 14E. A CO_2 meter with two calibration cans.

Figure 14F. Liquid or 'pure' CO_2 is an alternative for flue-gas CO_2.

CHAPTER 15

Biomass for greenhouse heating

Biomass such as waste wood is a possible fuel for greenhouses in New Zealand as an alternative for natural gas or coal. The Bio Energy Association writes on their website: *'Wood fuel is a sustainable, carbon-neutral fuel and offers a real opportunity for New Zealand to become greener and less dependent on fossil fuels'.*

Waste wood is used successfully in several greenhouses in New Zealand for instance at Zealandia Horticulture in Auckland and Christchurch. A shortcoming is that the flue gases from wood combustion are not suitable for CO_2 enrichment, unless a very expensive flue gas purification system is added. This chapter describes some advances in biomass combustion technology in the Netherlands, where decarbonisation started over a decade ago. Some innovative Dutch growers are generating heat and electricity from biomass, and others produce heat and indeed CO_2 by biomass combustion.

Figure 15A. Wood-based biofuel.

Biomass roller coaster

Biomass (e.g. wood waste) does contain carbon, but is not a fossil fuel, as it was not formed millions of years ago. Thus the decarbonisation plan allows the use of bio-fuels, because the bio matter would decay quickly and release CO_2 anyway.

The use of biomass for greenhouse heating in the Netherlands has ups and downs. Waste wood was recommended for several years as a promising green alternative to natural gas, both for combustion and for digestion to produce biogas. Several growers invested in a biomass burner, supported by a particular government subsidy aimed at stimulating the use of sustainable energy.

But the sustainability of waste wood is being debated. Some issues are: air pollution, emission of nitrogen, long-term availability, long-distance transport, import of biofuel from abroad and also the public opinion about cutting down trees/ forests.

Recently the Dutch government concluded that biomass combustion caused more air pollution than previously realised, unless an extremely expensive air treatment was applied. In 2021, the government suddenly changed the criteria for the particular subsidy, so that wood combustion for low temperature application (100°C) no longer qualifies. That subsidy is now shifting towards stimulating the capturing of CO_2 from wood combustion. Dutch growers who were planning to install a biomass boiler, but without the costly CO_2 capturing, are left in limbo.

Figure 15B. Bunker with biofuel at DES (Netherlands) *Source: des-bv.nl*

Biomass installation with CO_2 capturing[1]

Already in 2017, three large-scale tomato and eggplant growers formed a company (DES) that built a biomass installation for waste wood with a CO_2 capturing facility. In 2019, the installation started supplying heat and CO_2 to the three glasshouse complexes. It was the first in the Netherlands, and the third in the world. It can produce 8.5 MW of heat, and 2.2 ton of nearly pure CO_2 per hour.

Wood shred is delivered by road trucks several times per day, to a total of roughly 20,000 ton per year. A local company collects woody waste from over 20 nurseries, arborists and contractors in the region, who are keen to put their waste to a good use. The fuel contains circa 55% water. The flue gases are led through a 'wet scrubber', that extracts the residual heat from the flue gas and purifies it. This leads to 99.8% pure CO_2, ready for CO_2 enrichment. When not needed, the CO_2 is stored in two 16-meter-high balloons. The balloon capacity is found to be too small to cover the complete CO_2 need, so some extra CO_2 is bought in. Expansion of the CO_2 storage capacity is on the growers' wish list.

Figure 15C. Glasshouses of DES with one 16-meter high CO_2-balloon erected and the second one under construction. *Source: des-bv.nl*

Results

After a period of testing, learning and optimising, the three growers at DES are now satisfied with the installation's performance. Each of the three glasshouse complexes still has its own gas-fired heat supply, either a boiler or co-generator, to provide flexibility and back-up. Currently about 65% of the heat demand is covered by the biomass installation; the aim is to increase this to 85 - 90%. The result is a saving of roughly 6.5 million cubic meters of natural gas, the equivalent of 12 million kg of CO_2 per year. The growers say the investment of several million Euros is paying off: they do produce their own heat and CO_2, biomass is cheaper than natural gas, and they receive a government subsidy per unit heat produced. The result is a marked reduction of their heating costs.

Wood burner for heat and electricity

A Dutch grower (Wouter Moerman) produces tomatoes, cucumbers and beans in a four-hectare glasshouse complex in the South of the Netherlands. Since 2019, he has used a wood burner for heating and electricity generation. Heat from the wood burner drives an ORC (Organic Rankin Cycle, a small turbine), which generates electricity. The remaining heat (water of 90°C) is used for heating the glasshouses. In the winter it takes 6 truckloads per week of wood chips, that come from forest, park and garden maintenance. The wood burner works fine, but the ORC in combination with the wood burner needs attention. The system saves 2.5 million cubic meters of gas, and about 200,000 Euros per year, says the grower. In his opinion, this is the only energy technique that is affordable for his size of glasshouse.

Heat and CO_2 from waste combustion

Domestic waste in the Netherlands is burned in mega-large combustion ovens. The heat produced is used for heating homes and glasshouses, hence the name waste-to-energy plants. There are strict requirements for the flue gases to be stripped of soot and harmful gases. Since 2014, some waste-to-energy plants installed additional technology to extract CO_2 from the flue gases. The flue gas is cooled down and brought in contact with a dissolving fluid that absorbs most CO_2 gas. This fluid is heated to release the CO_2 gas, which is then cooled to around -20°C. The CO_2 is then liquid and pure and can be stored and/or transported. Although the CO_2 is excellent (high quality, suitable for CO_2 enrichment, available in massive volumes), it is hardly utilised by the greenhouse industry. Apparently, the current system of subsidies and tariffs stimulates burying CO_2 deep underground rather than supplying CO_2 to glasshouses. The greenhouse industry and the waste processing industry together are trying to change this situation.

Figure 15D. Fluegas condensor at a biomass burner.

Concluding

Above are only two examples of biomass-based glasshouse heating in the Netherlands. There are many more projects and also other techniques, such as using a digester to breakdown biomass and produce biogas, which is then burnt for heating. Several trials and projects with biomass are underway that may lead to new developments. Also other fuels and other energy techniques are being developed that compete with biomass. Government policies and subsidies will affect the direction of the decarbonisation journey in the Netherlands.

Nowadays, experts in the Netherlands consider biomass to be the best option for now for independent, medium-size glasshouses, provided the fuel supply is secure. A leading energy innovation specialist (Dennis Medema) says: wood burners will be needed in the energy transition, certainly until 2030. That gives us time to build regional heat distribution nets. Initially they will be fed with heat from a mix of energy sources, including biomass. Later the preferred heat source will be determined, which can be for instance reject heat, geothermal or aquathermal energy.

Sources: several paragraphs are based on info from Onder Glas, December 2021. (1) see also ***www.des-bv.nl***

Figure 15E. Various wood-based fuels.

CHAPTER 16

Alternative energy options?

Decarbonisation and setbacks in natural gas supply are causing incredibly tough challenges for the greenhouse industry in New Zealand and in other countries too. Growers are confronted with absurd price hikes, imminent reductions in supply, and a rise in predicted carbon emission charges.

Greenhouse operations in the North Island, including large corporates, are unable to get a reasonable natural gas contract for next winter. There will be little time for a gradual energy transition. This chapter outlines some energy solutions that work well in the Netherlands, where decarbonisation started several years ago. However, finding a fitting solution and implementing it in the New Zealand situation will be difficult.

Energy transition

In the last decades, many glasshouse operations in the Netherlands have installed a gas-fired co-generator and a heat buffer tank. This set-up caters for efficient control of the temperature and humidity (by heating), CO_2 enrichment, as well as lighting. Transitioning to another energy arrangement will have a great impact. Most new energy solutions provide heat, but no electricity and certainly no clean CO_2. Often, we see that various solutions must be combined to achieve what is needed.

Looking at the greenhouse industry in the Netherlands, it appears that different situations require different solutions, depending on:

- Size: large versus small glasshouses.
- Heat availability: potential access to heat supply.
- Networks: option to join a cluster or stay independent.
- CO_2 availability: can CO_2 be supplied via a pipe network or road tankers?
- Electricity need, especially for lighting

Solutions in New Zealand

The situation in New Zealand is very different, but also here, not one solution fits all situations. It will be very difficult, but potential energy arrangements can involve the use of:

- Low-grade heat from several external sources
- Low-grade heat harvested in own glasshouse in summer and stored underground
- High-grade heat from a geothermal or industrial source
- Green electricity from solar, wind, hydro or biomass, produced on-site or off-site
- Heat pumps possibly in combination with a low-grade heat source and (green) electricity
- Bio-energy including waste wood
- Hydrogen, a promising option for the future
- Combination of the above

Bio-energy

Bio-energy is being trialled by greenhouse growers worldwide. The obvious bio-fuel in New Zealand is waste wood from forestry, but it is a matter of securing sufficient supply and reliable transport for future years. Multi-hectare greenhouse operations will struggle with the sheer volume of waste wood needed. The use of other types of biomass, and innovative ways of pre-processing it, are being investigated. It must be noted that burning raw biomass produces flue gases with an inconsistent composition. Purification of flue gases to make them suitable for CO_2 enrichment is expensive. Perhaps the HotLime system could be an answer?

Large glasshouses

Large greenhouses would probably struggle with biomass, because it has a low energy content and would be needed in enormous volumes. Large greenhouses need a compact and powerful energy source. The best solution so far appears to be hot water of 80-100°C, either from a geothermal bore or industrial source. Overseas, reliable heat suppliers are industries and large waste incineration plants, but in New Zealand industrial high-grade heat sources are scarce.

Obviously, geothermal heat is found close to the surface in places in New Zealand. Some large greenhouses on the North Island have been using geothermal heat for greenhouse heating for nearly two decades. Geothermal heat has been adopted on a large scale by growers in the Netherlands, even though the hot water must be pumped up from 1.5 to 2.5 km deep. The enormous investments for a deep bore are shared between members of a so-called cluster of users. Geothermal bores can produce CO_2 gas, but it is mixed with huge amounts of sulphur, and so far it has been unfeasible to separate the CO_2 and sulphur gases.

Cluster or network (overseas)

In the Netherlands, where glasshouses are located relatively close together and close to urban and industrial environments, energy users and energy suppliers have formed ‘clusters’ and ‘networks’. A cluster is a strong consortium that can realise the extremely expensive infrastructure and geothermal bore. A cluster consists of a combination of large-scale glasshouses, office buildings, hundreds of homes, as well as industries and a reliable and powerful supply of hot water of 80 - 100°C. This heat is distributed through a heat distribution network that can stretch several hundreds of kilometres. Many clusters also have a CO_2 distribution network.

Independent sustainable glasshouse

If not part of a cluster, a glasshouse will be an ‘independent sustainable glasshouse’, with its own supply of heat, CO_2 and power. In the Netherlands, there are basically two energy options used in such situations: (a) electricity + heat pump + water (or air) to extract heat from, and (b) bio-energy, such as biogas, green gas, biomass e.g. waste wood or agricultural waste burned in a boiler.

Many Dutch growers have a hot-and-cold facility consisting of two bores, one for warm and one for cold storage either in the shallow underground or in deeper groundwater (aquifer). These allow seasonal storage of excess heat, and retrieval of heat in winter, with the use of heat pumps. In summer the water from the cold bore is used for cooling.

Independent glasshouses that use sustainable energy often have CO_2 for CO_2 enrichment delivered by a road tanker.

Low-grade heat and a heat pump

Low-grade heat is a stream of water or air with a moderate temperature. In freezing conditions in winter, water of say 5-10°C is relatively warm.

This water can be fed into a heat pump, which extracts the heat from the incoming stream and transfers it to the outgoing stream. The outgoing stream has a cranked-up temperature of for example 35°C, which is high enough for greenhouse heating. The heat pump uses electricity for this process in an efficient way: every 1 kWh electricity that goes in produces 3 to 4 kWh heat that comes out.

In cold climates, the input for a heat pump must be luke-warm water, because a heat pump cannot efficiently extract heat from freezing cold air. In milder climates, the input for a heat pump can be (lukewarm) outside air. Hence four types of heat pumps can be distinguished: air-to-air, air-to-water, water-to-air, and water-to-water. Lukewarm water can come from many sources, such as a (milk) factory, cooling water from a data centre, water treatment plant, aquifer (underground water bubble) or surface water (canals, ponds). A flower grower in Auckland intends to build a heat pump system with outside air as a low-grade heat source to extract heat from. If this is successful, it opens great possibilities for sustainable greenhouse heating for other growers too.

Future solutions

Energy is a very dynamic field, with new innovative approaches being developed and being tested all over the world. There are new developments in electricity generation, heat storage, heat pumps, climate (humidity) control, CO_2 enrichment, greenhouse structures, and more. Hydrogen is a promising energy carrier for the future.

A lot more about this in a downloadable e-book ‘Technology scan: innovative technology for transition to a low-carbon greenhouse industry’ See next page.

Figure 16B. Heatpump. *Source: Certhon.com*

Figure 16C. ‘Hot and cold storage’ in the aquifer. *Source: https://www.kasalsenergiebron.nl/*

Figure 16A. Geothermal energy transport pipe in Mokai.

Figure 16D. Heat is extracted from surface water in the UK.

REFERENCES

Further reading

'Technology scan; Innovative technology for transition to a low-carbon greenhouse industry' e-book by Elly Nederhoff (2021). Download from: **tomatoesnz.co.nz/hot-topics/energy-efficiency-for-growers/**

'How to grow in a modulair glasshouse' (about semi-closed glasshouses) by Godfried Dol. Order via: **glasshouse-consultancy.com/shop/ols/products/how-to-grow-in-a-modulair-glasshouse**

'Plant Empowerment: the basic principles' by Peter Geelen, Jan Voogt and Peter van Weel. Order via: **www.plantempowerment.com**

'Onder Glas' (monthly magazine produced in the Netherlands), December 2021. English version 'In Greenhouses' **www.ingreenhouses.com/**

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