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GUIDELINES TO IMPROVE

Greenhouse Industry Energy Efficiency

and Reduce CO_2 Emissions

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Energy Efficiency and Conservation Authority
Te Tari Tiaki Pūngao

Contents

Executive Summary

It is assumed most cost-conscious growers under the pressure of rising energy prices would have already applied a lot of energy saving options as a matter of competent business practice as most of the options to reduce energy costs and improve energy use efficiency are well known.

Innovative, enterprising growers who can manage to improve the thermal efficiency of their greenhouses and systems and can access the technology to enhance crop production could reduce the current cost of energy by about 70% to near 1990 levels.

The techniques for making energy savings and improving energy use efficiency under New Zealand climatic conditions are presented in these Guidelines in three stages by:

- reducing energy losses by about 20% by applying relatively simple and cheap measures to minimise annual energy demand immediately, thereafter,
- improving energy efficiency by a further 20% with better use of existing environment systems to improve crop performance by increasing CO_2 enrichment periods at modest costs within one year, and,
- further increasing energy use efficiency by improving crop performance by an additional 30+% through application of advanced environment control and crop management techniques over two or three years.

Consideration could be given by the greenhouse industry to negotiating bulk prices of liquefied CO_2 from industrial sources where Carbon Tax has already been paid or waived on CO_2 gas being discharged into the atmosphere. This approach, if found to be cost effective, would avoid the current practice of burning NG (natural gas) during the day to produce CO_2 for greenhouse enrichment when much of the heat is wasted, especially in summer.

The volume and cost of most greenhouse crop production inputs are fixed irrespective of crop production levels. Therefore, a poorly managed and low producing crop costs very much the same to grow as a high performing crop but the unit costs are much higher. This means by increasing marketable crop output by applying a more advanced environment control and management techniques the unit cost of production and of course, energy, is proportionally reduced.

However, the application of energy saving measures and the upgrading of crop management methods can cause unexpected and potentially costly reactions to the environment and crop conditions that are typically unique to a grower's operation. To avoid these adverse events a cautious management approach involving a step-by-step implementation process is recommended.

While a number of growers are already energy efficient and could apply the Stage 3 crop and energy management techniques immediately, most growers would need to allow a long implementation period to minimise the risks inherent in applying new technology.

Definitions

a) *"Energy"* means fuel used for heating and CO_2 production and electricity used for all purposes.

b) The term *"greenhouse"* means both glass and plastic covered structures, unless stated otherwise in the text.

c) *"Product Unit"* means, in the context of this Guideline, the unit of sale such as kg, stem, each, box, bunch, etc by which the greenhouse produce is sold.

d) *"CoP"* means cost –of production.

Introduction

The greenhouse industry, as with all New Zealanders, is faced with substantial permanent increases in global energy prices irrespective of whether the energy is obtained from fossil or non-fossil renewable[1] sources.

The aim of this Guideline is to demonstrate to greenhouse owners and managers (cut-flower, vegetable, fruit, herbs, plant propagators, etc) practical techniques to mitigate the adverse effects on business viability of the already high and rising energy costs.

Recent industry studies[2] show a surprisingly wide range of energy efficiency levels, a long list of energy loss pathways and an equally wide and sometimes confusing range of methods by which energy use can be measured.

There are several stages that can be followed to reduce energy demand for any greenhouse and crop type ranging from relatively cheap and simple through to more difficult and complex, but all are potentially cost effective provided any adverse side-effects are identified promptly and controlled.

Extending the CO_2 enrichment period by the strategies described in this Guideline can have a major beneficial effect on crop productivity and energy use efficiency.

This Guideline does not fully cover greenhouse cooling, crop lighting (low intensity day length/photoperiod control or high intensity PAR supplementary lighting), environment-related nutrition, crop physiology, environment-related disease control and product quality, crop management or the full integration of plant growth factors' growth and development systems or the diverse adverse reactions that might occur following changes to energy management. Not all the recommended options apply in all cases and in some instances expert advice or services are needed to solve heat loss problems and related crop management responses.

The Pending Carbon Tax

By increasing the efficiency of energy use the effect of the pending Carbon Tax on greenhouse business viability can be significantly reduced before the tax is applied in 2007. However, discussion on the Carbon Tax issue or subjects such as World's Best Practice related to Negotiated Greenhouse (emissions) Agreements (NGAs) are matters outside the scope of this Guideline.

Measuring Energy Use Efficiency

This Guideline suggests as money (net profitability) is the bottom line business denominator, monthly energy cost as a percentage of monthly product sold or costs of production (CoP) are measures which can give growers an immediate indication of the benefits of energy saving applications.

This method avoids complicated and diverse energy units and crop-type comparisons and can be easily applied when growers are recording monthly costs and income statements.

An Excel spreadsheet is provided with this Guideline to enable energy-efficiency-costs-to-sales results to be produced from 2002 to 2012 (the end of the first stage of the Carbon Tax implementation period).

[1] *Non-fossil energy sources such as bio-mass, use of waste heat, geothermal, etc, will not necessarily be cheaper as the cost of accessing these renewable sources is not cheap and will be priced to recover development capital and delivery costs indexed closely to fossil fuel prices.*

[2] *The MAF/VegFed Sustainable Farming Fund project No 03/158 study and AgriLink NZ reports "Greenhouse Energy Use and Carbon Emissions" 2003 & 2004 published as MAF technical Paper 2003/03.*

Greenhouse Business Issues Relevant to Energy Conservation

Review Business Viability

Because of the current and notified increases in energy costs there is relatively little time available for energy reduction measures to be put in place. Therefore, it is suggested growers carry out a cost-benefit analysis of their business's future viability with and without the application of the remedial actions as described in this paper. It may be prudent to discuss these matters with accountants or business advisors who may suggest a more comprehensive review of the future prospects for the business.

Balance Sheet Factors

Most of the expenditure on energy conservation measures can probably be written off as Repairs and Maintenance in the financial year when the costs were incurred.

Where new capital expenditure is involved, IRD Depreciation for 'continuously operating air conditioning' (fans, ducting, sensors, evaporative cooling systems, CO_2 gas application, etc), insulation, combustion and energy storage equipment may apply.

The Anomaly of Increasing Production

A side effect of increased production that could occur with increased energy use efficiency may lead to an over-supplied market and reduced prices; not a very satisfactory reward for taking the initiative to increase energy efficiency. However, the reduction in energy costs per unit of marketable product may enable lower prices to be accepted and profits maintained.

Alternatively, cropping area could be reduced and different crops grown in the surplus space. However, reducing either direct energy consumption or unit energy cost provides increased business management flexibility and added financial security.

Replace and Relocate Obsolete Greenhouses

For some growers the replacement of obsolete greenhouses with modern high energy efficient, high productivity units may be an option rather than to try a major costly upgrade of an existing unit. Retrofitting new systems, such as thermal screens, is often difficult and not fully effective. Cost-benefit and payback period analysis should be applied at all stages.

Alternative Energy Types

Consideration should be given to using non-fossil fuel, waste heat from factories (dairy) and thermal and geothermal power stations, sawmills and other high energy use rural industries where synergetic relationships may be established.

Risks Associated with Energy Saving Applications[3]

Most of the energy saving recommendations do not involve great expense but, there are side effects which can be costly if not properly managed. Each energy reduction step will almost certainly cause widespread reaction to the greenhouse environment and crop response as most growers will be aware that no change will act in isolation.

To secure maximum advantages from energy conservation growers will need to apply their invaluable plant husbandry skills with close observation of the crop and be ready to make timely management changes. Consider carefully the benefits or otherwise of those changes before rejecting the new technology. If in doubt a qualified advisor should be consulted.

[3] *Because of the risks of misunderstandings of the contents of these Guidelines and errors in application and the unpredictable nature of the adverse side effects that can occur following the application of energy saving recommendations, neither EECA nor the authors of these Guidelines accept any liability whatsoever for losses which growers may incur.*

Introduction to the Guidelines' Options for Increasing Energy Usage Efficiency

A number of growers are already efficient energy users in relative terms, but irrespective of greenhouse type or covers (glass or twin-skin plastic) very significant energy use reductions can still be made by most growers.

Therefore, this Guideline provides a range of initiatives that growers can undertake to reduce energy demand and costs. The implementation of the Guidelines will depend on grower initiative to discovering the areas where improvements can be made. Where practical, the underlining horticultural science and psychrometric engineering principles have been indicated[4].

In the early stages of applying recommendations in this Guideline, less energy may be used, but obviously there is a minimum level of energy that is needed for environment control for any greenhouse. However, as the more advanced recommendations are applied, increased production can be expected to reduce unit product energy costs thus increasing energy efficiency but not necessarily less energy is used. This effect is illustrated in Table 2.

The interaction of light, heat, moisture, air movement and CO_2 are factors that are often mentioned in the Guideline in combination but with different outcomes.

The basic greenhouse and environment systems design criteria that relate directly or indirectly to energy efficiency factors assume:

- all plants in the greenhouse receive the same environment conditions within close limits by appropriate adequate capacity and spacing of environment systems and active, continuous (24 hrs per day) air movement through the crop canopy and greenhouse. Horizontal overhead fans frequently fail to achieve sufficient air mixing and distribution;
- greenhouse heating, electricity and water requirements to achieve and maintain selected environment conditions and the related costs are generally fixed irrespective of the existence or state of a crop in the greenhouse;
- all structural, covers, environment and control systems are fully integrated at the design stage and are capable of providing the environment conditions needed to grow the particular crop at near optimum performance; and
- the greatest gain to crop performance and thus energy-use efficiency occurs by extending the number of hours each day of CO_2 gas enrichment of the greenhouse atmosphere which is achieved by applying the more advanced environment control options described in this Guideline. If in doubt a qualified advisor should be consulted.

[4] *For more in-depth technical information contact EECA or the Guideline authors.*

Stage 1 – To Minimise energy waste

Reduce greenhouse air leakage

Most, if not all, of the cost of the work in this stage can be written off as Repairs and Maintenance.

Air leakage occurs through a variety of often unnoticed channels. Even when all vents and doors are "shut tight" air leakage can siphon off large quantities of valuable heat and CO_2.

Older glasshouses are highly wind sensitive with total greenhouse air volume leakage rates in the range of 4-10 air changes/hr (AC/hr). Modern glasshouses have air-change rates of about 1.0 to 2.0 AC/hr and modern fan ventilation powered twin-skin plastic as low as 0.25 AC/hr.

Therefore:

- ensure all doors and vents are tightly fitting along all edges and are frequently given a thorough check for air leakage (re-face doors with a smooth material (twin-wall impact resistant, clear polycarbonate), install pressure seals and wedge action hand lever locks on doors;
- ensure glass fits tightly into glazing bars (use clear silicone sealants and weather tape), re-inspect after high winds as glass can move out of glazing bars due to normal structural movement;
- inspect covers regularly and repair broken glass and holes or tears to plastic covers;
- seal heat pipes at entry to glasshouse with flexible, insulating seals;
- seal water and hydroponic pipes, gas (NG & CO_2) and other pipe and cable entries;
- seal drainage pipes at entry and fit water/air traps;
- seal cover joining lines and wall and roof intersections of twin-skin greenhouses (use silicone mastic and all-weather tape);
- seal foundation perimeter line with sand, soil or even a mowing strip;
- plant or use artificial shelter against prevailing wind;
- hire an ultra-sonic scanner[5] to detect hard-to-find air leaks.

WARNING

Reducing air leakage will reduce heating demand, but will increase humidity by moisture retention resulting in condensation and the risk of fungus disease if canopy air movement and temperature control are inadequate. These environmental changes and crop management factors will require adjustments to the control system temperature, humidity and CO_2 settings primarily to bleed off excess moisture in a controlled manner and possibly to reduce heating system response sensitivity (heat system will not operate as often and will run for shorter periods). Benefits include the retention of CO_2 by day and night which will increase crop productivity.

Insulate Glasshouses and Facilities

There is a wide range of heat-loss factors related to primarily the thermal transmission values[6] of the covering material[7] used with which growers should familiarise themselves.

Contrary to popular belief, there is little practical difference, if any, between the light transmission values of the glass and multi-layer plastic covering materials. However, modern inflated greenhouse twin-skin plastic films and rigid plastic sheet systems result in significant long wave thermal resistant, providing enhanced energy conservation and solar light diffusity[8] benefits.

Therefore:

- consider covering or removing glass from glasshouse walls and replacing with inflated twin-skin IR greenhouse film where this is practical (see Table 1);
- consider replacing glass roof and walls on older greenhouses with twin-skin IR plastic as this measure could reduce energy demand by about 55% (see Table 1);

[5] *EECA can advise on ultrasonic scanner service suppliers.*

[6] *The heat transmission loss factors in $W/m^2/°C$ difference to inside and outside temperatures is given by many sources as about 8.0 $W/m^2/°C$ for modern single glass and about 3.6 $W/m^2/°C$ for modern twin-skin plastic with a wind speed of 7 m/sec.*

[7] *Specially formulated greenhouse covers include single-skin glass (rarely double glazing), flexible single and twin-skin plastic (special high strength, long life (5 years)) modified polyethylene, polycarbonate twin-wall rigid sheets, etc.*

[8] *Solar light diffusity means light is spread in many directions giving better canopy light penetration with no direct light shadows and reduced sun scald damage.*

- consider lining the inside of glasshouse walls with a single skin of IR greenhouse film;
- spray polyurethane on underside of metal gutters[9] where practical;
- some electricity lines companies provide an IR scanning service[10] to detect where energy is being lost through faults in covers and systems;
- to reduce solar heat load in summer, paint boiler rooms, cool-rooms, pack-houses, head-house, offices and staff facility exterior walls and roofs with heavily pigmented white titanium paint[11];
- consider recovery of waste heat from cool-room compressors for offices, staff rooms and pack-house heating in cold weather;
- consider collecting warm greenhouse roof zone air and recycling with fan and duct system to base of plant canopy.

Table 1
Effect of Differences in Greenhouse Type and Covers on Energy Demand

Location	Modern Twin-skin Plastic MJ/m^2	Modern Single Glass MJ/m^2	Ratio
North Island	700	1,600	2.29 x more energy needed
South Island	1,600	2,100	1.3 x more energy needed
Thermal Heat Transmission W/m^2.ºC	3.6	8.0	2.22 x more energy needed

Data from MAF Technical Paper 2003/03 "Energy use and Carbon Tax Emissions" and ECNZ "Guide for Marketing Electricity to the Greenhouse Industry", August 1991.

[9] *Metal gutters and glazing bars have no thermal resistance so siphon heat directing to the outside in cool weather and most nights.*

[10] *EECA can advise on IR scanner service suppliers.*

[11] *Titanium oxide paint has a high solar energy reflectance attribute.*

Check Environment Sensors

Aspirated Instrument Screens

It is essential to screen temperature sensors, thermostats, humidistats and preferably CO_2 sensors from direct and indirect solar radiation by day and cloud effects[12] by night. Always locate temperature and humidity sensors with check thermometers in an Aspirated Instrument Screen[13] designed to international standards. This will ensure temperature and humidity readings can be compared to worldwide horticultural science and crop management recommendations.

It is important to position aspirated screens (sensors) inside the top of the plant canopy as it is the environmental conditions in the canopy that determine plant performance, not the conditions in pathways or the air space above the crop. Use one set of sensors in aspirated screens per 1,000 m^2 of controlled area. The control system software should be able to display and average the sensor readings from each screen and controlled area.

Check Sensors

- Check Aspirator Screen's fans regularly and maintain if necessary and keep the body of the screen clean inside and out.
- Check the condition and accuracy of all temperature sensors on a monthly schedule using laboratory standard mercury or spirit-filled thermometers. (Ordinary thermometers can vary by +/- 2ºC which can cause significant errors and departure from the required preset conditions with consequent energy losses.)
- **Note: A +/-1ºC thermometer, temperature sensor or set-point selection error will change heating demand or heating system capacity by 5% and annual energy usage and costs by 40% to 100%.**
- Check humidity sensors for accuracy. The wet-dry-bulb humidity measuring system is normally very accurate if properly maintained.
- Humidity sensors are much harder to calibrate. Compare humidity sensor readings to a portable wet- and dry-bulb hygrometer and adjust when necessary.

  Where wet-bulb/dry-bulb sensors are installed as part of the control system, change the wet-wick or clean by boiling on a monthly schedule. Then remove the wet-wick and allow the sensor to dry; both dry-bulb and wet-bulb sensors and the test thermometer should read the same temperature; if not, follow maker's instruction to correct sensor errors. (When the VDU sensor readout is at a distance from the sensor then use two people with walkie-talkie radios to communicate readings as temperatures can change quickly if the tester has to walk any distance to study readings.)
- Ensure wet-wicks never run dry (inspect daily); use de-ionised water or melted ice to replenish.
- Consider using modern foil or chemical-type electronic humidity sensors if compatible with control software, instead of the wet-dry-bulb system. Modern humidity sensors that are accurate enough (typically ±3% RH) in the high RH range (80-100% RH) needed for greenhouse control are expensive, but avoid the tedium of servicing wet-bulb humidity thermometers. Early versions of solid-state humidity sensors were rather inaccurate (typically ±11% RH at high RH) and mechanical filament-type humidistats are not suitable for greenhouse use.
- Modern double-beam infrared CO_2 monitors/sensors will only require a calibration check about every five years[14] For older models, it is necessary to use bottled calibration gases (an inert gas mixed with a known CO_2 concentration, say 1,500 ppm is used to fix the "scale" and nitrogen to fix "zero").

[12] *On clear nights unshielded temperature sensors and thermometers see the cold outer space and thus give lower readings than when clouds are present.*

[13] *Heat radiating from Aspirated Screen fan motors and inside walls of the A-Screen should be shielded from the sensors; if not, replace with a higher quality A-Screen. The aspirating fan must be selected to move air across the wet and dry sensors at an internationally stated standard to avoid significant errors.*

[14] *Because high quality modern CO_2 sensors are now cheap (under $1,000 each) and CO_2 control is vital for crop productivity, it is prudent to have a spare for check calibration purposes.*

- Solar radiation sensors should be cleaned on a regular schedule and readings compared to a solar energy chart on very clear days. Maximum clear sky readings in the Auckland area are about 1,100 w/m^2 at midday, 21 December[15]. Up to 1.300 w/m^2 has often been recorded during periods of broken cloud as some radiation is reflected from the edges on the clouds.

Check the Efficiency of Heating and Electricity Powered Systems

Many fuel types[16] including electricity can be used cost effectively for greenhouse heating but great attention is needed to ensure fuel is used efficiently and heat delivery systems and controls are maintained at high levels of effectiveness.

For modern energy efficient greenhouses located in warmer climate zones the design problem of providing the small amount of infrequent heat needed at an acceptably low capital cost arises. When deciding on the required heating plant capacity it is better to accept a minimum greenhouse temperature slightly below the required set-point for a few days rather than install heating plant that is oversized to cope with extreme low climate temperature conditions which might occur for a very few days each year.

Therefore:

- to reduce fuel consumption ensure furnaces and boilers are installed correctly and insulated to the maker's specification or add insulation if the maker approves;
- check heating system to ensure the heating plant is correctly sized for the demand[17] and re-check after energy loss applications have been completed. If it is either under or over-sized the system may not operate efficiently;
- check boiler, furnaces and air heater burner combustion efficiency, heat exchangers and the associated control systems on a regular schedule (eg monthly when in regular use);
- call in the manufacturer's representative or a qualified heating technician who is familiar with the equipment at least twice a year to check[18] furnace efficiency with special instruments and adjust when necessary;
- ask if the coal-fired furnaces can be fitted with features to improve fuel efficiency and reduce fly-ash;
- ensure the burner air supply is always adequate to maintain efficient combustion even when doors, windows and other openings to the boiler or furnace room are closed. Therefore, provide a permanent fresh air supply opening (can be fitted with automatic shutters activated by the burner control system and dust filters if necessary) or a duct to deliver air directly to the vicinity of the burner. The burner manufacturer or a heating engineer can supply air supply duct or opening detail's dimensions;
- consider replacement of NG, diesel and waste-oil burner nozzles to smaller sizes and modification of the fuel supply rate of solid fuels may become necessary to maintain burner efficiency as energy losses are reduced;
- consider de-rating furnaces, burners or replacing with smaller capacity plant as energy losses are reduced;
- consider shutting down boilers and furnaces during summer if alternative economic CO_2 sources can be obtained and rely on fans to provide air movement to minimise energy losses;
- insulate head-house or separate boiler rooms by fitting insulation to walls and ceiling of head-houses or boiler rooms (use HD scuff-proof double-sided aluminium foil lining and tape joints as a cheap quick retrofit) and lag all hot-water pipes located inside and outside the boiler room;

[15] *Contact EECA for maximum clear sky midday solar radiation (w/m^2) for any day; these data can be used to check solar energy sensors' accuracy.*

[16] *Electricity, natural gas, coal, diesel, bio-mass (wood in various forms), waste oil, waste hot water or steam from industrial sources.*

[17] *Heating system capacity can be selected to meet the minimum temperature set-point 97% of the time.*

[18] *Typically, NG burner settings, coal feed rates, coal fire-bed, stack temperature and flue gas composition, condensers, heat-exchangers are tested.*

- use a fan and lay-flat perforated ducting to shift warm air from boiler/furnace room to heat the greenhouse;
- avoid installing hot-water pipes underground unless fitted with water-proof insulation (direct contact with ground water can cause heavy energy losses);
- check the insulation of hot-water buffer tanks; upgrade if found to be cost beneficial;
- arrange for boiler room hot air to be ducted into the greenhouse in cool weather (use fan-powered perforated plastic duct mounted over the central pathway);
- coal-fired furnaces can be very efficient if serviced and managed properly;
- add an extra flue heat exchanger and/or a hot-water buffer tank to coal-fire furnaces to enable faster response time;
- if coal is being used obtain a low-sulphur grade to reduce emission pollution and avoid damage to plastic covers from sulphur contained in fly ash;
- store coal and wood fuel under cover to avoid getting wet (ventilate to remove surplus water to increase calorific values);
- check waste oil burner systems for heavy metal contamination of workers and produce from handling the oil and from flue gases;
- in the greenhouse, insulate hot-water delivery and return pipelines and fittings to avoid radiant heat losses through nearby covers and damage to plants;
- in the greenhouse, distribution of heated air though fan-powered perforated light gauge polythene ducting may be a more cost effective means of heat distribution than using hot pipes for generating vertically directed canopy air movement. For best performance, all forms of ducting, especially perforated lay-flat ducting, should be engineer-designed;
- check the electricity system load-factor and if necessary have a suitable load-factor capacitor installed to reduce electricity cost and get the phases re-balanced if necessary;
- replace lamps in work areas with modern high efficiency lamps and fluorescent tubes;
- check all pumps for worn or eroded impellors', diaphragms', bearings' and seals' operating pressures, flow rates and general suitability for task, including electricity load;
- use an infrared scanner to pick up hot spots in electrical systems (indicates pending component failure) and energy leakage from buildings and greenhouses. Some lines companies provide an IR scanning service[19];
- consider installing variable frequency drives for fans, pumps or actuator drive motors but ensure correct type of double-shielded power cables between the motor and the speed controller are installed and maintained to prevent electro-magnetic interference to solid state sensors and digital (computer) control systems. Leakage from one VFD head-house or greenhouse motor can cause false intermittent greenhouse temperature readings (at a considerable distance) which would in turn cause costly heating and venting system operation;
- in cooler climate zones consider installing thermal screens[20]. Thermal screens are expensive to buy and expensive to install in existing greenhouses (about $150,000/ha). As with all equipment and structural members mounted over the crop, intercepted light is reduced by thermal screens[21] arising from crop shading;
- consider installing high intensity Photo-synthetic Radiation Active (PAR) lighting where a better balance of energy use and extended crop production and CO_2 use can be achieved;

[19]*EECA can advise on IR scanner service suppliers.*

[20]*See "Thermal Screen Test" VegFed "Grower" Jan/Feb 2005 which provides an introduction to thermal screen energy saving potential and warnings of the subsequent risks. A thorough cost-benefit analysis should be applied before commitment to this option.*

[21]*Solar screens are not considered here because shading is a sure indication of fault environment systems and reduces performance of most greenhouse vegetable crops.*

- for new greenhouses, consider lower wall heights as excessive wall heights increase construction costs, lose energy and only about 2m clearance to the ridge above the crop is needed for environment control purposes;
- for new greenhouses, consider use of unit NG air heaters installed at intervals in the greenhouse to increase heat distribution efficiency and reduce hot water boiler and pipe losses;
- for new greenhouses consider using precision-controlled fan-powered pressurised ventilation rather than passive, difficult to control roof vent systems.

WARNING: As can be foreseen when energy losses are reduced, less furnace demand will occur, which may lead to a drop in furnace or heater efficiency if the control systems prove inadequate to respond in changes to heat demand. Therefore, more frequent furnace efficiency checks are indicated as energy saving measures are applied.

Where substantial increases in energy efficiencies have been achieved a reduction furnace size may prove cost-beneficial.

Stage 2 – Energy Use Efficiency

Assuming the energy loss defects have been repaired or updated, this stage discusses more advanced temperature (averaging) and humidity control functions to reduce the energy demand and extend CO_2 enrichment. The control of these functions is intended to enhance crop performance and thus improve energy CoP efficiency. See Appendix 1 for notes on heat, moisture and CO_2 interactions.

Enhancing the Use of CO_2 Enrichment

Enriching the greenhouse atmosphere[22] with CO_2 gas typically to about 1,000 ppm has been mentioned several times in these Guidelines.

When CO_2 levels in the greenhouse atmosphere drop by day to the point where photosynthesis slows or even stops (at about 150 ppm) plant productivity also stops and the cost of all inputs, including energy, is lost. This condition can (often) occur when a greenhouse is closed to conserve heat and RH is low (below 75% RH).

With appropriate control software and environment systems CO_2 levels can be maintained by enrichment by day and valuable CO_2 generated by plants by night retained in the greenhouse for daytime use.

Use of high levels of CO_2 enrichment 1000-2000 ppm by using pure CO_2 gives additional crop responses with safety because there are no toxic gases to damage plants as pccirs with NG gas generated CO_2.

Canopy Air Movement

Positive air movement 24 hours per day through the crop canopy and the greenhouse reduces adverse effects of high humidity and condensation on plants and enhances water evaporation and plant activity. Canopy air movement measurable at about 1-5 m/sec is probably adequate when leaves can be seen moving gently.

Application of "DIF" Temperature Selection

A growth control and energy management technique that monitors and controls the difference between the day and night temperature was developed in the 1980s. This technique, commonly known as "DIF" for short, relies on the observation that some plants, like tomato, distinguish between the high and low temperatures experienced during the day or night[23].

As plant growth and development are strongly influenced by the difference between night and day temperatures, the DIF factor can be varied by the crop manager to manipulate vegetative and generative crop development.

Plant growth tends to be more rapid in sunny weather even if the temperature is not increased and lowering night temperatures normally increases internode growth and will reduce the number of harvestable trusses before the crop gets to the wire.

Some control programs integrate the amount of light (IR & PAR) entering the greenhouse and the air temperature to maximise plant development.

When light levels are lower (due to cloudiness or in winter) lower day temperatures can be matched with warmer night temperatures to maintain the average at the set-point. Operating in a negative DIF environment may produce more crop but at the increased cost of energy, whereas staying close to a zero DIF will usually minimise energy costs by maximising plant performance[24]

[22] *The current mean global atmospheric CO_2 level is 375 ppm as measured at the international CO_2 research station in Hawaii.*

[23] *Descriptions of the physiological reactions that are involved are not part of this paper.*

[24] *Internodal spacing controls tomato truss or capsicum fruit numbers relative to plant height.*

Temperature Averaging

Most modern greenhouse computer control software should provide for 'temperature averaging' over 24 hours. In practice this works because plants normally average the temperature they experience over a 24-hour or longer period.

Plant growth is more rapid in sunny weather and with greenhouse higher temperatures. However, when light levels are lower (due to cloudiness or in winter) lower day temperatures can be matched with warmer night temperatures to maintain the average at the set-point. Therefore the average day and night temperatures 'float' to maintain the average which needs careful tuning of temperature and humidity for optimum performance.

The result is that solar energy is used by the averaging and DIF functions to minimise night temperatures which can save about 25% of the energy otherwise used for heating, particularly in winter.

Environmental Control Computer Program Management

Most modern computer-based environment control programs are very complex with a large number of helpful options that are not always used effectively. With a properly configured and adjusted control program it should not be necessary to adjust most set-points more than a few times a year (unless for adjusting DIF setting for controlling crop development). If frequent (daily) adjustments are needed then software or environment systems are inadequate or not being properly set up and used.

As errors in program settings can cause substantial energy and CO_2 wastage it is most important to get a software technician to periodically review the operational settings and to advise on program management. If the program does not provide control options for achieving the environment conditions discussed in this Guideline then consideration should be given to replacing the program and perhaps the associated computer hardware and sensors.

Therefore to summarise:

- To manage greenhouse moisture content and stop water migrating from the sub-soil, install a high quality vapour barrier in the greenhouse floor to the same standards as for commercial buildings or cool-stores (use 0.5 mm black polythene with sealed joins, wall and post connections). Protect with heavy duty replaceable permanent overlay (mud-stop or modified concrete).
- Ensure the crop canopy and leaf boundary layer, temperature, humidity and CO_2 conditions are equalised to provide positive continuous air movement 24 hours per day through the plant canopy at about 1-2 m/sec. Air movement is adequate if most leaves move slightly due to air movement. Use fans and low-level perforated ducting to provide adequate canopy air movement[25] as overhead fans and ducts provide less efficient air distribution.
- Consider raising the Relative Humidity set-point to nearer 92% RH which is reported by horticulturalists to be the optimum level for plant growth and development, although some crops respond better to slightly lower RH%. By raising the humidity level, longer periods of CO_2 enrichment can take place.
- Consider discontinuing the humidity control programming that pre-heats the air before opening vents to discharge or purge large quantities of heated moist air.
- Use a humidity control program which provides more accurate humidity control enabling fan-generated air movement to assist discharging moist air through vents.
- Solar energy-to-water equivalents should show on the Control VDU screen as basic greenhouse energy control information, with comparisons to actual greenhouse water usage (supply less drain-to-waste) with the make-up water balance to be added to fully absorb solar energy which reduces venting and enhances CO_2 enrichment.
- Use temperature averaging to reduce energy usage.
- Consider the cost benefit of using pure liquid CO_2 supplied in bulk. This data will provide information needed to help assess the relative costs:

1 GJ NG = 52.8kg CO_2 1M^3 NG = 2kg CO_2

25 kg/ha/hr provides about 1,000 ppm = 0.5GJ NG

[25] *In New Zealand, use of electric fans and perforated polythene ducting for air movement may be more energy efficient than the use of hot–pipes in summer to create convection air movement.*

Stage 3 – Advanced Energy Conservation and Crop Productivity Programs

As noted in Stage 2, most modern greenhouse environmental computer control software provides for temperature averaging over 24 hours using degree-hour techniques to predict the average temperature to be targeted over the next 24 hours. Averaging only works because plants normally integrate the time they spend at each temperature and modify their response accordingly.

When CO_2 is optimised for the incident solar energy and temperature available to the plant during each day, this period is incorporated into the management model, the next level of environmental management becomes possible with adjustment of the day and night temperatures for the following day based on what has been experienced in the previous 24 hours.

The most sophisticated environmental and crop management programs extend temperature averaging for a number of days with further energy savings and production gains often becoming a reality. Environmental management programs that learn from historical data which has been accumulated on the greenhouse site have the potential to remove further uncertainty for the manager by automatically adjusting responses according to how the system performed in the past. However, this has yet to remove all the decision making from the grower who may find that control of temperature and humidity and related plant responses under long-period averaging still requires considerable grower observation and skill.

Using these programs, plant performance is monitored by real-time instantaneous feedback, often with a live display on the controller screen. When properly managed this can be a valuable management tool enabling harvest dates and yields to be predicted with increasing accuracy whilst normally using less energy.

While the forecast energy saving and production efficiency gains when combined can exceed 30% over and above the efficiency levels targeted in the previous stages of these Guidelines, most of the advanced greenhouse environmental management programs are still in their infancy. However, they do point to the way of the future with predictive modelling crop performance and the possibility of on-line monitoring of individual growers' operations becoming part of a wider industry quality assurance programme.

Often the proprietors of these advanced environmental management programs provide training with on-line monitoring and Crop Registration services.

Herein lie answers to the challenge of minimising the impact of high energy prices.

The sources used as the basis for the Guidelines' recommendations are largely traceable to technical documents in the public domain allowing growers to access further information.

Table 2 Accumulated Benefits of Applied Energy Saving Options

Based on energy (fuel and electricity) costs estimated at $150,000/ha or 24% of production cost for tomatoes in 2005.

Tasks	Energy Saving from Repairs & Maintenance	Repairs & Maintenance Cost/ha	Estimated Annual Energy Cost Saving: 2005	Notes
Stage 1 – Reduce Energy Losses				
Reduce greenhouse air leakage	5%	$500-$1,000?	$7,500	
Insulate greenhouse & facilities	5%	$1,000 to $20,000+?	$7,500	
Check sensors for suitability & accuracy	5%	$0-$5,000?	$7,500	Large losses can occur if there are temperature sensors or thermometer errors.
Check heating & electricity systems	5%	$0- $20,000+?	$7,500	
Total potential energy saving	**20% saving?**	**Up to $46,000?**	**$30,000?** energy saving, say, within 3 months	Use energy cost-to-sales Energy Saving Monitoring program. Payback about 1.5years.
Estimate annual energy costs 2005			**$120,000?**	This is probably not greatly reducable for tomatoes.

Tasks	Reduced Energy Costs due to Increased Production	Cost of Applying Energy Efficiency Factors	Estimated Annual Energy Cost Saving: 2005	Notes
Stage 2 – Improve Energy Efficency				
Check humidity control system; increase CO_2 use	5%	$0-$5,000+?	$7,500	
Check CO_2 supply options	5%	$0- $5,000+?	$7,500	Change to liquid CO_2
Upgrade control system management expertise	5%	$0-$5,000+?	$7,500	
Apply temp. averaging program	5%	$0-$5,000+?	$7,500	1 year to apply to operation.
Total potential energy efficiency saving	**20%?**, say, within 1 year by increasing production			Effect of profits will depend on market conditions
Potential energy efficiency cost savings & capital costs	**$30,000?**	**Up to $66,000+?**	**$30,000** as reduced unit (kg) CoP	**Annual effective energy cost could be reduced by 40%**

Tasks	Reduced Energy Costs due to Increased Sales	Cost of Applying Energy Efficiency Factors	Estimated Annual Energy Cost Saving: 2005	Notes
Stage 3 – Advanced Energy Conservation & Crop Efficiency				
Apply advanced environment & crop management control	**30+?%**	**$10,000-$100,000+?**	**$45,000?** as reduced unit (kg) CoP	2+years to apply to operation
Summary all energy saving options	**70% ± 10%**	**Up to $156,000+?**	**$105,000?** as energy saving & reduced CoP	Total potential energy saving 7%. Payback 2yrs?

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Appendix 1

Supplementary Environment Management Notes

1. Reducing Energy Losses Related to Humidity Control

Greenhouse humidity is the most difficult environmental factor to measure and control but it is inextricably linked with securing extended CO_2 enrichment periods.

The accurate control of humidity is of major importance to crop management, including control of fungus disease and fruit physiological defect incidence (fruit set, calcium deficiency and surface defects), the productivity of crops and quality of the marketable product.

The control of greenhouse humidity or moisture as vapour or liquid water is complex and involves more energy from the sun and the heating systems than is needed for cold weather temperature control. Therefore a properly configured computer program should enable humidity control to over-ride temperature control.

As a rough check, if the floor and pathways of a greenhouse are dry and dusty it is very probably much too dry to grow a commercial crop satisfactorily.

2. The Water Evaporation Process and Humidity Control Strategy

Most of the water used by the plants is evaporated from the leaves by solar energy. Water evaporated by plants or from wet surfaces absorbs about 2,400 kJ/kg (litre) of water evaporated.

The forces created by solar energy The evaporative force can also be generated by high intensity Photosynthetic Active Radiation (PAR) and air heating. by the evaporation processes generate a strong

transpirational deficit effectively pulling nutrients and water especially into the leaves and,

to a lesser extent, into fruit.

Provided there is adequate water in the plant root-zone and adequate air movement to avoid saturating the plant canopy with humid air, natural thermodynamic processes cool plants very efficiently under full sun radiation levels Note that the greenhouse sun energy transmitted through the cover is reduced due to cover/glass transmission loss to about 80% of the outside sun where plants grow normally. The cause of greenhouse overheating arises from the areas of the greenhouse where there is no plant canopy cover and no alternative cooling capacity.

As solar energy or energy from fuel-heated air evaporates water from the plant or from other sources (wet surfaces or spray), the energy is absorbed by the water vapour as latent-heat-of-vaporisation and in doing so reduces the temperature of the leaves and surrounding air by several degrees Evaporation of water reduced air and wet surfaces (leaves) by about 80% of the difference between wet- and dry-bulb temperatures. This occurs even on hot, very humid days as the greenhouse environment is a separate climate area responding separately to solar radiation if venting is limited.

It should be noted that a 10ºC increase in air temperature will double the air water holding capacity absorbing large quantities of energy/heat. Also, high levels of CO_2 enrichment (700+ ppm) will enable plants to tolerate higher temperatures.

Therefore, the environmental control program should allow the water evaporation and cooling process to proceed until the air is near saturation at say 95+% RH and the air temperature starts to increase Due to the Vapour Pressure Deficit factor a humidity gradient will still exist between the leaf stomata and the surrounding air. . At this point, venting can be activated when the minimum volume of latent heat and water vapour loaded air will be discharged to be replaced by cooler drier air. This strategy extends the CO_2 enrichment period.

Additional water can be safely added to the greenhouse to remove the remaining solar energy by evaporation The several supplementary cooling methods based on water evaporation are not covered in this paper. should temperatures increase at low RH.

3. **Condensation, Dew-point, Wet-bulb Temperature, Canopy Air Movement, Vapour Pressure Deficit (VPD) and CO_2 Enrichment:**

An understanding of these fundamental interactive functions is vital for advanced crop and greenhouse management. A Psychrometric Chart presents the interaction of heat and moisture transfer factors in an invaluable useable mathematical form Psychrometric Charts can be obtained from EECA.

Wet-bulb thermometer temperature represents the cooling effect the evaporisation of water (wind chill) when adequate air movement is present. For practical purposes the difference between dry and wet-bulb temperatures represents the amount of air cooling than can be expected at the time of measurement.

Dew-point is the temperature of the air when the vaporisation process is reversed reforming as water (condensation) releasing the heat of vaporisation and lowering the general air humidity level. The released heat warms the greenhouse air and the condensing surface.

Condensation forms on the inner greenhouse surfaces and leaves when the dew-point temperature of these surfaces is reached.

Condensation often occurs on inside cover surfaces that have cooled to dew-point, particularly at night. This can occur when the main volume of the greenhouse air is at a higher temperature.

Also, water vapour in the boundary layer on leaves and fruit can condense at dawn when plants start to transpire (not to be confused with guttation, seen as drops of water on the edges of leaves) so it is important to use heat before dawn to warm the plants Other crop physiology reactions also occur at this period involving root-zone water availability, calcium translocation, etc but discussion of these matters is outside the scope of this paper. (Setting the control program to slowly ramp up the air temperature in the pre-dawn control zone with the vents shut enables the overnight accumulation of CO_2 to be used by the plants as light levels increase.)

By utilising a control program dew-point control and a timer function, leaf condensation can be managed to limit the fungal diseases that are of great concern to growers.

However, if properly controlled, condensation is a valuable environment control function for removing water from the greenhouse without venting provided the greenhouse structure is designed to limit dripping from the covers on to plants.

By condensing water vapour from the air the need to vent is also reduced, therefore saving unnecessary energy losses and the water film also reduces energy losses through the covers.

Heat is used at night to evaporate surplus water drawing some from the media and any water seeping in from the subsoil or rainwater overflow, so it is important to reduce soil water seepage.

In fact, the more water that can be removed from the greenhouse as condensed water (direct condensed collected from the inside surfaces to the nutrient return drains thus conserving water) and venting reduced the greater the potential for more efficient energy usage and CO_2 assisted crop production.

Vapour Pressure Deficit (VPD), is the difference in pressure between the water vapour in the stomata and the surrounding air. VPD drives the movement of water vapour from the leaves to the canopy air. The lower the canopy RH the higher the VPD and vice versa.

Most computer control programs offer RH and VPD control options for managing humidity. The selection of which option to use depends on the capacity of the humidity control systems to provide optimum environment conditions. Where controlling plant responses at high humidity proves difficult, VPD control may be preferred, otherwise RH is the preferred control factor.