# Proceedings of the UK Controlled Environment Users' Group

## 2007 SCIENTIFIC MEETING

## "CUTTING THE COSTS: TOWARDS ENERGY EFFICIENT CONTROLLED ENVIRONMENTS"

**Volume 18**

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L.D. Incoll (editor)

## UK CONTROLLED ENVIRONMENT USERS' GROUP

## 2007 SCIENTIFIC MEETING

## CUTTING THE COSTS: TOWARDS ENERGY EFFICIENT CONTROLLED ENVIRONMENTS

The scientific part of the annual meeting consisted of six invited contributions. Summaries of these, supplied by the speakers, follow.

SUMMARIES OF PAPERS

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**M.P. Fuller** (The University of Plymouth, Plymouth, Devon, PL4 8AA, UK; E-mail: mfuller@plymouth.ac.uk) **An introduction to the concepts of sustainability and the challenge to Controlled Environments**

### History and definitions of sustainability

The term "sustainability" has now entered common parlance across the world and is freely used by virtually every profession, government (local and national) and by many individuals. Its meaning is context driven and it is used to justify policy, change and to prick the conscience of the concerned consumer.

Historically, it was initially a term chosen by environmentalists (Riddell, 1981; Sachs, 1979; Glaeser 1984) but became widely adopted as a mantra in inter-governmental commissions and conferences charged with the responsibility of looking forward and planning. Thus it first became widely used after the UN Congress in Stockholm in 1972 and subsequently became the central concept of the World Conservation Strategy 1980 (IUCN, 1980). By 1988 it came to symbolize a major shift of culture and policy in the World Commission on Environment and Development and the driving concept behind the UN summit in Rio de Janeiro in 1992 (UN, 1993). In the intervening 15 years since the Rio summit the term has enjoyed unprecedented usage and institutional sustainability policies abound and sustainability has implications for both the developed and the developing world alike (Adams, 2003).

Because the term "sustainable" has become so commonly used it is difficult to find an all embracing definition but one in common use is in Wikipedia (2007):

> "a *characteristic of a process or state that can be maintained at a certain level indefinitely*"

The problem with such a definition is tying it into a specific process or state.

Another definition which has stood the test of time is that emanating from the 1987 Brundtland Commission (Brundtland, 1987):

> "*meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

And a more recent definition attempts to bring socio-political context into sustainability (Maine, 2003):

> "*relates to the continuity of economic, social, institutional and environmental aspects of human society, as well as the non-human environment*"

**To what is the concept of sustainability applicable?**
There are 5 broad categories to which sustainable concepts are commonly applied:

- Energy consumption
    - In particular the use of non-renewable energy generation as measured by the commonly used term "carbon footprint"
- Food production
    - Agriculture is a prime recipient of sustainability concepts because it is easily analysed in terms of inputs and outputs and because it is crucial to the survival of the human population.
- Resource utilization
    - Finite resources associated with the earth's geology are clearly subject to sustainability concepts with a huge current interest in the production of technologies which utilize renewable resources.
        - Carbon resources (oil, coal and gas)
        - Mineral resources (metals and rocks)
        - Fresh water resources – defined as a finite resource in certain areas of the world where its demand is greater than its supply.
- Conservation of habitats
    - The recognition of the rarity of certain habitats in the world has sparked a huge interest in conservation with an appeal for a limit of the influence of man on these habitats. The maintenance of these habitats is frequently used as an indicator of the success of sustainability policies.
- Economic wealth
    - Social-political ideas have more recently entered into the thinking on sustainability recognizing that economic wealth has a greater ability to uphold sustainable policies than does poverty.

**Steady state**
It is clear that sustainability concepts are more easily applied to a steady state but for most human activity things are in constant development and motion. Indeed the human population of the earth is not in a steady state – currently there are about 6 billion inhabitants of earth, but demographic studies predict a 50% increase in population by 2050 (UN, 1998). In order to feed, clothe, house and satisfy the population demands in 2050 it is clear that agriculture and technology will continue to need to develop. The major inter-governmental challenge is whether 9 billion inhabitants is the eventual steady state level for the earth and whether this is sustainable into the future. Clearly population growth is unevenly distributed across the world with most developed countries having reached a more or less steady state whilst developing countries are witnessing big increases. There are difficulties in reaching global sustainability when huge inequalities exist between countries. Many developed countries have reached their position of stability (and wealth) through a profligate (and unsustainable) exploitation of natural resources which were chiefly carbon-based fossil fuels. Rapidly developing countries such as India are now where the developed countries were 100-150 years ago and claim that it is their right to exploit their carbon reserves to build their economies!

**Can the concepts of sustainability be applied to Controlled Environments (CEs) for plants and the research that utilizes them?**

Plant CEs fall into 2 categories – those designed to facilitate research in agriculturally based issues and those designed as a production system for agricultural products (the term agriculture is used generically to include horticulture). So most CEs are inextricably linked to the demands of agricultural production. Given the predicted population of the earth, it stands to reason that agricultural output must increase over the next 50 years and it has been estimated that more food will be required in the next 50 years than in the previous 10,000 years combined! If we do not choose to feed this burgeoning population then we may have to revert to the 1-2 billion carrying capacity of the planet as hunter gatherers and subsistence farmers. What will happen to the other 8 billion of us??

The purpose of plant CEs is to provide a growing space for plants where the environmental conditions are controlled to within defined limits to meet the needs of research and production. Typically close control means:

- Temperature – held at 4 to 40°C with a ±1°C tolerance
- Light – photoperiod, spectral distribution, photon flux density (PFD)
- Water – humidity and liquid water
- $CO_2$ – ambient and elevated

Furthermore managers of these facilities need CEs to fit a construction/purchase budget and a running budget and to remain fit for purpose for as long as possible.

But CEs are highly energy consumptive particularly because of the high lighting requirement where relatively small amounts of Photosynthetically Active Radiation (PAR) are generated together with lots of heat. The heat needs to be removed using refrigeration and units usually vent to the atmosphere.

CEs are also expensive and the cost per cubic metre of uniform space can be very high. Compromises in CE construction can threaten uniformity of environment leading to variability in experiments and/or crop production. Furthermore, most CEs are constructed from non-renewable mineral resources and at the end of their useful life are non-recyclable. They may also contain some elements or components which are proven harmful to the environment e.g., refrigerant gases; asbestos insulation, polystyrene and harmful electrical components.

The challenge of sustainability to the construction of CEs is:

- Use building materials which come from renewable resources which can be recycled at the end of use
- Use building materials with a low carbon footprint in their construction
- Use designs which couple energy consumption with energy conservation

Whilst the challenge of sustainability to the running of CEs is:

- Minimisation of energy consumption without jeopardising essential specifications e.g. no diminution on PFD or spectral distribution
- Coupling of heat generating elements with heat requiring elements e.g. waste heat from refrigeration used elsewhere or stored until required
- Recirculation (air and water) without jeopardising phytosanitary requirements

**Towards sustainable controlled environments**

There are many challenges to the future construction and use of CEs if managers are to stay both within their budgets and contribute to their institutions sustainability statements. Possible target areas for consideration in the future are:

- Renewable insulation materials
- Reduction in use of concrete
- Polymer sheeting in place of steel or aluminium
- More efficient lamps
- Non-HFC refrigeration
- Coupled heat-pumps
- Use of heat sinks
- More efficient glasshouse/plastic materials.

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**S. Goodhew** (Environmental Building Group, University of Plymouth; E-mail: s.goodhew@plymouth.ac.uk) **Sustainable building materials**

Sustainable buildings as a concept are both easy and difficult to come to terms with. Much of this aspect stems from the definition of sustainable development and its use or application to the world of construction, or more precisely buildings, their construction and design. The Brundtland World Commission on Environment and Development's definition of sustainable development (UN, 1993) is:

*"development which meets the needs of the present without compromising the ability of future generations to meet their own needs".*

When trying to understand how this definition should be applied it is often more manageable to split up the thrust of the Brundtland statement into three prongs, Environmental-, Economic- and Equity-based aspects of any issue. This is where many difficulties are experienced by those trying to apply these three aspects of sustainable development. Each of the three E's (as they are normally referred to) have an aspect to them that, depending upon the scenario that they are being applied to, can be mutually exclusive. The Environmental Building group at the University of Plymouth has the objective of training graduates to have the skills and knowledge to make and appropriately advise others to make such decisions.

An example of such decisions might occur when the economic aspects and environmental aspects of a sustainability-related decision are likely to clash. Energy often lies at the centre of the many debates and discussions leading to decisions relating to sustainable construction. The implied emissions, capital and running costs, embodied values and general usage/behaviour all generate benefits and drawbacks that pull protagonists to different ends of a debate. This debate might be exemplified by observing an attempt to fulfil the criteria for the code for sustainable homes, as guidelines or soon to be legislation, that is part of the UK government's push to ensure that all new homes are 'zero-carbon' by 2016. 'Zero-carbon' is taken by most commentators to mean that a building will be virtually free of carbon emissions due to its normal usage. This implies a conscious effort to maximize the environmental credentials of such a building, rather than necessarily the social or economic aspects of its construction, placing, use or value. In an effort to produce a 'zero-carbon' building, a client/developer/owner could look to the inclusion of renewables into the energy strategy. The payback periods of some of the popular renewable energy systems, such as photovoltaic panels, are generally accepted as being longer than that of many methods of reducing the energy consumption of the same building. They can sometimes be as long as 20-25 years, as long in time as the economic working life of such a system. This creates a tension between deciding to include standalone renewable energy systems into the design of a building and accruing the environmental rather than the economic benefits of such a decision.

Another aspect of such a decision is related to the characteristics of the materials used to produce the building's fabric. Questions about embodied energy, validity of manufacturing process, packaging, locality of production and end of use all bear upon the final decision of what to use, in what quantity and where? One set of materials that has a dual aspect to its nature and use are those classified as insulants. Their use as a method of reducing energy usage but also having an origin, performance characteristics and questions over their end of use ensure that insulants represent a group of construction materials that are pivotal when specifying products. Many 'man-made' insulants, such as foams, are very efficient thermal insulants, often with thermal conductivities below 0.03 W $m^{-1}$ $K^{-1}$, but often have oil-based ingredients and create issues as far as their end-of-life disposal. Natural insulants often have far better environmental credentials, local production, less damaging processing but higher thermal conductivities than most man-made insulants. Does the design of the building maximize the non-polluting or non-damaging aspects of the materials or its potential for energy reduction when included in the building fabric? What should be optimized? And should this balance be identical for all scenarios? Let us look at some of the potential materials, including some insulants, that are being marketed as being produced using less damaging processes and therefore are more appropriate to use in our buildings.

Walling systems as well as insulants have been the target of some designers with the main aim of attempting to increase the environmental credentials of larger sections of buildings. Walls, depending upon the configuration of a building's form, according to the Building Research Establishment, are responsible for approximately 45% of the heat loss through the fabric of a building.


**Plate 1.** Infra red image of heat loss through a building's façade. © S Goodhew

Because of this, there is much good sense in targeting the walls of any building when attempting to reduce heat loss. Because the thermal transmission or 'U' values of walls are regulated to just below the normal thermal transmission values for loft insulation, walls represent an appropriate target for improvement in this area. Combinations of unbaked earth and straw are being using in a number of ground breaking building designs in the UK and overseas. The impetus for this development in the use of alternative buildings materials is similar to the use of different more natural insulants. Building products that are sourced from waste materials, preferably from local sources will impart the same benefits as appropriate insulants, (Goodhew and Griffiths, 2005). However, many of these new building products are manufactured/sourced from organic materials leading to one obvious question, what is the long term performance of these building products? Moisture is one of the normal prerequisites for decay of organic based materials to take place. One of the major questions that needs to be answered concerning the long term performance of these materials is how does the moisture content of these new internal and external walling systems vary over a typical year and throughout the wall.

Over the past seven years the Environmental Building Group at the University of Plymouth have been researching the moisture take up of non-food-crop-based walling materials. A number of case studies varying in location from the South West of England to the Borders of Scotland, have been monitored. The main method of monitoring has been based upon the use of simple wood block sensors inserted into the walls at appropriate locations. The sensors are then monitored weekly until moisture levels stabilise, then fortnightly and finally monthly. The results of the monitoring are available in a number of publications (e.g. Goodhew *et al.*, 2004, 2005) both of which describe in more detail the systems used, results of monitoring and analysis of the results.

For more information on alternative construction materials that are being used in some of the more adventurous modern buildings today please see the references below or the Sustainable Building section of the University of Plymouth's website: http://www.plymouth.ac.uk/pages/view.asp?page=8936.

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**A. Padfield** (UniGro Ltd. Gay Dawn Offices, Valley Road, Fawkham, Kent DA3 8LY, UK; E-mail: angusp@unigro.co.uk) **Energy efficient greenhouse design**

Research on plants requires specialist controlled environments (CEs). They consume large amounts of resources in their construction and their use. Their design should have the objective of using such resources, and in particular energy, in a sustainable and efficient way. Systems are needed to control energy balance in such a way that temperature is always in the range suitable for plant growth whatever the external conditions. This paper considers more complex cooling, heating and control systems than have hitherto been used, especially for greenhouses, with the overall objective of reducing the use of electrical energy. Additional technologies enable rejected heat to be utilised along with resources in unconventional formats. None of these developments should detract from the CE facility's efficacy as a research tool.

It is possible that greenhouse CE facilities with similar capabilities to Plant Growth Rooms (PGRs) and having lower running costs may change the traditional way CE work is undertaken. The design process is largely governed by the need for, or exclusion of natural irradiance. However facilities with such capability and flexibility to operate like a PGR are not how CE users of greenhouses have previously used their facilities. Certain questions have not usually been asked during the design process for CE greenhouses of what is traditionally a largely unchanged design. For example, is it acceptable that air speed values fluctuate, and the PAR environment varies by 90% to parts of an experiment when air temperatures change? The use of shading is a good example that poses the question: is efficiency always in conflict with performance?

Developments in facility design have enabled significant advantages to be achieved, so ensuring that the two functions of efficiency and performance are not directly in conflict. The issue of screening to limit incoming irradiance is such an example. The psychrometric relationship between temperature and atmospheric moisture means that the parameters are not independent and with this in mind the design requirements of new facilities must very accurately specify the research requirements. Many assume that the removal of shading will increase the running costs dramatically and therefore the effects of shading on research are accepted, so the question continues to go unanswered. "Can we design a system with highly accurate parameter control and without shading at a sensible running cost?" Using a revised structural shape and a chilled water-cooling system designed for this application, this has become possible.

A self-supporting curved steel structure allows the cooled air exiting from the fan coil to be passed over the research area (Fig. 1). The Coanda effect[1] ensures that high-speed air follows the structure's perimeter, away from the research area until its speed falls and its increased density ensures it descends into the research area with a consistent velocity fluctuating across the research area by less than 1 m $s^{-1}$. This design allows high kilowatt thermal loads to be returned to the fan coil with high fan coil air volumes and therefore a low differential temperature between the chamber and the cooled air. Therefore a typical system with a set

[1] The Coandă effect: The tendency of a gas or liquid coming out of a jet to travel close to the wall contour even if the wall's direction of curvature is away from the jet's axis: a factor in the operation of a fluidic element. (Columbia Encyclopedia)

point of 25°C will require a coolant temperature of 16°C. High secondary circuit temperatures have a number of benefits, the most significant in terms of running costs are minimal latent cooling, coolth tank storage, and free cooling.

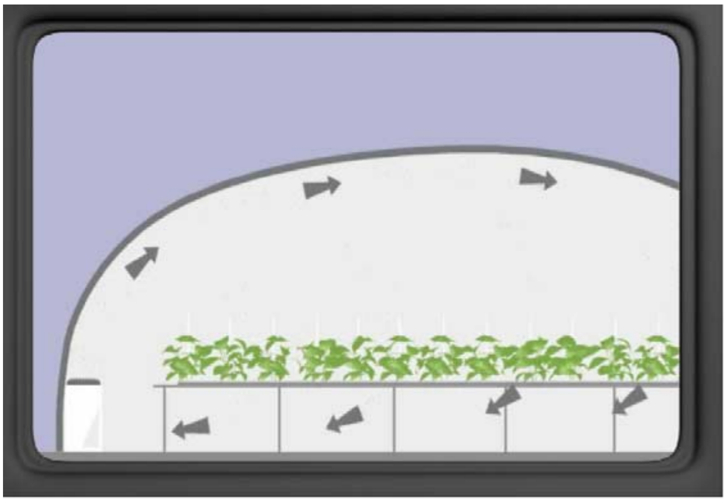

**Figure 1.** Diagram illustrating air movement within a curved greenhouse structure. © Unigro

**Latent cooling**

Low temperature cooling systems, direct expansion (DX) or low temperature chilled water can be particularly inefficient in CE with high r.h. values. Therefore the coolant supply temperature should always be as high as possible. In some systems the sensible heat ratio[2] can be above 50% i.e. in costing terms, the chiller is using more than 2 kW of cooling capacity, to achieve 1 kW of air temperature reduction[3], the remaining energy being used to condense water vapour. This water vapour in turn needs to be replaced as the chamber humidity falls multiplying the total running costs.

**Figure 2.** Two contrasting green-house buildings, on the left a conventional north-facing glass-house, on the right a newer and more efficient facility (Photograph © Unigro)

[2] A heat load has two separate components, sensible heat and latent heat. Removal or addition of sensible heat causes corresponding changes in air dry-bulb temperature. Latent heat is associated with the increase or decrease in the moisture content of the air. The total cooling capacity of an air conditioner is the sum of the sensible heat removed and the latent heat removed. The sensible heat ratio is the fraction of the total cooling that is sensible heat.

[3] Due to possible modulation of airflow or coolant flow rate, this temperature reduction effect is measured in kW rather than fan coil air off temperature reduction in degrees C.

Figure 2 illustrates a number of inefficiencies. The conventional north-facing glasshouse building on the left is a few years old, has heating and cooling systems and requires shading to maintain 25°C. The facility on the right is not fitted with shading and has higher light transmissivity. Additionally the newer facility has two twin-wall 10-mm polycarbonate glazing layers with greater containment and lower thermal losses. On a square meter basis the traditionally shaped building has installed four times the kilowatt cooling capacity of the curved design, although the compressors do not run for the same time periods.

**Free cooling**[4]

High secondary circuit temperatures allow water-based coolants to be pumped directly through external air blast coolers. Efficiency is dependant on the high circuit temperature and the ambient temperature differential.

**Coolth tanks**

Coolth tanks are used for a number of reasons, usually and traditionally to increase the short term capacity of a cooling system by storing previously supplied refrigerated water to be used as a large buffer vessel. We typically use a large butyl tank built into the foundations of the structure (Fig. 3). Other industries use alternatives including phase change materials, selected for varying freezing temperatures above zero to enable the absorption of greater thermal loads when space is limited. The higher the operating temperature of the secondary circuit, the greater the thermal capacity of the coolth tank before the secondary circuit set point temperatures cannot be maintained by this store should refrigeration capacity be lost.

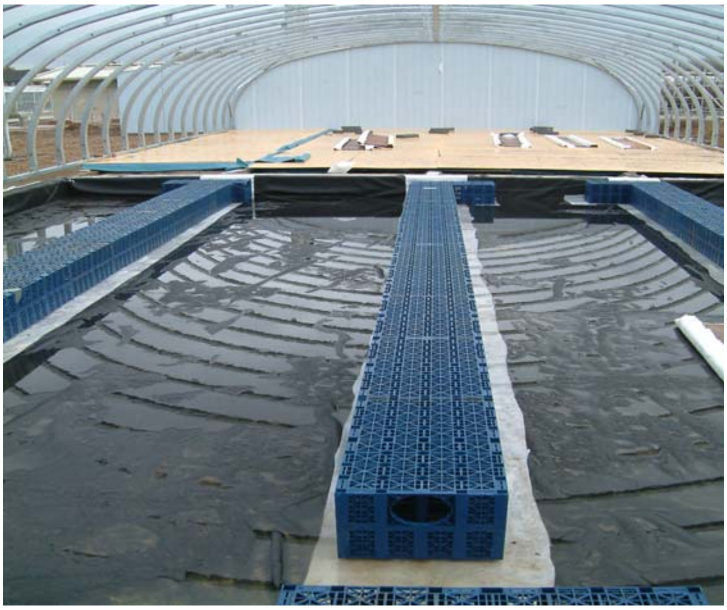

**Figure 3.** A coolth tank during installation into the foundations of a GroDome™-contained controlled environment facility at East Malling Research. (Photograph © Unigro)

The coolth tank is utilised differently throughout the year due to the unusual thermal loadings characteristics of this application and the need to maintain temperature control should chiller failure occur.

For efficiency reasons the chiller is sized to approx. 60% of the maximum load. Therefore when this capacity is exceeded during the high thermal load periods the coolth tank will be

[4] Free cooling is where a low outside air temperature is used to chill water in your process or air conditioning, rather than part or all of the output of an air-cooled chiller plant. (Industrial Cooling Services ICS)

used to supplement the cooling system (Fig. 4). By using the coolth tank on demand rather than as a buffer vessel, the temperature is kept as low as possible enabling the tank to cool the facility for c.36 hours without disrupting research should a chiller failure occur.

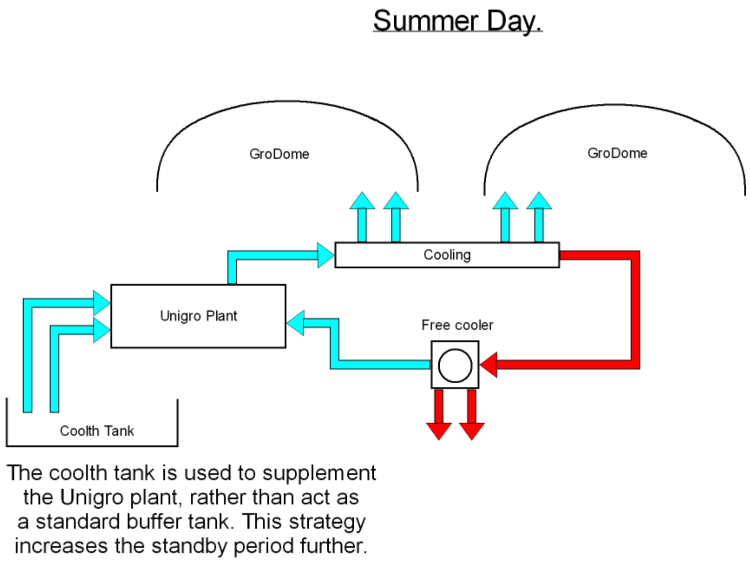


**Figure 4.** The daytime conrol stategy during the summer months (Diagram © Unigro)

During the daytime of spring, autumn and winter the process is reversed (Fig. 5). Due to the coolth tank capacity far outstripping the cooling demand, the coolth tank performs the only cooling function of the day and the chiller does not run. The free cooler is used regularly at this time of the year. At night the chiller and free cooler are used to chill the coolth tank. This enables the free cooler to run at its optimum efficiency and the chiller to utilise lower tariff electricity, significantly reducing the running costs.

The use of a coolth tank in this way means that accurate lower control temperatures can be used, the demand and supply relationship is extended to using lower cost electricity, and not all the cooling is provided by the refrigeration compressors.

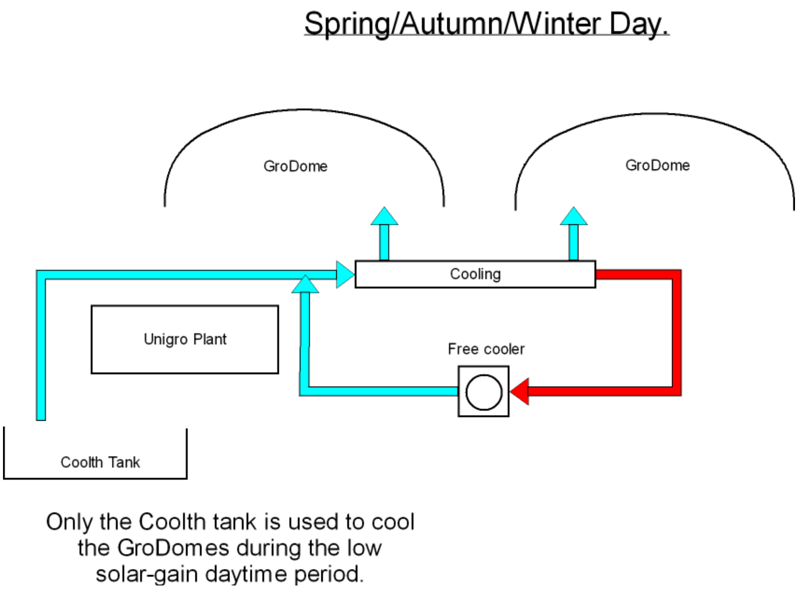


**Figure 5.** The daytime control strategy during spring, autumn and winter months (Diagram © Unigro).

Figure 6 illustrates the effect on the growth chamber's control and the coolth tank when a chiller failure does occur. During this four day summer period, the coolth tank temperature (red line) rises and falls through the 24-hour cycle until there is a chiller failure on the third day. From this point the coolth tank temperature continues to rise as the facility enters its second day without refrigeration. Through this period the chamber temperature (green line) does not fluctuate by more than 0.5°C around the set point despite high external temperatures and high and very variable external irradiance. This graphical illustration demonstrates that sustainability in terms of maintaining research during periods of ongoing mechanical failure, can be combined with unshaded temperature controlled facilities. This functionality is not due to additional refrigeration capacity with stand-by mechanical plant. Rather this is possible by utilising simple engineering designed to reduce the standard running costs and enabling a lower capital cost.

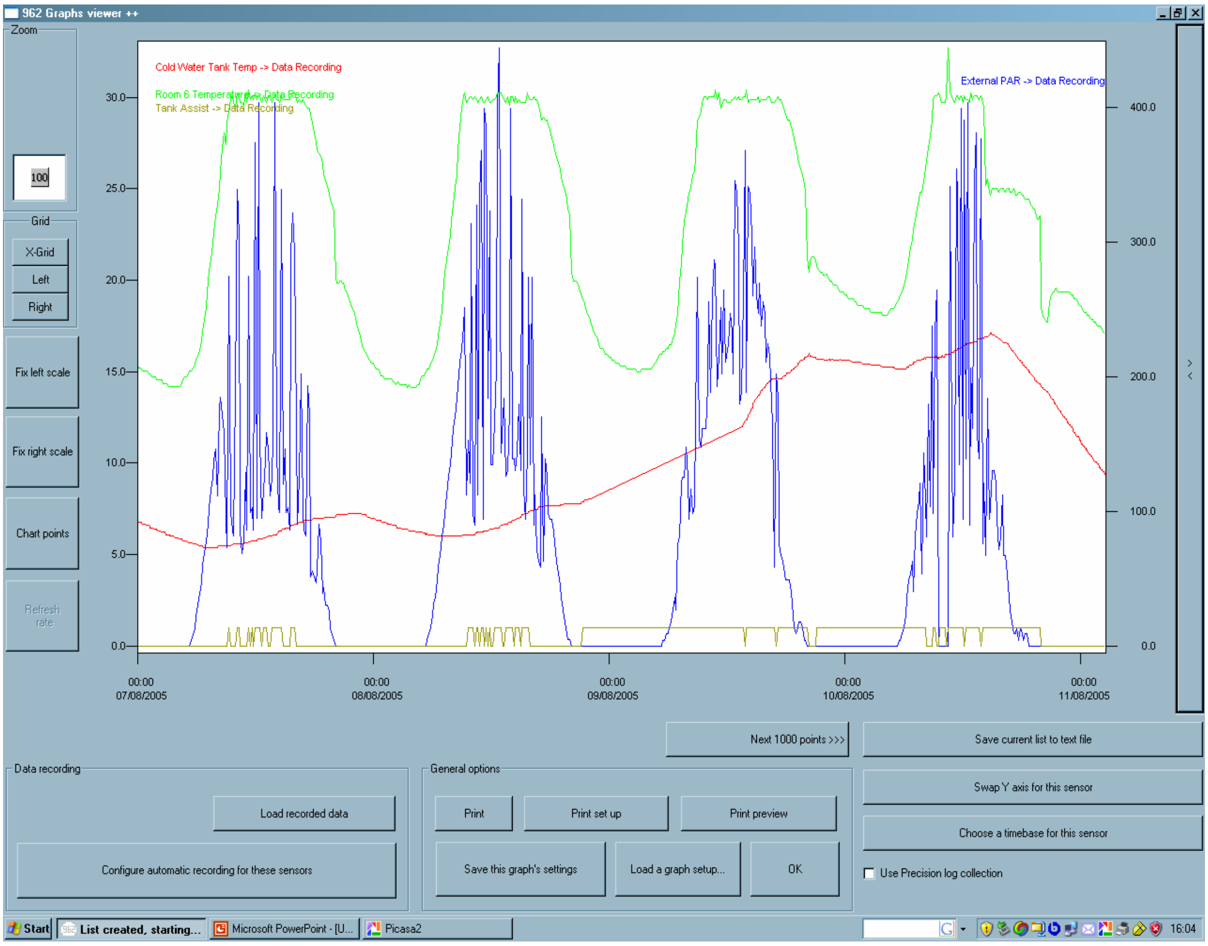


**Figure 6.** A screen display showing a continuous record of environmental variables (room temperature - green line and external PAR - blue line) for a CE chamber and coolth tank temperature (red line) before and after a chiller failure during the third of four days operation. Chiller control was re-established late on the third day © Unigro).

Now that the full implications of these higher coolant running temperatures can be observed, the resulting effects of high fan coil air volumes with low air temperature change and the influence of the buildings shape can be seen. This illustrates a single area of interdependence of the facility design and therefore the importance of the integrated thinking of the design team.

Another reason for the need for specialist cooling and heating capabilities is the speed at which the demands change. With cooling loads increasing by c.400% in twenty seconds and concurrent heating loads, integration of the refrigerant and BMS control systems is as important as the mechanical plant itself. Heating loads represent a substantial proportion of the total energy demand. Chillers with heat recovery can be used to redirect the removed heat to ancillary facilities, storage vessels or to the CE when there's a demand in the form of low pressure hot water (LPHW). Although typically using temperatures of 48-43°C these chiller units have co-efficients of performance (COPs) of c.5:1. Using a full heat recovery chiller, the thermal output from our facility will have the capacity to heat a standard commercial glasshouse of approx. 1.5 times the area of a conventional glasshouse for no additional cost, depending on the required parameters. We are currently installing a number of walk-in PGRs in an old building with insufficient electrical supply or LPHW to provide sufficient heating. The solution is to use a chiller with full heat recovery in addition to a reverse cycle heat pump functioning in a single unit with two separate and independent circuits. This unit can be used to generate heat when there is no chiller demand, similar to a heat pump unit. This allows a substantial infrastructure saving in addition to a break-even value for the additional chiller cost, an increase of c.40% over the standard chiller.

In another example a remote facility is required and only an unsuitable electrical supply is available. Additional installation of power supply is not feasible. The chosen solution involves using the heat from the site's Combined Heat and Power (CHP) woodchip plant to drive an adsorption chiller unit. Differing from an absorption chiller, this unit uses alternate chambers, vacuum pumps and silica beads to evaporate and condense water vapour. Water vapour is used as a non-polluting refrigerant to extract the energy from the coolant used in the research facility. The process energy is supplied by the CHP water and a minimal rejection of additional low-grade heat is expelled to waste. Although having low COPs and high capital costs, adsorption chillers are considerably more reliable than the similar absorption chillers and can utilise a waste hot water supply to lower temperatures.

Utilising the woodchip CHP coupled to the coolth tank means that the hot water supply does not have to be run simultaneously with the cooling demand and that the system is efficient and sustainable. Many research sites run CHP or hot water mains. Adsorption chillers offer an alternative to electrical energy for chilled water production. If waste heat is available, the cost increase is quickly offset and with detailed data these payback periods can be calculated with fixed maintenance costs.

Much of the technology illustrated is listed on the Carbon Trust's technology list enabling users to qualify for ECAs (Enhanced Capital Allowances). The implication for research should be investigated on an individual basis. Enquiries are dealt with quickly and succinctly by The Carbon Trust in my experience.

There are many other systems and technologies in place offering the potential of running cost efficiencies, many of which are not always suited to CE applications. Some interesting work at Manchester University demonstrated that polycarbonate could be made to transfer irradiance from one wavelength to another rather than blocking specific wavelengths. This gives the potential to increase the PAR spectrum and increase the wavelengths adding to solar gain, and work of this nature should be further explored.

The development of standard polycarbonate used in CE construction offers thermal efficiencies in terms of conduction and integrity, security and containment and high transmissivity values, partly due to its large sheet size. For example, with an air gap between two 10 mm skins the U values can be reduce from c.5.4 W $m^{-2}$ $K^{-1}$ for a standard glass structure to 1.63 W $m^{-2}$ $K^{-1}$. Large sheet sizes and compressible seals allow for greater integrity, reducing the extracted air volume to maintain negative pressure, and reducing electrical demands. The largest implication is for the air change rate. Although crossover heat exchangers should always be used on the extracted air, change rates should be minimised to control both heating and re-humidification costs. Air change rates of eight rather than four changes per hour may cost an additional £7.50 per 24 h in a chamber of c.92 $m^3$ at current electrical energy costs.

Other systems suited to local climates use heat sink functions of the local soils or simply the place large drums of water within a facility giving the building a huge thermal inertia and absorbing and releasing the energy as the conditions change.

In 2005 we conducted a survey of CE Facilities Managers, the two questions below were asked again in 2007of managers many of whom were involved in the original survey. Although there are many reasons why the results of these two polls should not be directly compared, this information is all that we have available and the questions alone aim to stimulate discussion around the topics of system performance when considering the design of energy efficient greenhouses.

*September 2005 Unigro Survey of CE Facilities Managers*
Managers were asked to place the following 6 aspects of CE management in order of priority, 1 being your highest priority and 6 being the lowest priority:

- Reduction in energy costs
- Containment
- Climate simulation
- All year round use
- Physical security
- Energy recycling function

2005 Unigro Survey of CE Facilities Managers' Survey Results:

- 14% of respondents put "Reduction in energy costs" as the highest priority of the six
- No respondents put "Energy recycling function" any higher than the 4th highest priorities of the six

In 2007 more than 50% of the CE Facilities Managers who had an influence on the purchasing of CE facilities signalled that they would place "Reduction in Energy Costs" as the highest priority. Additionally, an estimated 30% placed "Heat recycling" above 4th highest priority of the six. (No option for none of the six priorities was offered.)

**Reference**

Carbon Trust web site: http://www.eca.gov.uk

**M. Buchholz** (Building Technology and Design, Technische Universität, Strasse des 17 Juni 152, Sek. A 59, 10623 Berlin, Germany; E-mail: martin.buchholz@tu-berlin.de) **The Watergy Project, a closed greenhouse urban supply system**

## Introduction

A closed greenhouse concept has been developed in the WATERGY project (funded by the European Union's 5th Framework Programme, see http://www.watergy.de) that implements a new method of passive climate control and water treatment (desalination and irrigation water recycling) by only using solar energy.

Air in a closed greenhouse is humidified by plants and heated by solar energy, it rises up into the roof area where it is further humidified by an additional humidifier (Fig. 1). The heated and humidified air rises further, driven by buoyancy, reaching the upper end of a cooling duct. In the duct, air is cooled by a heat exchanger and water vapour condenses after reaching the dew point. The cooled air increases in density and falls through the duct into the vegetation area at ground level. The released heat is transported into thermal storage and heated water is taken back into the greenhouse during night in order to heat the house and regenerate the cooling capacity of the thermal storage for the next day.

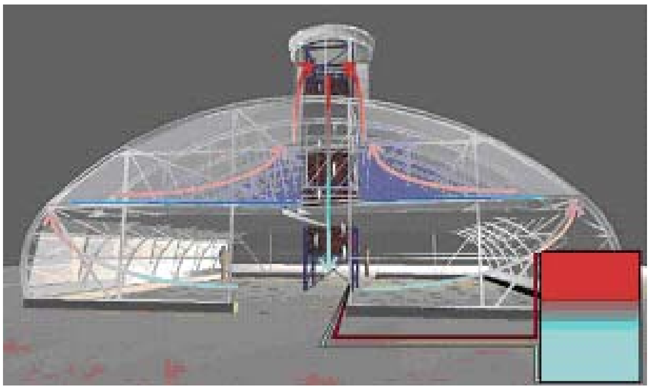

**Figure 1.** Scheme of the prototype greenhouse with buoyancy-driven air circulation and thermal storage for passive cooling with day-night temperature equalisation.

The concept is aimed at using wastewater and saline water as an input while producing potable water, salt and food or non-eatable biomass, while at the same time reducing pollution of water resources.

Further positive aspects of the closed greenhouse are redundancy of insecticides (no insects can enter) and a method of horticultural production at increased $CO_2$ levels. Having optimised light, temperature, nutrient, water and $CO_2$ supply, all growth factors of the plants are served and the system is designed for maximising photosynthetic activity and related plant growth.

Two prototypes have been built, one in Almería, Spain (with recovery of 75% of irrigation water, resulting in water needs below 0.5 litres $m^{-2}$ $d^{-1}$ for growth, zero chemical pesticides needed, plant growth at ~$1200 \cdot 10^{-6}$ volume fraction $CO_2$ in air) (Fig. 2) and one in Berlin, Germany (with loading of a seasonal thermal heat storage using the solar input into the greenhouse).

This paper describes the main basis of applications that together will form an integrated tool for water and land management in arid areas facing rising water demands for food production, by households and by industry on the consumer side and growing drought, irregular rainfall, dehydration of landscape and related nutrient losses on the supply side.

**Intensive horticulture with extremely reduced water demand**

Greenhouse horticulture has undergone a period of enormous growth during the last 20 years in many arid areas, as a very successful method of crop production, mainly based on the combination of mild winter climate and relatively simple and cost effective construction methods which make the process viable. The fact of enhanced water efficiency, caused by higher air humidity and reduced air velocity compared to open field horticulture, and effective possibilities of rainwater harvesting from the roof did also contribute to the growth, so that available water sources in the arid climate could be exploited relatively effectively. Now, as in many places groundwater basins are more and more overexploited or even running out of water, the specific possibilities of greenhouses for water saving are becoming of general interest. The focus is now changing from production rates calculated per unit area (square meters) to those calculated per unit consumption of water (litres).

Closing the greenhouse means that internal cooling and dehumidification processes have to be installed instead of climate control driven by internal/external air exchange.

**Figure 2.** Prototype greenhouse in Almería, Spain

A closed greenhouse theoretically does not need any water input as it is cycling within the closed internal atmosphere between evaporation and condensation. In reality, there will always be some small losses through the greenhouse envelope, but water efficiency has already been proved at below 0.5 litres $m^{-2}$ daily water demand for intensive cultivation. This relates to water autarky of intensive crop production at annual rainfalls under 200 mm/a.

**Urban wastewater recycling and protected soil/nutrient management**

Closed greenhouse technology is aimed at recovering water from atmospheric humidity and allowing the water evapo-transpired by the plants to recycle. An adapted and secure use of wastewater for greenhouse irrigation will allow recycling of these water sources into drinkable fresh water, using the vegetation's root membranes as the most effective and self-renewing water filter available.

Communal wastewater has a high content of plant nutrients but careless use increases the danger of exposure to microscopic organisms that may cause diseases. Therefore, it has to be fed into irrigation systems without contact to above ground parts of the crops.

In many cases, urban wastewater is not further treated and by not using it already means a high level of hygiene-related and general environmental problems for any kind of water body and related fresh water supply. Its use in irrigation also may replace more complicated nitrogen and phosphorus elimination strategies. Biological pre-treatment can already reduce the content of plant nutrients, so a wastewater treatment system integrated into horticultural irrigation can be interpreted as a complete alternative method, only using minor and simple pre-treatment strategies.

Grey water is the wastewater of an urban area without faeces i.e. water collected from washing machines, showers, wash bowls etc. The separation of grey water allows a radical reduction of the hygienic or odour problems associated with wastewater and also allows further reduction of pre-treatment measures. As its nutrient content is much lower, urine can be re-added after separate collection and simple pre-treatment without hygienic problems e.g. in modern automated nutrient supply irrigation systems. Urine contains more than 70% of the plant nutrients of urban wastewater. Faeces can be re-added after separate collection and pre-treatment in composting or biogas devices.

**Closed greenhouses and related soil systems as a $CO_2$ sink**

A closed greenhouse allows carbon dioxide to accumulate to the optimum for plant growth. In cases where other productive factors like water, nutrients, temperature and light are optimised, $CO_2$ supply triggers the growth and optimum rates can be at around $1200 \cdot 10^{-6}$ volume fraction $CO_2$ in air (~triple atmospheric level), thus allowing growth rates much higher than in open field agriculture. The higher growth also contributes to a higher production rate per unit of water used. $CO_2$ can be supplied directly from combustion processes, except that in certain cases, emissions have to be cleaned to allow a supply of pure $CO_2$. These technologies are commonly used in greenhouse horticulture, but only a closed greenhouse can keep the gas in the vegetation area where it can be used efficiently and an optimum concentration can be maintained accurately throughout the whole volume.

Carbon can be stored in the soil if added as compost or charcoal. The use of non-eatable biomass in manufactured products (as wood, fibres, plastic etc.) can result in long term carbon storage too. Also energetic use of the non-eatable parts of the plants or other biological waste can result in carbon accumulation, if charcoal is constantly produced as a by-product in a combustion process (e.g. pyrolysis) and then stored as a soil enhancer.

**Seawater desalination**

In parallel to the plant evapo-transpiration, seawater can be evaporated in the roof zone of the closed greenhouse, where air temperatures are higher than in the vegetation canopy, and thus can take up much more water vapour and associated latent heat. In the greenhouse, a continuous air circulation enables energy transport from the vegetation zone through the roof area to the heat exchanger duct that is entered from the rooftop. Increasing the humidity in this zone allows transporting a much higher amount of the total solar energy input at the same air velocity. This process allows storing a larger amount of heat that then can be released through the following night, where it can be further used for desalination.

Seawater desalination is a major component of the system, as at certain regions it allows the cultivation system to be established in previously uncultivated, even steppe or desert landscapes where sufficient rain or wastewater is not available.

**Thermo-chemical energy storage and climate control strategies**
Instead of desalination of seawater, the roof integrated evaporation devices can also be applied for the regeneration of desiccants in open cooling or heating systems, thus reducing the need for fossil energy for building climate control and related $CO_2$ emissions. For this method, a mixture of water and a soluble salt (e.g. $MgCl_2$, $CaCl_2$, $NaNO_3$) is distributed on evaporation pads. The water is evaporated and the salt content in the liquid is subsequently increased. The concentrated solution has hygroscopic properties, meaning that it can absorb water vapour from air. In desiccant cooling systems, this process can be used e.g. to dry the air at the ventilation inlet of a building e.g. Figure 3, while in a second step, the released latent heat from this process is withdrawn by a heat exchanger and transferred to the air outlet of the building. The resulting dehumidified and moderately cooled air can then be further humidified and thereby significantly cooled down. The saline solution is diluted by the water content of the incoming air and can be redirected into the greenhouse for further regeneration. The process can also be used for greenhouse cooling of extremely hot areas or for areas, where night temperatures are too high for a passive regeneration of the cooling load.

A further application is the absorption of water out of humid air from the environment. In areas with high night time air humidity, the greenhouse is opened during the night and the hygroscopic solution can absorb external vapour, that is transformed to usable fresh water by desorption and condensation processes during the following day.

**Figure 3.** A closed greenhouse attached to a building (Watergy Prototype in Berlin, Germany) which can be used for the direct recycling of grey water and for the concentration of desiccant solutions during summer. The hygroscopic concentrated solution can be stored and be used during winter to absorb water vapour from the greenhouse. The system works as a heat pump, shifting winter greenhouse temperatures to a level, where it can be used for the building's heat supply.

**Closed ecosystems with productive producer and consumer populations**
As in a closed greenhouse, oxygen is constantly produced by plants and $CO_2$ is constantly needed as a plant nutrient, it is possible to go one step further in imitating processes of the biosphere by implementing consumer populations that consume oxygen and produce $CO_2$. These can be established by integrating productive components of solid-state-fermentation, where biomass is transferred into useful products like protein enriched vegetables, de-lignified fibre products with smoother quality, de-lignified wooden biomass for pulp and paper products or a large numbers of enzymes for use in diverse chemical processes.

Solid-state fermentation is the management of fungal growth on the wet surface of the treated biomass. The process includes the constant removal of heat and $CO_2$ and the addition of oxygen by ventilation but also has to guarantee a constant level of humidity that is provided by humid air and possibly further watering of the substrates. This process can be perfectly combined with the climate control of the greenhouse by using the induced internal air circulation and by creating the hot and tropical-like basic climate.

Tempe is a food product produced by solid-state fermentation on a base of soybean or peanut. The quality of the synthesized proteins is very high and production cycles are much faster than those of meat or fish. It has a high potential as a major protein source in future human nutrition. This is of further importance as resources of sea fish are limited and mass production of animals is associated with growing environmental and health problems and is a major source of greenhouse gas emissions. Solid State Fermentation can also be used for delignification of linen or hemp fibres. As these fibres can be transformed to higher textile qualities at lower costs and lower environmental impact compared to chemical treatment, it can be possible to replace cotton which is an extremely water demanding crop and which is associated with major environmental problems like soil salinisation.

**Closed greenhouses for large-scale surface cooling around urban areas and coastal landscapes**

Evaporative cooling in cities can be essential to lower the effect of the urban heat island. For closed greenhouses, the function of surface cooling is working in a different way. Evaporative cooling is again the major driving force, but related condensation is forced to take place within the closed environment. The released sensible heat is transferred to water in a heat exchanger and stored in the soil. Water and heat are kept on the site and are released during the night. By lowering the temperature during daytime, the climatic conditions of the surroundings can be stabilised. The energy balance of the prototype greenhouse (Fig. 4) shows that still a major part of the radiated energy is going out through the greenhouse envelope. However for the cooling of the radiation peak levels during daytime, already more than 50% of the radiation peak levels during daytime are captured and released during the night. Also reflection of the greenhouse cover leads to about 10% of the temperature reduction. Anyway, the method of evaporation in the roof zone can be further developed and will enable a further retention of the thermal energy as well as a related higher yield of condensed water.

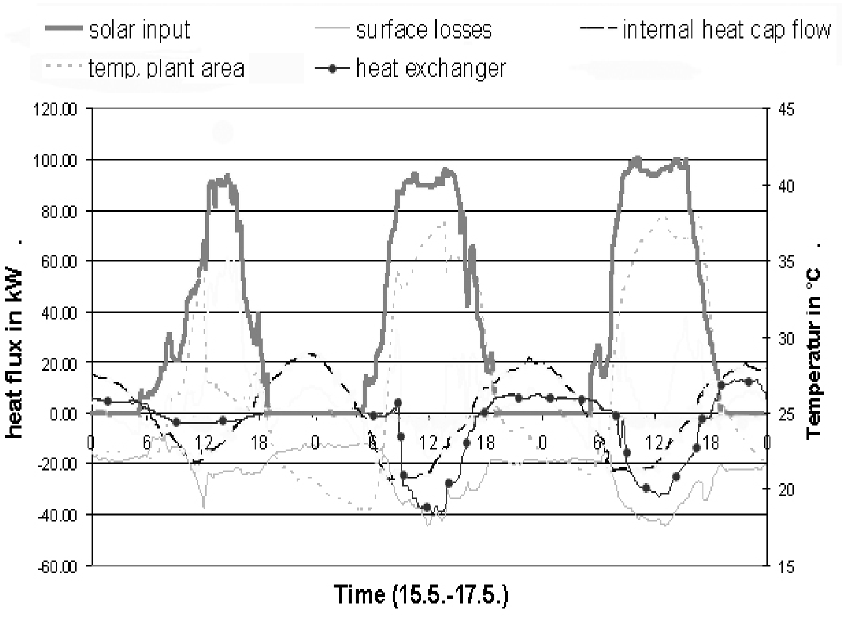


**Figure 4.** Heat flux in the closed greenhouse: While in arid climates, a major part of the solar radiation (continuous thick grey line) is directly transferred into sensible heat and is warming the surrounding air above the soil, part of the energy here is first transferred into evaporation of water, condensed on a heat exchanger and then buffered in a heat store to be released during the night (continuous line with closed circles). The higher water content of the soil does not result in water losses and allows a higher heat transfer into the soil, which contributes to another major heat retention (dark dotted line). Evaporation that normally leads

to water losses is limited to minor losses out of the enclosure and can almost be neglected (light green/grey continuous line).

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**E. van Echtelt** (Philips Lighting BV, Horticultural Lighting, P.O. Box 90050, 5600 PB Eindhoven, The Netherlands; E-mail: Esther.van.Echtelt@philips.com) **Sustainable use of artificial lighting in horticulture**

All over the world it is seen that more and more attention is being paid to sustainability. It can be interpreted in many different ways. For horticulture in the Netherlands we see it in guidelines/goals to be reached in 2020:

- Make new greenhouses (fossil) 'energy neutral'
- Establish 2500 ha of closed greenhouses
- Heat 500 ha of greenhouses with 'earth heat'
- Improve lighting sources and light use strategy to decrease energy use by 40%
- Introduce strict rules for limiting light pollution (by 2008 and 2014)
- Reduce $CO_2$ emission
- Reduce use of chemicals i.e. for biological crop protection

Of course this is not only important for the Netherlands, but it is important to include sustainability in everybody's way of working.

As a manufacturer of artificial lighting systems we ask ourselves the question:
*How can we improve our lighting systems and lighting strategies to help to achieve these goals?*

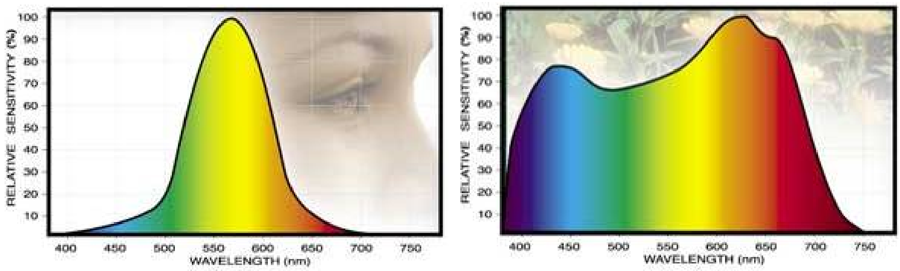
We see an important role in stimulating ourselves and our users to more sustainable use of artificial lighting. In general lighting this is being done by investing in LED lighting and by discouraging the use of energy-inefficient incandescent lamps. In lighting for controlled environments it is even more important to look at efficient lighting systems, because in this case light is a "production" tool. Any light or energy wasted could have been used for more, better and/or faster growth. Focussing on efficiency thus gives a direct method to save money e.g. looking at the actual running costs of an high-pressure sodium lamp, shows that energy costs during its life time are much higher (10-20x) than the initial capital cost.

We are working on three aspects that are very important for efficient lighting by:

1. Developing efficient light sources/lighting systems
2. Stimulating research and co-operating with partners on improving light penetration in crop (as much as possible of the light should reach the plant)
3. Being involved in research on optimising the strategy of light use (making sure the light level is optimal for the type of crop, the growth stage of the plant and the time of the day to get efficient growth).

## 1. Development of efficient light sources/lighting systems

For efficient lighting of plants, the most important aspect is to know what kind of light is 'seen' by plants. For quite a long time we know that it is the number of photons between 400-700 nm that is determining the photosynthetic rate (when all other factors are not limiting). This is what Philips calls GrowthLight. Efficiency of a lamp is indicated in micromole/joule. For humans this value if always corrected for greater sensitivity to yellow light, and is thus indicated by a different value, lumen/joule.




"Human eye" "Green Plants"

**Figure 1.** The spectral sensitivity of the human eye and of green plants (Source: Philips brochure: Growing your Profit)

The past ten years a lot has been done on development of lamps and systems. One of the most important developments is the change of focus from evaluating by lumen/joule to micromole/joule. The spectrum of conventional high pressure sodium lamps (SON-T Plus) was further optimized to give higher micromole/joule values. These lamps can be recognized by the name, GreenPower. These lamps are constantly being improved to keep the initial GrowthLight constant for a longer time. An example can be seen in Figure 2, where it is shown that over a lifetime 5% more light is gained with the new Constant GrowthLight lamps.

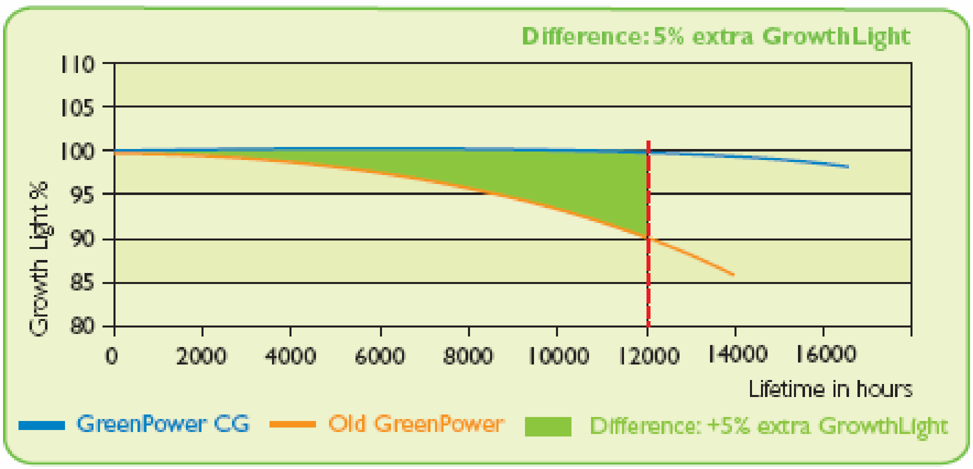



**Figure 2.** A comparison between maintenance of the output of GrowthLight from old and new designs of HPS GreenPower lamps (400/600 W 230 V EM) **(**Source: Philips)

Also, at the system level, improvements on efficiency have been made. First there was the change from 230 V to more energy efficient 400 V systems and now we see the development from the conventional electromagnetic control gear to electronic gear (GreenVision), which results in lower energy losses. Another advantage of electronic gear compared to conventional gear is its size. The luminaires are much smaller so that less daylight is intercepted. Further, in GreenVision there are no lead (Pb) components used any more. Another development has been the design of higher power lamps and systems (1000 W), resulting in less luminaires per unit area being required to achieve the same GrowthLight level. This gives, among others, advantages of less daylight interception and the use of fewer materials, resulting in less waste.

## 2. Stimulation of research and co-operation with partners on improving light penetration in glasshouse crops

***Experiments with intracanopy lighting of vegetables:***

By bringing the light "into" the crop a more even light distribution in the crop can be established. It was found that efficiency of total light use can increase by 10% and result in better quality product. In Finland and Norway this was shown very clearly, in the Netherlands this was more difficult to demonstrate because of problems with the use of fluorescent tubes and high pressure sodium lamps. The fluorescent tubes are not really efficient light sources and the heat produced by high pressure sodium lamps damaged some of the plants . However, research on this topic is still going on at the University of Wageningen, but now working with LEDs, which might not be the most efficient light source at the moment, but which are supposed to be in future.

***Experiments with mobile lighting:***

Mobile lighting was expected to give a better light penetration, deeper in the crop. In experiments no significant positive results were found. However there are growers who are using it in practice and who say that they have a 4% higher production of roses because of their mobile lighting systems.

## 3. Research on optimising the light use strategy

It is very important to know how much light your plants need at what time of the day and in what stage of the plant and how efficiently the plant is using the light. This research is getting more and more important to make optimal use of systems as energy prices are increasing. An example of research on strategy of lighting was done on tomato crops last year. This was in co-operation with Plant Research International. The objective was to answer the following questions:

- What is the optimal duration for lighting?
- What is most efficient: short duration intense level lighting or long duration low level lighting?

The results of the experiment were:

1. 18-h lighting at high light level gave the greatest production with the highest energy efficiency.
2. When comparing 2 equal light sum treatments, but with different light level and duration, it became clear that the treatment of 15-h lighting at high light level gave more production than 18-h lighting at low light level.
3. For highest energy efficiency (kg produced/energy used), 18-h at low light level was more efficient than 15 h at high level, mostly because of more savings on heating when lighting for 18 h.

It is a grower's choice to decide what is more important, more production or higher energy efficiency. (It also depends on his/her energy/heating situation.)

These kinds of experiments are very useful for showing what will lead to more efficient growing of greenhouse crops. An example of another experiment we are doing is to see how we can improve quality of pot plants by using spectrally tuned light (blue light). An interesting tool for this kind of research on tuning effects is now available: LED light.

## Other aspects of sustainable lighting in horticulture

***Lamp lifetime***

Often it is said: "We have to replace the lamps so often! Isn't it possible to keep them longer?" Our answer refers to a general saying that "1% more light gives 1% more growth" (especially in winter time). On the other hand 1% less output is already a big loss to production because a lamp still uses the same amount of energy as its light output declines. Therefore high standards should apply for deciding the economic life of horticultural lamps. Replacement is advised when light output has decreased 10%. This is at 10,000-12,000 h for most lamps. For research facilities the standards might be even higher! If a lamp is developed with a longer lifetime, it is almost inevitable that efficiency will decrease. You always have to find the correct balance between lifetime, light output and efficiency!

***Reduction of the chemicals used in horticulture***

The variety and quantity of chemicals used in horticulture can be reduced by management of lighting. There are several opportunities. One is using UV-C light to disinfect water. Another forthcoming application of UV-C light is crop protection against, amongst others, powdery mildew on cucumber, *Botrytis* on roses and *Phytophthera* on potato. This could lead to a large reduction in the use of pesticides.

Also many chemical growth regulators (hormones) are being used for cultivation of plants. Currently, research on pot plants is being done to find out whether specific spectra of the light can influence plant growth in such a way that it could take over certain roles of growth regulators (e.g. reducing stem elongation).

***Reduction of materials/energy used for production of lamps***

All new lamp products are being evaluated for their ecological impact compared to other products in the market. Philips new products always need to be above average of the market ('Ecodesign' concept). Production lines are constantly mechanised and improved for efficiency and for less use of hazardous components (e.g. lead) etc. All fluorescent tubes and high pressure sodium lamps are being collected and recycled.

***Light pollution***

Light pollution for humans and animals is becoming more and more of an issue. For horticulture this could be solved in greenhouses by using light screens that close at night. A disadvantage of the use of these light screens is that the trapped heat from lamps cannot dissipate. Temperatures are too high in the greenhouse for good crop growth and extra cooling is needed. Another solution for light pollution could be to choose lighting with wavelengths for which the human eye is less sensitive (e.g. red and blue). These colours could still have an effect on animals and plants outside the greenhouse.

Both aspects could be (partly) solved by the use of LEDs. Heat produced by the LED can be controlled more easily and spectrum can be chosen more specifically to growers' wishes. The extra advantage of LEDs is that light can be applied closer to the crop which will result in less scattered light.

***Light Emitting Diodes***

It has already mentioned above that Light Emitting Diodes (LEDs) are a very promising sustainable light source for horticulture, which are getting more and more attention in recent years, not only in horticulture, but in many other lighting applications as well. For horticulture the advantages are, amongst others, that they:

+ Are efficient in optical design

+ Do not produce radiant heat. Heat is conducted down the electrical leads and convected away, which makes it more easy to cool.
+ Could be spectrally optimised for plant growth. The two colours that are most important for plant growth (red and blue) are at present the most efficient LEDs compared to, for instance, green or yellow LEDs.
+ Can be dimmed and spectral ratios can be varied.
+ Have a long technical life time

At this moment however there are also some disadvantages:

- Efficiency in micromole per joule is less than that of an high pressure sodium lamp
- Knowledge is lacking about what colours, in what ratio, and with what kind of light distribution is best for plant growth
- Cost per unit is high

Development of efficiency and output of LEDs has been huge over the last 20 years, and it is expected to go on. Prices are decreasing. At the moment GrowthLight efficiency is almost the same as that of fluorescent tubes but it is predicted that they will be more efficient than high pressure sodium lamps in the coming years. We are therefore carrying out research on how to apply LED light to crops in controlled (daylightless) environments at research stations, universities etc. (Figure 3). Experiments will follow on practice in greenhouses combining technical knowledge about greenhouse systems with plant growth to ensure that when LEDs are efficient enough for GrowthLight, LED systems can be used in practice.

**Figure 3.** Controlled environment cabinet of Snijders Scientific with GreenPower LED modules (produced for PlantLab BV.)

In conclusion, sustainability in lamps and lighting systems for controlled environments will depend on bringing innovations for efficient lighting. It is important to reach this by further developing GrowthLight efficient light sources, investing in research to find efficient methods for application and use of light systems and to translate this into practice. Further it is Philips' responsibility to constantly improve sustainability in production processes of light systems and stimulate sustainable after care of light systems (i.e. collection and recycling of used lamps and lighting systems.

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**G.M. Waimann** (Controlled Environment Engineer, Technical Support Services Division, Rothamsted Research, West Common, Harpenden AL5 2JQ, UK; E-mail: george.waimann@bbsrc.ac.uk) **Sustainability and innovative application of refrigeration and refrigerants in controlled environments: A UK perspective.**

## Introduction

Sustainability with respect to CEs is very complex! However for my purposes is it hoped a system will have an operational life of at least 20-30 years, and beyond if designed with sustainability and adaptability. Currently the main drivers for sustainability in the UK are refrigerants, energy and the Energy Performance of Buildings Directive and serviceability i.e. the ability to service, and maintain, a system throughout its life span. Many new systems, or parts thereof, offered today are often obsolete within 5–6 years. This paper will concentrate on sustainability of refrigerants, refrigeration systems and associated systems.

## A simple refrigeration system

The Second Law of Thermodynamics states that:
*"Heat cannot of itself pass from one body to a hotter body"* (Clausius)[5].

The important words are "of itself" therefore it is necessary to do some mechanical work if refrigeration is to take place. Latent Heat of evaporation and condensation is what makes it work, 90% of systems in the world use mechanical vapour compression refrigeration systems which are represented schematically in Figure 1.

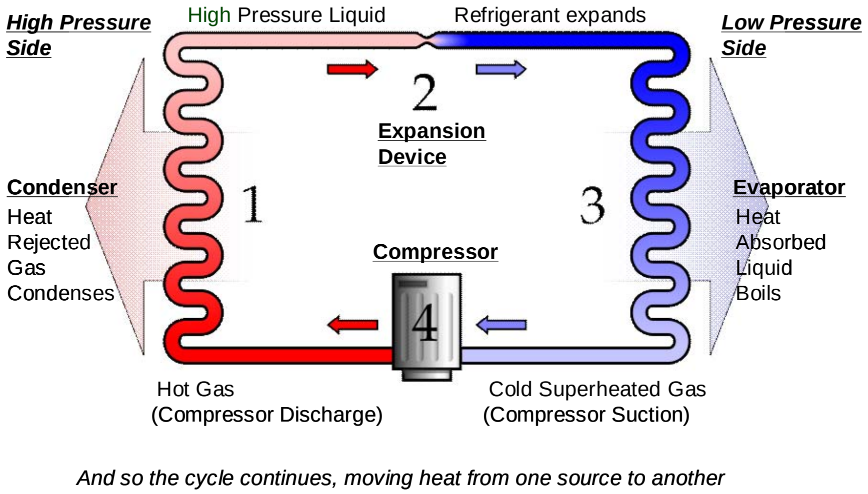


**Figure 1.** A simple refrigeration system. (Rothamsted Research)

There are many variants of compressors; reciprocating piston compressors, screw compressors, centrifugal compressors, rotary and rotary vane compressors, scroll compressors, turbine compressors, and variants thereof, all work on the same principles;

[5] Clausius (1822-1888) According to philosopher of science Thomas Kuhn, the second law was first put into words by two scientists, Rudolph Clausius and William Thomson (Lord Kelvin), using different examples, in 1850-51

however some are better suited to some applications than others. For example, centrifugal compressors are particularly suited to applications where high refrigerant volumetric duties are required. The refrigerant is also important in determining the choice of suitable compressors.

The correct selection, sizing and application of all the components of a system design are crucial in producing reliable and efficient systems.

There are other methods of refrigeration such as absorption where an absorbent is used to carry the refrigerant and heat is used to drive the refrigerant out of the absorbent. A common example is lithium bromide acting as an absorbent to water where water is the refrigerant. Adsorbent systems use desiccant materials to achieve the same effect. However the COP's of these systems (see Glossary for explanations of acronyms) is generally poor and they are only viable when a ready supply of waste heat is available.

## Refrigerants

### *What are they?*

Refrigerants are liquefied gases that evaporate at pressures and temperatures that are useful to us, and ideally also having benign characteristics to the system, humans and the environment. They must be stable over many years, possess good thermal transfer coefficients and demonstrate good Carnot [6] efficiencies.

The most universal refrigerants are F-gases which include HFCs (fluorinated refrigerants) and CFCs (chlorinated refrigerants). It was the chlorine component that was responsible for damage to the Ozone Layer. As a consequence CFCs are banned. Unfortunately 'F gases' generally have a high global warming potential (GWP), hence the introduction of regulations. There may be a danger that history will repeat itself and HFCs may go the same way as CFCs. The other property of interest is the total equivalent warming impact (TEWI). TEWI methodology identifies both the 'direct' effect of greenhouse gas emissions and the 'indirect' effect of carbon dioxide emissions related to energy consumption of the system during its operational life.

HFCs are used in domestic and commercial refrigeration where they play a vital role in the food chain, in air conditioning systems including automotive, domestic, commercial and industrial cooling and heating applications, in the building construction sector e.g. for foaming thermal insulation, in the health care sector e.g. medical sprays, metered dose inhalers, as a propellant in aerosols, and many other medical applications, and in controlled environments.

The HCFC R22 is being phased out as are the drop-ins for the CFC R12. The phase out of HCFCs will begin on 1st January 2010 with a complete ban in place by 1st of January 2015 (for details see the Appendix).

### *Natural refrigerants and their benefits*

Ammonia ($NH_3$), carbon dioxide ($CO_2$) and hydrocarbons (HCs) are three of the original refrigerants going back some 100 years to the beginnings of refrigeration and have stood the test of time; the abundance and longevity of these refrigerants assure their future. They were

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[6] **Nicolas Léonard Sadi Carnot** (June 1, 1796 - August 24, 1832) was a French physicist and military engineer who, in his 1824 *Reflections on the Motive Power of Fire*, gave the first successful theoretical account of heat engines, now known as the Carnot cycle, thereby laying the foundations of the second law of thermodynamics.

used historically mainly in industrial applications. They do not deplete atmospheric ozone. They are efficient refrigerants and each has its particular advantages, it is essential that they are correctly applied. In most cases they are more efficient than the current HFC's and the TEWI on either ammonia or $CO_2$ will usually be better on a properly applied system. They are certainly cheaper, for example per kg: $CO_2$ = £0.30, Ammonia = £1.00, HFCs (R404a) £10.00 and likely to increase in time. Ammonia, $NH_3$ (R717), has a GWP of zero, is toxic and its leaks are easily detected. Carbon dioxide, $CO_2$ (R744), has a GWP = 1, it is inert and its leaks are not easily detected. A high level of $CO_2$ in the body, known as hypercapnia, initially causes hyperventilation followed by $CO_2$ narcosis, followed by brain damage and then death. However the symptoms are easily recognised.

Hydrocarbons (HC), propane based refrigerants, known commercially in the UK as Care (BOC trade name) are non-toxic and are potentially explosive, and are used extensively in Europe in domestic refrigerators and freezers. They are being used increasingly in larger installations and chillers.

With these natural refrigerants training is of paramount importance; they are safe if properly selected and handled, gas leakage monitoring systems are applied to these systems and an alarm is generated in event of a leakage.

The Global Warming Potentials (GWPs) of refrigerants are being continually revised as scientific knowledge increases. Table 1 compares the GWPs published in the IPCC's Third Assessment Report (2001)2 with the 2006 United Nations Environment Programme (UNEP) assessment report3, which encompasses the latest data from the IPCC special report and the 2006 World Meteorological Organisation (WMO) Scientific Assessment. .

**Table 1.** Refrigerants and their GWPs as reported in 2001 and 2006

| Fluid | Formula | Scientific GWP IPCC, 2001# | Scientific GWP UNEP, 2006# |
|---|---|---|---|
| HCFC-R22 | CHClF2 | 1,700 | 1,810 |
| HFC-23 | CHF3 | 12,000 | 14,760 |
| HFC-32 | CH2F2 | 550 | 675 |
| HFC-125 | CHF2CF3 | 3,400 | 3,500 |
| HFC-R134a | CH2FCF3 | 1,300 | 1,430 |
| HFC-143a | CF3CH3 | 4,300 | 4,470 |
| HFC-152a | CH3CHF2 | 120 | 124 |
| HFC-R404A | - | 3,780 | 3,900 |
| HFC-R407C | - | 1,600 | 1,800 |
| HFC-R410A | - | 1,900 | 2,100 |
| R744 | $CO_2$ | | 1 |
| R717 Ammonia | $NH_3$ | | 0 |
| CARE refrigerants 10,30,40,45,50 | $C_mH_n$ Hydrocarbons | | 3 |

# Values are direct GWPs (as opposed to indirect or net GWPs)

It can be clearly seen from the Table 3 that the natural refrigerants have outstanding advantages in terms of GWP that will increasingly outweigh the inherent problems in applying them.

***The UK Government's current policy on HFCs***

The UK Government's current policy can be seen in the following extract (in italics) from the DEFRA document: EC Regulation No 842/2006 on certain fluorinated greenhouse gases. Frequently Asked Questions, October 2006. Page 7.

*.. 5.* ***Question:*** *What is the Government's policy on HFCs?*
***Answer:*** *There has been uncertainty regarding the use of HFCs since the adoption of the Kyoto Protocol. The Government recognises that the successful phase out of ozone-depleting substances under the Montreal Protocol is being achieved with a range of technologies, and accepts that HFCs are necessary to replace ozone-depleting substances in some applications. In view of this, the Government's position on HFCs is as follows:*

- *HFCs should only be used where other safe, technically feasible, cost-effective and more environmentally acceptable alternatives do not exist;*

- *HFCs are not sustainable in the long term – the Government believes that continued technological developments will mean the HFCs may eventually be able to be replaced in the applications where they are used;*

- *HFC emission reduction strategies should not undermine commitments to phase-out ozone depleting substances under the Montreal Protocol;*

- *HFC emissions will not be allowed to rise unchecked.*

We must be aware of the Governments policy; in the future we may find HFC's being phased out, as with CFC's and now HCFC's. Given the opportunity it is likely that all fluorinated refrigerants will be phased out, except for use in specialised applications. The refrigeration industry is being encouraged to find alternatives to fluorinated refrigerants.

**Systems and technologies**

***Existing systems and technologies: Advice***

Air movement systems

a. Ensure filters and fans are clean. Dirty filters and fans are inefficient.
b. Ensure the belts in good condition and adjusted correctly. Slack belts or belts to tight waste energy, and wear the drive systems and motors.
c. Ensure fans are running at the correct speed Fans running faster than necessary and developing to much pressure waste energy. Open-up dampers, rebalance and slow down the fan. Many systems develop far more pressure than is necessary, this also has a bonus because it reduces noise.
d. Fit an inverter (Variable Speed Drive) if the air flow demand fluctuates. Ask does the airflow volume have to be maintained continuously? If there are periods where loads reduce, slow it down or switch it OFF.
e. Fully utilise the facilities control systems. Ensure fans are neither running more than necessary nor cycling too frequently.

Pumped wet fluid systems; water and glycol

a. Make sure all water coils and heat exchangers are clean.
b. Ensure pump belts are in good condition and are adjusted correctly.

c. Correctly balance the systems, and adjust the pump duty. Pumps developing more pressure than is necessary waste energy. Many systems often develop more pressure than is required..
d. Fit an inverter if the load (flow rate) fluctuates. At Rothamsted we have reduced the power absorbed by a district heating pump from 37 kW to 3.4 kW for most of the year, especially summer, the pump runs continuously and the full duty is only required for about 15% of the year. This reduces running costs for both the energy usage and wear on the pump/motor. Electricity cost savings were £64.51 per day. If we assume this is achievable for 70% of the year we will save £17,660 per year on electricity cost alone ON ONE PUMP.
e. Ensure pump controls are setup correctly.

### Refrigeration systems

a. Make sure condensers and evaporators are clean.
b. Operate condensing (head) pressures no higher than necessary and if possible allow the head pressure to float.
c. Avoid and/or remove hot gas bypass systems, utilise instead inverter and compressor unloading technologies.
d. Operate evaporating pressures/temps as high as possible because higher suction pressures are more efficient in terms of both the efficiency of the compressor and the reduced latent cooling. Excessive latent cooling dehumidifies at a higher rate, which is often undesirable, for example in a CE facility, the more water that is used the more it is extracted creating an inefficient cycle.
e. Ensure refrigerant charge is correct, an undercharged system will run longer whilst an overcharged system will use excessive energy overcoming the higher pressures and will likely also run longer. In either case the system will also be unreliable.
f. Setup controls correctly and ensure defrost periods are not excessive.
g. Introduce free cooling if possible, directly by utilising cool fresh air on air systems or indirectly via a dry cooler (or adiabatic cooler) introduced into the chilled water system.

### Control systems

a. Work to integrate your control systems.
b. Allow only knowledgeable and competent persons to make critical adjustments.
c. Tune control loops, ensure systems do not hunt, or are not slow to respond; both result in greater energy use and often also lead to unreliable systems.
d. Use the time control features and utilise the inbuilt optimisation (this function optimises the start and stop times in relation to both the space and ambient temperatures) and compensation (compensates the heating water circuit temperature in relation to the ambient temperature) facilities that are available in BMS systems.
e. Take the time and trouble to make sure systems are properly setup, use the plotting facilities built into the control systems to monitor temperature trends and manage energy usage by monitoring energy profiles. A properly managed and setup control system will pay back dividends,
f. Setup alarms to let you know when things go wrong, that's what they are for.
g. Do not run heating circuits at a higher temperature than needed, conversely do not run chilled/glycol systems at a lower temperature than necessary, it costs money.

### Planned Preventive Maintenance (PPM)

Maintenance is the single most effective action we can make in achieving efficient and sustainable systems. No matter how good a system is upon commissioning it will not remain so without good planned maintenance. It is equally important that we have well trained and experienced technical personal; this is key to achieving and maintaining reliable, efficient and sustainable systems.

***New systems and technologies: Advice***

### Planning and design

a. Explore all opportunities and alternatives when considering a new project.
b. Ask does the new facility need mechanical control methods?
c. Ask is the proposed facility required at all?
d. Having determined the facility is required, carefully consider what systems apply and build in energy efficiency and sustainability.
e. Do not 'value engineer' out every aspect of a project that adds value in terms of energy savings and sustainability. Unfortunately all too often this is the case and a project ends up with the bare bones of a design that will just about meet the specification of the proposed facility, rather than its long term sustainability. We hear much today of life cycle costs (as opposed to short return capital costs), it is to be hoped that we will see an improvement in the support of projects that can demonstrate good life cycle costs, and as a result we should see the emergence of sustainable systems.

### Application of systems and concepts

a. Consider natural as opposed to mechanical ventilation e.g. glasshouse vents.
b. Consider free cooling where cooling is required. In the UK the ambient air temperature is below 15°C for much of the year (allowing also for night time temperatures). There is potentially a considerable saving over running mechanical refrigeration. Free cooling combined with mechanical cooling is an extremely effective and sustainable means of cooling.
c. Consider reverse cycle heat pumps. They can be an efficient and effective way of providing both heating and cooling. Consider air to air/water heat pumps. They are much easier and cheaper to apply, and generally more reliable, than ground source heat pumps. They are efficient in the UK due to our temperate climate. Often there is only a short period (in the morning) when heating is actually required; the heat gain from surroundings (solar, power users, etc) often provides sufficient heat for the remaining period.
d. Consider adiabatic cooling for both space cooling and process cooling. It may be feasible given the application. Wet coolers and condensers have fallen out of favour due to the scares of *Legionella*, however the risks can be properly managed. They are very efficient, their use will increase as energy costs begin to outweigh the costs of not using them.
e. Consider ground source cooling and heating which may be simply via pipes laid horizontally in the ground, or a more complex vertical system, with possibly a cold sink and a heat sink for seasonal thermal storage.
f. Consider thermal storage systems which allow short-or long-term storage of heat or cold when one is surplus or cheaper to produce, load sharing and/or load lopping. Short-term storage may take the form of tanks, with, or without a state-changing medium and above or below ground. This may be combined with long-term i.e. seasonal, ground source thermal storage, however, great care and specialist

knowledge is required when applying 'Ground Source' technologies. The design, geological assessment and the process of obtaining extraction licenses from the Environment Agency can be a long process.

g. Consider heat recovery from the refrigeration compressor of hot gas discharge produced during cooling. This may be via a simple de-superheater which can produce water at 60°C for domestic hot water, or a water cooled condenser recovering close to 100%. Heat recovery from a de-superheater is relatively easy to introduce and can provide all the hot water required for cleaning etc, its non-application is often a missed opportunity.
h. Consider inverter technology where appropriate, particularly on air and water systems where the load fluctuates. This technology is now very advanced with proven reliability.
i. Consider renewable energy. Ask if there an opportunity on your site to use it.

### Compressor technologies

a. Compressor technologies are moving apace to satisfy the demands on the refrigeration industry to meet its environmental obligations.
b. Compressors are increasingly available with inverters already fitted.
c. Ammonia compressors suitable for smaller systems are becoming available.
d. $CO_2$ compressors, from commercial refrigeration sizes and upwards, are increasingly appearing on the market. A number of manufacturers are now producing compressors, condensing units and evaporators suitable for $CO_2$. $CO_2$ systems, both sub-critical and trans-critical, have been installed and are proving to be successful and in most cases are more efficient than HFC systems, resulting in a better TEWI.

### Refrigerants and systems

a. Do not dismiss natural refrigerants, especially $CO_2$ and ammonia.
b. Compressors and components are being developed at an ever increasing pace and viable systems using natural refrigerants will be available.
c. It is important that we have available the personnel to handle these systems.
d. Be wary of systems requiring extensive refrigerant runs and sophisticated technologies to make them work, example the mainstream manufactured VRV and VRF systems, VRV type systems are generally designed for office and hotel type installations and as a consequence are not often suitable for CE applications.
e. On medium to larger systems consider chillers, water or glycol, it is a lot easier to contain the refrigerant in a single point and as a result chillers lend themselves to natural refrigerants. The problems of ammonia, $CO_2$ and hydrocarbons are easily managed when contained in a chiller. It is also easier to maintain the rest of the system without the need of specialist refrigeration skills and minimal disruption to the rest of the system. In the event of a chiller replacement there is no necessity to change the rest of the system, the fan coils and controls; this is not the case with current VRV/VRF systems.

## Conclusion

How we design and integrate systems is of paramount importance if we are to achieve systems that are indeed sustainable in terms of life cycle costs. When choosing refrigerants, we should be aware of the possible consequences for the environment, sustainability and long term energy efficiency. We should consider installation costs, operating costs and energy usage through the system's life and ask if operational and maintenance costs are realistic during the system's life? This is often overlooked when planning a new project. We should not neglect the proper commissioning of new systems. We should ensure existing systems are working efficiently and improve them where possible as saving money on maintenance, repairs and improvements is false economy.

Where do we go from here? We must be proactive and address the issues facing us if we are to remain competitive in the world's research markets. We should be vigilant in developing and operating sustainable Controlled Environments. We should lead by innovating. To innovate is to find better ways of doing things with existing, new and emerging technologies. To innovate is to survive!

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**Glossary of acronyms and abbreviations**

**BMS** Building Management Control System: control systems designed to control building services, such as HVAC systems, lighting controls and CE. They are used also for energy monitoring BEMS (Building Energy Management Control System)

**CFC** Chlorofluorocarbon refrigerant: compounds containing chlorine, fluorine and carbon only i.e. they contain no hydrogen.

**COP** Coefficient of Performance: energy output divided by energy input.

**GWP** Global Warming Potential: gases with potential to cause warming of the atmosphere by the greenhouse effect if released into the atmosphere

**HC** Hydrocarbon refrigerant: naturally occurring refrigerant produced in the UK by BOC Ltd

**HCFC** Hydrochlorofluorocarbon refrigerants: a class of haloalkanes where not all hydrogen has been replaced by chlorine or fluorine.

**HFC** Hydrofluorocarbon refrigerants: contain no chlorine i.e. they are composed entirely of carbon, hydrogen, and fluorine.

**HVAC** Heating Ventilating and Air Conditioning

**ODS** Ozone Depleting Substances: gases containing chlorine i.e. CFCs and HCFCs

**TEWI** Total Equivalent Warming Impact: identifies both the 'direct' effect of greenhouse gas emissions and the 'indirect' effect of carbon dioxide emissions related to energy consumption of a system during its operational life.

**VRF** Variable Refrigerant Flow: proprietary multi-split systems with inverter driven compressors produced by companies such as Mitsubishi, Toshiba, and Hitachi.

**VRV** Variable Refrigerant Volume: similar to VRF except that VRV is a protected abbreviation belonging to Daikin Air Conditioning Ltd.

**APPENDIX**

## Key refrigerant deadline dates and guidance notes

### Deadline dates

9th April 2007

The UK **O**zone **D**epleting **S**ubstances (ODS) Regulations require anyone handling ODSs e.g. R22 and drop-ins, to have a specified qualification in Refrigerant Handling (C&G 2078 or CITB equivalent)

4th July 2007

Under new UK legislation to support the F gas regulation, "interim" qualification arrangements will apply for anyone involved in the recovery of HFC refrigerant to be certified as competent.

Also from this date:

- Operators will be legally obliged to prevent HFC leakage, to repair leaks as soon as possible and to keep full service records.
- Systems within the scope of the regulation are subject to regular inspection.
- Systems with a charge of over 300 kg need leak detectors, and operators must maintain records on type and quantity of refrigerant used including additions and recovery.
- Products placed on the market containing HFCs will have to have to be appropriately labelled.
- Non-refillable containers will be banned.

The European Commission will also establish the European minimum requirements for training and certification of personnel involved in installation, maintenance, servicing, containment, and recovery activities and lay down the standard leak checking requirements. The UK has until 4th July 2008 to introduce legislation to support this.

### 4th July 2008

Under the F gas regulation: It will be offence to handle HFCs for installation, maintenance or servicing unless personnel are suitably qualified.

### 4th July 2009

Only companies with certified personal can purchase HFCs.

### 1st January 2010

The use of Virgin HCFCs will be banned; after this date only recycled refrigerant may be used.. This means that the production, in Europe, of Virgin R22 will cease and only recycled R22 will be available.

### 1st January 2015

The use of all HCFC refrigerants, including recycled refrigerant, will be banned: after 1st January 2015 it will illegal to replace and/or recharge HCFC refrigerant into a system, whether reclaimed or not. It will not be illegal to continue to operate the system, however this is a dangerous strategy and effective and realistic plans must be put in place to either convert existing plant or replace the plant operating with HCFCs.

## *Notes:*

1. Although this is a brief summary of the current (October 2007) important dates, it is essential that the situation is monitored for any changes.

2. CFCs (R12 etc)
   a. For some time now have been banned in their use, it is illegal to charge, or recharge reclaimed CFCs into a system.
   b. It is not illegal to recover CFC for proper disposal (recovery must be done by a qualified person), but the refrigerant must not be recharged into a system.
   c. It is still legal to operate a system on operating on CFCs as long as the system containing the refrigerant does not leak or does not require opening to carry out repairs, the moment the system develops a leak or requires the system opening the CFC refrigerant must be recovered for proper disposal. This may, or may not, condemn the system, if the system is still mechanically sound it may be possible to adapt the system to accept an HFC gas charge, however its unlikely this will be economical to do.

3. HCFCs include the R22 refrigerants, and some of the drop-in 'cocktails' contain proportions of HCFC,. HCFCs contain a small fraction of CFC refrigerant hence they still have Ozone Depletion Potential.

4. It is absolutely essential to understand that there are two issues at play and that the two are not confused:

   a. For HCFCs: The ***Ozone Depleting Substances Regulations:*** The HCFC phase out from the 1st Jan 2010 and complete banning by the 1st January 2015 means you should be putting in place measures to replace plant containing HCFCs (R22) now. Be assured that after 2010 R22 will become increasingly scarce, drop-ins may, or may not; be viable depending upon the type and condition of plant, but the drop-ins in turn will become obsolete.

   b. For HFCs: The ***F Gas regulations*** will have an impact on our plant and we need to be putting refrigerant usage monitoring records in place now and also maintain good records of the work done on refrigeration systems. The use of qualified personal is essential, whether your own staff or external contractors. This applies to all new systems/plant that are charged with the common HFCs. 404a, 407c, 410a, 134a and others not specified here.

   What both have in common is the requirement to be vigilant in our use of refrigerant, to control and prevent refrigerant leaks, and to maintain good records.

5. *Regular leakage checking:* Equipment containing 3 kg or more of F gas refrigerant must be checked for leakage by certified personnel on a regular basis. "Checked for leakage" means that the equipment or system is examined for leakage using direct or indirect measuring methods, focusing on those parts of the equipment or system most likely to leak. The frequency of testing depends on refrigerant charge and system type (Table 3).

**Table 3**. Leakage checking frequencies (DEFRA EC Regulation 842/2006 on certain fluorinated greenhouse gases. Guidance for Stationary Refrigeration Air-Conditioning and Heat Pump Users.)

| Frequency* | Normal systems | Hermetically sealed systems |
|---|---|---|
| None | < 3 kg | < 6 kg |
| Annual | 3 kg to 30 kg | 6 kg to 30 kg |
| 6-monthly** | 30 kg to 300 kg | 30 kg to 300 kg |
| Quarterly** | > 300 kg | > 300 kg |

**Notes:**
* Refrigeration plants must be rechecked within one month after a leak has been repaired to ensure that the repair has been effective
** Half this frequency if fitted with automatic leak detection.

6. *Who is responsible?* We all are end-users and contractors alike. There is guidance and assistance to help you to comply with the regulations. If your organisation does not have refrigeration personnel on the staff ensure that you have a reliable contractor and work with them. All competent companies are fully conversant with the regulations and will assist you. If your organisation employs refrigeration personnel you definitely have a responsibility to comply with the regulations, bearing in mind that they must be competent, trained and at least qualified to C&G 2078 or the CITB equivalent. Record keeping is required: The following examples of documents and links will assist you.

7. *Complying with the F gas regulations:* Information is readily, and freely, available from the links below:

DEFRA The Department for Environment, Food and Rural Affairs has issued a number of Guidance notes, see the following links:
http://www.defra.gov.uk/environment/climatechange/index.htm
http://www.defra.gov.uk/environment/climatechange/uk/fgas/index.htm
http://www.defra.gov.uk/environment/climatechange/internat/fluorinated.htm

ACRIB The Air Conditioning and Refrigeration Industry Board is providing guidance to the Industry and also playing its part in developing policy, and representing the UK's interests in Europe.
http://www.acrib.org.uk/
http://www.acrib.org.uk/MG7P8M60352
http://www.acrib.org.uk/MIMCS366616

IOR The Institute of Refrigeration plays a major role in the UK, Europe and internationally.
http://www.ior.org.uk/

Wikipedia Information on refrigerants
http://en.wikipedia.org/wiki/Chlorofluorocarbon#_note-0