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Headline

The closed greenhouse concept as used in the Netherlands is not currently viable in the UK mainly because of geological problems and unfavourable aspects in the UK energy market. However, some of the component parts of the system could be applied including air treatment units and evaporative cooling.

Background and objectives

High energy costs continue to threaten the viability of greenhouse horticultural production in the UK. Increasing awareness of global warming and the desire to combat environmental pollution by reducing fossil fuel use has already driven the UK Government to introduce a Climate Change Levy (CCL). In addition, some larger horticultural businesses are now subject to carbon 'quotas' under the European Emission Trading Scheme (EUETS). Similar economic and legislative pressure is also affecting growers in other northern European countries.

These factors have forced growers to explore new methods to significantly reduce their dependence on fossil fuel inputs. The Dutch response to this has been to commit significant R&D effort to this end. The publicly stated aim of the Dutch Product Board for Horticulture (PT) is to develop a commercially viable greenhouse system with zero net fossil fuel input by 2020.

The closed greenhouse design developed by Innogrow B.V. is one product of this commitment with the first commercial installation in the Netherlands being at Themato B.V. Many UK growers are aware of this project which has stimulated a large amount of interest worldwide. However, many questions remain over the validity of the results claimed and the ability to adopt the technology in the UK.

Objectives

The objectives of this project were to:

- Provide guidance to the protected cropping sector on the suitability of recent closed greenhouse technology developments for application in the UK.
- Determine the current and future economic viability of closed greenhouse technology in the UK.
- Identify if any of the component parts of closed greenhouse systems could be used to enhance the performance of current best practice methods.

- Make recommendations with regard to any future work which might be required to enable closed greenhouse technologies to be successfully used in the UK.

These objectives were met by gathering and assessing information from a variety of sources including scientific publications/papers, the horticultural press and a study tour of closed greenhouse facilities in the Netherlands.

Results

Overview of the closed greenhouse concept

Innogrow B.V. installed a 'closed greenhouse' on a commercial nursery (Themato B.V.) in the Netherlands in the latter part of 2003. In the summer the greenhouse is cooled using chilled water. The warm water returning from the greenhouse is stored in an aquifer and used for heating during the winter. Heating costs and CO_2 emissions are therefore reduced. A second important benefit is that, without the need for venting in the summer, CO_2 concentrations can be maintained at much higher levels than those currently considered to be practical with a conventional greenhouse. This can lead to significant increases in yield. Cooling also gives better control of summer temperatures which can give improved crop management.

The other benefits claimed are:

- Reduced pest incidence as a result of the lack of open ventilators.
- Reduced disease incidence because of improved air movement and a more uniform greenhouse environment.

When operating to provide cooling, cold water (approx. 6°C) is drawn from a borehole. This is supplied to air treatment units (ATU's) located in the greenhouse which comprise water to air heat exchangers and a fan. The fan draws air through the heat exchangers and blows it into the greenhouse. Plastic ducts tend to be connected to the ATU outlet to ensure good air distribution (see Figure 1 below).

Figure 1 – A ducted Air Treatment Unit

The cooling water returns from the greenhouse at 20 – 24°C. This water is returned to a second 'warm' borehole where it is stored in the aquifer until it is required to heat the greenhouse. When operating to provide heat, water is pumped from the warm borehole to a heat pump. The heat pump 'upgrades' the heat from the 'warm' water to produce hot water (45 – 55°C) for greenhouse heating. At the same time the heat pump produces cold water (approx. 5°C) which is pumped into the 'cold' borehole where it is stored for use when cooling is required. In this way, the Innogrow closed greenhouse system has the ability to store low grade energy for long periods of time.

Performance of the Themato closed greenhouse

Energy

The headline energy saving widely quoted for the whole Themato nursery when compared with a conventional greenhouse is 36%. However, this relates to gas consumption alone and has been derived by comparing the energy use in 2005 for the closed greenhouse with that used in 2003 when the whole nursery was conventional (open) greenhouse. However, this direct comparison is too simplistic as it is widely acknowledged that 2003 was a colder year than 2005. Also fixed screens were used in 2003 whilst moveable screens were used from 2004 onwards. Taking account of these factors, the reduction in gas use attributable to the closed greenhouse falls to 29%. In addition, increased mains electricity consumption associated with running fans and pumps during the summer did not appear to be accounted for in the energy use figures.

The assessment of the energy saving is complicated by another factor, that being the use of a CHP system on site, and the interaction between it and an open greenhouse (40,000m^2) operating alongside the closed greenhouse (14,000m^2). The CHP produced electricity to power the heat pump together with relatively high grade heat. To maximise the use of 'free' heat in the closed greenhouse and therefore enhance the overall energy saving, heating came from the aquifer/heat pump. The high-grade CHP heat was used in the open greenhouse. If this CHP heat had been used in the closed greenhouse it would have reduced the amount of low grade (free) heat used hence producing lower energy savings. Figures suggest that a nursery comprising 100% closed greenhouses will only give an energy saving of 20%.

Yield

In 2005 the closed greenhouse yielded 17% more crop than the adjacent open greenhouse. The open greenhouse also yielded 6% more than it did in 2003. This was claimed to be the result of reduced CO_2 demand in the closed greenhouse and therefore greater CO_2 availability for the open greenhouse. However, increased use of bought-in CO_2 was acknowledged as an annual cost. Therefore the true reason for the 6% yield increase in the open greenhouse is open to question and is dependent on the CO_2 supply/demand balance for the site.

A yield increase of 20 - 22% has been regularly claimed for the closed greenhouse. This figure originates from trials carried out in 2002 by Applied Plant Research, Naaldwijk. The yield from a 1,400m^2 closed greenhouse was compared to that predicted by plant growth models for a conventional greenhouse. However there has been no practical comparison between two crops grown side by side in the same year. Prior to these trials the same crop model predicted a yield increase in a closed greenhouse of only 10%. The difference between this and the yield actually achieved was thought to be due to increased air movement stimulating transpiration and CO_2 exchange. This has since been dismissed as refinements to the crop model taking into account high light and high CO_2 levels now predict a yield increase of 16%.

Overall the 17% yield increase in the closed greenhouse at Themato compared to an adjacent compartment in 2005 is the most reliable figure available.

Pest and Disease

An 80% reduction in the use of pesticides has been claimed. Although there is potential for a reduction in pesticide use with this technology no data was available to verify this claim.

Financial

Published financial data for the Themato closed greenhouse is shown in Table 1 below.

Table 1 – Published financial evaluation for Themato

Item	**Euros/m^2**
Investment Costs	
CHP & aquifer	75
ATU, heat storage	40
Total investment cost	115
Operating Costs	*Euros/m^2 p.a.*

Energy saving – 200kWh/m² (36% whole nursery)	5.00
Increased yield (9% whole nursery)	3.50
Minus extra annual costs (whole nursery)*	6.50
Net gain	2.00

* Includes 1 euro for energy screens, higher electricity and CO_2 costs, offset by reduced water and crop protection costs.

The total investment in the sealed greenhouse technology was 1.6m euros (115 x 14,000m²). The net annual increase in margin over conventional growing was 108,000 euros (2 x 54,000m²). This gives a payback on investment of 14.9 years. These figures have assumed the somewhat optimistic performance figures discussed earlier. The actual payback is therefore expected to be longer.

An assessment of improvements in the design of more recent semi-closed greenhouses suggests that the payback could reduce to 5 years. The reason for this performance improvement is a 50% reduction in ATU electricity consumption.

Market development

The continued development of closed greenhouse designs demonstrates that the horticultural industry in the Netherlands believes that this concept offers significant benefits. Developments have concentrated on reducing the demand for cooling water as this has been identified as a cause of both high capital and running costs. One result is the concept of the semi-closed greenhouse which allows outside air to be used to aid cooling and dehumidification. This is particularly suited to times when CO_2 enrichment is not important (for example during the night). Outside air is also used in extreme summer daytime conditions when the cooling demand is highest. This avoids the need for the large investment in equipment sized to deliver a cooling capacity that may only be required for 100 hours each year.

To pay back the high investment costs of a closed greenhouse, a significant increase in both crop performance and energy savings is required. The greatest cropping benefit is most likely to come from higher yields in response to higher CO_2 levels. As such, edible crops are the most likely to deliver the increased value required. In contrast, the majority of ornamental crops are unlikely to deliver the improvements necessary for the system to be economically viable. The notable exception to this is for a crop like orchids where cooling at a key stage in production stimulates the development of additional flowering shoots. With orchids the benefit is so great that around 20 growers in the Netherlands have now installed cooling systems. Many of these simply reject the recovered heat to waste.

Excluding installations for orchids, three semi-closed greenhouses have been built using the same basic ATU and ducting design as at Themato. All of these produce tomatoes using supplementary lighting.

Closed greenhouse technology and its application in the UK

Air treatment units (ATU)

A basic ATU contains a fan and at least one heat exchanger. The fan draws air through the heat exchanger where it is heated and/or cooled before being blown into the greenhouse. The air may then either disperse naturally or be distributed using ducting. Ducting ensures greater control over air distribution and therefore uniformity (see Figure 1). ATU technology is simple and well proven in a wide range of commercial and industrial applications and there are no technical barriers prohibiting its use in UK greenhouses.

Non-ducted systems tend to be mounted in the roof space. Potential problems with this approach include excessive shading and poor air distribution. Ducted systems allow the ATU's to be installed around the perimeter of the greenhouse where they are more accessible. Although the ducting can be installed above the crop this is not common due to the shading effect. Installation underneath benches or hanging gutters is preferable. All of this is easily accommodated in UK greenhouses. However, additional investment may be required in hanging gutters or raised benches if they are not already in use.

Although not used at Themato, more recent semi-closed greenhouse designs use the ATU to introduce outside air into the greenhouse and to provide low cost cooling and dehumidification.

Heat pumps

A heat pump uses refrigeration technology in combination with a low grade heat sink/source to produce heating and/or cooling. The heat sink/source used at Themato is an aquifer. The technology is essentially the same as that used in a conventional refrigerator where ambient air is used as the heat sink. Heat pump technology is well proven and there is no technical reason why it cannot be used in the UK.

Heat pumps typically produce water at 50 - 55°C whereas conventional piped heating systems require water up to 90°C in extreme conditions to maintain glasshouse temperatures. ATU's are currently the only method of successfully utilising the lower temperature water from heat pumps.

Depending on the heat source/sink, a heat pump produces between 3.0 and 5.0kWh of useful heat for every 1kWh of electricity consumed. Therefore, depending on the relative price of electricity compared to other heating fuels, heat pumps may deliver a useful reduction in heating cost and fossil fuel energy use.

The heat pump at Themato was powered by electricity from a CHP unit. The cost of this electricity was essentially based on its alternative destination, that being for the wholesale market rather than the retail cost of mains electricity which is much more expensive. Unlike the UK, the energy market in the Netherlands enables growers to justify investment in CHP not withstanding its synergy with the closed greenhouse. This is an additional financial barrier faced by UK growers.

Long-term energy storage

The Netherlands is recognised as a world leader in the use of aquifer thermal energy storage (ATES) because the geology it requires is prevalent in the country. To be successful, aquifers need to be easily accessible, and relatively immobile, otherwise any heat or cooling put into them would disperse by the time it is required. As a rule the water in the aquifer must move less than 1 meter per year.

In contrast to the Netherlands, the geology of the UK is highly variable and there is little experience with ATES. Information on the suitability of ATES for use in the UK is contradictory. Geothermal International Ltd, a company with extensive ground source heat pump experience who would benefit if ATES was possible in the UK, claims that ATES is not possible for most of the UK. Others claim that it is theoretically possible but that it has yet to be proven. However, even if it is possible, the cost is likely to be much higher than in the Netherlands. ATES is therefore not currently considered to be a viable long-term energy storage solution for the UK. This is a significant limiting factor for the application of the closed greenhouse concept as ATES delivers cold water for cooling during the summer without the high costs associated with running a heat pump. Nevertheless, research into the application of ATES for wider commercial applications in the UK continues. It may therefore present some opportunities in the future.

Alternatives such as phase-change materials and lakes/reservoirs have been considered but have proved to be impractical/not cost effective.

Ground source heat pump technology (GSHP) may prove to be a potential solution to the difficulties of ATES. It employs fundamentally similar technology, the difference is that the heat recovered from a greenhouse is not stored in the ground or an aquifer but dissipated. The major disadvantage compared to ATES is that GSHP will not provide cooling water at <10°C without running the heat pump. It is possible to install a GSHP just about anywhere in the UK. However, they are much more expensive than ATES. Where an aquifer is available (does not have to be static) costs may be similar to ATES. As a guide, if it is possible for a nursery to have a borehole for irrigation water it may be possible to use the same aquifer for GSHP. It should also be noted that water quality is not important so a saline aquifer can be used for GSHP. A GSHP combined with CHP has the potential to reduce fossil fuel energy use for heating by 50%.

Cooling

With long-term energy storage and conventional refrigeration systems seemingly not currently cost effective in the UK, alternative cooling methods might be considered.

Absorption chillers are a potentially useful technology which uses a heat source to deliver cooling. Two designs are available, either direct fired gas or hot water (90°C) fed. Their performance is relatively poor and they require an input of around 1.7kWh of heat for every 1kWh of cooling produced. Absorption chillers are only likely to be viable where a suitable source of waste heat is available. This may be a problem because the heat required to power them is of high quality and might not be available as a 'waste stream'.

Cooling using the latent heat of evaporation of water might provide a cost effective partial solution. The Aircokas semi-closed greenhouse design uses misting and flooded pad evaporative cooling techniques are being considered in other closed greenhouse designs. The amount of cooling that can be delivered depends on the potential moisture carrying ability of the air so if humidities are already high this may be limited. However, generally the maximum cooling capacity (100-150W/m^2) tends to coincide with the peak cooling demand. Although this will not provide sufficient cooling on its own for a fully closed greenhouse (500W/m^2) it could make a useful contribution.

Potential in the UK

Two technologies have been identified as technically feasible and not so expensive to be discounted on cost grounds alone. These are:

1. Air treatment units.
2. Evaporative cooling.

Although these technologies cannot deliver all of the benefits associated with the closed greenhouse, they are considered to offer sufficient potential to warrant further investigation. The benefits they offer are applicable to both edible and ornamental crop production.

When installed in an open greenhouse an ATU with a ducted air distribution system offers the following potential benefits:

- Improved crop uniformity and reduced disease levels through better air movement and a more uniform temperature and humidity profile within the crop canopy.
- Energy savings through improved heating system efficiency and a reduction in energy use for humidity control.
- The ability to use a wider range of waste heat sources.
- Greater reliability, ease of use and reduced cost of misting systems.

Evaporative cooling systems offer the following potential benefits:

- Improved temperature control and the associated better control over plant development and scheduling and quality according to market requirements.
- Reduced temperature peaks delivering a potentially positive benefit for crop quality, e.g. the quality problems in tomato associated with high temperatures.
- Reduced plant stress in high temperature/low RH conditions.
- Increased CO_2 levels are theoretically possible but in practice might be too small to be significant.

The cost of these systems is far from certain but estimates are:

- Up to £5/m^2 for a network of roof mounted high pressure misting nozzles.
- Less than £5/m^2 for a simple ducted air re-circulation system.
- £10 - £15/m^2 for a ducted heating, recirculation and outside air mixing system.

Conclusions

Analysis of the data available for the Themato closed greenhouse shows that the claimed performance is optimistic.

- A reduction in gas use of 29%, not 36% as stated in many horticultural publications, seems realistic. It should be noted that increased mains electricity use does not appear to have been accounted for in any of the energy saving figures.
- The yield increase at Themato was 17% in 2005. Where CO_2 availability is limited the yield increase could be much closer to the widely quoted figure of 20 - 22% which originates from crop models.
- Although a reduction in pest and disease incidence can be expected there was no data to support the 80% reduction in crop protection requirements claimed.
- At current performance and costs the payback on investment at Themato is in the order of 15 years.

Closed greenhouse developments

- The closed greenhouse concept continues to be developed in the Netherlands. This demonstrates a continued belief that it offers significant benefits in the long-term.
- An assessment of alternative designs suggests that the payback may reduce to 5 years if the claimed improvements are proven in practice.

Application of the closed greenhouse in the UK

- The closed greenhouse is not currently economically viable in the UK. This is principally due to the lack of an economically viable energy storage solution.
- The greatest opportunities are for edible crops where the biggest increase in crop value is likely.
- Ornamentals growers are unlikely to achieve the necessary increase in crop value required to justify the investment. The exception is for orchid growers.
- Aquifer thermal energy storage (ATES), a key component of the closed greenhouse, is not currently possible in the UK. However, there are developments in this area and they should be monitored.
- Ground source heat pumps are a technically proven alternative to ATES for heating and combined with CHP have the potential to reduce fossil fuel energy use for heating by 50%. However, unlike ATES they do not provide ‘free’ cooling

Opportunities for UK growers

- Ducted air treatment units have the potential to deliver up to 10% energy saving with improved yield and pest and disease control.
- Evaporative cooling techniques such as misting have the potential to deliver a limited degree of low cost cooling and therefore some of the benefits associated with the closed greenhouse.

Recommendations

- Closed greenhouse developments in the Netherlands should continue to be monitored to ensure that UK growers remain fully informed about their progress.
- The use of ducted air treatment units to provide warm air heating and air mixing in UK greenhouses should be investigated in much greater detail. This should include the specification and accurate costing of 'blueprint' designs with a view to carrying out commercial trials of the most promising technologies.
- Evaporative cooling techniques should be reviewed to determine their potential for application in the UK, bearing in mind developments in both misting and control technology.
- The economics and performance of ground source heat pumps should be explored in greater depth.

Science Section

Introduction and Background

High energy costs continue to threaten the viability of greenhouse horticultural production in the UK. Increasing awareness of global warming and the desire to reduce fossil fuel energy use in all aspects of life has already resulted in the introduction of the Climate Change Levy (CCL). In addition, some larger horticultural businesses are now subject to carbon 'quotas' under the European Emission Trading Scheme (ETS). Similar economic and legislative pressure is also affecting growers in other northern European countries.

These factors have forced growers to search for new techniques to significantly reduce their dependence on fossil fuel inputs. The Dutch response to this has been to commit significant R&D effort to this end. The publicly stated aim of the Dutch Product Board for Horticulture (PT) is to have a commercially viable system with zero net fossil fuel input available by 2020.

The Innogrow (Themato) closed greenhouse

The closed greenhouse (Gesloten Kas) concept was originally developed by the Dutch environmental/engineering consultancy Ecofys B.V. who have since formed Innogrow B.V. to commercialise the idea. The concept utilises the fact that during the summer a greenhouse vents off more heat (solar gain) than it requires in the form of fossil fuel heat during the winter. Therefore if the summer heat can be captured and stored until it is required during the winter significant reductions in fossil fuel use can be achieved.

In the summer cold water (6^{o}C) is drawn from a borehole and passed through water-to-air heat exchangers in the greenhouse. The recovered warm water (around 20^{o}C), is returned to the aquifer via a second 'warm' borehole. When heat is required during the winter a heat pump recovers the heat from the warm aquifer water boosting it to 45 - 55^{o}C. This in turn leads to the production of cold water (6^{o}C) that is stored in the aquifer and used the following summer for cooling. An important benefit of cooling in this way is that the vents do not open in the summer and CO_2 levels can therefore be maintained at higher levels than would normally be possible. A significant yield increase results. A reduction in pest and disease incidence is also claimed due to reduced pest invasion (no venting) and more reliable, accurate and uniform temperature and humidity control.

Following preliminary trials carried out at Applied Plant Research in Naaldwijk a commercial installation was completed at Themato B.V. in the Westland area of the Netherlands. The first closed greenhouse tomato crop was grown at Themato in 2004. This was followed by a second crop in 2005. In 2006 a sweet pepper crop was grown. During the second year of production the facility claimed to have saved 36% on energy inputs and increased yield by 20% compared to conventional production systems.

Why study in more detail?

Economics

There are a number of concerns regarding the validity of the results claimed by the project company. Also the viability of the closed greenhouse for use in the UK is in doubt. With capital cost significantly higher than conventional greenhouse systems the uptake in the Netherlands has been notably minimal.

Energy storage

The energy storage system relies on the availability of suitable ground water aquifers. These are readily accessible in the Netherlands. However, their availability is thought to be restricted in the UK. With this in mind, it may be necessary for businesses to relocate or find alternative energy storage methods if they want to apply the complete closed greenhouse concept. Therefore a further question relates to what other energy storage methods might be suitable for use in the UK.

Can any of the component parts of the system be used individually?

The Innogrow system uses a number of technologies. It might be possible to use one or more of these to enhance current commercial best practice methods in the UK at a much lower investment cost.

Objectives

The objectives of this project were to:

1. Provide guidance to the UK protected cropping sector on the suitability of recent closed greenhouse technology developments.
2. Determine the economic viability of closed greenhouse technology in the UK.
3. Identify if any of the component parts of the closed greenhouse system can be used to enhance the performance of current best practice methods.
4. Make recommendations with regard to any future work which might be required to enable closed greenhouse technology to be developed in the UK.

These objectives were met by gathering and assessing information from a variety of sources including:

- Scientific publications/papers.
- The horticultural press.
- A study tour to the Netherlands to visit closed greenhouse facilities, growers and installers/manufacturers.

Technology Assessment

Current developments / market overview

Prior to the Innogrow (Themato) design the only commercial greenhouses with any form of mechanical cooling in Northern Europe were almost exclusively used for growing orchids. These are dominated by refrigeration based cooling systems. There is estimated to be around 20 orchid growers in the Netherlands using mechanical cooling systems. Many of these reject the heat to waste, with only a small number using short-term heat storage to gain some benefit from the 'free' heat produced. With the increase in crop value being so great investment in cooling equipment can be justified without the need for even greater investment in aquifers etc. to maximise energy saving. However, with rising energy costs one orchid grower has recently added aquifer thermal energy storage to his installation.

The closed greenhouse is regarded by many as the specific combination of technologies that were installed at Themato by Innogrow. To date, the technical success of the Themato installation has not stimulated widespread adoption of this 'blueprint' design by the greenhouse industry in the Netherlands. This suggests that the benefits may not be large enough to justify the high investment required. Although, admittedly widespread adoption of such a significantly different and high cost system might be considered unlikely to occur within 2 years of the first commercial trials. The Themato project has however stimulated a number of alternative approaches that have focussed on reducing the cost of the system whilst keeping as much of the benefit as possible. The main focus of the alternative designs has been to reduce the capital and running cost associated with providing cooling. Two approaches have been used to achieve this:

1. Low cost, non heat recovery cooling such as shading, roof sprinklers and misting.
2. Allowing ventilation with outside air, accepting that CO_2 levels will be compromised.

It is claimed that adopting such an approach allows the chilled water cooling capacity to be reduced by 30% and that practically the CO_2 levels only fall below the optimum (approx. 1,000ppm) for 100 hours p.a. Therefore the impact on yield is considered to be small. These are commonly referred to as semi-closed greenhouses.

At the time of the study tour, excluding orchids, there were four closed and semi-closed greenhouses in commercial use in the Netherlands:

1. **Themato** – 14,000m^2, fully closed, first crop in 2004.
2. **Van der Lans** – 15,000m^2 with supplementary lighting, semi-closed, first crop in early 2006.

3. **FA & AW Tas** – 6,500m^2 with supplementary lighting, semi-closed, first crop starting in late 2006.
4. **Prominent** – 34,000m^2 with supplementary lighting, semi-closed, first crop starting in late 2006.

All three of the installations carried out after Themato allow outside air to be used for cooling. Various combinations of shading, roof sprinklers and misting have also been installed to reduce cooling demand.

In all cases the crop grown has been tomatoes. Even with current high energy prices it is clear that there has to be a significant crop benefit in addition to the energy saving to justify the investment required. It is therefore understandable why, to date, only growers of orchids and 'CO_2 hungry' edible crops have adopted this approach. It has been suggested that the total financial benefits of the closed greenhouse can be split into 2/3 energy saving and 1/3 yield increase. As the area of orchids grown in the UK is minimal, it would seem the greatest potential for the closed greenhouse in the UK is in high energy use edible crop production e.g. tomatoes, cucumbers and peppers.

New concepts

Following the study tour additional information about a number of alternative closed greenhouse designs that are worthy of comment became available. These are:

- Energy producing greenhouse.
- Greenhouse without gas.
- Aircokas.

Energy producing greenhouse

The overall concept of the energy producing greenhouse is similar to Themato. However, there are two main differences:

1. The intention is to sell surplus heat to other industries.
2. Fiwihex heat exchangers are used.

It is possible to recover more heat from a greenhouse during the summer than is required to heat it during the winter. There is therefore the potential to sell the surplus heat to other neighbouring businesses.

Fiwihex is an abbreviation of fine wire heat exchanger. They have a much greater heat exchange surface than conventional tube and fin heat exchangers and claim to be able to operate with a water-air temperature differential as low as 1°C. In specific circumstances this removes the need for a heat pump with consequent reductions in capital and running costs. However, the structure of the heat exchange surface could lead to problems with fouling/blockage and cleaning may be difficult (see Figure 2 below).

Additional information can be found at www.fiwihex.nl/ and www.fiwihex-international.com/. These are likely to be updated as further work is carried out on the technology.

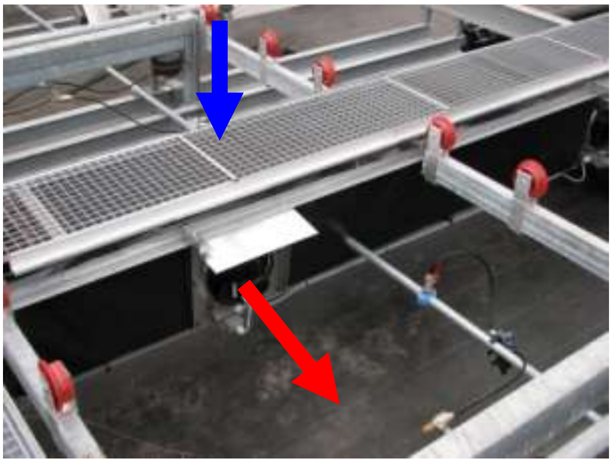
Figure 2 – Fiwihex heat exchange surface

Greenhouse without gas

This is being developed by Fans Van Zaal (www.vanzaal.com). The most novel part of this design is that the heat pump, unlike all the projects listed in section 3.1, is powered by mains electricity. The size of the heat pump, in combination with short-term energy storage is such that is operates mainly during cheap rate electricity tariff periods.

This system also uses heat exchangers built into a walk-way between benches with fans that blow the air underneath benches without the need for additional plastic ducts (Figure 3 below).

Figure 3 – Heat exchangers built intowalk-way (greenhouse without gas)



Aircokas

The Aircokas is being developed by Hoogendoorn Automation. This uses relatively low cost, low technology equipment as the first stage of a semi-closed greenhouse. Notable differences include:

- Cooling using a network of high pressure nozzles to deliver evaporative cooling.
- Roof mounted vertical de-stratification fans to aid air movement.

Engineering of the Dutch system

This section of the report describes:

- The technologies used in existing closed/semi-closed greenhouses.
- Their suitability for application in the UK.
- Alternative approaches that can deliver a similar effect.

Air treatment units

For the purposes of this report an air treatment unit (ATU) comprises a fan in combination with a range of other components to deliver one or more of the following effects:

- Air movement/distribution.
- Heating/cooling.
- Humidification/dehumidification.
- Air mixing – principally greenhouse air with outside air.

Air movement/distribution

The air exiting an ATU either blows straight into the greenhouse airspace or is distributed using ducting. In non-ducted systems the air exiting the ATU is allowed to disperse in the airspace without any further influence or control. An example of a non-ducted system is shown in Figure 4 below. The photograph was taken at the Van der Lans nursery visited as part of the study tour. Although this ATU was only used for cooling they can be used for heating and/or cooling if required.

Figure 4 – A non-ducted ATU

A well designed ducted system will give much greater uniformity of air distribution than a non-ducted system and therefore much more uniform greenhouse conditions. An example of a ducted ATU in a greenhouse is shown in Figure 5 below. The photograph on the left shows the fan and heat exchanger housing. The photograph on the right shows the ducting suspended beneath a hanging gutter in a tomato crop. The photographs were taken at the Van der Lans nursery visited as part of the study tour. A similar type of ducted air ATU was also used at Themato and FA & AW Tas.

Figure 5 – A ducted ATU

The air flow rate that an ATU installation is required to deliver varies depending on the heating and cooling demand and the temperature of the heating or cooling water. However, air flow rates were typically 60 – 90m^3/hour per m^2 of glasshouse area. This effectively 'turns over' the greenhouse air 12 – 18 times every hour. Air change rates at this level also ensure fast response to changing external conditions. At the Themato closed greenhouse this required fan power of 22W/m^2. More recent installations claim to have reduced this to 12W/m^2 through improved design. However, even at the lower level (120kW/Ha) it still represents a significant running cost.

Air mixing

At Themato the ATU fans continued to operate even when there was no demand for heating, cooling or dehumidification. This was to maintain uniform conditions and stimulate transpiration through improved air movement at the air - leaf interface.

It is also possible to supply an ATU with variable ratios of greenhouse air and outside air. This can provide cooling and dehumidification without using water from the aquifer. This approach was used at Van der Lans and Tas but not at Themato. The disadvantage of drawing in colder outside air is that warm greenhouse air is expelled. This in turn reduces the CO_2 level in the greenhouse. It would also reduce the amount of heat available in the aquifer for heating in the winter.

Use of outside air in ATU's can significantly reduce the peak cooling requirement that may only occur for a few hours per year. This reduces the capital requirement for boreholes and associated cold water supply hardware. The running cost of pumps is also reduced. These cost savings have to be weighed against the effect on yield due to lower $C0_2$ levels in extreme conditions. As previously mentioned few fully closed greenhouses have been built since the one at Themato. Many of the recent projects have used outside air to aid cooling and dehumidification. It was expected that CO_2 levels would only be below 1,000ppm for around 100 hours per year. Therefore the potential yield penalty was considered to be small.

Heating and cooling

Heating and cooling was provided by water-to-air heat exchangers built into the ATU. The heat exchangers are essentially the same basic design as a car radiator. Their capacity was such that the peak heating demand could be satisfied with a water temperature of 55°C.

Figure 6 below shows a heat exchanger matrix just above the fan motor in an ATU at FA & AW Tas.

Figure 6 – Heat exchanger

Although not used at Themato, some of the more recent semi-closed greenhouse installations have used a variety of methods to supplement the heating and cooling duty of the ATU. At Sion Orchids the original piped hot water heating system continued to be used when heat demand was high. They also used triple wall plastic cladding and shade screens to limit heating and cooling requirement. At the Van der Lans nursery roof sprinklers were installed, the energy screen was used to provide shading and in addition the ATU could draw in cooler ambient air. Although not installed when the nursery was visited, Innogrow were considering the use of fogging within the ATU to deliver additional cooling at FA & AW Tas. Thermal screens were used in all the greenhouses to reduce winter heat demand.

Humidification / dehumidification

In the fully closed greenhouse at Themato the plants provided sufficient humidification through transpiration to avoid excessively low relative humidity during the summer. Therefore only dehumidification was required. This was achieved by cooling the warm, high water content air entering the ATU to below its dew point. This causes water to condense on the heat exchanger and this is collected for reuse as irrigation water. The cool, lower water content but high RH air is then re-heated by a second heat exchanger to the required temperature which has the effect of reducing air RH before it re-enters the greenhouse.

It was also possible to use outside air for dehumidification at the Tas and Van der Lans installations when conditions were appropriate. Where ambient air is used for cooling or where plant transpiration is low the greenhouse RH can fall below ideal conditions during the summer months and benefit from humidification. This is most easily delivered by installing fogging or wet pads on the air inlets. This has the added benefit of providing evaporative cooling.

Heat/cool generation

The Themato installation had a number of heat sources. Their integration/operation in heating and cooling mode is shown in Figures 7 and 8 overleaf.

Figure 8 shows a simplified schematic of the greenhouse in cooling mode. Cold water is drawn from the aquifer at around 6°C. After passing through the heat exchanger this delivers water at 7°C to the ATU in the greenhouse. The specification of the ATU's meant that this is cold enough to cool the greenhouse without additional cooling by the heat pump. The warm water returning from the ATU is 22 - 25°C. After passing through the heat exchanger water at 23°C is fed into the warm aquifer, once again without using the heat pump.

Figure 7 shows a simplified schematic of the greenhouse in heating mode. Warm water is drawn from the aquifer at 20 - 23°C and after passing through the heat exchanger is supplied to the heat pump at 18 - 20°C. The heat pump extracts heat from the water to produce water at 55°C. This is pumped to the ATU to heat the greenhouse. The cool by-product water at 5°C is pumped into the cold aquifer (via the heat exchanger) where it is stored to provide cooling during the summer.

Figure 7 – Heating mode

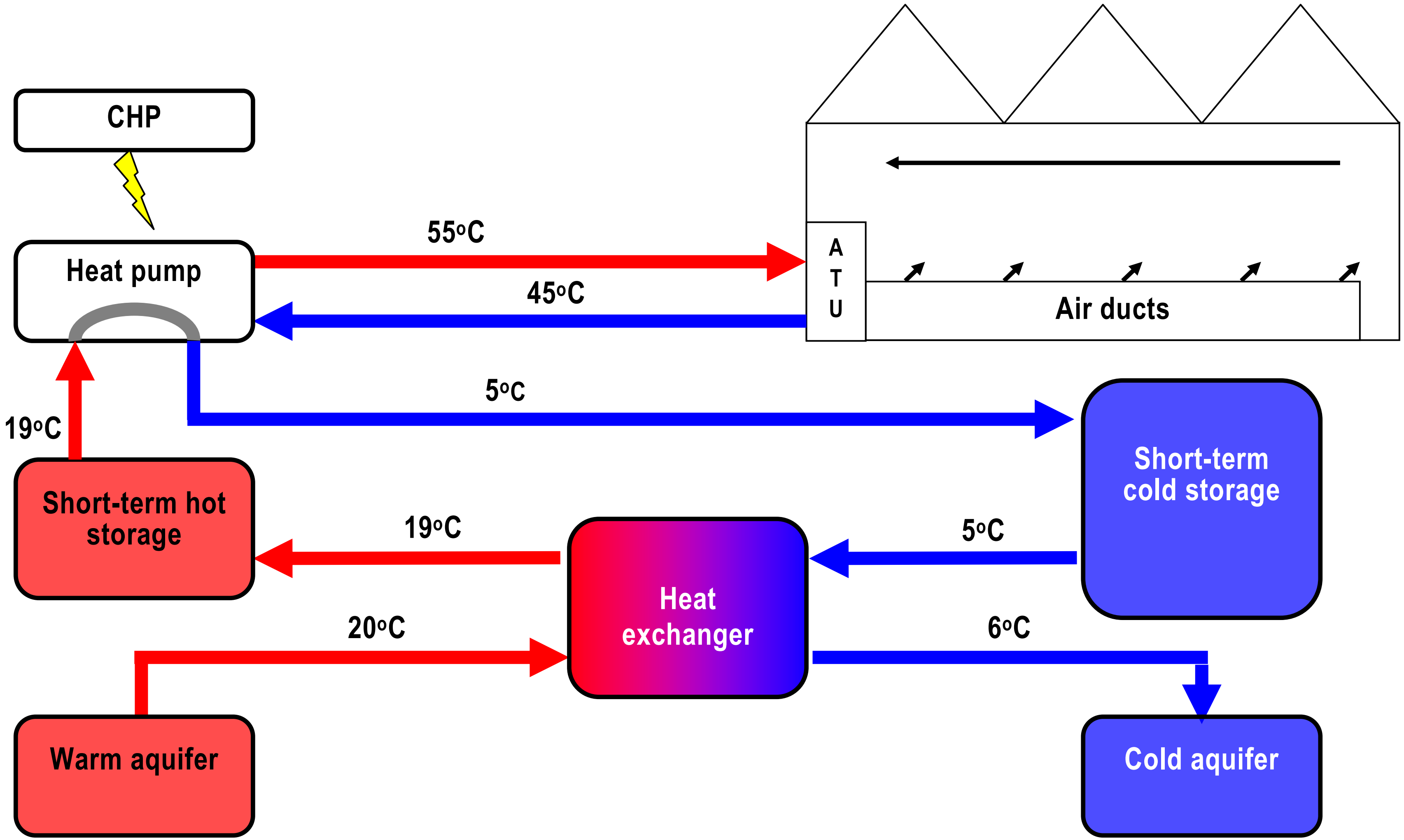
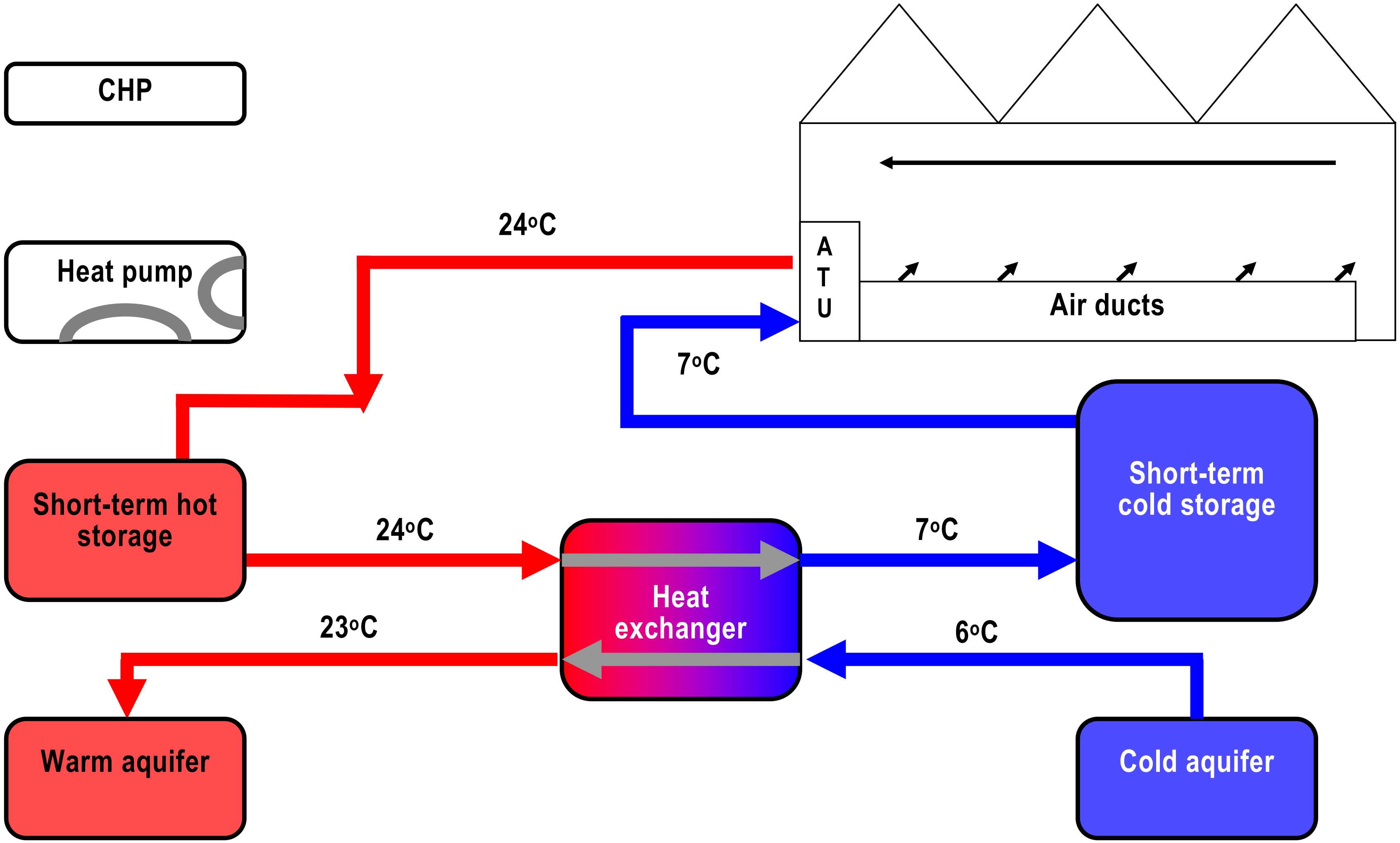


Figure 8 – Cooling mode



Gas fired boiler

This was a remnant from the existing open greenhouse installation and was used to provide additional heat when the capacity of the other systems was insufficient. It was also retained to provide backup in the event of any breakdowns.

Combined heat and power unit (CHP)

This was used to generate electricity to power the heat pump and fans. The relatively high temperature water produced by the CHP was used to heat the conventional (open) greenhouse.

Heat pumps

All the heat pumps were based on refrigeration technology. When in heating mode, these take low grade heat - in this case water from the warm aquifer (19°C) - and extract energy from this water, cooling it to about 5°C. This energy is 'upgraded' in temperature (55°C) and transferred as a hot water feed to the ATU's. The cold water from the heat pumps is stored in a second aquifer for use when cooling is required. The performance of a heat pump is highly dependent on the temperature of the water entering and leaving it. At these temperatures a heat pump can be expected to produce between 3.0 and 5.0kWh of heat for every 1kWh of electricity used to power it. This ratio of heat transferred to electricity consumed is called the coefficient of performance (COP).

In cooling mode water is drawn from the 5°C aquifer and supplied directly to the ATU's to cool the air. The warm water returning from the ATU (20°C) is stored and used to supply the heat pump when heat is required.

Evaporative cooling

The process of converting water from liquid to vapour requires a lot of energy. Therefore where water is vaporised into warm dry air its RH will rise and its temperature will fall. There were no evaporative cooling systems seen in use in any of the closed greenhouses visited during the study. The Aircokas (Hoogendoorn), which was being promoted at the 2006 Hortifair, used misting for cooling. During the meeting with Priva, an ATU with pad and fan cooling installed on a greenhouse in Arizona was described. Innogrow were also considering installing misting nozzles within the ATU / ducting at FA & AW Tas.

The key to delivering a worthwhile level of cooling with this method is the availability of dry air which can be humidified and therefore cooled. In a fully closed greenhouse the RH tends to be high when cooling is required.

Therefore evaporative cooling will only deliver a worthwhile effect where outside air is introduced using an air mixing system.

Heat / cool energy storage

Heat/cool energy storage is required over two timescales:

1. Short-term – 24 hours.
2. Long-term – several months to 1 year.

Short-term

The starting point for energy storage is recovering heat from a greenhouse during a summer day (producing 20°C water) and using this to provide a heat source for the heat pump when heating is required during the following night. Conventional insulated hot water heat stores can satisfy this need. However, they normally operate over a temperature range of 95°C to 40°C i.e. a temperature difference of 55°C. As a rule, with conventional greenhouses the size of heat store required is 200m^3/Ha. In the case of a closed greenhouse the temperature range is 20°C to 5°C, a temperature difference of only 15°C. Therefore for the same heat storage capacity the volume required is almost 4 times bigger i.e. 800m^3/Ha.

In practice the heat and cool storage capacity required is dictated by balancing:

- The instantaneous heating/cooling demand of the greenhouse.
- The size of the heat pump.
- The rate at which water can be pumped into and out of the aquifer.

The biggest short-term energy storage requirement is for cooling. To give an indication of the size of short-term storage facilities Themato used approx. 1,600m^3/Ha of cool storage. Whereas Van Der Lans, where supplementary cooling methods were employed (roof sprinklers, ambient air), used 1,300m^3/Ha.

With cool water storage and the associated pipes and pumps, care must be taken to avoid condensation forming and causing corrosion. This means that Rockwool™ type insulating products that do not adhere to the surface of the tank are not suitable. One solution seen was a type of insulated quilt encapsulated in a waterproof cover that was placed inside the tank wall rather than on the outside. Pumps and pipes were insulated with sealed cell rubber insulation with a grease-like coating between the insulation and the pipe. In addition all the joints were glued to ensure a complete seal. An example of this pipe insulation is shown in Figure 9 below.

Figure 9 – Cold pipe insulation

An alternative short-term storage solution was seen at the Van Der Lans nursery where flexible 'bags' were placed in the bottom of irrigation water reservoirs.

Long-term storage

Storing large quantities of relatively low grade heat/cool requires large volumes of water. With an operating temperature range of 5 – 20^{o}C a greenhouse using 500kWh/m^2 p.a. of gas for heating would require 250,000m^3/Ha of water storage. Building conventional above ground water based heat stores for this purpose is clearly not feasible.

In the Netherlands long-term heat/cool storage for closed greenhouses is provided by aquifer thermal energy storage (ATES) where the aquifer provides the large volume of water required. A minimum of two boreholes are required, one 'warm' and one 'cool'. The number of pairs of boreholes required depends on the rate that water can be pumped into/out of them and the heating/cooling demand. Three pairs of boreholes were required at Themato.

The water extracted from/pumped into the aquifer is passed through a heat exchanger to transfer heat/cool to the greenhouse loop. The reason for this is that the aquifer water is salty in the Netherlands and it would corrode any greenhouse pipes. It also ensures that no pollutants from the greenhouse loop enter the aquifer.

There are two key requirements for ATES to be successful. Most importantly the water in the aquifer must be virtually static. Otherwise the heat/cool put into it will dissipate during the storage period. The second requirement is for a sufficiently high extraction/absorption capacity per borehole otherwise a large number of boreholes will have to be drilled and the cost would be prohibitive.

Guidelines used for commercial scale ATES installations in the Netherlands are that each borehole should have:

- An extraction/absorption rate of >60m^3/hour.
- The speed of water movement in the aquifer should be a maximum of 1m p.a.
- The warm and cold boreholes should be a minimum of 300m apart to ensure that the water does not mix.

Specific environmental requirements set by the Dutch government are:

- In any 12 month period the amount of heat put into the aquifer should be equal to the amount taken out.
- The maximum water temperature that can be put into the aquifer is 25°C.

Due to the cost of drilling a borehole the most economic solution has been to integrate ATES with short-term above ground heat/cool storage. Short-term storage provides fast response to brief high heating/cooling demands and it is almost continuously 'charged' at a slower rate from the aquifers. This avoids the cost of a large number of boreholes to satisfy peak cooling demand which occurs for less than 100 hours p.a.

Engineering – application in the UK

Air treatment units (ATU)

An ATU with heat exchanger allows the use of low grade heat. This is a key requirement for the closed greenhouse concept. Issues relating to the ease of installation and use of an ATU within the greenhouse are no different for the UK than they are in the Netherlands.

The majority of ducted air systems are installed below crop level to:

- Reduce the shading effect of the installation.
- Work with the natural buoyancy of the air.

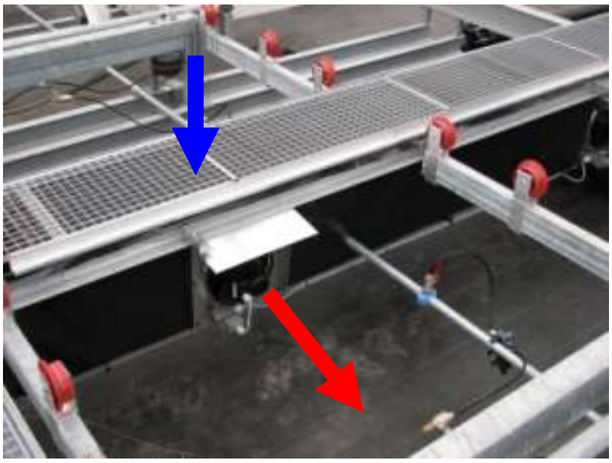
- Allow the air coming from them to mix prior to rising through the crop.

It is possible to install ducts above the crop but, because these fail to meet the above criteria, this configuration is not ideal. Therefore, if low level ducting is to be used for edible crops (tomato, cucumber, pepper), hanging gutters are required with a ground clearance of around 0.8m. Although increasing in popularity hanging gutters are not in widespread use in the UK therefore additional investment may be required.

Similar issues apply to ornamental crops. Crops grown on benches are therefore better placed to adopt ducted air systems than those grown on the floor. Ducted air systems can deliver heating and cooling where benches with solid floors are used but to benefit from improved airflow within the crop canopy, perforated benches are required.

An alternative approach uses the void beneath the benches as an air distribution system alleviating the need for plastic tubes. As shown in Figure 10, the access path is boxed in. Heat exchangers are positioned just underneath the mesh surface walkway and the fans blow air out underneath the benches at right angles to the walkway.

Figure 10 – An alternative to ducting with benches



Air mixing

To allow greenhouse and outside air to be mixed within an ATU, ready access to outside air is required. For ease of construction the ideal situation is to have ground level air inlets as shown in Figure 11 below. However, heat, CO_2 and irrigation pipes tend to be placed here in a conventional greenhouse. Such pipes can be relocated, or the air inlet can be placed in a different position. However, additional costs will clearly be incurred.

Figure 11 – Ground level air inlets at Van Der Lans

Dehumidification

The ability to provide dehumidification as used in the Netherlands is dependent on:

- The installation of an ATU with heating and cooling heat exchangers.
- An adequate source of heat and cooling. This is discussed in the following sections of the report.

Heat / cool generation

Heat pumps are based on well proven technology and used in a wide range of applications in many industries. Their application and economic viability in the UK depends on ready access to a low grade heat source (for heating) or heat dump (if they are used for cooling).

Closed greenhouses in the Netherlands tend not to use the heat pump to produce cold water for immediate use. The temperature of cold water produced as a by-product of heating in winter and stored in the aquifer is low enough to use in the summer without reducing it further through the heat pump. Where such a source of cold water is not available a heat pump can be used to produce cold water to use immediately for greenhouse cooling. However, there are electrical running cost implications associated with this option.

Heat / cool storage

Short-term heat storage in above ground tanks is already used in the UK. The provision of short-term cool storage could use similar facilities given the potential for condensation is dealt with appropriately. There is therefore no technical reason why short-term heat/cool storage cannot be applied in the UK. However lower differential temperatures between flow and return temperatures compared with conventional heat storage would require much greater volumes of short-term storage. The volume required would vary significantly depending on other system parameters but the following are guideline figures:

- Short-term heat storage – 800m^3/Ha.
- Short-term cool storage – 1,600m^3/Ha.

Technically, the biggest question relating to the application of the closed greenhouse in the UK is the ability to provide long-term heat/cool storage. The only known commercial ATES installation in the UK supplies heating and cooling for an office block in London. Consequently, guidelines for the application of ATES in the UK are vague at best. Unlike the Netherlands, the hydro-geological map of the UK shows highly variable conditions. This means that specific recommendations are difficult to make. Communication with Dr Rae MacKay (Professor of

Hydrogeology, University of Birmingham) suggests that, as long as appropriate measures are taken in the design of the borehole, any UK aquifer could be used for ATES. However, Geothermal International, an installer of ground source heat pumps claims that ATES is not possible in most areas of the UK. It is worth noting that maps of aquifers in the UK focus on water that can be used for drinking, irrigation etc. In East Yorkshire many greenhouses are located along the boundary of the river Humber and the aquifers beneath them can be saline. Although saline aquifers are of no use in the traditional sense, they have the potential to be used for ATES if they are static.

As well as technical aspects of using ATES in the UK, environmental issues also need to be considered. In general, extracting heat from an aquifer and returning cold water into it is not considered to be problematic but putting heat into an aquifer is. The impact of ATES on any given aquifer in the UK is dependent on the characteristics of the aquifer itself and the heating/cooling demand. It is therefore unique to each installation.

ATES is similar in concept to ground source heat pumps (GSHP). Increased interest in GSHP as a partially renewable heating system has prompted the Environment Agency to develop policy guidelines. These are currently in the draft consultation stage but are broadly similar to those applied in the Netherlands.

- The net heat flow to/from an aquifer should be zero across a year.
- Appropriate measures should be taken to avoid the pollution of the aquifer with foreign substances i.e. chemicals.
- Various environmental impact assessments must be carried out.

Engineering – alternative approaches

From a technical perspective, there appears to be no insurmountable issue that restricts the use of ATU's in a UK greenhouse. Their ability to allow the use of lower grade heat has significant positive benefits on the performance and cost of the heat/cool supply and storage requirements. An alternative to an ATU with heat exchangers would be to install more heating pipes. However, the amount of pipe and consequent cost and practical constraints tend to rule it out.

For the remainder of this section of the report it has therefore been assumed that ATU's would be the preferred heat/cool transfer device.

The technical/engineering aspects of the closed greenhouse, as applied in the Netherlands, which appear to be potentially problematic if transferred to the UK are:

- The availability of a cost effective source of low grade heating/cooling.
- The ability to store heat/cool for long periods of time.

These are financially and technically connected. If the means of providing cooling was low cost and the cost of long-term energy storage was very high, the best financial solution might be to reject all the recovered heat to waste. The financial benefits would then be exclusively related to improved crop performance. In contrast, if the value of the heat was very high, the cost of long-term storage could possibly be justified.

Cooling

The provision of a cost effective source of cooling is as much of an issue in the Netherlands as it is in the UK. Therefore the use of lower cost cooling systems such as shading, roof sprinklers and misting should be maximised. This will reduce the additional cooling capacity required and therefore the cost.

The delivery of cooling to large areas such as greenhouses tends to rule out the use of air to refrigerant heat exchangers. The provision of cold water therefore forms the basis for this section. The water temperature required is dependent on many factors including the desired greenhouse temperature, ATU design and whether other forms of cooling are used e.g. natural ventilation or misting and shading. However, 5 - 7°C is a typical temperature range. There is no natural source of water at this temperature in the UK. It is therefore likely that, if long term energy storage is not possible, additional cooling will be required. There are currently 2 options:

1. Direct refrigeration.
2. Absorption cooling.

Direct refrigeration

Electrically powered refrigeration based water cooling with all the waste heat rejected to the atmosphere would satisfy the need for cooling and require no long-term heat/cool storage. However, the high running costs and no benefit from reduced heating costs mean this would only be economically viable in exceptional cases such as with orchids. Short-term (24 hour) reject heat storage could be used to provide heating overnight but the saving would be significantly less than that recorded at Themato. Energy savings of 15% have been suggested for such a system applied to orchid nurseries.

Absorption cooler

The most common type of absorption cooler uses a lithium bromide solution in combination with a source of heat. This can deliver water at a temperature of 5°C.

The heat source needs to be either water at a minimum temperature of 90°C or direct fired gas heating can be used. Reject heat is produced in the form of water at approximately 35°C. An absorption cooler requires 1.7kWh of input energy to produce 1kWh of cooling and 2.7kWh of reject heat.

Absorption chillers are not in widespread use. They only tend to be used where heat at the required temperature is available as a waste product. As the temperature of the heat required (90°C) is relatively high this would not generally be available as a 'waste' stream in horticulture.

The exception might be with CHP installations where heat is destroyed or where boilers are operated just to produce CO_2 and the heat is also destroyed. In the latter case the absorption chiller would operate more efficiently if it was heated directly by the gas.

Long-term energy storage

There are a number of slightly different techniques which use the ground as a heat/cool source/sink. Fundamentally there is little difference between them and ATES. However, ATES has a number of benefits compared to these alternative approaches:

- Energy storage – heat or cool can be placed in the aquifer and recovered up to a year later.
- High storage capacities – the relatively easy movement of water within the aquifer means that a single borehole can provide a large storage capacity.

Ground source heat pumps

Ground source heat pumps (GSHP) are increasing in popularity in the UK, especially for domestic heating and cooling. They rely on the fact that at a depth of more than 2m from the surface, the temperature of the earth is almost constantly 10°C irrespective of the time of year. They are not designed to store heat or cool but to dissipate it to the surrounding earth and deliver water to the heat pump at a constant 10°C irrespective of the time of year.

A GSHP can be used with boreholes using the ground water as the heat sink/source. Heat/cooling dissipation is more effective and, where possible, is preferable for larger installations as the capital cost can be significantly less.

The benefit of GSHP compared to ATES is that it is possible to install one almost anywhere. However, they have the following drawbacks compared to ATES:

- No energy storage – water at 10°C is unlikely to provide sufficient cooling without using the heat pump to chill the water during the summer.
- Reduced heat transfer rates – the size of installation required for a commercial greenhouse means that boreholes are likely to be the best option. However, where heat transfer relies on conduction rather than water flow into an aquifer more boreholes are required compared to ATES. The capital cost will therefore be higher.

Surface water

In essence ATES provides access to an underground lake that is heated/cooled to provide long-term energy storage. A possible alternative is an above ground lake/reservoir. Calculations carried out in section 3.2.2 show that a 1Ha greenhouse would require a 250,000m^3 (55million gallon) lake. Existing irrigation reservoirs are unlikely to be suitable as they are emptied over the summer when they would be required for cooling and to be charged with heat for winter use.

Rivers are a possible heat sink and are already used by some UK power stations for cooling. However, the water temperature varies with the time of year and it is likely that a heat pump would be needed at all times to produce the required water temperature for heating and cooling. The COP of the heat pump would be less than with GSHP and therefore significantly less than with ATES.

Phase change materials (PCM)

A significant amount of research is being carried out on energy storage systems. One branch of this technology relates to energy stored in substances that change 'phase' while being heated/ cooled i.e. gas – liquid – solid and vice-versa. Liquid to solid phase change materials are most common. These are available in many forms, most common are wax pellets encapsulated in a plastic shell. These could theoretically be added to a hot water store to increase its energy storage capacity. PCM's have an energy storage density of around 100kWh/m^3. The theoretical combined PCM and water heat storage capacity at 99°C would be 180kWh/m^3. Putting this into perspective, to store sufficient heat in a PCM/water mix to satisfy the needs of a typical 1Ha greenhouse for 1 year would require 27,777m^3 of highly insulated water storage. Even if technically possible this appears to be impractical.

Energy performance

Themato

It is possible to recover more heat from a closed greenhouse during the summer months than is required to keep it warm during the winter leading to a potential heat surplus. At Themato there was also additional high quality 'waste' heat available from the CHP, the electricity from which was used to power the heat pump. Converting the whole of the nursery into a closed greenhouse would therefore have produced a significant heat surplus. Therefore, to optimise the whole site energy use only 14,000m^2 of the 54,000m^2 (26%) of greenhouse was closed. The high quality heat from the CHP was used to heat the open greenhouse area.

Energy data for the whole Themato nursery is shown in Table 2 below. Due to commissioning, fine tuning etc., the energy data for 2004 is misleading. Therefore the most reliable comparison is between 2003 and 2005. This formed the basis for the 36% energy saving widely quoted in the horticultural press.

Table 2 – Themato, annual energy consumption

	Total gas use kWh/m^2	% saving compared to 2003	Notes
2003	546	n.a.	Benchmark year, whole nursery as open greenhouse. Fixed screens used.
2004	494	10%	Closed greenhouse operational but not optimised. Moveable thermal screens installed.
2005	348	36%	Closed greenhouse fully operational.

Two important points do not appear to have been accounted for in the energy saving claimed:

1. Replacement of fixed (temporary) thermal screens (2003) with moveable (permanent) thermal screens (2004).
2. 2003 is widely acknowledged as a good year for yield but was also colder than average especially early in the year.

There is no doubt that the installation of moveable thermal screens delivered energy savings independently of the closed greenhouse. It is estimated that this could have been 30 - 50kWh/m^2. Analysis of the effect of the colder weather in 2003 compared to 2005 using UK degree-day heating data shows that a 3% (16kWh/m^2) reduction in energy use might have been expected. Adjusting the 2003 energy data to account for these effects changes the benchmark energy figure from 546kWh/m^2 to 490kWh and the final energy saving figure to 142kWh/m^2 (29%).

Innogro have produced a ready-reckoner promotional tool. This claims energy savings of 27.5% where the ratio of open closed greenhouse is 3:1

(similar to Themato). This is similar to the above assessment and seems to acknowledge the over-optimism of the data presented in the horticultural press. The same promotional tool suggests that, operated on its own, a closed greenhouse will deliver an energy saving of 20% compared to an open greenhouse.

Theoretical energy performance

The following section examines the theoretical energy performance of a CHP, heat pump and ATES heating system. Assumptions are as follows:

- CHP efficiency – 40% electricity, 50% heat and 90% total thermal efficiency.
- Heat pump – COP of 4.0.
- Traditional boiler efficiency – 85%.

1kWh of gas supplied to a CHP produces 0.4kWh of electricity and 0.5kWh of heat. If the 0.4kWh of electricity is used to power the heat pump 1.6kWh of heat is produced. This gives a total of 2.1kWh of heat for every 1kWh of gas supplied. This compares to 0.85kWh of heat for every 1kWh of gas supplied to a boiler i.e. 147% more. A less optimistic COP of 3.0 gives 1.7kWh of heat, still 100% more than a boiler. These figures would imply that the actual saving of 29% appears low.

The explanation for this difference lies in the amount of electricity used to pump water in and out of the aquifer and for the fans in the ATU's. The peak cooling demand at Themato is around 500W/m^2; this requires a water flow rate of 700m^3/hr. The peak heating demand is less than 200W/m^2. The amount of cooling required therefore dictates the airflow rates (fan power) and water flow rate (pump power). This explains why the closed greenhouse projects that have followed the Themato project have focussed on reducing the peak cooling demand. As an example of the progress that has been made, the most recent semi-closed greenhouse built for Prominent claims an installed fan power of 12W/m^2 compared to 23W/m^2 at Themato. This represents an installed electrical load of 120kW/Ha compared to 230kW/Ha.

Plant physiology / yield

This section summarises a report written by Dr Steve Adams. A complete copy of Dr Adams' report is given in Appendix 2. Contributions from Derek Hargeaves have also been included.

Yield data was not available from many of the closed greenhouse sites due to the fact that the systems have not been operational for long. Also as commercial entities this information has not been released into the public domain. Therefore, this study has concentrated on the response of tomatoes in a prototype facility at Naaldwijk and Themato.

Tomatoes

Initial trials at Naaldwijk

A crop model was used to predict the yield of cv. Aromata in both open and closed greenhouses. The yield results were 46.2kg/m^2 and 51.2kg/m^2 respectively; an increase of 11%.

In 2002 trials with a 1,400m^2 closed greenhouse produced a yield of 56.2kg/m^2 in a 1,400m^2 closed greenhouse; an increase of 22% compared to 46.2kg/m^2 predicted by the model. Unfortunately, the experiment did not include a conventionally grown crop of the same cultivar so no direct comparison was possible. This is the origin of the widely published yield increase of 22%. This indirect method of estimating the yield increase is not ideal, and therefore this figure should be regarded with some caution.

The difference between the yield actually achieved and that predicted by the crop model was initially thought to be due to limitations in the crop model. In particular, the potential for improved air movement to enhance water and CO_2 exchange at the air – leaf interface. However, it now appears that the model's predictions under high light and CO_2 concentrations were inaccurate and that the yield increase was almost entirely a result of elevated CO_2 concentrations.

The Themato project

2004

A crop of tomato cv. Celine was grown in 14,000m^2 of closed greenhouse and 40,000m^2 of open greenhouse. By the end of the year the crop in the closed house yielded an extra 10%. This increase was lower than expected and was attributed to smaller leaves, lower greenhouse temperatures, plant balance and the fact that they were still learning how to grow a crop under such different conditions.

2005

The same crop was grown as in 2004. The yield increase recorded was claimed to be 16 or 17% depending on the source of the information. This was still somewhat below the 22% claimed by the work carried out at Naaldwijk. However, it is also worth noting that the yields in the open greenhouse in 2005 were 6% higher compared with the base year of 2003. This was claimed to be due to greater availability of CO_2 thanks to reduced losses from the closed section. Assuming that this was the case implies a yield increase in the closed greenhouse of 22 - 23%.

General physiological effects

A consequence of air distribution tubes blowing out cold air below the hanging gutters, is that the temperature at the base of the plant is often cooler (up to 5°C) than that at the head. This can delay fruit ripening. At Themato they raised night temperatures to compensate for this effect, which also hastened fruit setting and increased fruit weight.

The ability to cool in summer had an impact on the pattern of yield. There were weeks in June when the open glasshouse had very high yields due to periods of high temperature. In the closed greenhouse, where there was better control of the temperature, the fruits stayed on the vine resulting in a more stable pattern of yield.

Better control of humidity means that very low day-time RH's can be avoided. As a consequence transpiration was reduced and plants required slightly less water during the day. However, active dehumidification and higher night temperatures meant that more water was required at night. This would have had an impact on calcium transport and may explain why less blossom-end rot occurred. The changes in water relations may also explain the increase in fruit cracking which was noted as a significant problem at the Van Der Lans installation in its first year of operation.

Other crops

While species will vary slightly in their response, it is likely that most (which have a C3 photosynthetic pathway) will show a similar response to elevated CO_2 concentrations as a result of growing in a closed greenhouse. However, increased photosynthesis, and therefore plant weight, will not result in a similar increase in value for all crops. Generally speaking there are likely to be greater benefits with species such as tomato, which are sold by weight. While all of the information to date is on tomatoes, sweet peppers were grown at Themato in 2006. The target there was for a 20% yield increase (36kg/m^2) although at the time of writing this report, no data were available.

With ornamental species, increased photosynthesis as a result of elevated CO_2 is likely to result in a smaller increase in economic returns. However, there may be other benefits in, for example, orchids where increased flowering can be promoted in the summer through the use of chilling. There are quite a few growers in the Netherlands using some form of cooling in the production of *Phalaenopsis* orchids. Reducing the temperature to around 18°C increases the number of flower spikes per plant and therefore the value of the crop. However, the magnitude of this effect is hard to quantify.

Other crops in which there may be an improvement in flowering as a result of (soil) cooling include Lily and Alstroemeria.

Summary

- Yield increases of 20% or 22% are frequently quoted for tomato. However, these appear over optimistic as such a big increase in yield has yet to be achieved in verifiable commercial trials. It would be safer to budget for a 16% increase.
- The yield increases as a result of growing tomato in closed greenhouses are primarily due to increased CO_2 concentrations, rather than increased air movement or better temperature control.
- Other species are likely to show similar response to elevated CO_2 concentrations. However, increased photosynthesis will not result in a similar increase in value for all crops. Generally speaking there are likely to be greater benefits with species, such as tomato, which are sold by weight.
- There may be additional benefits of improved temperature control in summer. For example, improved fruit quality and more predictable yield with tomatoes and an increase in the number of flower spikes per plant with orchids.

Pest and disease

General claims

Various claims have been made regarding significant reductions in pest and disease (P&D) incidence and therefore reduced use of crop protection chemicals. Opdam et al (2005) state an 80% reduction in pesticide usage in projects at Naaldwijk and/or Themato (it is not clear which) and cite the source of the information as de Gelder et al (2005). In fact, this paper doesn't substantiate it, but it does refer to Government targets of 72% and 88% reduction in pesticides by 2010 compared to 1984 - 88 figures, which conveniently fits with the 80% figure. However, there is no data available to verify this. Personal communication with Opdam during the study tour suggested that 80% was a figure claimed by Themato and no supporting data had been provided.

Specific information about the crops visited

During the visit access to growers was extremely limited. As such it was not possible to gauge any real insight into the history of the crops seen in relation to P&D problems and the control measures taken.

Similarly bold but unsubstantiated claims were made as described in section 3.7.1 above.

The observations of significance at the time of the study tour were at the Van Der Lans nursery.

Pests

- Due to inter-planting, the crop consisted of plants of varying age. Mobile pests should have been most easily found on the youngest foliage but none were seen.
- Whiteflies were found on yellow sticky traps but not on the plants. Some action (biological or chemical) must have been taken against this pest. No evidence of Encarsia release cards or tubs were seen. At the time of the visit, there was too little leaf on the plants to allow Encarsia to complete their development.
- Some caterpillar damage to leaves was seen but no specimens were found on the plants.

Disease

- The crop was free from disease – the only fungal growth seen was saprophytic species colonising the dead stems in the bundles and on the considerable amount of crop debris on the floor.
- Stem Botrytis was searched for but not found.
- PepMV was evident in the crop.

It is worth bearing in mind that Dutch growers prefer to apply pesticides through the irrigation so all types of P&D can be controlled without leaving a deposit on the crop. Sulphur burners were also installed.

1.1.1 Potential benefits

In the absence of verifiable data to substantiate the claims made, the following are expected to be the likely effects of the closed greenhouse with regards to P&D.

Improved uniformity of temperature & humidity

This should reduce the incidence of P&D incubator areas or "hot spots", making it easier to manage the causal organisms. For example, biological control agents may be released more evenly and there should be less need to intervene locally with crop protection chemicals. The use of energy to reduce humidity and thereby suppress the development of pathogens should also be more effective.

It has been suggested that ATU's could increase disease levels by aiding the distribution of spores. However, whether such an effect will occur in practice is unknown.

Improved control of temperature

Red spider mites thrive in the tops of vine crops such as tomatoes during hot summer days. Whereas their predators remain lower down the plant allowing the spider mite population to increase. A reduction in peak daytime temperatures at the head of the crop will allow the predators to work more effectively thereby improving control.

Rapid changes in greenhouse temperature combined with marginal humidity conditions can cause condensation events on the crop which in turn aid the development of disease. The fast heating and cooling response delivered by ATU's should help to reduce this.

Improved control of humidity

It is well known that the avoidance of high RH conditions is a key factor in achieving good disease control. There is little doubt that a reduction in disease incidence and/or disease control measures will be achieved. There are no known effects on pest control.

Reduction in plant stress incidents

Plant stress incidents that cause physical damage to the plant itself leave the plant more prone to infection and disease development. The avoidance of excessively high greenhouse temperatures is one area where benefits may be achieved. A second area of potential benefit is the avoidance of 'leaf burn' in high wire crops. Venting when the outside temperature is low is considered to cause this. The introduction of outside air via an ATU will reduce this.

Screening

Invasion by pests is not a serious problem in the UK unless other heavily infested crops are in the immediate vicinity. Hence, very few (if any) crops are screened. However, screening could be beneficial for cucumbers, peppers and ornamentals against thrips, aphids, moths and capsids. There are also benefits from preventing certain biological control species (such as *Orius*) from escaping. Therefore some benefit can be expected from closing a greenhouse but it is expected to be less in the UK than in the Netherlands.

Other effects / benefits

The following subjects were considered to be worthy of comment individually but did not fall within the other subjects already discussed.

CO_2 enrichment

One of the biggest benefits associated with the closed greenhouse is its ability to maintain high CO_2 levels during the summer and therefore produce increased yields. Also, less CO_2 needs to be supplied to maintain required concentrations. Figures quoted suggest that an open greenhouse producing tomatoes in the Netherlands requires 100 - 120kg of CO_2/m^2 p.a. compared to 50kg/m^2 p.a. in a closed greenhouse.

Reduced energy use of the closed greenhouse also reduces the availability of CO_2 from burning gas. It is claimed that at Themato there was a net surplus in CO_2 availability for the open greenhouse which resulted in a yield increase. However, the financial data available for Themato suggests an increased use of piped CO_2 direct from oil refineries in 2005 compared to 2003. These are clearly contradictory.

Growers in the Netherlands benefit from piped CO_2 and pure CO_2 costs are much lower than in the UK. More favourable economics also allow extensive use of CHP which leads to cheaper/greater CO_2 availability. The CO_2 supply/utilisation relationship is complex and is critical in ensuring the claimed yield increase is achieved. CO_2 availability and economics are equally as important as the technical ability to install and operate all the component parts of the closed greenhouse.

Water use

A 50% reduction in water use was also claimed. This is due to:

- Reduced plant transpiration for cooling during the summer months.
- Condensate collected from the dehumidification process.

The water collected can be as much as 25m^3/Ha/day in the summer. It is of a high quality (low salts) and can be easily reused for irrigation.

Greenhouse structures

The Van Der Lans closed greenhouse had small vents at each end of the structure to enable air blown in by the ATU fans to escape. The main body of the greenhouse had no conventional vents. The absence of vents should theoretically result in a stronger greenhouse structure and the consequential possibility of using larger panes of glass and/or smaller glazing bars. Such structural changes would improve light transmission and ultimately result in higher yield. An increase of around 3% was suggested as being possible. This benefit was not realised at Themato because the closed greenhouse was originally open and the vents remained in place.

Figure 12 – Vents at the Van Der Lans nursery

Economic Analysis

Themato

The published financial evaluation of the Themato installation is given in Table 3 below.

Table 3 – Published financial evaluation for Themato

Item	**Euros/m²**
Investment costs	
CHP & aquifer	75
ATU, heat storage	40
Total investment cost	115
Operating costs changes (compared with a conventional greenhouse)	*Euros/m² p.a.*
Energy saving – 200kWh/m² (36% whole nursery)	5.00
Increased yield (9% whole nursery)	3.50
Minus extra annual costs (whole nursery)*	6.50
Net gain	2.00

* Includes 1 euro for energy screens, higher electricity and CO_2 costs, offset by reduced water and crop protection costs.

The tabulated costs imply total investment of 1.6m euros (115 x 14,000m²). The net return was 108,000 euros (2 x 54,000m²) giving a payback on investment of 14.9 years.

The figures above assume a somewhat optimistic energy saving of 36% for the whole nursery. Closer analysis of this in section 3.5.1 showed that a saving of only 29% could be attributed to the closed greenhouse. However, it should be noted that a cost of 1 euro/m² p.a. has been included for the thermal screens, presumably the depreciation cost. The net effect of allowing for this is a small reduction in the payback to 14.7 years.

The recorded increase in yield for the closed greenhouse of 17% was used in the financial analysis and is justifiable given the theoretical prediction of yield increase discussed in section 3.6.1. However, the incidental 6%

yield increase recorded in the open greenhouse, also used in the calculations, is more questionable. Whether this can be achieved in the UK is dependent on the CO_2 supply situation. If not the payback time will be significantly longer.

Although savings were made in water and crop protection costs, these were more than offset by cost increases in electricity and CO_2. Clearly these items have a significant impact on the payback time. An indicated increase in CO_2 cost - presumably due to the use of piped CO_2 - suggests that the reduction in fossil fuel energy did limit CO_2 availability from gas burning. Equivalent costs for bought-in CO_2 would be much higher in the UK.

The financial analysis highlights the widely acknowledged fact that the running cost of ATU fans and summer cooling water pumps are a key factor influencing the financial viability of the closed greenhouse. The cost of running the ATU fans at Themato (23W/m^2) is estimated to be 8 euros/m^2 p.a. Verbakel Bomkas, who are building a closed greenhouse for Prominent, claim to have reduced the installed fan power to 12W/m^2. If substantiated, this would deliver running cost savings of 4 euros/m^2, and increase the net financial gain to 6 euros/m^2. These savings would reduce the payback on the system to 4.9 years. However, this has yet to be proven commercially.

Other costs and potential savings

Air treatment units for heating alone

Costs

- The budget cost to install ATU's including fans, heating and cooling heat exchangers and ducting was quoted to be 20 - 30 euros/m^2.
- A system to provide heating alone was estimated to be 15 - 20 euros/m^2.
- A hybrid heating system using 50°C water in the existing pipe rail heating system with a lower capacity ATU is expected to cost closer to 10 euros/m^2.

With careful control the additional running cost of the fans in the last option is expected to be 2 euros/m^2 p.a. Therefore to deliver a payback on investment in 5 years a total benefit from the system of 4 euros/m^2 p.a. would be required.

Savings / benefits

Although the benefits which might result from ATU for heating alone are commercially unproven an estimated heating energy saving of 10% might be achieved when used with a conventional boiler system.

Half of this would result from the ability to use reduced system operating temperatures (better boiler efficiency), and half would come from improved heating system response speed (obviating the need to run high minimum pipe to give an insurance against disease risk conditions).

Assuming a typical UK tomato heating cost of 15 euros/m^2 p.a. this would give a total potential energy saving of 1.50 euros/m^2 p.a. This leaves an additional 2.50 euros/m^2 p.a. of non-energy related cost saving or yield improvement needed to produce a payback within 5 years.

Although opportunities are site specific, ATU heating allows lower grade heat to be used. This would increase the ability of greenhouse businesses to use waste heat from other industries.

If the ATU allows outside air mixing, low cost cooling in the form of misting could be employed. This would help to reduce peak greenhouse temperatures during the summer. The outcome would be that some of the financial benefits of better temperature control and crop management could be realised. However, the degree of improvement and hence the financial returns will be somewhat less compared with that achieved though the application of the complete closed greenhouse concept.

Air treatment units for air mixing alone

Cost

An air handling system without heat exchangers used to re-circulate greenhouse air to improve the uniformity of temperature and humidity in a greenhouse should cost less than 5 euros/m^2 to install. Running costs are expected to be less than 1 euro/m^2 p.a. A payback within 5 years would require an annual energy/crop performance gain of 2 euros/m^2 p.a.

Savings / benefits

An energy saving of 3 - 5% is considered possible with this option. This is due to improved uniformity of temperature and humidity, the reduction in disease pressure and therefore a reduction in minimum pipe heat requirement. This gives a potential energy saving of 0.50 - 0.75 euro/m^2 p.a. requiring an additional 1.25 euros/m^2 p.a. of non-energy related cost saving or yield improvement to produce a payback within 5 years.

Although potentially less effective even if outside air mixing is not possible, low cost cooling in the form of misting could deliver some CO_2 and crop management benefits.

Aquifer thermal energy storage & ground source heat pumps

ATES represents the cheapest and most practical means of providing long-term energy storage in the Netherlands. It also costs much less than any of the alternatives available in the UK. At the time of writing, ATES, although claimed by some to be theoretically possible, has not been demonstrated in the UK and costs are unknown.

GSHP currently represents the only possible alternative in the UK. Budget costs obtained from Geothermal International Ltd are £900,000 for:

- 1MW heating capacity and 1MW cooling capacity.
- Supply and installation of boreholes, all connecting pipes and heat pump.
- Not included – CHP, connection to or supply of the heating system.

Allowing for some supplementary heat during periods of peak demand this should be able to provide the majority of the heat for 1.5 - 2.0Ha. This would require an investment cost for GSHP alone of £45-£60/m^2 (68-90 euros). It should also be noted that unlike ATES, GSHP requires the heat pump to operate to provide cooling during the summer.

Discussion

Detailed, verifiable independent data describing the closed greenhouse environment, crop yield, pest and disease and energy use continued to be difficult to obtain.

This project has therefore taken what data is available, whether incomplete, anecdotal or unverifiable and assessed its likely value to give a broad overview of the potential of the technology in the UK.

Various 'headline' claims have been made in the horticultural press for the closed greenhouse system. These can be summarised and assessed as follows:

Yield

- *22% yield increase in the closed greenhouse* – this was a theoretical figure derived from early work carried out at Naaldwijk. The actual yield increase in the closed greenhouse at Themato in 2005 was 16% compared to the yield in an adjacent open greenhouse. Analysis by Dr Adams suggests that 22% is overly optimistic and that 16% should be used for any economic analysis.
- *6% increase in the open greenhouse* – this was claimed to be due to increased CO_2 availability as a consequence of reduced use in the closed greenhouse. However, reduced fossil fuel use and therefore CO_2 availability appears to have been compensated for by the use of piped CO_2. This yield increase forms a significant part of the additional income at Themato and may not be possible without incurring significant costs by buying pure CO_2 in the UK.

Pest and disease

- *80% reduction in crop protection* – although there are numerous mechanisms which could lead to a reduction in P&D incidence no data was available to validate the claim.

Energy

- *36% whole site saving at Themato* – this appears to account for gas use only. Increased electricity costs associated with fans and pumps in the summer when the CHP was not operating have been acknowledged as an additional annual cost but have not been included to offset the saving. 2003, the base year used for comparison, had a notably colder winter. Fixed screens were used in 2003 whereas moveable screens were installed in 2004. Both will have resulted in energy savings independent of the closed greenhouse. Taking these issues into account, a true gas saving of

29% appears to be attributable to the closed greenhouse. However, it was not possible to identify the energy use associated with the additional electricity.

Uptake in the Netherlands / market development

The original closed greenhouse design used at Themato has not been replicated on any other nursery in the Netherlands. The financial assessment in section 4.1 might well explain why this is the case as it suggests an un-commercial payback time of almost 15 years. Nevertheless, there is still significant interest in the closed greenhouse concept in the Netherlands and it is being continuously refined and developed to reduce both investment and running costs. If improvements being claimed for some of the more recent installations are realised in practice, the payback could well reduce to a more realistic 5 years. There is also little doubt that the yield achieved at Themato has further room for improvement as growers are still learning how to grow crops in the closed greenhouse environment.

Potential in the UK

Long term energy storage

The unique advantage available to Dutch growers is the potential to use ATES. Even outside commercial horticulture the Netherlands is recognised as a world leader in ATES technology and expertise. In contrast there is only one known ATES installation in the UK in London and whether it is truly ATES is open to question. Preliminary investigations and discussions with hydro-geological experts suggest that it may be theoretically possible to use ATES in the UK wherever aquifers are available. But Geothermal International Ltd, who has significant experience installing GSHP in the UK, claims that ATES is not possible. As a business they would benefit if ATES was possible and as such they have no vested interest in dismissing its technical feasibility. Therefore, with their practical experience and knowledge, their assessment might be considered to be the most realistic indication of the viability of ATES in the UK. Despite this, long-term heat storage (including ATES) is an area attracting considerable interest in the UK. It should not therefore be discounted completely as technological developments may make it viable in the future.

An alternative to ATES that is proven in the UK is GSHP. However, this is considerably more expensive and does not deliver 'free' cooling as ATES does. Therefore although GSHP is technically viable it is unlikely to be economically viable as a direct replacement for ATES in the closed greenhouse. However, GSHP used for heating alone, may have some potential for reduced heating costs, especially where an aquifer can be used as the heat source.

An additional component of the closed greenhouse and a key factor in the economic case for it is the availability of CHP. The economic viability for CHP irrespective of the closed greenhouse is almost taken for granted in the Netherlands. This means that the cost of the electricity to run the heat pumps in the closed greenhouse system is based on the CHP electricity selling price (wholesale prices) rather than the bought-in price (retail price) of mains electricity. As the installation of new CHP is not currently considered to be economically viable in the UK this poses an additional economic barrier to UK growers.

Alternative cooling options

If ATES and the cooling that it delivers are not technically possible or economically viable there are other alternatives such as direct refrigeration which might be considered. However, they may be economically difficult to justify in all but very specialist situations such as orchid growing where the cropping benefit is extremely high.

Absorption chillers have also been considered. They can use 90°C water or be direct fired with gas to produce water at 5°C. However, heat consumption is high in relation to the amount of cooling delivered and, once again, it is unlikely that they will deliver an economically viable solution. There may be opportunities to use absorption chillers where an adequate supply of high grade waste heat is available but these are likely to be rare.

Evaporative cooling techniques such as misting/fogging and pad and fan have the ability to provide limited cooling at relatively low cost. In the UK, the level of cooling delivered cannot be guaranteed as it is dependent on the temperature and humidity of the air being cooled. The limited opportunities to deliver a useful level of cooling for reasonable periods of time and the risks associated with excessive humidification mean that to date evaporative cooling has not been widely used in the UK. However, developments in greenhouse structures, misting and control technology are improving the prospects for evaporative cooling and benefits may now be worthwhile.

Air treatment units (ATU)

There are no technical barriers to the adoption of ATU's in UK greenhouses. Installations in greenhouses with hanging gutters or raised benches would be technically simpler to engineer. They avoid the shading effect of ducts suspended above the crop and unlike overhead installations they give the benefit of improved air movement within the crop canopy. Installed in an open greenhouse ATU's with a ducted air distribution system offer the following potential benefits:

- Improved crop uniformity and reduced disease levels through better air movement and therefore more uniform temperature and humidity within the crop canopy.

- Energy savings through improved heating system efficiency and a reduction in energy use for humidity control.
- Greater reliability and ease of use of misting systems.
- The ability to use lower quality heat sources to heat greenhouses.

The final point is considered to be a key issue and might become more important in the future. Many alternative heat sources such as GSHP provide low quality heat and/or operate most efficiently at lower temperatures. The potential to use waste heat from other industries will also be significantly increased if lower grade heat can be used.

Conclusions

Themato closed greenhouse

- Little detailed data is available in the public domain to fully verify the widely quoted performance of the closed greenhouse at Themato.
- Analysis of the available data shows that the performance claimed is optimistic.
- Energy savings of 29%, not 36% as claimed in many horticultural publications, seem realistically attributable to the closed greenhouse system.
- The yield increase at Themato was 17% in 2005. The widely quoted figure of 20 - 22% originates from crop models and trials carried out at Naaldwijk where there was no direct comparison with a control treatment.
- Although a reduction in pest and disease can be expected there was no data to support the claimed 80% reduction in crop protection requirements.
- Based on current performance and costs the payback on investment at Themato would be 15 years.

Closed greenhouse developments

- Development of alternative closed greenhouse designs continues in the Netherlands. This demonstrates a continued belief that it offers significant benefits in the long-term.
- Payback on investment will fall to 5 years if alternative designs are proven to perform as predicted.

Application of the closed greenhouse in the UK

- Application of the complete closed greenhouse concept is not currently feasible, due principally to the lack of an economically viable energy storage solution.
- A significant increase in crop value would be required to produce the necessary return on investment. Growers of edible crops stand to gain the most if the benefits of higher CO_2 levels can be realised.
- Ornamentals growers are unlikely to achieve a big enough increase in crop value to justify the investment required. The exception is orchid growers.

- Aquifer thermal energy storage (ATES), a key component of the closed greenhouse in the Netherlands, is not currently possible to implement in the UK.
- Ground source heat pumps are a technically proven alternative to ATES but their economic viability is questionable.

Opportunities for UK growers

- The independent use of ducted air treatment units (ATU) has the potential to deliver up to 10% energy saving plus improved yield and benefits in pest and disease control.
- Evaporative cooling techniques such as misting have the potential to deliver some low cost cooling and therefore some of the benefits associated with the closed greenhouse.
- Ground source heat pumps have the potential to reduce heating costs in specific circumstances.

Recommendations

Closed greenhouse

- The performance of new designs should continue to be monitored in the Netherlands. This will allow UK growers to assess the constantly changing economics and to make well informed investment decisions.

Air treatment units

- Their immediate benefits to UK growers need to be proven and should be investigated in much greater detail. Blue print designs should be developed and accurately costed prior to commercial trials.

Evaporative cooling techniques

- Evaporative cooling techniques should be reviewed to determine their potential for application in the UK bearing in mind developments in both misting and control technology.

Appendix 1 – Study tour notes

The study tour to the Netherlands was carried out on the 18 - 19th September 2006. The itinerary included visits to:

- Sion Orchids B.V., De Leir
- Priva B.V., De Leir
- FA & AW Tas, Zevenhuizen
- Cees & Leo van der Lans, Zeeland
- Innogrow B.V., Utrect

Sion Orchids

Overview / production system

As the name suggests this nursery grows orchids (*Phalaenopsis*). The total nursery area was approximately 4Ha.

For optimum production and quality orchids require quite specific growing conditions. A 'warm phase', typically 28°C is required for initial plant development. This is followed by a cool phase, typically 16 - 18°C, to aid flower initiation. Finally more conventional growing temperatures of around 20°C are employed. The cool phase is especially important as an extra spike can increase the value of the end product by as much as 1 euro per plant. The high additional value associated with a reliable cool phase is enough to lead many specialist orchid growers to use simple refrigeration systems and reject the 'waste' heat to the atmosphere.

The need to maximise light transmission with orchids is less important than with most crops. The unusual growing environment meant that the greenhouse facilities at this specialist producer were considerably different to that which would normally be found in a more conventional greenhouse. The main differences, excluding closed greenhouse technologies were:

- Triple wall plastic cladding – to reduce both heat gain (cool phase) and heat loss (warm phase).
- Multiple shade screens – to maximise light receipt whilst avoiding high light levels.
- Supplementary lighting – to ensure continuity of supply and quality during the winter.

A high level of automation, as tends to be common on Dutch nurseries, was also present.

There was no doubt that the increase in crop value delivered by cooling during the flower initiation stage was the key driver behind the adoption of closed greenhouse technologies.

Closed greenhouse technology

Energy storage

Both long-term and short-term heat and cool storage were provided. Short-term storage was provided by above ground insulated water tanks. Long-term heat storage was provided by an aquifer. This was the same approach as that taken at Themato.

Heating / cooling system

Heat and cool generation equipment was the same as that used at Themato. However, the delivery of heat and cooling to the greenhouse was different. The traditional piped heat system continued to utilise high quality heat (>60°C). Lower quality heat and cooling was delivered by a water to air heat exchanger mounted high up in the greenhouse (Figure 13 below).

Figure 13 – Water to air heat exchanger at Sion Orchids

Energy performance

Due to the specialist construction of the greenhouse and no direct comparison reliable and relevant energy data was not available. Unsubstantiated claims were that energy savings in the order of 15% were possible.

Crop performance

As with energy performance no valid comparisons were available. The benefits of cooling in the flower initiation phase are un-doubtable. However, orchid production in the UK is not common and takes place in considerably different greenhouse structures. Double H Nurseries grow some orchids and Neil Stevenson (Managing Director) estimates that the increase in double spike (flower) orchids could we worth £6/m^2 p.a.

Other observations

The greenhouse was not 100% closed i.e. vents were still used when adequate cooling could be achieved using ambient air. CO_2 enrichment was not used because it did not give a benefit with this crop. Therefore CO_2 loss due to venting was not a problem.

Peak cooling demand, which tends to have a major influence on capital cost, was significantly reduced by the extensive use of shade screens.

The position of the water-to-air heat exchangers within the greenhouse appeared to have been constrained by practical considerations. A system delivering warm/cold air underneath the growing benches could have been expected to give better overall performance.

Overall, although interesting, this specific application had little direct relevance to the majority of UK growers.

Priva

Andre De Raadt from Priva gave a comprehensive presentation to the project team describing the work that they have been involved in and their views on the future development of the closed greenhouse concept. Due to their close involvement with the Themato closed greenhouse and many of the more recent closed greenhouse installations, Priva appear to be dominating the control system aspects of the market at the time of writing this report.

The original 100% closed greenhouse as developed by Innogrow and applied at Themato was not considered to be the most cost effective way forward. This is supported by the fact that no 100% closed greenhouses have been built since the Themato project.

A summary of Priva's opinions vision is:

- Within 5 years no more conventional greenhouses would be built.
- The cost of installing and operating a heat pump is difficult to justify.
- The starting point is to use forced air ventilation. Then consider alternative cooling options such as pad and fan or misting.

F A & AW Tas

Overview / production system

The nursery owners were considering redeveloping the whole site. In preparation for this they had commissioned Innogrow to convert an existing 6,500m^2 conventional greenhouse into a semi-closed greenhouse. The conversion was almost complete, supplementary lighting was also included to produce tomatoes all year round. Results achieved during 2007 will be used to decide whether or not they incorporate the semi-closed greenhouse into their development plans.

Energy storage

This was the same as that used at Themato and Sion Orchids.

Heating / cooling system

All heating and cooling was provided by a ducted air distribution system. Dehumidification was rendered possible by cooling (to below dew-point) and then re-heating the air. This was the same as the installation at Themato.

Apart from supplementary lighting the main difference between this installation and the one at Themato was that the air handling units were also able to draw in ambient air. This allowed ambient air to be used for cooling and dehumidification when appropriate. Although this would reduce CO_2 levels when used during the daytime, it was only expected to have a significant effect for 50 – 100 hours p.a. However, the reduction in heat pump/aquifer cooling capacity was expected to be 30% delivering significant capital and running cost savings.

Misting nozzles in the air ducting were also being considered as a means of providing humidification and cooling.

Crop & energy performance

Although close to completion the installation had not been operational at all. Therefore no data was available.

Cees & Leo van der Lans

Overview / production system

The nursery area was built in 2005/2006 and comprised 15,000m^2 of semi-closed greenhouse and 55,000m^2 of conventional (open) greenhouse. As at FA & AW Tas, supplementary lighting was installed in the closed greenhouse section to produce all year round tomatoes.

Energy storage

Similar to the other installations visited, short-term and long-term storage was used. Once again long-term storage used aquifers. However, short-term storage used flexible 'bags' located in the bottom of the irrigation water reservoirs rather than above ground stores.

Heating / cooling system

A ducted air distribution system was used for heating. However, unlike the Tas and Themato installations it only included one heat exchanger. Heating or cooling could be delivered by the single heat exchanger and the switch from one to the other was done manually rather than automatically. As at Tas, ambient air could be drawn in to the greenhouse via the air distribution system.

The primary cooling system was similar to that used at Sion Orchids. Water to air heat exchangers, providing cooling only, were mounted in the roof space.

As this greenhouse was specifically built to be closed, the only vents installed were at the gable end to allow warm greenhouse air to escape when ambient air was being drawn in by the air treatment units. Both these vents and the ambient air intake had insect screening fitted.

A unique feature of this greenhouse was the installation of roof sprinklers to provide cooling and further reduce the peak cooling demand.

A number of other new techniques/materials not directly connected with the 'closed' greenhouse concept were used in the construction of this greenhouse. These were high light transmission etched glass and a thermal screen installation that ran across the rows rather than along them.

Energy performance

No data was available.

Crop performance, pest and disease

Once again, the somewhat unique construction and operation of this greenhouse meant that no reliable comparison could be made with a conventional greenhouse.

Due to inter-planting, the crop consisted of plants of varying age. Mobile pests are normally easily spotted on the youngest foliage but none were seen. Whitefly was found on sticky traps but not on the plants and no evidence of control (biological or chemical) was evident. It was suspected that chemicals were applied using the irrigation system. However, it was not possible to confirm this.

There was very little disease (botrytis) on the stems of the older plants. No chemical deposits were visible on the plants.

Comments received from another group of UK growers who visited the site were that the nursery was generally unhappy with the performance of the crop in the closed greenhouse. Fruit quality and splitting were the major issues.

Other observations

The location of the cooling units in the roof space appeared to be inappropriate. Cold, high RH air was likely to exit them at low speed causing localised chilling in spite of the ducted air distribution system beneath. Similarly hot spots were also likely to develop at the same time. Such conditions are known to cause the types of fruit quality problems encountered.

Innogrow

Aad de Koning & Coen Ruijsbroek from Innogrow organised the visits to both the FA & AW Tas and Van der Lans nurseries. In addition, the project team met Hans Opdam and Peter Quaak at the Innogrow offices. The focus of the discussions was the results from Themato previously quoted in the horticultural press. The outcome of these discussions is given in sections 3.5.1 & 3.6.1 which specifically focus on the Themato closed greenhouse.

Appendix 2 - The closed greenhouse: Impacts on crop physiology

Dr S. Adams, Warwick HRI

Yield data is not available from many of the closed greenhouse sites due to the fact that the systems are only just operational and the commercial nature of these projects. Therefore, this study will concentrate primarily on the response of tomatoes in a prototype facility at Naaldwijk and Themato.

Tomatoes

Trials at Naaldwijk

Initial calculations with a crop model (ECP) predicted that tomato yields could be increased by 14% if the CO_2 concentration could be maintained at 1000ppm in a closed greenhouse (Houter, 1991). However, the model was limited in its accuracy under high light and high CO_2 concentrations and there was limited experimental evidence to back this up. Therefore, an experiment was carried out at Naaldwijk, the Netherlands, in a 1,400 m^2 greenhouse that was cooled with forced air ventilation (no aquifers). A crop of cv. Aromata was planted on 24 January 2002 and cropped until 15 November. The CO_2 concentration was maintained at 1000ppm, the maximum temperature in summer was 26°C and the relative humidity was kept below 90%.

Unfortunately, the experiment at Naaldwijk did not include a conventionally grown crop of the same cultivar. This makes comparison of any yield increase slightly problematic. The researchers involved therefore compared the achieved yields with those predicted using a crop model (TOMSIM) simulated using environmental data from conventional and closed environments (De Gelder *et al*., 2005). The model predicted a yield of 46.2kg/m^2 for a conventionally grown crop and 51.2kg/m^2 for a crop grown in the closed greenhouse. The closed greenhouse actually produced 56.2kg/m^2.

The published yield increase of 22% is derived by comparing the predicted yield from a conventional greenhouse with the achieved yield in the closed greenhouse. This indirect method of estimating the yield increase is not ideal, and therefore this figure should be taken with some caution. Furthermore, rather than question the accuracy of the model they concluded that only half of the extra 10kg/m^2 could be attributed to increased CO_2 concentration and that the other 5kg/m^2 must have been due to another factor, probably air movement reducing boundary layer resistance (de Gelder *et al*., 2005).

Having spoken to Arie de Gelder (PPO), Leo Marcelis (PRI) and Ep Heuvelink (Wageningen University) it would appear to now be agreed that the yield increases seen with the closed greenhouse are almost entirely as a result of elevated CO_2 concentrations; air movement has little direct effect on yield. The model TOMSIM was used for the initial simulations; this uses a summary model of Von Cammaerer for predicting crop photosynthesis. However, the team are now conducting simulations based on INTKAM which has a slightly different leaf photosynthesis model. INTKAM uses the complete biochemical model and this predicts much larger yield increases at elevated CO_2, which are in line with those recorded experimentally (Ep Heuvelink, personal communication).

The Themato project

During 2003-2004 Innogrow designed a 1.4ha closed greenhouse at the site of a commercial tomato grower Themato in Berkel en Rodenrijs, the excess heat from this is used in the 4ha of open glass. This system became operational in March 2004. In the first year a crop of tomato cv. Celine was grown. By the end of June the yields in the closed section were already 5% ahead of the open section mainly due to increase average fruit weight (Visser, 2004). By the end of the year the crop in the closed house yielded an extra 10% (Heller, 2005). This increase was lower than expected and was attributed to smaller leaves, lower greenhouse temperatures, plant balance and the fact that they were still learning.

Tomato plants were again grown in the closed house at Themato in 2005. A 20% yield increase was expected, although according to Visser (2006) the yield increased reached 14% and then stopped, the difference then increased to 17% in October. Whereas Heller (2005) reported that yields in the closed greenhouse were 17% up when compared to the open house in week 36. Information from Ep Heuvelink would suggest that a 16% yield increase was recorded in the closed house at the end of the crop. However, it is also worth noting that the yields in the open greenhouse in 2005 were 6% higher when compared with the base year of 2003. This was due to the fact that more CO_2 was available thanks to reduced losses from the closed section and the fact that additional piped CO_2 was used in 2004 and 2005.

A consequence of air distribution tubes blowing out cold air below the hanging gutters, is that the temperature at the base of the plant is often cooler (up to 5°C) than that at the head. This can delay fruit ripening and so at Themato they raised night temperatures, which also hastened fruit setting and increased fruit weight (Visser, 2004). Furthermore, the ability to cool in summer had an impact on the pattern of yield. There were weeks in June when the open glasshouse had very high yields due to periods of high temperature, whereas in the closed greenhouse, where there was better control of the temperature, the fruits stayed on the vine resulting in a more stable pattern of yield (Visser, 2005).

Better control of humidity means that very low day-time RH's can be avoided. As a consequence transpiration was reduced and plants required slightly less water during the day. However, active dehumidification (and higher night temperatures) meant that more water was required at night (Visser, 2004). This will have an impact on calcium transport and may explain why less blossom-end rot occurred (Boonekamp, 2004). The changes in water relations may also explain the increase in fruit cracking.

Other crops

While species will vary slightly in their response, it is likely that most species (which have a C3 photosynthetic pathway) will show a similar response to elevated CO_2 concentrations as a result of growing in a closed greenhouse. However, increased photosynthesis, and therefore plant weight, will not result in a similar increase in value of all crops. Generally speaking there are likely to be greater benefits with species, such as tomato, which are sold by weight. While all of the information to date is on tomatoes, sweet peppers were grown at Themato in 2006. Their target was a 20% yield increase (36kg/m^2) although at the time of writing this report no data was available. It is likely that strawberries will be grown at Themato in 2007.

With ornamental species increased photosynthesis as a result of elevated CO_2 is likely to result in a smaller increase in economic returns. However, there may be other benefits in, for example, orchids where flowering can be promoted in the summer through the use of chilling. Other crops in which there may be an improvement in flowering as a result of (soil) cooling include Lilly and Alstromeria.

Orchids

Sales of orchid have increased dramatically over recent years and now flowering pot orchids are one of the largest segments of floriculture worldwide. The most popular genera is currently *Phalaenopsis* which comprises of 30% of the market in Japan, 70 - 80% of the market in the US and is the most valuable potted plant grown in the Netherlands with 18 million pots sold at auction in 2003 (Lopez and Runkle, 2005). *Phalaenopsis* contain over 50 species originating from tropical and sub-tropical areas of the South Pacific Islands and Asia.

Phalaenopsis will initiate flowers at higher temperatures when compared with many other genera of orchid. Temperatures of 27 - 30°C will keep plants vegetative and they can tolerate temperatures of 32 - 35°C for short periods. Temperatures of 15 - 25°C are required to initiate a flower spike (Lopez and Runkle, 2005). Kataoka *et al*. (2004) showed that heating (average of 27°C) delayed spiking of *Phalaenopsis* White Dream x *Phalaenopsis* Yukimai Dream by 9 days when compared with the control (average 23°C). There was no difference in the number of spikes per plant or flowers per spike, however, plants were moved to a common glasshouse (kept above 18°C) after just 4 weeks of treatment.

There are quite a few growers in the Netherlands using some form of cooling with orchids (*Phalaenopsis*), reducing the temperature to around 18°C, on the basis that this will increase the number of flower spikes per plant and therefore the value of the crop. However, the magnitude of this effect is hard to quantify.

Conclusions

- Yield increases of 20% or 22% are frequently quoted for tomato. However, this is perhaps slightly over optimistic as such a big increase in yield has yet to be achieved in trials. It would be safer to budget on a 16% increase.
- The yield increases as a result of growing tomato in closed greenhouses are primarily due to increased CO_2 concentrations, rather than increased air movement or better temperature control.
- Other species are likely to show a similar response to elevated CO_2 concentrations. However, increased photosynthesis will not result in a similar increase in value of all crops. Generally speaking there are likely to be greater benefits with species, such as tomato, which are sold by weight.
- There may be additional benefits of improved temperature control in summer, in for example, orchids (*Phalaenopsis*) where temperatures of 15 - 25°C are required to initiate a flower spike, and reducing the temperature to around 18°C can increase the number of flower spikes per plant and therefore the value of the crop.

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