Project Title:	A technical & economic appraisal of technologies & practices to improve the energy efficiency of protected salad crop production in the UK
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Grower Summary

Headline

A number of key technologies have been identified that will allow growers of protected edible crops in the UK to reduce energy costs and assist them in meeting the energy efficiency targets set by the Government.

The most promising technologies identified were:

- Improved humidity control;
- Temperature integration;
- Thermal screens.

By successfully using the most promising technologies, growers will be able to achieve energy savings in the range of 10-15% in the short to medium term. In the longer term, savings of 25% are realistic. All of these savings could be made without adversely affecting crop yield or quality.

Background & Expected Deliverables

Recent increases in the cost of energy together with the introduction of the Climate Change Levy (CCL) have focused the attention of growers towards ways of improving the efficiency of energy inputs and not since the 1970's has the efficient use of energy been such a high priority for growers. For salad crop production in the UK, energy can account for up to 40% of the total costs of production. Any further increase in the cost of energy will therefore pose a serious threat to the future profitability of this sector of horticulture in the UK.

As a pre-condition of securing a temporary 50% reduction in the CCL rates, the UK protected horticultural industry needs to achieve a 15% improvement in energy efficiency over the next 10 years. All businesses in this sector therefore need to act quickly to achieve savings for both commercial and political reasons. Whilst growers have made significant improvements in energy efficiency over the last 15 years, these economic and regulatory pressures are dictating that further advances are secured.

A number of approaches and technologies are available to help reduce energy costs. The key deliverable that is expected from this project is to identify the most promising methods and highlight the economic viability of these techniques.

Summary of Project and Main Conclusions

- A number of key technologies are available that can enable the energy efficiency of protected edible crop production in the UK to be improved. These technologies give rise to reduced energy costs without threatening crop yield and quality;
- By using even the simplest of the techniques it will be possible to meet the Government's energy efficiency target over the next 10 years. Companies prepared to make medium and long-term investments will be able to exceed the 15% target;
- The table below outlines the techniques that are considered to have the best short to medium-term potential;

Technique	Energy saving potential (%)	Typical cost £/m^2	Likely payback period	Comments
Improved Humidity Control	6-8%	Minimal – limited to increased staff costs	3 – 6 months	Requires further training and management / monitoring inputs.
Temperature Integration	15-20%	£1-£2/m^2	1 ½ years	Costs dependent on greenhouse size & existing equipment.
Thermal Screens	18-20%	£3.50 - £4.00/m^2	3 ½ years	Further practical demonstrations needed to confirm that crop losses do not occur when using this technology.

- In the longer term supplementary lighting is potentially one of the most exciting prospects for improving both the current yield of greenhouse edible crops and the energy efficiency of production. Current information is limited however, and because of the large capital commitment required, it is unlikely to become a common technology in the short to medium term. Backed by a programme of research, development & demonstration however, the technology could achieve wide commercial uptake in the future;
- Many of the technologies are inter-related in their impact on energy use. In practice therefore an integrated approach to energy management and the practical application of the techniques needs to be taken.

Financial Benefits

The major benefit of UK edible growers adopting energy saving technologies is a reduction in energy costs and compliance with the Government's CCL energy targets. Savings in the order of 12-15% of energy costs per annum over the next 5 years are anticipated if growers adopt the key technologies highlighted in this report. Based on current energy prices, heating costs for edible crop production are in the order of £5.50 - £6.00/m^2/annum. Consequently, savings of around £0.80/m^2/annum might be achieved through use of the technologies identified.

Action Points for Growers

In response to the findings of this study, growers should carry out the following actions:

- Commission an energy audit of key production facilities to identify areas of potential energy efficiency imporvements;
- Investigate how humidity control strategies can be improved on their nurseries. This may involve additional training of staff and devoting more management time to the monitoring of the greenhouse environmental conditions;
- Investigate how temperature integration can be used on their nursery. In its simplest form this may simply involve the modification of heating and ventilation set-points either by broadening the dead-band between them or by modifying them in relation to light receipt. However, to fully embrace this technology, many nurseries will be required to upgrade or replace their climate control computer systems. The costs associated with these changes should be investigated;
- Closely follow commercial development and demonstration work associated with the use of thermal screens. Once practical demonstrations illustrating the success of this technique have been completed, growers should carry out investigations to establish the cost and practicality of installing the equipment on their nurseries.

Science Section

1 Introduction

1.1 Background

Recent increases in the cost of energy have alarmed many growers and highlighted the need to keep energy costs under control. In addition the Climate Change Levy (CCL), which was introduced in April 2001, has further inflated the cost of energy for growers. Both of these changes are clear indications that, in the future, improving the energy efficiency of crop production is going to be of increasing importance to all businesses in the protected cropping sector.

Although horticulture has been granted a 50% rebate on CCL, it is the intention of the UK Government that this will only initially be available for up to 5 years. To strengthen the case for continuation of this rebate, and to comply with requirements of EU State Aid, a voluntary energy efficiency agreement between the horticultural industry and the Government has been established. This agreement requires a 15% reduction in the specific primary energy consumption to be achieved over the 10-year period beginning in October 2000. Improvements will be assessed in terms of the quantity of primary energy used per unit area of production (i.e. kWh/m^2). This has been chosen as the universal unit of measurement for all the sub-sectors of UK horticulture by the NFU (who are acting as the trade association and representing the UK industry). An alternative measure is the quantity of energy used to produce a given quantity of produce (e.g. kWh/kg). Many producers favour this unit, as they believe it gives a better indication of the effectiveness of energy inputs in production terms.

1.2 Recent Energy Efficiency Improvements

Advances in crop production methods have seen the efficiency of energy use by protected salad crop producers significantly improve over the last 15 years. For example, data from tomato producers in the UK shows that leading growers can now produce a crop of 'classic' round tomatoes yielding up to $60kg/m^2$ by using around 11kWh/kg. This compares to the mid 1980's when a crop of $35kg/m^2$ was considered to be good and energy use was typically 16 kWh/kg. This sector of the industry has therefore demonstrated an efficiency improvement in excess of 30%.

These improvements have been achieved through advances in production techniques including the increased use of CO_2, improved pest & disease control and better varieties. All of these factors have combined to increase yields, thus improving the efficiency of energy use. Examination of energy use per unit of greenhouse area shows that the production systems currently used are more energy intensive than in the past. For example energy consumption in the mid 1980's would have typically been in the order of 500kWh/m^2 whilst current levels of inputs are more typically around 650kWh/m^2. Whilst this strategy has worked well during a period when energy costs were low, the recent energy price increases have led growers to question this approach.

Energy consumption in other areas of protected edible crop production in the UK is very similar to that for tomatoes. For example confidential data obtained for the 10 largest UK cucumber growers (by production area) shows the average energy consumption to be 650kWh/m^2/annum.

In the Netherlands the 'Covenant Cultivation Under Glass and the Environment' (Projectbureau Glastuinbouw en Milieu, 2000) publishes target energy consumption data for each of the major protected horticultural crops. These form the basis of the energy efficiency targets for Dutch growers. The targets for the period 2000 to 2010 are given in the following table:

Crop	**Energy Consumption Target (kWh/m^2)**										
	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Tomato	563	557	550	543	537	530	524	517	511	504	498
Cucumber	492	484	476	468	460	452	444	436	429	421	413
Pepper	453	446	439	432	425	418	410	404	397	390	383

It should be noted that these target figures include an allowance for electricity use as supplied from a grid connection. All electricity inputs of this type are multiplied by a conversion factor of 2.6 to take account of the efficiency of electricity generation at the central power station. Where electricity is delivered from an on-site CHP unit, only the fuel used to power the CHP is included.

The above targets are useful for UK growers in that they show the levels of energy inputs that will be required if the industry is to remain competitive.

1.3 Energy Saving Technologies

Previous research has suggested that using many of the commercially available energy saving techniques were uneconomic because the value of the resulting yield reductions outweighed the energy cost savings that could be achieved. However, in some cases, these assessments were based on data that dates back over 20 years.

Recent changes in the balance of energy costs to crop values together with developments in energy saving technologies may have changed these conclusions. As a result the research results need re-addressing in light of the current economics of protected crop production.

Whilst UK-based research on energy efficiency has resulted in little commercial adoption over the past 20 years, growers in other parts of Europe have been quicker to apply energy-saving techniques commercially. Rising energy costs and increasingly stringent environmental legislation, especially in the Netherlands, have combined to force growers to seek out ways of optimising both crop yield and quality whilst reducing energy consumption. As a result of recent R&D programmes in Europe, a number of new techniques including improved climate controls and supplementary lighting techniques are now being considered on a commercial basis.

Therefore, UK growers now need to appraise these available technologies and consider how new production methods can enable them to become more competitive in the future.

2 Research Method

A literature review and desk study was carried out to critically evaluate both existing technologies and recent commercial developments.

Information sources used included published research, information obtained from research scientists currently carrying out ongoing work and commercially available data. Investigations concentrated on the production of tomato, cucumber and pepper. Where appropriate, consideration was also given to other protected crops including herbs, celery and lettuce.

Technical and economic assessments were carried out to identify the potential for technologies to achieve energy efficiency improvements and reduce the primary energy consumption per unit of crop output (e.g. kWh/kg).

3 Discussion – Assessment of Key Technologies

3.1 Background

A range of energy technologies and cultural practices were examined to determine their likely impact on energy efficiency and appraise the potential for commercial uptake. Of the technologies that have been examined, the following sections focus on the most promising and cost-effective approaches. In addition comments relating to the less promising technologies are included where considered appropriate.

3.2 Optimisation of Inputs

Although there are a number of simple energy-saving techniques that can be employed to improve the efficiency of energy usage in the production of protected salad crops, the main advances are likely to come from a better understanding of the response of crops to their aerial environments. The application of such knowledge should enable new techniques to be developed and allow maximum benefit to be gained from existing ones. Both approaches are required if growers are to optimise yield production per unit of energy derived from a fossil fuel and so retain their rebate on the CCL.

3.2.1 Factors affecting photosynthesis

Most growers of salad crops are well aware that their plants grow by creating new organic compounds through photosynthesis, a process that is highly dependent both upon light and carbon dioxide (CO_2). The characteristics of the photosynthetic response to light and CO_2 concentration have been established by measuring the net photosynthesis of leaf canopies of different crops under a range of different environmental conditions and then using this information to generate mathematical models of the responses. The resulting models simulate the response of the mature crop and are necessary in order to cope with the complexities of the interactions between the effects of light, CO_2, temperature, humidity, and leaf area index. Mathematical models of crop processes enable biological information and responses to be readily incorporated into the activities of environmental control computers. This approach is especially desirable if one objective is to optimise the inputs of either CO_2 or energy.

Because of its central position as a determinant of crop productivity, the response of photosynthesis to environmental factors has been the subject of a huge number of studies. The following account, therefore, is meant only to indicate the sort of studies that have been conducted and is not an exhaustive survey even of the work that has been done on salad crops. With cucumber, measurements of net photosynthesis were made on a mature leaf canopy grown at near ambient concentrations of CO_2 (see Fig 3.1) (Hand, Clark, Hannah, Thornley & Warren Wilson, 1992). The data shows how dependent the process is upon the amount of light incident upon and intercepted by the leaf canopy. The data was then used to create a model of the response of cucumber to light and CO_2 (Thornley, Hand & Warren Wilson, 1992). Similar approaches were used by Nederhoff, Gijzen and Vegter (1988) and Nederhoff (1994), also with cucumber crops but with different models of photosynthesis. Some of the most comprehensive investigations of canopy photosynthesis in tomato were made by Heuvelink and colleagues (Heuvelink, 1996). The latter investigations were incorporated into the TOMSIM model of tomato growth and development that was developed and then validated in independent experiments and on commercially grown crops.

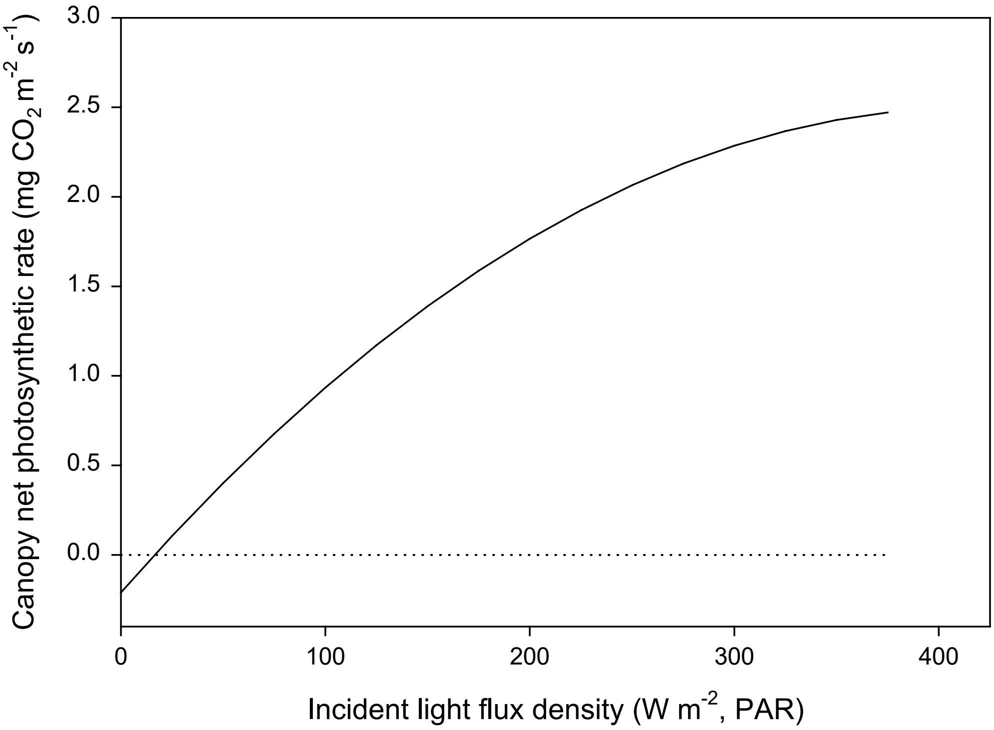

Fig. 3.1 Effect of incident solar radiation on canopy photosynthesis of cucumber (after Hand, Clark, Hannah, Thornley & Warren Wilson, 1992)

Most of the models developed from the above studies have been used to estimate the effects of variables including CO_2 concentration, solar radiation, plant density and row orientation upon crop photosynthesis and ultimately, crop yield.

3.2.2 CO_2 enrichment

Nederhoff & Vegter (1994a,b) used the model produced by Acock (1991) to generate detailed photosynthetic responses to CO_2 for cucumber (Fig. 3.2), sweet pepper, and tomato. As the responses of all three crops approached a similar maximum rate of photosynthesis at about 1000vpm CO_2 and were similar in other respects, Nederhoff (1994) proposed a general 'CO_2 rule' to estimate the relative effect of CO_2 concentration on photosynthesis. This rule indicates that the effectiveness of successive 100vpm increments in CO_2 diminishes as the CO_2 concentration in the glasshouse increases. The benefits of CO_2 enrichment for eggplant (aubergine), were demonstrated by Hand, Warren Wilson & Acock (1993).

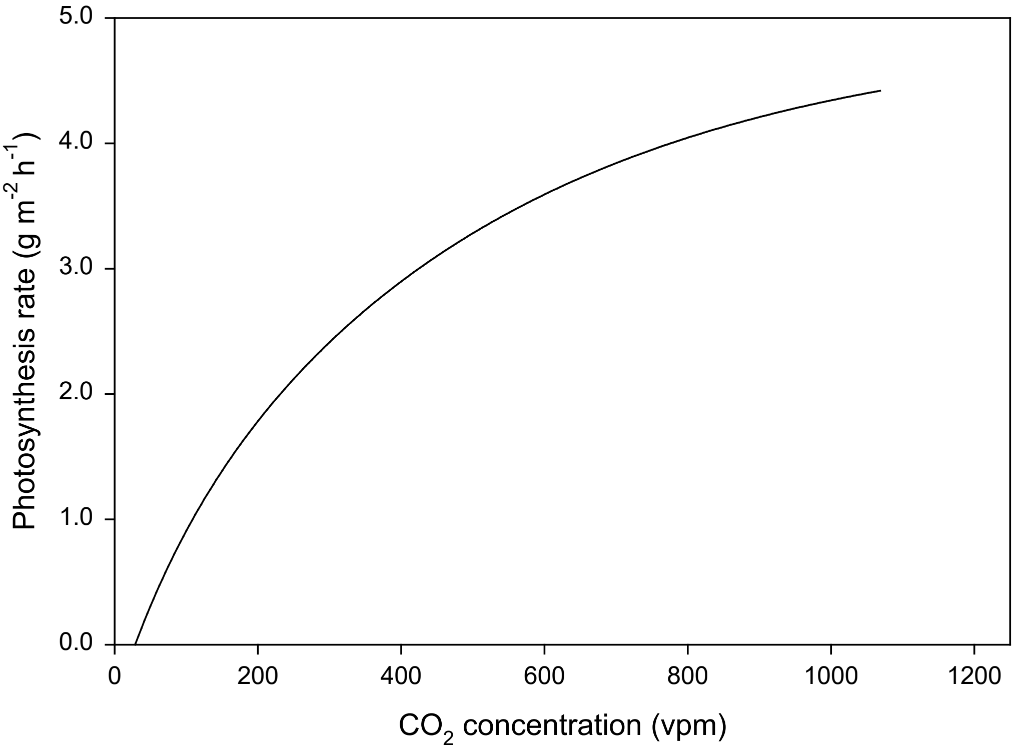

Fig. 3.2 Effect of CO_2 concentration on canopy photosynthesis of cucumber (after Nederhoff & Vegter, 1994a)

Warren Wilson, Hand & Hannah (1992) compared the efficiencies with which glasshouse crops utilised solar radiation and concluded that while their efficiency of utilisation of light at a normal CO_2 concentration was similar to that of field crops, the efficiency was greatly improved by CO_2 enrichment. Indeed, Hand, Warren Wilson & Acock (1993) established that when eggplant was grown at 1200vpm CO_2, this crop had one of the highest light utilisation efficiencies recorded for crop stands. The importance of these observations is that, by adding CO_2 to the glasshouse atmosphere, more assimilate is formed per unit of light and without using any more energy derived from a fossil fuel. Thus, it is a means of improving the efficiency of energy usage in glasshouses by making the best use of the available light. Warren Wilson, Hand & Hannah (1992) also stressed the importance of avoiding depletion of the normal ambient CO_2 concentration as depletion will lower the efficiency of light utilisation.

These conclusions from studies of photosynthesis are complemented by R&D on whole crops. Such R&D has shown, for example, that fruit yield both of cucumber (Slack and Hand, 1985) and tomato (Slack, Fenlon and Hand, 1988) is directly proportional to the average daily CO_2 concentration within the range 250 to 500vpm (Fig. 3.3). With tomato, the main effect of CO_2 enrichment in summer is to increase the average fruit size (Fig. 3.4) (Slack, Fenlon and Hand, 1989). A broadly similar yield response to increasing CO_2 concentration is also shown by sweet pepper and eggplant (Nederhoff, 1994). In general, crop studies show that there is a benefit to be gained from continuing to enrich the glasshouse atmosphere up to at least 1000vpm CO_2, although the response to CO_2 is no longer linear at these higher concentrations (Hand, 1984), as predicted by Nederhoff's 'CO_2 rule' (Nederhoff, 1994). Normally, enrichment to these higher concentrations is also unlikely to be economically worthwhile in summer when the CO_2 can escape to the external atmosphere through open ventilators; hence, there is much interest in being able to cool glasshouses without excessive ventilation.

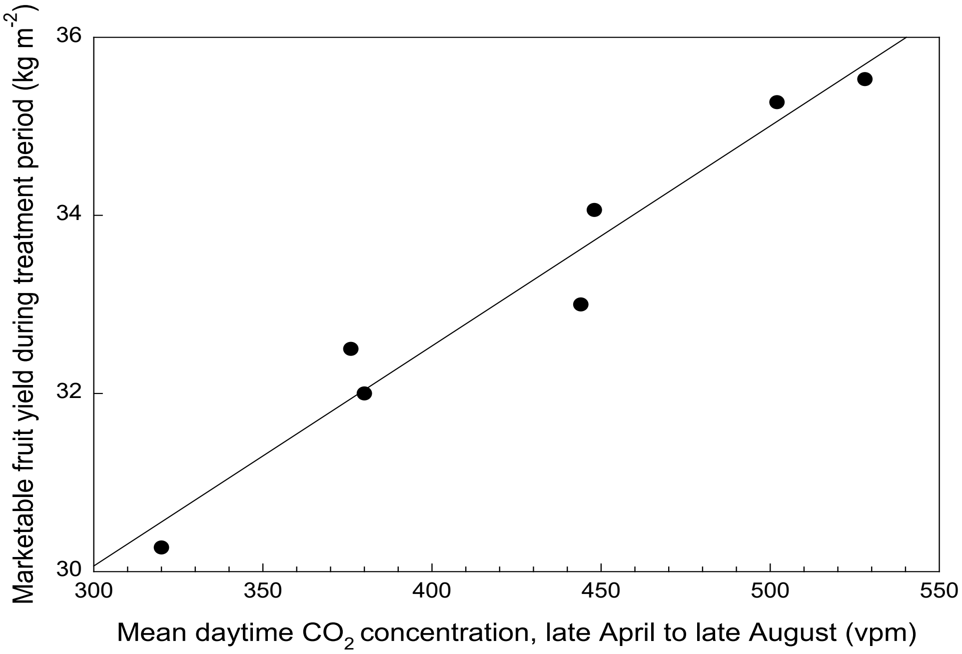

Fig. 3.3 The effect of increasing CO_2 concentration during the summer months on marketable fruit yield of tomato (after Slack, Fenlon and Hand, 1988)

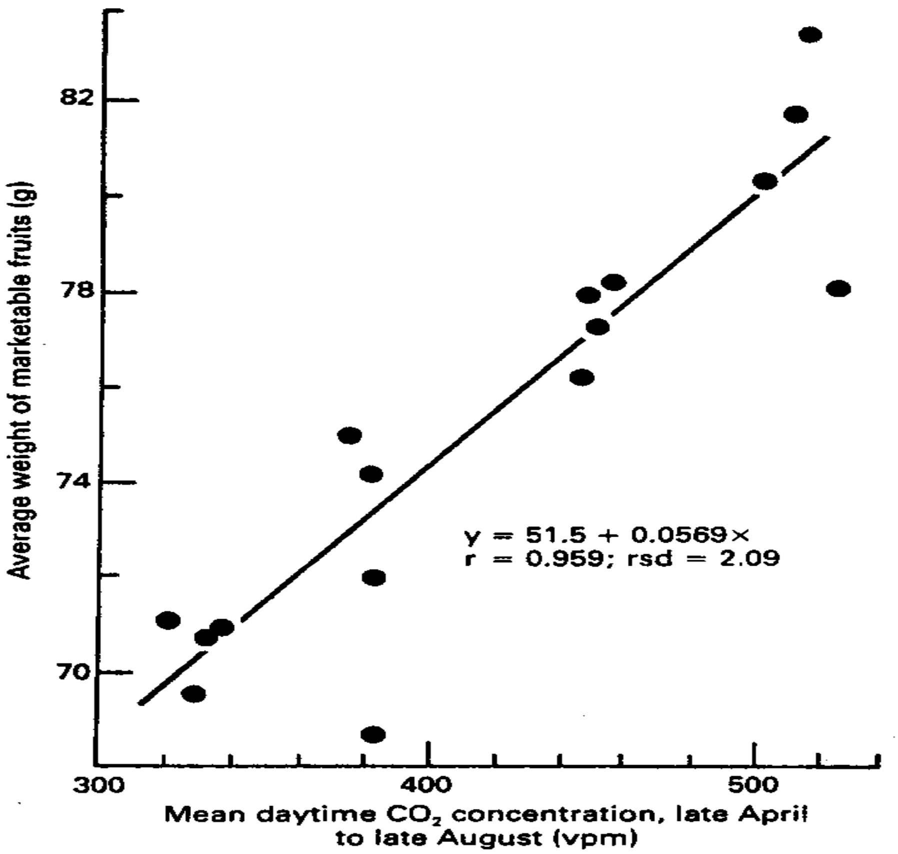

Fig 3.4 Effect of increasing CO_2 concentration during the summer months on average weight of marketable fruit of tomato (after Slack, Fenlon & Hand, 1988)

The CO_2 can be sourced from supplies of the pure gas, from the activity of biological agents, or from the combustion of a hydrocarbon fuel in either a boiler or an engine. Taking the exhaust gases from a natural-gas-fired boiler or even from a CHP unit running on natural gas has proved to be a popular and cost-effective source of CO_2 for enrichment of the CO_2 concentration in glasshouse atmospheres. However, the exhaust gases from these systems must first be cooled and cleaned before they can be introduced to the glasshouse. Furthermore, as the exhaust gases may also contain carbon monoxide (CO), ethylene (C_2H_4), and oxides of nitrogen (NO_x), the concentrations of these pollutant gases must be reduced to safe levels before the exhaust gases can be used in the glasshouse.

3.2.3 Maximising light transmission and light interception

Studies of photosynthesis have demonstrated that the process is proportional to the amount of light absorbed by leaves and although the process slows at high light levels, it is important to maximise the amount of light reaching the crop. Hence the importance of minimising light wastage by maximising light transmission, reducing headland areas, and minimising the passage of light to the glasshouse floor through gaps between rows (Warren Wilson, Hand & Hannah, 1992). With whole crops, it has been shown that fruit yield of tomato is directly proportional to the amount of light incident on the crop within the glasshouse (Cockshull, Graves & Cave, 1992). These authors demonstrated that tomato produced 2kg fresh weight of marketable fruit per 100MJ of solar radiation incident upon the crop. This ratio provides another means of assessing improvements in the efficiency of light usage, whether due to improved cultivars or improved cultural techniques. Yield of tomato is also highly dependent upon crop density (e.g. Papadopoulos & Ormrod, 1990; Cockshull and Ho, 1995) and although these examples are drawn from work on tomato, there is every reason to believe that similar effects of crop density would be obtained with other protected salad crops.

To achieve high light transmissions, all unnecessary obstructions in the roof of the glasshouse should be removed and the outer and inner surfaces of the glass cladding should be cleaned frequently. With the technology that is available today, the need for glass cleaning could be 'flagged up' by a system that detects any reduction in light transmission. In addition, the crop rows and the crop density should be arranged so that as much as possible of the light that enters the glasshouse is absorbed by green leaves, especially those that are almost at full-size as they are the most effective at photosynthesis. Modern training and cultivation systems for tomato and pepper do place these leaves near the top of the leaf canopy.

3.2.4 Dynamic optimisation

Crop models can also be employed together with computer programs to control the aerial environment so as to optimise it in terms either of photosynthesis, yield, profit, or even energy efficiency. In general, once light transmission by a glasshouse and light interception by the crop have both been maximised, optimisation of the environment depends mainly upon the control of temperature, humidity and CO_2 concentration. The stress laid on optimising the process of photosynthesis has led to the development of various computer-driven aids to cultivation of glasshouse crops including systems such as 'IntelliGrow' (Rosenquist & Aaslyng, 2000). This system provides dynamic control of the aerial environment of glasshouses for its main function is to modify the glasshouse climate so as to optimise photosynthesis at whatever irradiance is currently incident on the crop. In trying to optimise photosynthesis, 'IntelliGrow' will result in warmer days when the solar gain is high and, in doing so, may save energy in a manner that is similar to that of temperature integration software (see chapter on 'Temperature Integration'). The system also aims to save some energy by providing set points for temperature and CO_2 concentration that achieve only 80 to 90% of the optimal photosynthesis. It has been estimated that the 'IntelliGrow' system saved between 33 and 40% of the energy used by a standard climate control system when used in conjunction with the production of pot-plants (Rosenquist & Aaslyng, 2000). Hoogendoorn, the Dutch automation group, has within the 'Hoogendoorn Growlab' a crop photosynthesis kit that can be linked to its climate control computer for optimising crop photosynthesis.

Chalabi, Biro, Bailey, Aikman & Cockshull (2002a,b) described a computer program that controlled the CO_2 concentration in a glasshouse dynamically so as to optimise tomato production in terms of maximising the financial return. This has not yet been incorporated into any commercial computer program but the more grower-friendly elements of the research were distilled into a *Grower Guide* under HDC Project PC 110a (Bailey, 2002) and included in a 'CO_2 Optimiser™' program that can be run on a PC.

3.2.5 Conclusions

- Models of crop responses to light, CO_2 temperature, and humidity are needed in order to optimise photosynthesis in terms of energy efficiency. Such models enable computers to control the environment in a dynamic manner in relation to changes in the amount of light reaching the crop; the one factor that is not under the grower's immediate control;
- As much as possible of the sunlight that falls on a glasshouse should reach the crop below. The crop rows and the crop density should then be arranged so that most of the transmitted light is absorbed by green leaves and preferably by green leaves that are almost at full-size as these are the most effective photosynthetically;
- Adding CO_2 to the glasshouse atmosphere by day improves the efficiency with which light is used and so improves energy efficiency. The increase in the rate of photosynthesis is approximately linear between 250 and 700vpm CO_2 (Slack, Fenlon and Hand, 1989) and, for most salad crops, photosynthesis approaches a maximum rate at about 1000vpm CO_2;
- Under the high light of summer, the rate of CO_2 uptake by the crop may exceed the rate at which it can be replenished by ventilation. Under these conditions, the CO_2 concentration around the crop will fall below 350vpm and the efficiency of light utilisation will fall correspondingly.

3.3 Temperature Integration

For many years, it was thought that successful crop cultivation required the night temperature to be controlled at a setting that was optimal for the particular biochemical processes that occur in the dark. Similarly, it was thought that the day temperature had to be controlled at a different, usually higher temperature; one that would be optimal for the processes that occur in the light. During the 1980s, however, it became evident that the development of many crops was not responding to the specific temperatures of the day and night periods but to temperature integrated over a period of time that could include both days and nights. This integral could be expressed as either a temperature sum, e.g. in degree-days, or it could be averaged over the course of one or more complete diurnal cycles and expressed as a 24-hour average temperature. Furthermore, it was demonstrated that although the convention was to control the minimum air temperature in a glasshouse at one fixed value by day and another by night, producing what has been termed "square wave" control, this was not essential to plants.

That plants respond to temperature integration was first demonstrated with some aspects of development of cucumber (Krug and Liebig, 1980). Later, Cockshull, Langton and Hand (1981) showed that time of flowering of chrysanthemum was directly related to the 24-hour average temperature. Hence, even though chrysanthemum needs long dark periods for its flowers to develop to anthesis, those dark periods can be spent at 10ºC and flowering need not be delayed provided that the temperature of the following day is high enough to compensate.

Although many developmental processes are controlled by average 24-hour temperature, internode extension is not one of them. Instead, internode extension appears to be controlled by the magnitude and sign of the difference between the day and night temperatures (e.g. Erwin and Heins, 1995). Other experiments have shown that the effect of the day temperature on stem extension is often different from that of the night temperature and so the overall response is controlled by the actual temperature of the day and night periods separately (Langton and Cockshull, 1997).

In some cases, growth in weight may appear to respond to temperature integration. In general, however, photosynthesis, the basic process underlying growth, is not greatly influenced by temperature in the range 15 to 25ºC and is not directly related to average temperature (e.g. Reddy, Pachepsky & Acock, 1994). The apparent growth response to average temperature probably arises because both leaf initiation and leaf expansion are controlled by average temperature and so a higher average temperature creates more leaf surface, leading to more light interception and hence, more growth.

3.3.1 Temperature integration and salad crops

It is now well established that temperature integration controls the development of most salad crops.

Tomato. Hurd and Graves (1984) demonstrated that crop yields were the same in a conventional regimen and in one with temperatures that fluctuated continually throughout the day and the night, provided that both regimens produced the same 24-hour average temperature. Those same authors also showed that it was not essential that the required average temperature be achieved every day for no loss of yield occurred when the average temperature was not restored for as long as a week. Later, de Koning (1990) demonstrated that there was no yield penalty even if 12 days elapsed before the desired average temperature was restored, provided that the amplitude of variation about the standard day or night temperature was no more than 6ºC.

Cockshull, Adams and Plackett (2002) recently reported upon an experiment conducted at HRI, Stockbridge House in the 1996/97 growing season. In the most extreme treatment, neither total nor marketable yields were affected when eight nights in succession were spent at 3ºC below the temperature setting of the 'control', just so long as the average 24-hour temperature was restored to that of the control over the next eight nights. The day temperature and vent settings were kept the same in all treatments, including the control, so as to ensure that the average CO_2 concentration was unaffected by the treatments. The results indicated that yield of tomato was unaffected if the treated plants and the 'control' received the same 24-hour average temperature every 16 days and provided that the deviation from the average was never more than 3ºC above or below the 'control'.

Cucumber. Krug and Liebig (1980) were first to show that some aspects of the development of cucumber were best described as responding to temperature integration but Slack and Hand (1983) were the first to demonstrate that temperature integration controlled yield. They showed that the weight of fruit produced in the first four weeks of harvest was directly related to the 24-hour average temperature within the range 15.2 to 22.6ºC (Fig. 3.5). Later, Papadopoulos and Hao (2000) demonstrated that both early and final yields were related to the 24-hour average temperature and calculated that the optimum average temperature was about 19.5ºC for the cvs Aramon and Corona when grown under the environmental conditions of Ontario, Canada.

Van den Berg, Buwalda & Rijpsma (2001) suggested that recent research on cucumber in Holland had shown that the crop can tolerate exposure to 12ºC for 3 days in succession, without loss of production or quality, provided that this period was subsequently followed by an appropriate period of temperature compensation. If the temperature was lowered only to 16ºC, this could be tolerated for up to for 6 days in succession, without loss of yield or quality, provided that the required average temperature was subsequently achieved by raising the temperature by 2 ºC above the standard for the requisite number of days.

Other Salad Crops. With lettuce, Langhans, Wolfe and Albright (1981) showed that plants grown with a night temperature that fell steadily from 25 to 15ºC each night, produced the same yield as those grown at a constant night temperature of 20ºC. It has also been reported that yields of sweet pepper (Bakker and van Uffelen, 1988) and of kohlrabi (Liebig, 1988) are related to the 24-hour average temperature.

3.3.2 The potential for energy saving

All of the above information offers the potential to reduce fuel costs, particularly if computer control systems are used and equipped with appropriate control algorithms (e.g. de Koning, 1988a, Bailey, 1994). Computers have the ability to vary temperature settings continually, if required and although many computer control systems still use "square wave" control, that is a relic of the days when the air temperature of glasshouses was controlled via thermostats. One approach to reducing fuel costs is to maximise the benefits from "solar gain" by allowing glasshouse air temperature to rise under the influence of solar radiation. When the energy input from solar radiation has diminished or disappeared, any temperature "credits" that have been accumulated can be "cashed in" by lowering temperature settings below normal, the object being to approach the required 24-hour average temperature. With tomato, credits do not have to be utilised within 24 hours but, as indicated above, can be cashed in over a longer period of up to 12 days.

Another approach is to lower temperature settings when the energy cost of maintaining normal temperatures is high and then to compensate for this later by raising temperature settings above normal when the energy cost of doing so is not so high. The rate at which energy is lost from a glasshouse is strongly influenced by the wind speed over the structure and various authors have suggested lowering set temperatures when the external wind-speed is high, e.g. Bailey, 1985; Aikman and Picken, 1989; Aikman, Dungey and Graves, 1992. Temperature settings might also be lowered to save energy when the external temperature is very low. Conversely, most heat should be put into a glasshouse when the energy losses are least, i.e. when the external wind speed is low. A very interesting application of this approach is to add energy at night when a thermal screen is being used for then the energy losses are very low (Bailey and Seginer, 1989). The ideal computer program might well incorporate all of the above approaches.

Temperature integration could also have a useful part to play in maximising the benefits from waste heat. Waste heat is usually available at a relatively low temperature and is delivered at a constant rate (e.g. Drakes, 1980). It is best suited, therefore, to meeting the basic heating load of a glasshouse; a more expensive fuel can then be used to "top-up" the heat input so as to achieve the actual temperature required at that moment. With our present knowledge, it might be suggested that the expensive fuel should be used only when energy losses are least and it should be used so as to restore the required average temperature only when the longest acceptable period of imbalance has elapsed (de Koning, 1988b). There is also the potential to make savings in capital expenditure on new glasshouses. This arises because the maximum temperature “lift” required from the heating system would be less if air temperature settings were allowed to fall when outside air temperatures were low, and so it would be feasible to install heat generation and distribution systems with a smaller capacity than now.

3.3.3 Practical experience of temperature integration

Although the use of temperature integration offers the potential to save energy without loss of yield or fruit quality, the principle has not yet been widely exploited commercially. Up to now, the main reasons for this lack of uptake seem to be that growers lack confidence in the approach and are unsure of the financial benefits. Part of the problem is that most of the relevant earlier experiments were looking at the crop response to temperature integration and not the actual energy savings. Furthermore, the aerial environments in those experiments were modified according to predetermined patterns and not in response to the prevailing weather conditions and not with the object of making energy savings. There is also a lack of reliable information about the safe limits over which temperature integration will operate for all crops. This is reinforced by concerns that the grower will lose the ability to control humidity and other aspects of the environment if they abdicate some measure of environmental control to a temperature integration control algorithm.

Some of these questions can be answered only by additional R&D but acceptance by growers may also require that demonstrations be organised on growers' holdings in order that they can see the advantages of the approach at first hand and potential problems can be speedily revealed and resolved. Practical demonstrations have been conducted in the UK (HDC PC49 - Bailey, 1994) as well as on some Dutch nurseries (e.g. van den Berg, Buwalda & Rijpsma, 2001). A demonstration of this kind forms the practical element of the present project (HDC PC188) and is currently being run on a tomato nursery.

In the earlier UK trial (HDC PC49 - Bailey, 1994), an optimal control strategy was employed that changed the temperature set point hourly in order to minimise heating costs while maintaining the temperature within bounds set by the grower. The model was driven by weather forecasts but it was also required to achieve the required temperature integral within a period of time set by the grower. Initially, the grower used the control system in a very cautious manner but, as he grew familiar with it and gained confidence, he slackened the constraints within which it had to operate. The energy saving was calculated to be approximately 15% when the integration period was set to be five days.

In the Dutch trials (van den Berg, Buwalda & Rijpsma, 2001), a temperature integration program developed by Hoogendoorn (the Econaut CTI) was used together with weather forecasts to effect both 24-hour and multi-day integration on three modern, commercial nurseries; one producing tomatoes, one producing cucumber, and one producing sweet pepper. Hoogendoorn anticipated that the program would allow energy savings of 10 to 15% to be made. With the tomato crop, the energy saving was only about 2%, mainly, it was thought, because the grower limited the range over which temperature was allowed to deviate to just 1 to 2°C. No energy was saved on the sweet pepper nursery but the principles used by the grower to control temperature in the reference section of the glasshouse were very similar to those employed by the 'Econaut CTI' program. With cucumber, the grower was more adventurous and allowed temperature under the integration program to vary freely between 18 and 25°C. The outcome was a saving of 12.3% of the energy used by the conventional control program between February and October, without any detrimental effects upon either the fresh weight or the number of fruits, or their quality.

The results of the above trials suggest that considerable energy savings are possible but they also show that even experienced growers are distrustful of accepting the results of research without the opportunity of testing the work for themselves. Furthermore, growers are often fearful of allowing the crop's appearance to differ from their mental picture of the "perfect crop" and of allowing the aerial environment to differ from the one they are used to. Consequently, growers must be given time to develop confidence in the computer programs and the more dynamic environments that they produce for they must be certain that the programs are both more energy efficient and more profitable than the current systems of production.

3.3.4 Conclusions

- Making use of temperature integration by plants has the *potential* to save between 10 and 15% of the energy currently used to produce most protected edible crops. As yet, however, there is little information about the *actual* amounts of energy that can be saved. Trials are needed in which temperature integration, in conjunction with prevailing and forecast weather conditions, is used for the sole purpose of making energy savings;
- This dynamic approach to temperature control produces environmental conditions that may be very different from those that most growers are used to and so, in order for the approach to be widely accepted, it may be necessary to run a number of demonstration projects in different areas of the country;
- Further R&D is required to establish the limits of temperature integration for different crops and to provide the information that will give growers more confidence in the technique.

3.3.5 Research Requirements

Growers need to know:

- the actual energy savings that are likely to be achieved. For this, trials need to be conducted in which temperature integration is used, in conjunction with prevailing and forecast weather conditions, for the sole purpose of making energy savings;
- the optimum 24-hour average temperature for the most rapid development commensurate with satisfactory yield and quality for each of the main protected edible crops;
- the largest temperature variation that can be tolerated by these crops, especially tomato, cucumber, and sweet pepper;
- the maximum duration over which such deviations from the temperature norm can be tolerated;
- whether the optimum 24-hour average temperature varies with the stage of crop development or with other aspects of the aerial environment, especially the daily integral of solar radiation.

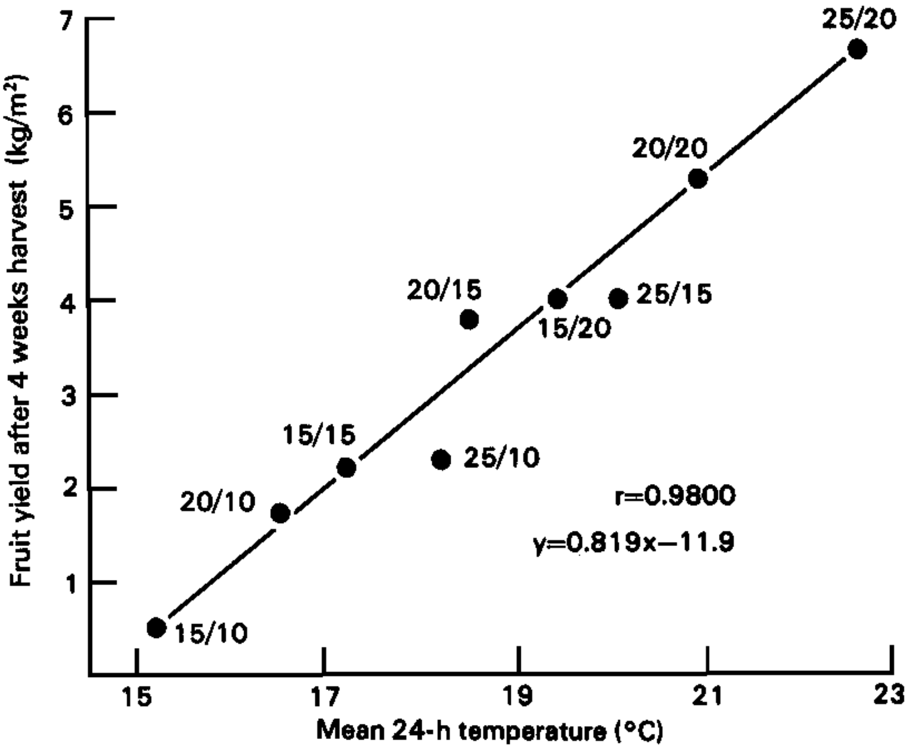

Fig. 3.5 The response of early yield of cucumber to a range of day/night temperatures and to the resulting 24-hour average temperatures. (After Slack &Hand, 1983)

3.4 Humidity Control

It is generally accepted that some measure of humidity control must be practised if the performance of salad crops in glasshouses is to be optimised. Low atmospheric humidity could inhibit growth by causing stomata to close due to water stress, while at the other extreme, high humidity reduces transpiration and can also encourage the spread of certain diseases. Attempts to overcome the effects of low humidity by humidifying glasshouses in summer (HDC Projects PC30 and 30a) were not very successful (e.g. Cockshull & Hand, 1993). On the other hand, limiting the occurrence of high humidity is easier to achieve and has been shown to benefit crop production, especially in winter. At present, high humidity is limited by strategies employing either a 'minimum pipe temperature', a 'minimum vent opening', or some combination of both of them (Kamp & Timmerman, 2002). Control of humidity is then achieved by monitoring the humidity in the glasshouse and initiating either additional ventilation or heating as required. However, as operating these strategies probably accounts for 15 to 25% of all the fossil fuel required to heat a glasshouse (Bakker, 1991,1999; O'Neill, 2001) it is reasonable to question whether the strategies for humidity control could be modified without prejudicing either crop yield or quality.

3.4.1 The influence of high humidity

As mentioned earlier, high humidity influences the growth, development and quality of crop plants in two different ways - via effects on transpiration and via effects on disease.

Transpiration. During the day, when the stomata in the leaves are usually open, plants will lose water from their leaves while the air surrounding them is drier than the moist air in the spaces within the leaves. Consequently, if the humidity of the surrounding air is high, water loss by transpiration is reduced. This is undesirable because the essential element calcium is transported about the plant only within the transpiration stream. Hence, prolonged exposure to high humidity is likely to induce a deficiency of calcium within the leaves. The same response to humidity occurs at night for, although the stomata are then usually closed, there is still some water loss through the cuticle covering the leaf surface.

Other factors are also involved in the loss of water by plants. Energy for the evaporation of water comes largely from solar radiation absorbed by the leaves. The absorption of solar radiation also raises the temperature of the leaf, allowing the air within it to contain even more water. This increases the gradient in humidity from the interior of the leaf to the surrounding air and so promotes the loss of water from the leaf. Thus, transpiration is likely to be faster in summer and calcium deficiency is likely to be less of a problem than in winter. These influences are well summarised in *Greenhouse Climate Control* by Bakker, Bot, Challa & Van de Braak (1995). Because of the importance of solar radiation, it has been suggested that radiant energy from other sources, such as conventional lamps or even infra-red lamps might be used to boost transpiration on dull days when the natural level of transpiration is low. However, a theoretical study indicates that this not likely to influence transpiration greatly (Stanghellini, 1987). Increasing air movement might also be expected to increase transpiration because it will bring relatively dry air to the leaf and displace more humid air. This leads to the proposal that perhaps a more promising approach to environmental control would be to control transpiration directly via a 'transpiration set-point controller' (Stanghellini & Van Meurs, 1992).

Disease. High humidity provides ideal conditions for the development of many diseases, especially *Botrytis* in tomato and *Didymella bryoniae* in cucumber. The spores of many fungal diseases germinate either in free water or under conditions of high humidity. However, in the case of glasshouse crops, it is especially important to establish which of these two conditions is the more important because it has a considerable bearing on the measures used to control the disease by environmental means. Appropriate sensors can detect high atmospheric humidity and this information is also needed to estimate when condensation will occur on fruits and leaves. Condensation will not occur on these organs until their surface temperature is equal to or lower than the dew point of the surrounding air. Sensors now exist that, together with appropriate computer programs can detect when condensation has occurred on leaves or fruit, or will predict when it is likely to occur.

3.4.2 Measuring Humidity

The actual humidity of a sample of greenhouse air can be expressed in various ways. Some are more useful than others when estimating the effect of humidity upon crop transpiration. However, it is feasible, though not always easy, to relate one unit to another.

1. *Relative Humidity* (RH) is the term that most growers are familiar with. Air that is saturated with moisture is said to be at an RH of 100% while lower ratios indicate how far the water content of the air is from saturation. Thus, air having an RH of 50% contains one half of the moisture of saturated air at the same temperature. The disadvantage of expressing humidity in this way is that warm air can hold much more water than cool air. Consequently, air at 50% RH can accept much more water at 20°C than at 10°C and so the warmer air will have a greater influence on transpiration.
2. *Humidity Deficit* (HD) is a more direct measure of the 'drying power of the air' because it indicates the actual quantity of moisture the air can hold before it becomes saturated. Thus, a humidity deficit of $2.6 g/m^3$ means that each cubic metre of air is able to accept a further 2.6g of water. As such, it gives a measure of the ability of the air to 'draw' water from leaves by transpiration. Furthermore, as a deficit of $2.6 g/m^3$ has much the same drying power over the normal range of glasshouse temperatures, this measure is of more value than RH when considering water loss.
3. *Vapour Pressure Deficit* (VPD) is the term that indicates the actual 'drying power of the air'. In this case, it refers to the partial pressure that water vapour contributes to the total pressure of all the gases in a sample of air and the difference between the partial vapour pressure of moisture in the sample and its partial vapour pressure at saturation. This

difference, or vapour pressure deficit (VPD), actually drives transpiration because the air within a leaf is saturated with water at a vapour pressure appropriate to its temperature, while the moisture in the surrounding air is likely to be at a smaller vapour pressure. The VPD is usually expressed in terms either of Pascals (Pa) or of kilo Pascals (kPa).

3.4.2.1 Which to use?

The relationship between HD and VPD is quite consistent and although that between RH and either VPD or HD is not so straightforward, it can be calculated provided that the temperature of the air is known. To assist growers to make these comparisons, some conversions and relationships are shown below in more detail.

a) HD (g/m^3) to VPD (kPa)

$$HD = (VPD \times 1000) \times (2.17/(273 + T)) \text{ where } T = \text{the temperature in } ^oC.$$

b) RH to HD (g/m^3) shown in Fig 3.6

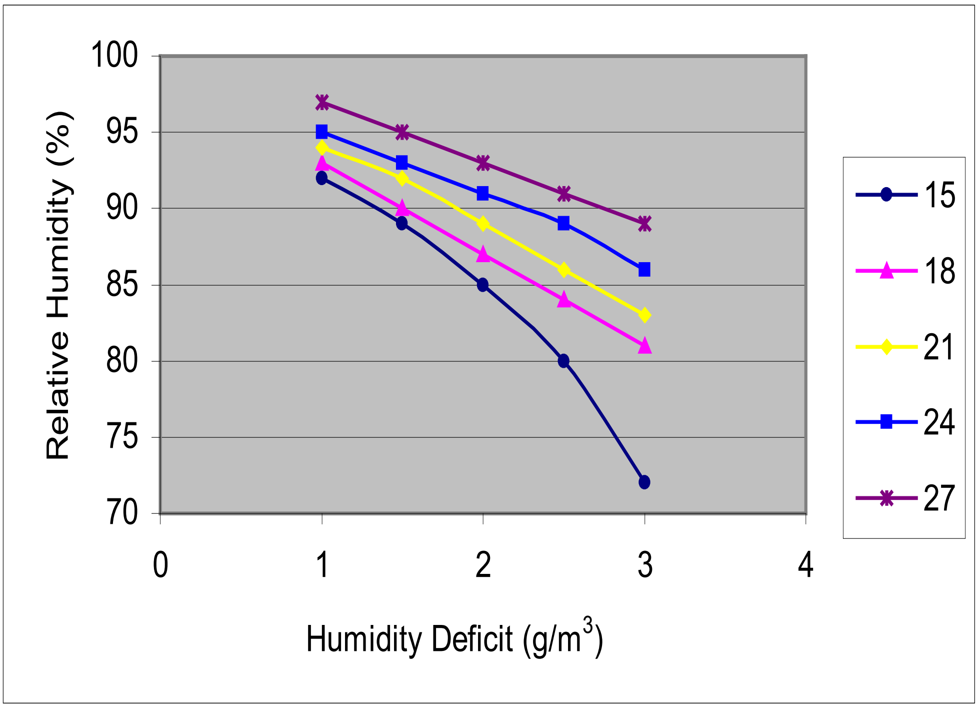

Fig.3.6 The effect of temperature on the relationship between RH and HD

c) RH to VPD (kPA) shown in Fig 3.7

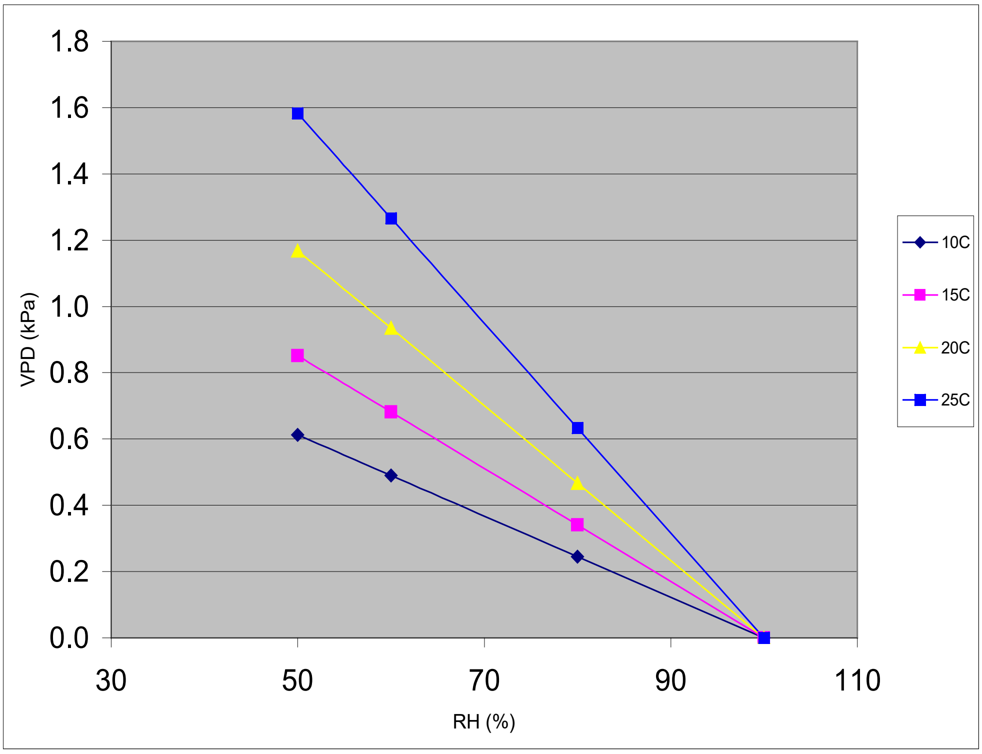

Fig 3.7 Effect of temperature on the relationship between RH and VPD

3.4.2.2 Using HD, VPD and RH

In practice, the manufacturers of environmental control computers have adopted HD as their preferred unit of measurement and so it is now also becoming the unit of choice for most growers of edible crops. On the other hand, most crop physiologists have adopted VPD as their preferred unit, largely because of its direct relationship to transpiration. In practice, these two units can be inter-converted and so the separate uses are not a huge inconvenience. Unfortunately, however, although some modern information on the effect of humidity on diseases is expressed in terms of VPD, much of the information is presented in terms of RH. Consequently, it is not certain which measure is the more important in relation to the control of disease nor which should be used as the basis of an effective disease control system. It is possible, therefore, that it is incorrect as well as being inconvenient to convert RH data into comparable HD units.

3.4.3 The influence of humidity on growth of salad crops

In their review of the effects of humidity on plants, Grange and Hand (1987) concluded that neither growth nor development was affected by humidity below about 90% RH (i.e. a VPD of 0.2 kPa or more) and above about 55% RH (a VPD of 1.0 kPa).

Tomato. Holder and Cockshull (1990) showed that the yield of tomato plants was reduced if they were grown for 28 days at a VPD of 0.3kPa or smaller in winter. When an average VPD of only 0.15 kPa was maintained for the whole 28 days, the yield produced in a subsequent 28-day period was reduced by about 11%. Consequently, periods of less than 28 days at very high humidity or periods spent at a VPD larger than 0.15 kPa are likely to have a smaller effect on short-term yields and the effect will be very small when considered over the whole season. For comparison, a VPD of 0.3kPa represents a HD of $2.25 g/m^3$.

The main effect of high humidity is to restrict calcium movement leading to reduced leaf expansion, reduced light interception and, hence, reduced yield. The deleterious effects of high humidity were also demonstrated by Bakker (1990a) who found that high humidity was deleterious by both day and by night and, most importantly, that final yield was probably related to the average 24-hour VPD. Indeed, Jolliet, Bailey, Hand & Cockshull (1993) proposed that that the increase in yield due to a decrease in humidity could be expressed as a simple function of the vapour pressure deficit weighted by the solar radiation transmitted into the glasshouse. The latter element allowed the relationship to cope with different transpiration rates produced by day and by night and between the different transpiration rates of winter, spring and summer.

Cucumber. Visible symptoms of calcium deficiency in leaves of cucumber were correlated with the average 24-hour VPD, being worst at high humidity (Bakker & Sonneveld, 1988). Despite this, neither early nor overall yields were correlated with the average 24-hour VPD, although total yield was often increased as daytime humidity increased from an average VPD of 0.9kPa to one of 0.5kPa (Bakker, Welles & Uffelen, 1987). Fruit quality, as assessed by fruit colour, was adversely affected by high 24-h average humidity.

Sweet pepper. No detrimental effects of humidity were detected and fruit yield was unaffected by either day or night humidity in the range tested, i.e. from 0.27 to 0.79 kPa (Bakker, 1989a). However, mean fruit weight was increased by high humidity at night. In other experiments (Bakker, 1989b), the increase in fruit weight was not due to any reduction in fruit set but low humidity at night did increase flower and fruit number. In the same experiments, seed set was increased by high humidity by day.

Eggplant. Fruit yields of the eggplant (*Solanum melongena* L.) were reduced by continuously high humidity (small VPD), largely due to fewer fruit being picked. Mean fruit weight was larger at high humidity by day, while exposure to a large VPD increased calyx withering (Bakker, 1990b).

3.4.4 The influence of humidity on diseases of salad crops

Many general correlations between high humidity and the incidence of disease have been demonstrated. The incidence of *Botrytis cinerea* on eggplant was promoted at low VPD (high humidity) (Bakker, 1990b) and the incidence of *Didymella bryoniae* on cucumber was also greatest when the VPD was small in either the day or the night (Steekelenburg &

Welles, 1988). With tomato, the incidence of *Botrytis cinerea* was reduced by controlling ventilation using a humidistat set to operate at 90% RH (Winspear, Postlethwaite, & Cotton, 1970) and Morgan (1984a) showed that its incidence on tomato leaves, stems and fruits was significantly reduced by continual ventilation at night. The average RH in the unventilated compartments at night was 95%, while it was 90% in the ventilated ones. Morgan (1984a) concluded that these differences in RH at least partly explained the effects of the treatments on disease. However, he did realise that if the night temperature setting were lowered, RH values above 90% would be quite common even with ventilation.

Morgan's observations highlight the dilemma that while it is evident that the spores of many fungal diseases germinate only under conditions of high humidity, the problem is whether humidity is best expressed as RH, HD or VPD. An associated difficulty is that the germination of fungal spores may require the presence of free water, in which case, it is necessary also to know the surface temperature of the leaves and fruit.

Although the spores of *Botrytis* will not germinate if the humidity never rises above 90% RH, they will if the RH is 97% or more. A very important recent observation demonstrated that while they will not germinate when exposed to 97% RH for just three hours they will germinate if the same RH is maintained for four hours (O'Neill, 2001). The critical RH is presumably that in the immediate vicinity of the spores rather than that of the glasshouse air (i.e. the air that is sampled in an aspirated screen) which is likely to be lower.

Finally, for growers using the current recommendations on disease risk, it should be noted that, because RH is strongly influenced by temperature, an acceptable HD level (e.g. $2.25 g/m^3$ and above) can give an unacceptable level of RH (i.e. in excess of 90%) at higher temperatures. The likelihood of operating at these temperatures is increased when using temperature integration. Consequently, growers should review their HD settings at higher greenhouse temperatures, especially when using temperature integration strategies. This might entail applying a temperature influence to the HD set point so that it increases as greenhouse temperatures rise above 22^0C. Although this approach will help to maintain an acceptable RH, energy waste is likely to occur. The preferred option might be to retain conventional HD settings and apply an RH influence to the ventilation.

3.4.5 Conclusions

- At present, control of humidity uses about 15 to 25% of all the energy required to produce a crop of heated tomatoes. It should be possible, therefore, to relax the current humidity control settings and, provided that it is done within the above constraints, the strategy should generate energy savings without any significant loss of either yield or quality with any of the major salad crops;
- In order to maximise crop growth the average humidity should be kept to a VPD equal to or larger than 0.3 kPa. This VPD does not have to be maintained continuously but, most probably, can be averaged over at least 24-hour. With cucumber, however, it

seems that it cannot be averaged over 24 hours as fruit yield was increased by high humidity by day;

- Humidity control is also required to restrict the spread of fungal diseases. Indeed, ventilation has been recommended as the simplest way of controlling such diseases of tomato and lettuce (e.g. Morgan, 1984a,b). The current dilemma, is whether to control humidity at a specific RH at all temperatures, at a specific VPD or to produce an environment that avoids condensation on leaves and fruits. Until these uncertainties are resolved, any relaxation of the criteria for humidity control should be gradual and the grower should be satisfied that the relaxation has not led to any increased incidence of fungal disease before they are relaxed further;
- Most importantly, with *Botrytis*, there is evidence now that a very high RH (>90%) can be tolerated for up to three hours provided that the RH is then lowered by means of, for example, a heat boost (O'Neill, 2001);
- If growers are using a policy of temperature integration, they should review their HD settings at higher greenhouse temperatures because the strategy may give unacceptable levels of RH (i.e. in excess of 90%) at higher temperatures.

3.4.6 Research requirements

- An urgent priority is to establish the moisture-related factors that control germination of fungal spores and the spread of fungal diseases on crop plants. In particular, it is important to know whether the spores of specific diseases require to be in free water or to have the surrounding air at a particular RH, HD, or VPD;
- If it is the humidity of the surrounding air that is more important than the presence of free water, it is most important to establish the maximum length of time that a specific high humidity can be tolerated without risk of disease. This needs to be established for each of the main fungal diseases of tomato, cucumber, and sweet pepper;
- Further R&D is required to confirm that the growth and yield of protected salad crops responds either to humidity or to transpiration integrated over time and to establish the limits of such integration for the different salad crops;
- All of the above findings from R&D need to be incorporated into realistic procedures that will save energy as well as avoiding both risk of disease and risk of calcium deficiency;
- There is also a need to develop, test and demonstrate cost-effective dehumidification systems. These might include heat pump dehumidification linked to a CHP unit. Other commercial systems have also been proposed and these need independent evaluation at a practical demonstration level.

3.5 Thermal Screens

3.5.1 Background

The energy crisis of the late 1970's saw the development of screen materials and systems that were effective in saving energy. As a result it is accepted that thermal screens can make a significant contribution to reducing the energy consumption of a greenhouse (Cockshull, Edmondson, Butters and Bailey, 1989). However, whether thermal screens are actually used on a commercial nursery is dependent upon the crop being grown. Whilst growers of ornamental crops widely acknowledge the value of the technology and most leading producers use them, use in the edible crops sector is not commonplace.

Although all growers recognise the importance of the relationship between the amount of light received and crop yield, it is especially important for growers of edible crops because their products are sold by weight. Consequently, any light loss has a direct impact on profitability and so the growers of such crops make every effort to maximise the light transmission of their greenhouses. Introducing and using a thermal screen inevitably increases the amount of shading and growers believe that the resulting decrease in crop yield is of greater value than the energy that can be saved. Whilst this belief was true in earlier days when energy costs were lower than today, the recent changes in energy pricing have significantly affected the economics of using thermal screens.

3.5.2 Use of screens in the edibles sector

Fixed screen systems, based on the use of semi-permanent polythene sheets, have been used by a number of growers of protected edible crops (particularly cucumbers). They have several disadvantages however including the continual light loss and the increased humidity levels below the screen (Starkey, 1985). To overcome these major drawbacks, perforated material with a high light transmission can be used. Even with these improvements, use is limited to the winter months when crops are in the early stages of development.

Using movable screens can make further improvements. With systems of this type the screen can be partly pushed back ('gapped') to assist with ventilation and avoid the build up of high humidities (De Graff, 1985). Despite this the major disadvantage of continual shading and thus, light loss still remains. The light loss under a retracted and 'parked' moveable screen was reported to be between 3 and 5% during the day (Grange and Hurd, 1983; Butters, 1987). This fact alone prohibited the widespread uptake of screens in the edible crops sector due to concerns about the potential effect of this light loss on crop yield.

3.5.3 Modern developments in screen materials

Because of the need to achieve energy savings whilst minimising shading, manufacturers of screen materials have recently concentrated on developing materials that have a high light transmission and pack more tightly when retracted. These materials therefore have the potential to reduce the shading effect both when they are drawn over the crop during daylight and when they are retracted.

Typically, these materials are of a woven polyester construction that is designed to allow transmission of water vapour. This has the potential to prevent excessive humidity build up under the screen and remove the necessity for gapping back.

Plaisier (2001) detailed work carried out by the screen material manufacturer Ludvig Svensson using their SLS10 material. This work involved four tomato growers located in the Netherlands who had installed screens and studied the effects on energy consumption, relative humidity, disease (*Botrytis)* and yield. The operating regime for the screen was based on closing the screen during the night when ambient temperature dropped below 7ºC in the winter months. In addition the screen was also closed during the day when ambient temperatures and light levels were very low (the exact levels were not specified).

The results indicated that a saving of approximately 130kWh/m^2 could be achieved with no excessive increase in humidity or disease problems. No specific details of yield performance were given, but it was indicated that the effect was negligible. It was however suggested that the expected yield effect was a loss of 0.6% or 0.3kg/m^2 over the year.

3.5.4 Economic assessment of screens

Based on the above work (Plaisier, 2001), the energy savings that can be realised by using thermal screens are typically worth in the region of £1.10/m^2/ annum. Current costs for an installed thermal screen using materials suitable for edible crop production are in the range of £3.50 to £4.00/m^2. This therefore indicates that, so long as there is no effect on yield, payback periods in the region of 3$^1/_2$ years can be expected. This calculation does not take into consideration any financial benefit that can be obtained through the enhanced capital allowances that are available for thermal screen installations.

If yield is at all suppressed, then the economics of screens needs to be more closely examined. With classic round tomato and cucumber, calculations show that a yield suppression of less than 1% must be achieved if the payback is to be 5 years or less.

3.5.5 Summary

Although thermal screens have not traditionally been used in the edibles sector, with improvements in their design, the technology is likely to have a significant role to play in the future. Research suggests that energy savings of the order of 20% can be expected and based on current energy prices, the payback period would be expected to be in the region of 3$^1/_2$ years.

Growers will require evidence that increased humidity and disease problems will not occur and that the value of the energy savings will outweigh the value of any yield that is lost. It is suggested that this can only be achieved through successful commercial demonstration of the technique on grower holdings. Once this has been proven, it is not unreasonable to expect significant market uptake of this technology.

3.6 Combined Heat & Power (CHP)

Combined Heat & Power (CHP) systems simultaneously generate electricity and heat from a single system. The overall efficiency of a CHP system is much greater than that achieved when generating each one separately (e.g. from a boiler and electricity generator). An additional benefit exclusive to horticulture is the recovery of carbon dioxide from the flue gases for enrichment of the greenhouse atmosphere. CHP has been embraced by horticultural businesses on the continent for some time (e.g. CADDET 1999). Aided by strong political drivers to reduce greenhouse gas emissions and a good economic argument due to the differing energy markets, CHP has been proven to work in practice.

In the UK installations have been dominated by reciprocating engine systems with an electrical output typically over 1MW. A common arrangement with this type of machine is where the grower provides the 'host' site for the CHP and agrees to buy the heat and a small amount of the generated electricity. The CO_2, which can be recovered from the CHP flue gasses, is also supplied free of charge. In this situation the CHP developer pays for the installation and operation of the CHP system and retains ownership. Their main income is then derived from selling the majority of the electricity generated onto the national grid.

This approach copies that used in other northern European countries (e.g. the Netherlands) and overcomes the main problem with using CHP on a greenhouse site, namely being the fact that the demand for heat far outweighs that for electricity. Much of the literature available from Holland concentrates on the arrangements needed to put together a successful business case for CHP and the arrangements required for selling electricity. There is little information available therefore relating to the engineering of CHP systems for horticulture and novel methods of integrating CHP into a nursery infrastructure.

Bailey and Ellis (1989) investigated the use of CHP on nurseries and concluded that there were two key scenarios where such an installation could be economically viable. These were:

- Where a CHP unit is installed purely to deliver energy to the host site. Generated electricity is used to displace that currently bought in at retail price levels. An economically viable installation of this type uses the reduced cost of generating electricity on site to offset the high installation cost for CHP;

  Under this scenario, the CHP is sized to meet the 'base' electricity requirement for the site. This is the electricity demand that is available for a large proportion of the year, which for most greenhouses comes from equipment such as pumps, motors, etc. For most edibles nurseries this accounts for an electricity demand in the region of $2.5W/m^2$.

Therefore, in a greenhouse situation where there is normally a low electrical demand when compared to the heat demand, this will lead to a situation where a relatively small proportion of the heat and CO_2 demand for the site are supplied by the CHP;

- A CHP unit installed to meet periods of peak electricity demand. In this case it is likely that a new electrical installation is being carried out (e.g. supplementary lighting) and the existing mains electricity supply is not large enough to meet the power demand. Here all of the energy generated by the CHP (heat, electricity and CO_2) will be used on the host site.

Obviously these two scenarios concentrate on using the energy on the greenhouse site whilst the method used both in countries like the Netherlands and previously in the UK concentrate on exporting electricity off-site to third party customers.

3.6.1 Conclusions

There is no doubt that CHP is an energy efficient technology that has a role to play in horticulture in the future. However, under the current situation of relatively high gas prices and low electricity prices, widespread uptake is unlikely. Even in the scenarios described above, payback periods of 5 years or more are likely.

For the majority of growers, other 'energy utilisation' technologies need to be embraced before 'energy supply' technologies such as CHP are adopted. This approach enables the energy demands of a nursery to be reduced before such a scheme becomes economically viable. This approach also prevents over-sizing of the installed equipment leading to potential under utilisation and energy waste.

With this in mind horticulture should take a 'watching brief' on developments in both CHP technology and CHP markets such that it is in a position to adopt the technology when it is economically viable to do so.

3.7 Supplementary Lighting

3.7.1 Background

It is well accepted that all of the important UK greenhouse edible crops have a very high light requirement (see section 3.2.3). As a result the seasonal availability of light has become a dominant factor in the way crop production systems have developed. For example the time at which it becomes uneconomic to heat a crop due to low light levels determines both the planting and termination dates of all of the popular protected salad crops.

Hand et al (1992) showed that even at irradiances above 350 W/m^2 PAR (typically 1200 W/m^2 total global radiation outside the greenhouse), the response of cucumber is still not maximised because, although the upper leaves may be light-saturated, light also penetrates to lower leaves that are not light-saturated. Since light levels of this magnitude only occur during the summer months, there is clearly scope in further optimising production levels through the addition of supplementary light. Until recently the viability of using electrically powered lighting systems to supply supplementary light has not been considered to be either practical or economic. However recent developments in both energy and lighting systems together with increased market demand for year-round production have increased commercial interest in the subject.

In addition, a number of growers in Finland and the Netherlands are using supplementary lighting for commercial production of both cucumber and tomato. As a result growers in the UK are now examining the likely role of the technique in their business.

Many of the comments below relate to the use of lighting for tomato production. The literature suggests however that similar responses will be valid for cucumber and sweet pepper.

3.7.2 Crop response to light

A review of the response of all of the major edible crops to light is given in *Supplemental Lighting for Greenhouse Crops* (Spaargaren, 2001). In this publication, details of the major fundamental research that has been carried out to determine the relationships between crop response and light are given. These relationships are then used to develop recommendations regarding supplementary lighting treatments for all of the major edible crops.

One of the most notable pieces of work is that carried out by Nederhoff (1994). This work provides information on the growth rate and light use efficiency for 3 of the major greenhouse edible crops. The results obtained are summarised in the following table.

Table 1 - Growth rate (dry matter) and light use efficiency for cucumber, sweet pepper and tomato

Crop	Growth rate ($g/m^2/day$)	Light use efficiency (g/MJ)	CO_2 concentration (vpm)
Cucumber	9.9	3.4	364
	12.3	4.3	620
Sweet pepper	4.56	1.7	306
	5.15	2.1	448
Tomato	14.9	2.8	370
	17.5	3.4	510

Other notable pieces of work are those carried out by Cockshull, Graves and Cave (1992) and De Koning (1989). This work is the basis of the commonly held relationship that tomato yields at between 2.1 to 2.5 kg (fresh weight) per $100MJ/m^2$ (total global radiation falling on the crop) or *"1% light is equivalent to 1% crop yield"*.

The published literature shows that the potential performance of crops under supplementary lighting systems is now being based on the above pieces of research, all of which were carried out to establish how crops react to natural light. This therefore involves extrapolating the relationships detailed above and assuming that the relationships developed can be extended to provide information on crop response to supplementary light.

For example, the work carried out at Naaldwijk by van den Berg, (2000) has received considerable interest as it provides data on the response of a tomato crop to the introduction of supplementary light at various levels. The key results of this work were as shown in Table 2 below.

Table 2 - The yield of tomato it is anticipated would be obtained if supplementary lighting were provided at various different irradiances (van den Berg, 2000)

Supplementary lighting level (W/m^2 PAR)	Yield (kg/m^2/annum)	Increase (%)	Cropping period
Nil	55	Nil	Week 48-45
24	92	67	Year-round
36	106	93	Year-round
48	118	115	Year-round

Examinations of this work show that the above data is based on computer based models that assume that the environmental conditions (light, temperature and CO_2) within the greenhouse are optimised for plant growth. Therefore the basis of the work is existing crop response relationships which have been extrapolated to predict the likely response under supplementary light. There is little evidence in the literature of independent verification of the above predictions through the use of commercial scale trials. This is largely because much of the development of the technique is in the commercial sector, and the results are therefore not available for wide public access.

What is clear from examination of van den Berg's predictions is that simply applying the general rule of 1% PAR = 1% yield and assuming that it is valid across the range of lighting levels applied, the yield responses predicted for the Naaldwijk site considered are not achieved. This therefore suggests that further optimisation processes influence the crop response at the higher light levels.

Work carried out by Blain (1987) investigated the effect of high-pressure sodium supplementary light on the growth and yield of cucumber. Results showed that some cultivars had a linear yield response to supplementary light of increasing intensity and the best yields were obtained at the highest irradiance investigated (60 W/m^2 PAR). In addition to improved yield other advantages related to the use of supplementary lighting were identified including earlier first yield and improved quality. The outcome of this and subsequent work in Canada carried out by Gosselin (1988) is the indication that with a supplementary lighting intensity of 60 W/m^2 PAR, production on a year round basis can be increased to 240 fruits per m^2.

3.7.3 Economic analysis of supplementary lighting

Installing and operating a supplementary lighting installation to achieve the levels of production suggested in the literature is expensive, both from a capital and energy cost standpoint. Therefore, in order that such a technique is economically viable, it must be clearly demonstrated that the additional yields (and incomes) achieved will re-pay the investment and running costs that are needed. Simple calculations based on the current market value of classic round tomato and typical energy and equipment costs suggest that while the technology shows promise it is unlikely to provide high returns in the short term. However, if premium prices can be obtained for a crop grown 'out of season' then the returns are likely to be more attractive.

Simple analysis also shows that, because of the lower levels of solar radiation, lighting at a given intensity is likely to give better returns for sites located in the north of the UK when compared to those in the south.

3.7.4 Energy efficiency performance

The use of supplementary lighting can significantly improve the energy efficiency of tomato production. For example the current 'best practice' for round tomato production in the UK is 11kWh/kg. Using lighting can reduce this to an input figure of 8 kWh/kg. Further gains can be made if CHP is used to meet the heat, electricity and CO_2 demands and calculations show that a specific energy consumption of 6 kWh/kg could be achieved.

In assessing improvements it must be noted however that, in order to comply with the CCL voluntary agreement targets, performance is based on primary energy units. This requires that the energy inputs are adjusted to take account of the relative amounts of CO_2 released to the atmosphere when the energy is used. This has its most significant effect when considering electricity inputs when supplied by a 'grid' supply'. In this case all electricity inputs are multiplied by a factor of 2.6 to take account of the inefficiency of generation at the power station. Where CHP is used on-site this is not the case as generated electricity is considered as a by-product and only the CHP fuel (usually gas) is taken into consideration. Taking this into account the comparative performance of 'traditional' and supplementary lighting-based systems is shown in Table 3.

Table 3 - The comparative performance of 'traditional' and supplementary lighting-based systems

System	Specific Energy Consumption (kWh/kg)
Traditional	12.6
Supplementary lighting – electricity supplied from grid	17.5
Supplementary lighting – with CHP*	6.0

* Assumes that the heat supplied by CHP can be fully utilised by heating other cropping areas where supplementary lighting is not used.

From the above data, it can be seen that CHP is essential if energy efficiency is to be improved based on the performance of traditional production systems.

3.7.5 Conclusions

Supplementary lighting is an interesting technology that promises many benefits for the key protected edible crops in the UK. Under the current combination of crop values, energy prices and equipment capital costs it is unlikely that significant returns will be obtained on classic varieties. However if premium prices can be achieved for out of season production and/or speciality varieties, then the viability of the technique is far more attractive.

3.7.6 Research requirements

Further work will be required if the technique is to be adopted on a widespread commercial basis. This work should investigate:

- the physiological response of crops to supplementary lighting;
- the effect of supplementary lighting (and the resulting greenhouse environment) on the incidence of pests & diseases;
- the requirements for all year round production including inter-planting and the optimisation of cultural practices including irrigation, CO_2 enrichment, etc.;
- the energy balance of greenhouses equipped with supplementary lighting equipment at the intensities required to optimise production.

Completion of the above work will ensure that the economic and environmental performance of production systems using supplementary lighting is optimised.

3.8 Manipulation of Sowing Dates

In recent years, seed of long-season tomato crops has usually been sown in late October or early November in the south of England (later in the north of England) and the young plants introduced into the main growing house before the end of December. This enables growers to produce marketable yield by late February or early March. The original reason for adopting such schedules was the price premium commanded by early English fruit. That premium is now considerably reduced and so it is worth considering the advantages and disadvantages of employing other sowing dates. In theory, at least, delaying the date of sowing has the potential to save energy, as the glasshouse will not need to be heated for so many days in the coldest part of the year. However, it is not known whether the energy will be used more efficiently, nor whether the procedure is likely to be cost effective. Work carried out at IHR, Littlehampton, in 1989/90 attempted to address this issue.

3.8.1 The experiment

Seeds of tomato cultivars Calypso and Counter were sown on 11 Sept. ('Sowing 1'), 23 Oct. ('Sowing 2') and 4 Dec. ('Sowing 3'). Plants were allowed to make contact with the rockwool slabs when the first truss of 50% of the plants reached anthesis; 23 Oct., 18 Dec. and 12 Feb., respectively. Plants were grown at a density of 2.87 plants/m^2 and trained as a long-season layered crop. To avoid the confounding of temperature with treatment, the then ADAS blueprint was used in all compartments, with the set-points changed in relation to the stage of development for Sowing 1. Pure carbon dioxide was injected into the compartments by day to maintain 1000 ppm, or 340 ppm when the vents were open.

3.8.2 The results

The results showed that the date of 'first pick' was much earlier in the early sown crop; weeks 1, 8 and 15 for Sowing 1, 2 and 3, respectively. However, sowing date had little effect on the cumulative yields up to week 40 (see Table 4). While Sowing 1 produced marketable fruits as early as week 1, the yield in subsequent weeks (before week 11) was very low, whereas Sowing 3 produced very high yields when the first trusses were picked (Fig. 3.8). Consequently, the cumulative yields were similar by week 25. Sowing date affected fruit size for, at times, as little as 40% of the early yield in the first sowing was graded D or larger (> 47 mm), compared with around 95 % for the third sowing (over 35% of which was grade C or B (> 57 mm)). By the end of the experiment, however, the proportional distribution of fruit sizes was similar in all three crops. Sowing date also affected fruit quality with Sowing 1 having a lower percentage of Class I fruit and, in weeks 9 to 12, more than 40% of its total yield was waste, much of it with blossom-end-rot.

The problem of large fruit might be overcome either by planting at a higher initial density or by retaining side-shoots at the earliest possible date or by doing both. Other options for reducing fruit size, such as raising air temperature settings to make fruit ripen faster or stopping CO_2 enrichment would seem to be counter-productive.

Table 4 - The effect of date of sowing on yield of tomato

	Sowing 1 (11.09.89)	**Sowing 2 (23.10.89)**	**Sowing 3 (04.12.89)**
Total yield (kg/m^2)	53.86	51.99	52.22
Marketable yield	48.75	49.15	49.52
Class I (kg/m^2)	42.77	44.73	44.96
Waste (kg/m^2)	5.12	2.84	2.70
Marketable % total	90.5	94.5	94.8
Class I % marketable	87.7	91.0	90.8

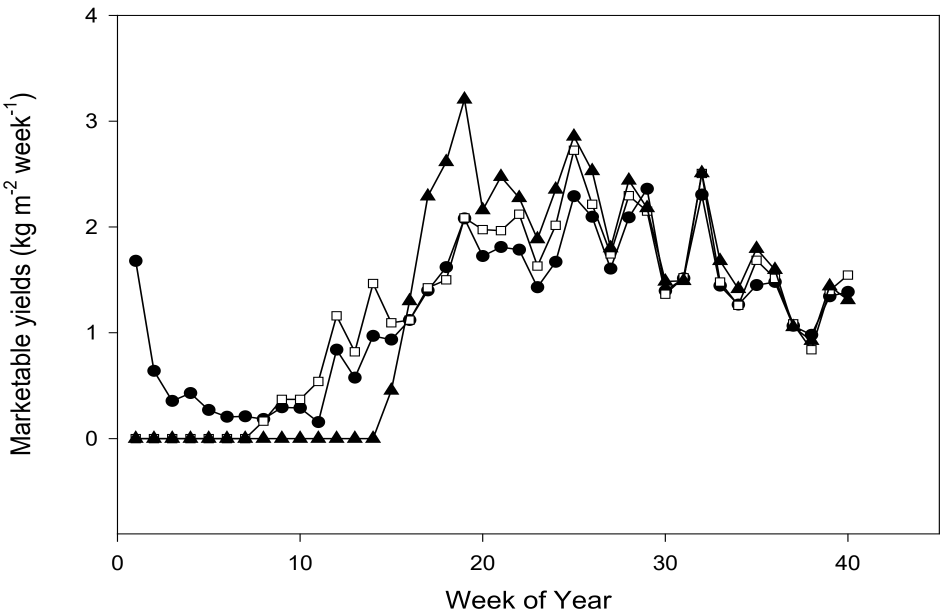

Fig. 3.8 The effect of sowing date on the weight of marketable yield produced per week
□ Sowing 1; □ Sowing 2; □ Sowing 3

The results demonstrate that while early sowing dates give earlier yields, later sowing dates tend to catch up and may even surpass them. Similar, though less dramatic results were obtained in the 1966/67 and 1967/68 trials at Fairfield EHS. Sowing on 16 November 1967 resulted in a yield of 5.9kg/m^2 to 24 May 1968 while sowing on 16 January 1968 produced less than one half the yield by that date. However, by 19 July 1968, the difference between the sowings was only 2.1kg/m^2 (14.0 as compared with 11.9kg/m^2).

Thus, overall yields would not necessarily be adversely affected by sowing later than normal. If so, not only could substantial energy savings be made by leaving glasshouses empty and unheated, except for frost-protection, for relatively long periods in December and January, but also considerable gains in energy efficiency would be made. The actual gains would depend upon the weather encountered in that growing season but roughly 12% of the energy required to heat glasshouses for tomato production is used in any four-week period in December and January. However, the grower would have to balance the gains in energy efficiency against other issues; in particular, the market's need for continuity of supply and today, the need to continue heating in order to lessen the chance of pepino-mosaic virus being able to overwinter in the glasshouse. Somewhat similar issues may apply in relation to changing the conventional sowing dates of other protected salad crops.

At present, the best-organised tomato growers in the UK may leave less than three weeks between the removal of one crop and the planting of the next and they do not turn off the heating. It seems unlikely, therefore, that many UK growers will want to leave glasshouses empty and unheated for long periods in the present economic climate and with the risk of encouraging disease. Instead, they might combine later sowing dates with later dates for "pulling out" the crop, especially if the premium price for early fruit is further eroded.

3.8.3 Inter-cropping

An associated concept that is designed to maintain continuity of supply is the idea of sowing the next crop before the old crop is removed from the house and then growing the young plants between the older ones, ready to take over from them when the older ones are removed. This "inter-cropping" approach is discussed further in the Chapter on 'Developments in Other Countries' but the approach may benefit from investigating the optimal sowing dates for both the old and the replacement crops. The optimal sowing date is also likely to be affected by whether supplementary lighting can be used in the growing house and sited so as to benefit especially the younger crop. Historically, breaks between crops have been used as an opportunity to clean and sterilise the glasshouse and to remove the host plant in an attempt to stop pests and diseases from passing from one crop to the next. Pest and disease issues may also require re-assessment with inter-cropping.

3.8.4 Conclusions

The results demonstrate that while early sowing dates give earlier yields of tomato, later sowing dates tend to catch up and may even surpass them in terms of overall yield. Consequently, by sowing tomatoes later than normal, it is possible to obtain the same yield as before but with the use of less energy. However, the grower has to balance this improvement in the energy efficiency of production against other issues, such as the market's need for continuity of supply.

3.8.5 Research requirements

- Further research is required to assess the optimum dates for sowing when inter-cropping of tomatoes is used. In addition, it is important to examine how supplementary lighting might be used with inter-cropping, including where to put the lamps in relation to the plants that are to benefit, the best type of lamp to use, and the likely interaction between sowing date and use of supplementary lighting. These requirements are also discussed elsewhere;
- There is a case for re-examining the effect of sowing date on the efficiency of energy usage by other protected salad crops.

3.9 Other Energy Saving Techniques

The previous sections of this report have considered a number of areas of technology, all of which have the potential to improve the energy efficiency of protected crop production. One area that has not been mentioned is that of good housekeeping, equipment maintenance, etc. Although the role of these areas is not well documented in the scientific literature, there is clear practical evidence that these techniques can have a significant impact on the energy efficiency of a business. For example the government's Action Energy programme quotes that many businesses in both the commercial and industrial sectors can save up to 10% on energy costs through improved energy management procedures and the use of techniques such as energy monitoring and targeting. All growers should therefore address this area before considering investment in more complex techniques and technologies.

Practical evidence suggests that many growers know their energy bill down to the last £1, but what they don't know is how much energy they have actually used, or the levels of production associated with it. An example of good practice is that used by the tomato growers in the UK that participate in the tomato working groups. The energy and crop registration data they collect forms an excellent basis for comparing performance, both between individual businesses and from year to year. By collecting detailed energy use data and relating it to factors including crop production, weather conditions, etc., benchmarks can be set and performance exceptions easily identified. It is therefore recommended that the role of these schemes should be extended and replicated across all protected crop sectors.

Other simple management tasks which involve 'no cost' or 'low cost' solutions should also be examined by all growers. These include actions such as replacement of broken panes of glass, glass cleaning and replacing inefficient pipe insulation.

In response to the introduction of CCL, and to focus the attentions of growers towards simple housekeeping and management, the NFU, in association with the Government's Action Energy programme, published a 'Top 10 Tips' poster for growers (2001). All growers should take note of the points detailed on this document and apply the technologies to their business if they have not already done so. Furthermore growers need to examine energy use on a more regular basis than is currently carried out. This should be done by regularly carrying out energy audits, setting action plans and reviewing performance improvements against targets that have been set.

3.9.1 Conclusions

General housekeeping and maintenance is an area that is overlooked by many growers but has the potential for excellent short-term returns. Growers should therefore first address simple areas where improvements can be made.

4 Developments in Other Countries

The political and economic needs for energy saving and for improved energy efficiency are driving developments in many countries. Not surprisingly, in view of the size and importance of its protected cropping industry and its geographic proximity to the UK, developments in the Netherlands seem most relevant to our own needs. However, as funding for R&D becomes ever more competitive and is more likely to be provided by commercial customers, so there is increasing reluctance to disclose sensitive information about specific, ongoing work.

4.1 Optimisation of the Environment

The optimisation of aerial environments, especially in relation to CO_2 concentration, humidity and even temperature for specific crops remains an important target of R&D. The topic of whether the present guidelines for humidity control in tomato production could be relaxed in order to improve energy saving is the subject of a current research programme by Dr. Stanghellini and her colleagues at IMAG, Wageningen. In addition, Professor Challa of the Horticultural Farm Technology Group at Wageningen, is developing a humidity control regime based more closely on the responses of crops to humidity. The regime is designed to be operated together with temperature integration strategies. At present, Körner & Challa have tested the approach with AYR chrysanthemum, where they found that annual energy consumption could be reduced by at least 19%. It is their intention to extend the programme to salad crops. In a rather similar but much broader project, Westland Energie Services is developing a decision support system called 'Dymos' that has the objective of enabling growers to optimise the use of energy and enhance the quantity, quality, and timing of production. It uses simulation models to predict plant growth and greenhouse climate based on actual weather and weather forecasts. The project is intended to cover the production of tomato, cucumber and sweet pepper as well as ornamental crops and the models were developed at Plant Research International, Wageningen and at Wageningen University (Kamp & van der Veen, 2002).

As discussed in the Chapter on 'Optimisation of Inputs', CO_2 would be used more efficiently if its concentration could be allowed to rise under the high light levels of summer. Restricting ventilation permits this to occur but then the problem is how to deal with the high temperatures that result. Professor Challa also has a research programme at Wageningen that has the objective of producing models of crop photosynthesis that more accurately reflect the photosynthetic performance of different crops at high temperatures and at high concentrations of CO_2. The models will then be used to evaluate optimal ventilation regimes under these extreme conditions. Their work on tomato is about to be published (Körner, Challa & Van Ooteghem, 2002). The Department headed by Dr Derikx at IMAG is looking at the engineering difficulties associated with operating glasshouses with restricted ventilation and at the possibility of cooling glasshouses by means other than ventilation. Evaporative cooling is common in the USA but is thought to require the external ambient humidity to be much lower than is common in northern Europe, even in summer. Alternatives, such as refrigerative cooling and heat pumps have been proposed but have not yet been demonstrated to operate cost-effectively under European conditions.

4.2 Temperature Integration

From discussions with colleagues in the Netherlands it is evident that the topic of temperature integration is currently receiving considerable attention. Work at Plant Research International in Wageningen, at IMAG in Wageningen, at PPO in Naaldwijk and at various computer companies is investigating the potential of using temperature integration with a variety of protected crops. Current trials at PPO and elsewhere are concentrating largely on ornamental crops, but there is continuing interest in the potential of this technique for salad crops, including sweet pepper, cucumber, tomato and lettuce. Recent unpublished research at Plant Research International, Wageningen established that growth of sweet pepper plants was determined by temperature sum in the range of 14-26ºC, irrespective of changes in temperature. However, fruit set was sensitive to temporary changes in temperature and a temporary increase could lead to an increase in flower abortion. It was also observed that large and fast changes in temperature tended to reduce the rate of photosynthesis for a number of days afterwards.

Dutch manufacturers of environmental control computers have developed and are continuing to develop software that uses the principle of temperature integration as at least one component of a package designed to improve the efficiency of energy usage. Many of these computer programs, such as the Hoogendoorn 'Econaut' and Priva's 'Intégro', simply utilise temperature integration to make better use of the solar gain within a glasshouse. However, future developments are likely to make better use of the principle and allow energy saving under what would normally be conditions that have a high energy cost while compensating for this later when the energy cost of raising glasshouse temperature is less. The 'Intelligrow' system also appears to use something akin to temperature integration although the principal objective of the system is to optimise photosynthesis and thereby, growth and yield.

Improved meteorological forecasting is also an important element of maximising the benefit from temperature integration and improved forecasting systems are being developed by the Dutch and the UK meteorological services. The group working under Dr van Henten at IMAG, Wageningen, has developed a climate control system that considers energy efficiency explicitly. It requires the grower to input the cost of energy, the anticipated value of the crop and any limits on the environmental conditions that the grower wishes to impose. The programme then controls the environment dynamically so as to maximise income and to reduce energy consumption. It does this by basing its action upon the known responses of the crop and the glasshouse to changes in internal and external environments and by taking account of the predicted short-term and long-term weather patterns. It is claimed that the system reduces the current usage of natural gas by 10-15%.

4.3 Humidity

We are not aware of any R&D programmes that are currently investigating the direct effect of humidity on crop growth. On the other hand, the topic remains an important element of work on diseases. Mr. Campen at IMAG, Wageningen, has described a project that is investigating methods of dehumidifying well-insulated glasshouses by systems that improve energy efficiency. These systems usually rely on recovering the latent heat of evaporation by condensing water and then returning that energy to the glasshouse. Mr. Campen's system uses a heat pump to do this.

4.4 Thermal Screens

Thermal screens offer the biggest opportunity to improve energy efficiency as, on average, the use of a thermal screen at night enables up to 38-45% less energy to be used over each 24-hour period in winter (see Chapter on 'Thermal Screens'). Consequently, various companies in Scandinavia and the Netherlands are developing improved thermal screens as well as screens that can serve both as shade screens and as energy-saving screens. Some of these are being tested under UK conditions but there is a need to maintain a 'watching brief' on developments in this field and to ensure that the most effective screen materials are tested in appropriate demonstration projects and the results given wide publicity.

4.5 Light

Many glasshouse manufacturers in the Netherlands are introducing tempered glass sheets that are wider and longer than before and so improve overall light transmission. One novel development in cladding materials is the double polycarbonate, 'ZigZag' sheet, made by General Electric Plastics of Belgium. This was exhibited in the 'Greenhouse of the Future' at the Floriade 2002 and is claimed to improve insulation and roof rigidity with less light-loss than with conventional double-glazed claddings with glazing bars. The material is being evaluated by IMAG in Wageningen. The Greenhouse Production Engineering Department of IMAG is also continuing to investigate novel glasshouse designs with the twin objectives of improving light transmission and insulation. These objectives may require the development of entirely new glazing materials, one of which might be “Nano-foam” which was discussed by Dr Derikx at the HDC/HRIA/TGA 2000 Tomato Conference. Supplementary lighting for salad crops is being investigated by Hortilux Schréder in the Netherlands, both in collaboration with PPO, Naaldwijk and with individual growers and especially in connection with the use of electricity generated by dedicated CHP units.

4.6 New Cultivars

There is a tendency to overlook the contribution that new cultivars have made to improved energy efficiency and will probably continue to make to this objective. Unfortunately, none of the important breeders of protected salad crops are based in the UK. Nevertheless, Dutch companies are breeding for similar environments to our own and the needs of the Dutch industry are also similar to our own. Within the Horticultural Chains Group in Wageningen University, Dr. Heuvelink and his colleagues are investigating the anatomical and physiological characteristics of tomato that might be required if breeders are to succeed in producing new cultivars that are less energy demanding. Preliminary results suggest that the most desirable traits include the production of fewer and thinner leaves between trusses and the diversion of a greater proportion of available assimilates to fruits.

4.7 Management of the Energy Supply

In addition to temperature integration, there are other software improvements relating to energy saving. Priva's 'Intégro' program has specific energy management sub-routines that are designed to improve the total energy management of the glasshouse, covering everything from boilers and dump tanks to the generation and supply of CO_2 and the co-operative purchasing of energy.

Another example of this approach is the 'Kebus' system developed by Westland Energie Services that optimises heating systems by controlling the burning rates of boilers or CHP units so as to maintain buffer tanks at a constant temperature. One objective of this system is to smooth the 'maximum demand' requirements for gas as this is an important determinant of energy costs in the Netherlands. Much of the monitoring and control of such systems can be done via telephone links to a central computer.

Although the participating nurseries do not have to be in close proximity to one another there are advantages in having glasshouses concentrated in specific regions, such as the Westland area of the Netherlands. From the perspective of improving energy efficiency, one distinct advantage is that it is feasible for a number of growers to share CO_2, heat and electricity supplies from very local generation facilities as well as sharing information and expertise. Hence, perhaps, the increased interest in the UK in locating glasshouses adjacent to generators of waste or surplus heat, such as sugar refining plants run with CHP units.

The Westland Energie Services company also operates energy audits for glasshouse owners, advising on temperature uniformity within glasshouses and on energy sensitive components of the glasshouse growing system. The company has the capability too to advise on sources of energy and is a supplier of energy. However, many aspects of energy supply and energy pricing are very different from those in the UK and so a number of developments that are cost-effective in the Netherlands may not be so effective in the UK.

4.8 Improved Technology

At present, many new technologies are on trial around the world but few appear to be likely to have much of a direct impact upon the efficiency of energy usage in edible crops. The cultivation of high density, short-life salad crops using supplementary lighting may increase the efficiency of energy usage but it also requires high capital investment. An intensive system of tomato production such as that developed some years ago at Rutgers University, USA (e.g. McAvoy & Giacomelli, 1986), is very dependent upon a source of cheap electricity to power the supplementary lighting that is needed to maintain high levels of productivity in winter. Such systems, employing high crop densities growing on mobile benches, have appeal in the UK while electricity prices are relatively low for they reduce labour costs and could also easily be linked to systems of robotic picking.

There is much interest in the potential of "inter-cropping", which in the present context means starting a second crop in the same glasshouse as the first crop. The system has some impact on energy efficiency as the second crop is raised in the same environment as the first and it extends the cropping season and may even make it almost year-round. In terms of efficiency of energy usage rather than the desire to secure continuity of supply, the main problem must be that any solar radiation absorbed by the second crop is largely at the expense of the first crop. Hence, it represents a probable reduction in yield of the first crop. However, the financial benefits from continuity of supply to the markets may justify the approach and may also justify the use of supplementary lighting to boost the amount of light intercepted by the second crop and hence its yield in winter. There is a strong case for examining which type of lamp to use and where to locate the lamps in relation to the second crop in the case of tomato and to consider inter-cropping systems in relation to the production of other protected salad crops.

Economic considerations are also the major barrier to the adoption of other technological advances that offer the opportunity to make production more intensive. 'Rotagrow' is one such system that uses only artificial light sources to maintain tomato plants producing fruits all year round. However, the capital cost of such a system is likely to be considerable. Similar economic problems apply to closed systems that depend upon refrigeration either for cooling or for dehumidifying, such as the recently promoted 'Greengro' system marketed by Unigro Ltd. (Rogers, 2002). Such systems have more chance of becoming economically worthwhile if the cost of electricity falls further or if they are allied to a cost-effective CHP system that enables them to use the low-cost electricity for cooling or for dehumidification.

'Hanging gutter' systems for tomato are on trial in the Netherlands and also at the Windsor Research Station in Ontario, Canada but their contribution to energy efficiency may be only through their possible use in inter-cropping.

Developments in the use of renewable energy sources, such as solar, wind and biomass, especially when they are generated locally, are being pursued both in the UK and within

Europe. They offer possible energy and cost savings in the longer term and glasshouse growers should keep a 'watching brief' on such developments (e.g. Von Zabeltitz, 1988).

4.9 Conclusions

UK researchers and growers need to maintain contact with researchers at Plant Research International and IMAG, both of which are in Wageningen, as well as with PPO in Naaldwijk as there are many developments taking place at these centres that have bearing on improved energy efficiency.

5 Conclusions

The literature examined and analyses carried out have revealed that there are a number of established technologies that can be used to improve the current energy performance of edible crop production in the UK. However, it must be noted that changes in one factor may have impact on others for most of them are interconnected. For example, the production of CO_2 from flue gases may require heat to be dissipated, which might impact on humidity and temperature control. Similarly, temperature integration can have impact both on humidity and on the average CO_2 concentration, especially if vents are kept closed for longer by day. Finally, humidity control may impact directly upon productivity, via an influence on the average CO_2 concentration, if the control measure affects vent opening by day. To help growers asses these interactions and allow optimisation of inputs and outputs to be achieved models of crop responses to light, CO_2 temperature, and humidity are needed in order to optimise photosynthesis in terms of energy efficiency. Such models will enable computers to control the environment in a dynamic manner in relation to changes in the amount of light reaching the crop; the one factor that is not under the grower's immediate control.

Putting aside any reservations relating to the interaction of variables, the most promising technologies are as follows:

5.1 Temperature Integration

The literature shows that edible crops can be successfully grown using temperature averaging or temperature integration control strategies. What is less certain, however, is that the technology is being widely used on a commercial basis. Commercial demonstrations have shown that growers remain to be convinced of the practicality of such an approach and, as a result, uptake to date is limited. From an economic point of view however, the use of this technology is one of the most attractive as it has the ability to payback in periods of less than 18 months.

Specific conclusions are:

- Making use of temperature integration by plants has the *potential* to save between 10 and 15% of the energy currently used to produce most protected edible crops. As yet, however, there is little information about the *actual* amounts of energy that can be saved. Trials are needed in which temperature integration, in conjunction with prevailing and forecast weather conditions, is used for the sole purpose of making energy savings;
- This dynamic approach to temperature control produces environmental conditions that may be very different from those that most growers are used to and so, in order for the

approach to be widely accepted, it may be necessary to run a number of demonstration projects in different areas of the country;

- Further R&D is required to establish the limits of temperature integration for different crops and to provide the information that will give growers more confidence in the technique.

5.2 Humidity Control

The conservative use of 'minimum pipe' temperatures is considered to be prevalent throughout the protected edibles sector in the UK. Whilst this offers an excellent 'insurance policy' by maintaining crop development and preventing disease (e.g. *Botrytis*), it is expensive from an energy consumption point of view. Use of more relevant humidity control strategies, which in turn lead to less dependence on pipe heat, can make a significant impact on energy consumption for little or no capital outlay.

Against this background the specific conclusions are:

- At present, control of humidity uses about 15 to 25% of all the energy required to produce a crop of heated tomatoes. It should be possible, therefore, to relax the current humidity control settings and, provided that it is done within the above constraints, the strategy should generate energy savings without any significant loss of either yield or quality with any of the major salad crops;
- In order to maximise crop growth the average humidity should be kept to a VPD equal to or larger than 0.3 kPa. This VPD does not have to be maintained continuously but, most probably, can be averaged over at least 24 hours. With cucumber, however, it seems that it cannot be averaged over 24 hours as fruit yield was increased by high humidity by day;
- Humidity control is also required to restrict the spread of fungal diseases. Indeed, ventilation has been recommended as the simplest way of controlling such diseases of tomato and lettuce (e.g. Morgan, 1984a,b). The current dilemma, is whether to control humidity at a specific RH at all temperatures, at a specific VPD or to produce an environment that avoids condensation on leaves and fruits. Until these uncertainties are resolved, any relaxation of the criteria for humidity control should be gradual and the grower should be satisfied that the relaxation has not led to any increased incidence of fungal disease before they are relaxed further;
- Most importantly, with *Botrytis*, there is evidence now that a very high RH (>90%) can be tolerated for up to three hours provided that the RH is then lowered by means of, for example, a heat boost (O'Neill, 2001);

- If growers are using a policy of temperature integration, they should review their HD settings at higher greenhouse temperatures because the strategy may give unacceptable levels of RH (i.e. in excess of 90%) at higher temperatures.

5.3 Thermal Screens

From an energy-saving perspective, thermal screens undoubtedly have an important role to play in the future. Recent designs have significant advantages over those previously used, especially in terms of the shade they cause, and also humidity control. What remains unanswered is what is the effect of new screen designs on crop yield. Limited commercial trials and the claims of manufacturers suggest that the effect is minimal. If this is the case then thermal screens offer a good potential for medium term investments.

Specific conclusions are therefore:

- Thermal screens have the potential to produce even greater savings in energy efficiency if they are combined with temperature integration, for higher temperatures might be run when the screen is drawn over the crop and lower ones when it is retracted;
- Demonstrations of the commercial uptake of the use of screens on edible crops are required before wide commercial uptake across all protected edible crops is achieved.

5.4 Combined Heat & Power (CHP)

The current balance between gas price and electricity price is such that CHP is unlikely to be an economic proposition for edible crop nurseries in the UK. Because the heat demand of a greenhouse is considerably greater than the electricity demand, CHP is only viable if a third party buyer for the electricity can be found. Because of the current low retail price of electricity this is likely to be difficult but this is likely to change in the future.

Alternative installation approaches may be taken. One of the most promising is to use small scale CHP to provide the ‘base load’ electricity demand of the nursery. In this case the heat (and CO_2) generated by the CHP will only make a small contribution to the overall site demand. Even using this approach, the high capital costs of CHP and long payback periods are likely to make installations unattractive.

The specific conclusion is therefore that:

- UK horticulture should take a ‘watching brief’ on developments in both CHP technology and CHP markets such that it is in a position to adopt the technology when it is economically viable to do so.

5.5 Supplementary Lighting

Supplementary lighting potentially offers edible crop growers enormous promise for improving current production systems. Not only does it have a role to play in improving the energy efficiency of production, it can also help in areas such as market development, efficiency of labour use and better utilisation of greenhouse facilities. There are currently a number of areas which are likely to inhibit commercial uptake however, not least being the capital expenditure that is required to equip a greenhouse with the lighting equipment and energy supply infrastructure required for a successful project.

Specific conclusions are:

- Many of the predictions regarding the effectiveness of supplementary lighting are based on theoretical predictions of crop response;
- There is little evidence of practical information on commercial application of the technique;
- From an energy efficiency perspective, the most successful lighting installations are likely to require the use of CHP. This further complicates the situation as further capital investment is then required.

5.6 Planting Date

Although research suggests it is advantageous to clear out glasshouses and prepare for the next crop when the cost of heating is at its maximum (and the solar radiation levels are at their lowest) it is not necessarily the most economically successful strategy. Therefore, while it is possible to improve the energy efficiency of production using a later sowing, and obtain the same yield with the use of less energy or an even greater yield if “pulling out” is delayed, the grower has to balance these aspects against other issues. In particular, there is the market's need for continuity of supply and the tomato crop's tendency to produce very large fruit if planted later. Bearing these comments in mind it is unlikely that a delayed planting date has widespread appeal for the broad range of edible crops that are grown.

The specific conclusion is therefore that:

- Experimental results demonstrate that while early sowing dates give earlier yields of tomato, later sowing dates tend to catch up and may even surpass them in terms of overall yield. Consequently, by sowing tomatoes later than normal, it is possible to obtain the same yield as before but with the use of less energy. However, the grower has to balance this improvement in the energy efficiency of production against other issues, such as the market's need for continuity of supply.

5.7 General Housekeeping

Although this is a simple technology it has widespread application over all protected crops sectors. In addition it can give excellent rewards with quick payback.

Because it is viewed by many growers as being unexciting, many growers ignore many of the simple improvements that can be made. With this in mind growers should be encouraged to go 'back to basics' and carry out more formal energy management practices including energy monitoring and targeting, energy auditing and regular maintenance of energy equipment.

5.8 Overall Summary

Taking all of the above conclusions into consideration, growers should immediately focus on the use of improved control strategies to improve energy efficiency. In the medium term, thermal screens should be considered. Growers that have already addressed these areas or who are considering longer-term solutions may further examine the role of technologies such as supplementary lighting.

It is often felt that much of the R&D work required by UK growers is already being carried out in the Netherlands. In the area of energy efficiency this is not necessarily the case, especially bearing in mind that the Dutch have very different energy market pressures when compared to those in the UK. For example their new gas laws are driving growers to reduce peak demands for gas, which is resulting in the development of technologies which are specific to the needs of the Dutch industry (e.g. Kebus and open buffer heat storage systems). Also technologies such as temperature integration are being used in a different way, again with the prime purpose of reducing peak demands. Having said that, work in other countries, and particularly the Netherlands, can provide excellent information for specific application to the UK. It is therefore recommended that:

- UK researchers and growers need to maintain contact with researchers at Plant Research International and IMAG, both of which are in Wageningen, as well as with PPO in Naaldwijk as there are many developments taking place at these centres that have bearing on improved energy efficiency.

6 Recommendations for Future Work

It must be recognised that there are a number of barriers to uptake of even the most promising technologies. With this in mind both technology transfer and research must continue in order that growers achieve the potential improvements that are available.

This project highlights a number of areas where UK growers require further work to be carried out before energy-saving technologies can be widely commercially adopted. The key areas are as follows.

6.1 Temperature Integration

It has been highlighted that growers are reluctant to apply temperature-integration techniques because they remain to be convinced that crop performance will not suffer when the technique is used on a commercial basis.

To overcome this barrier to uptake growers need to know:

- the actual energy savings that are likely to be achieved. For this, trials need to be conducted in which temperature integration is used, in conjunction with prevailing and forecast weather conditions, for the sole purpose of making energy savings;
- the optimum 24-hour average temperature for the most rapid development commensurate with satisfactory yield and quality for each of the main protected edible crops;
- the largest temperature variation that can be tolerated by these crops, especially tomato, cucumber, and sweet pepper;
- the maximum duration over which such deviations from the temperature norm can be tolerated;
- whether the optimum 24-hour average temperature varies with the stage of crop development or with other aspects of the aerial environment, especially the daily integral of solar radiation.

6.2 Humidity Control

Better knowledge of the limiting factors for both crop transpiration and disease control would enable tighter limits on humidity control to be set. Also, in the longer term, the use of leaf & fruit temperature measurement will enable a better indication of the plant/air microenvironment to be obtained. Again this will assist in allowing energy inputs for humidity control to be better managed. It is therefore recommended that some work on the fundamental aspects of plant/humidity relationships be carried out together with work on defining more closely the precise humidity conditions that favour spread of disease and whether these conditions are best defined by RH or HD. Any work should specifically address the following areas:

- An urgent priority is to establish the moisture-related factors that control germination of fungal spores and the spread of fungal diseases on crop plants. In particular, it is important to know whether the spores of specific diseases require to be in free water or to have the surrounding air at a particular RH, HD, or VPD;
- If it is the humidity of the surrounding air that is more important than the presence of free water, it is most important to establish the maximum length of time that a specific high humidity can be tolerated without risk of disease. This needs to be established for each of the main fungal diseases of tomato, cucumber, and sweet pepper;
- Further R&D is required to confirm that the growth and yield of protected salad crops responds either to humidity or to transpiration integrated over time and to establish the limits of such integration for the different salad crops;
- All of the above findings from R&D need to be incorporated into realistic procedures that will save energy as well as avoiding both risk of disease and risk of calcium deficiency;
- There is also a need to develop, test and demonstrate cost-effective dehumidification systems. These might include heat pump dehumidification linked to a CHP unit. Other commercial systems have also been proposed and these need independent evaluation at a practical demonstration level.

6.3 Thermal Screens

The main barrier to the uptake of thermal screens is convincing evidence that, when screens are used, crop yield and quality will not be depressed so much as to make the use of the screens uneconomic. To over come this the following work is recommended.

- Development and demonstration work should be carried out to allow growers to see that crops can be successfully and profitably grown in greenhouses equipped with the new generation of thermal screens.

6.4 Supplementary Lighting

Potentially this technology could have an enormous impact on the protected edibles sector in the UK. However, before the technology can advance to wider commercial uptake, further investigations will be required at the levels both of strategic and applied science. These investigations should include the following:

- the physiological response of crops to supplementary lighting;
- the effect of supplementary lighting (and the resulting greenhouse environment) on the incidence of pests & diseases;

- the requirements for all year round production including inter-planting and the optimisation of cultural practices including irrigation, CO_2 enrichment, etc.;
- the energy balance of greenhouses equipped with supplementary lighting equipment at the intensities required to optimise production.

Completion of the above work will ensure that the economic and environmental performance of production systems using supplementary lighting is optimised. It is likely that some of this work could proceed in partnership with many of the leading companies, all of whom are looking at the technology with interest.

6.5 General Housekeeping

There is a shortage of up to date concise information giving practical details on energy management practices and procedures. In addition many growers do not have the access to information that enables them to assess the financial impact of simple upgrades such as insulation replacement, glass cleaning, etc. With this in mind the following is recommended:

- Simple 'grower guides' should be produced. These should contain accessible facts that will enable growers to improve energy management practices and evaluate the financial benefit of making simple improvements on the nursery;
- Standard energy audit packages/protocols should be developed to enable growers to easily asses performance on a regular basis.

References

Aaslyng, J.M., Ehler, N., Karlsen, P. & Rosenquist, E. (1999). IntelliGrow: a component-based climate control system for decreasing greenhouse energy consumption. *Acta Horticulturae,* 507: 35-41.

Acock, B. (1991). Modeling canopy photosynthetic response to carbon dioxide, light interception, temperature and leaf traits. In: Boote, K.J. & R.S. Loomis (Eds). *Modeling Crop Photosynthesis from Biochemistry to Canopy*. Crop Science Society of America, Special Publication 19; 41-55. CSSA, Madison, USA.

Anon, (1998). Application of energy saving cultivation method based on temperature integration within 24 hours. Research Station for Floriculture & Glasshouse Vegetables, Netherlands. 1998.

Aikman, D.P. & Picken, A.J.F. (1989). Wind-related temperature setting in glasshouses. *Journal of Horticultural Science*, 64; 649-654.

Aikman, D., Dungey, N. & Graves, C. (1992). The answer is blowing in the wind. *Grower* (05.03.1992); 34-35.

Bailey, B.J. (1985). Wind dependent control of greenhouse temperature. *Acta Horticulturae*, 174; 381-386.

Bailey, B. (1993). New ways to save energy. *Grower,* 119, (16), 27-28.

Bailey, B.J. (1994). *Optimal Control of Greenhouse Climate.* Final Report, HDC PC 49.

Bailey, B.J. (2002). *Tomatoes: Guidelines for CO_2 enrichment.* HDC Grower Guide.

Bailey. B J & Ellis, R.G. (1989). The potential for using Combined Heat & Power (CHP) in greenhouses. AFRC Institute of Engineering DN1523.

Bailey, B.J. & Seginer, I. (1989). Optimum control of greenhouse heating. *Acta Horticulturae*, 245; 512-518.

Bakker, J.C. (1989a). The effects of air humidity on growth and fruit production of sweet pepper (*Capsicum annuum* L.). *Journal of Horticultural Science* 64; 41-46.

Bakker, J.C. (1989b). The effects of air humidity on flowering, fruit set, seed set and fruit growth of glasshouse sweet pepper (*Capsicum annuum* L.). *Scientia Horticulturae* 40; 1-8.

Bakker, J.C. (1990a). Effects of day and night humidity on yield and fruit quality of glasshouse tomatoes (*Lycopersicon esculentum* Mill.). *Journal of Horticultural Science* 65; 323-331.

Bakker, J.C. (1990b). Effects of day and night humidity on yield and fruit quality of glasshouse eggplant (*Solanum melongena* L.). *Journal of Horticultural Science* 65; 747-753.

Bakker, J.C. (1991). Analysis of humidity effects on growth and production of glasshouse fruit vegetables. Dissertation, Agricultural University, Wageningen, The Netherlands, 155pp.

Bakker, J.C. (1998). Handhaven minimum buis beperkt energiebesparing, *Groenten en Fruit (Glasgroenten)*, 8(45)(06.11.98); 22-23.

Bakker, J.C. & Sonneveld, C. (1988). Calcium deficiency of glasshouse cucumber as affected by environmental humidity and mineral nutrition. *Journal of Horticultural Science*, 63; 241-246.

Bakker, J.C. & van Uffelen, J.A.M. (1988). The effects of diurnal temperature regimes on growth and yield of glasshouse sweet pepper. *Netherlands Journal of Agricultural Science*, 36; 201-208.

Bakker, J.C., Welles, G.W.H. & van Uffelen, J.A.M. (1987). The effects of day and night humidity on yield and quality of glasshouse cucumbers. *Journal of Horticultural Science*, 62; 363-370.

Bakker, J.C., Bot, G.P.A., Challa, H. & Van de Braak, N.J. (1995). *Greenhouse Climate Control*. Wageningen Pers, Wageningen, The Netherlands, 279pp.

Blain, J,. Gosselin, A. & Trudel, M.J., (1987). The effect of HPS supplementary lighting on the growth and yield of greenhouse cucumbers. HortScience 22: 36-38.

Bot,G.P.A. (1983).Greenhouse climate: from physical processes to a dynamic model. Ph.D. thesis, Agricultural University, Wageningen, Netherlands.

Butters, R.E. (1987). Is it worth gapping back? *Grower* (19.03.87).

CADDET Energy Efficiency. (1999). CHP plant supplies energy and CO_2 fertiliser for greenhouses. *Result Factsheet No.358.*

Chalabi, Z.S., Bailey, B.J. & Wilkinson, D.J. (1998), A Real Time Optimal Control Algorithm for Greenhouse Heating. *Computers in Agriculture*.

Chalabi, Z.S., Biro, A., Bailey, B.J., Aikman, D.P. & Cockshull, K.E. (2002a). Optimal control strategies for carbon dioxide enrichment in greenhouse tomato crops – Part 1: Using pure carbon dioxide. *Biosystems Engineering* 81; 421-431.

Chalabi, Z.S., Biro, A., Bailey, B.J., Aikman, D.P. & Cockshull, K.E. (2002b). Optimal control strategies for carbon dioxide enrichment in greenhouse tomato crops, Part II: Using the exhaust gases of natural gas fired boilers. *Biosystems Engineering* 81; 323-332.

Cockshull, K. E. (1989). The influence of energy conservation on crop productivity. *Acta Horticulturae*, 245; 530-536.

Cockshull, K. E. (1992). Crop environments. *Acta Horticulturae*, 312; 77-85.

Cockshull, K. E. (1993). Temperature averaging. *Grower,* 119, (16), 27-28.

Cockshull, K.E. & Hand, D.J. (1993). The effects of summer humidification on fruit quality and yield. Report on HDC Projects 30 and 30a.

Cockshull, K.E., Adams, S.R., & Plackett, C.W. (2002). Smart temperature control. *Grower* (03.10.02), 20-21.

Cockshull, K.E., Graves, C.J. & Cave, C.R.J. (1992). The influence of shading on yield of glasshouse tomatoes. *Journal of Horticultural Science*, 67; 11-24.

Cockshull, K.E., Langton, F.A. & Hand, D.W. (1981). The effects of day and night temperature on flower initiation and development in chrysanthemum. *Acta Horticulturae*, 125; 101-110.

Cockshull, K. Edmondson, R., Butters. R. & Bailey, B. (1989). Screened for the benefits. *Grower*, 112 (2) Suppl; (37-44).

De Graff, R. (1985). The influence of thermal screening and moisture gap on the transpiration of glasshouse tomatoes during the night. *Acta Horticulturae* 174: 57-66.

Drakes, G.D. (1980). The use of industrial heat in protected cropping. *ADAS Quarterly Review*, 37; 63-68.

de Koning, A.N.M. (1988a). An algorithm for controlling the average 24-hour temperature in glasshouses. *Journal of Horticultural Science*, 63; 473-477.

de Koning, A.N.M. (1988b). More efficient use of base load heating with a temperature integrating control programme. Effect on development, growth and production of tomato. *Acta Horticulturae*, 229; 233-237.

de Koning, A.N.M. (1988c). The effect of different day/night temperature regimes on growth, development and yield of glasshouse tomatoes. *Journal of Horticultural Science*, 63; 465-471.

de Koning A.N.M. (1990). Long-term temperature integration of tomato. Growth and development under alternating temperature regimes. *Scientia Horticulturae*, 45; 117-127.

Erwin, J.E. & Heins, R.D. (1987). Thermomorphogenic responses in stem and leaf development. *HortScience*, 30; 940-949.
Gosselin, A., (1988). Profitability of high irradiance supplemental lighting for greenhouse production in Canada. Report 636 U 582 for the Canadian Electrical Association, Montreal. 73pp.
Grange. R.I. & Hurd, R.G. (1983). Thermal screens - Environmental and plant studies. *Scientia Horticulturae*, 19; 201-211.
Hand, D.W. (1984). Crop responses to winter and summer CO_2 enrichment. *Acta Horticulturae* 162; 45-63.
Hand, D.W., Warren Wilson, J. & Acock, B. (1993). Effects of light and CO_2 on net photosynthetic rates of stands of aubergine and *Amaranthus*. *Annals of Botany*, 71; 209-216.
Hand, D.W., Clark, G., Hannah, M.A., Thornley, J.H.M. & Warren Wilson, J. (1992). Measuring the canopy net photosynthesis of glasshouse crops. *Journal of Experimental Botany*, 43; 375-381.
Heuvelink, E. (1996). Tomato growth and yield: quantitative analysis and synthesis. Dissertation, Wageningen Agricultural University, Wageningen, The Netherlands, 326pp.
Holder, R. & Cockshull, K.E. (1990). Effects of humidity on the growth and yield of glasshouse tomatoes. *Journal of Horticultural Science*, 65; 31-39.
Huber, L. & Gillespie, T.J. (1992). Modeling leaf wetness in realtion to plant disease epidemiology. *Annual Review of Phytopathology*, 30; 553-557.
Hurd, R.G. & Graves, C.J. (1984). The influence of different temperature patterns having the same integral on the earliness and yield of tomatoes. *Acta Horticulturae*, 148; 547-554.
Jolliet, O., Bailey, B.J., Hand, D.J. & Cockshull, K.E. (1993). Tomato yield in greenhouses related to humidity and transpiration. *Acta Horticulturae* 328; 115- 124.
Jolliet, O., Danloy, L., Gay, J.B., Munday, G.L. & Reist, A. (1991). HORTICERN: An improved static model for predicting the energy consumption of a greenhouse. *Agricultural and Forest Meteorology,* 55; 265-294.
Kamp, P.G.H. & van der Veen, W.M.P. (2002). The integration of monitoring and decision support systems in Dutch horticulture. *Acta Horticulturae* (in press).
Kamp, P.G.H. & Timmerman, G.J. (2002). *Computerised Environmental Control in Greenhouses*. (2nd Edn.). IPC Plant, Dier Ede, The Netherlands, 260pp.
Körner, O., Challa, H. & Van Ooteghem, R.J.C. (2002). Modelling temperature effects on crop photosynthesis at high radiation in a solar greenhouse. *Acta Horticulturae* (in press).
Krug, H. & Liebig, H.-P. (1980). Diurnal thermoperiodism of the cucumber. *Acta Horticulturae*, 118; 83-94.
Langhans, R.W., Wolfe, M. & Albright, L.D. (1981). Use of average temperatures for plant growth for potential energy savings. *Acta Horticulturae*, 115; 31-37.
Langton, F.A. & Cockshull, K.E. (1997). Is stem extension determined by DIF or by absolute day and night temperatures? *Scientia Horticulturae*, 69; 229-237.
Liebig, H.-P. (1988). Temperature integration by kohlrabi growth. *Acta Horticulturae*, 230; 371-380.
McAvoy, R.J. & Giacomelli, G.A. (1986). Greenhouse tomato production in a transportable, potted plant cropping system. *Acta Horticulturae*, 187; 107-113.
Morgan, W.M. (1984a). The effect of night temperature and glasshouse ventilation on the incidence of *Botrytis cinerea* in a late-planted tomato crop. *Crop Protection* 3; 243-251.

Morgan, W.M. (1984b). Integration of environmental and fungicidal control of *Bremia lactucae* in a glasshouse lettuce crop. *Crop Protection* 3; 349-361.
Nederhoff, E.M. (1994). Effects of CO_2 concentration on photosynthesis, transpiration and production of greenhouse fruit vegetable crops. Dissertation, Agricultural University, Wageningen, The Netherlands, 213pp.
Nederhoff, E.M. & Vegter, J.G. (1994a). Photosynthesis of stands of tomato, cucumber and sweet pepper measured in greenhouses under various CO_2 concentrations. *Annals of Botany* 73; 353-361.
Nederhoff, E.M. & Vegter, J.G. (1994b). Canopy photosynthesis of tomato, cucumber and sweet pepper measured in greenhouse; measurement compared to models. *Annals of Botany* 73; 421-427.
O'Neill, T. (2001). Integrated chemical and environmental control of grey mould (*Botrytis cinerea*) in protected container-grown ornamentals. Fourth Annual Progress Report LINK Project (Hort 25).
Papadopoulos, A.P. & Hao, X. (2000). Effects of day and night air temperature on growth productivity and energy use of long English cucumber. *Canadian Journal of Plant Science*, 80; 143-150.
Papadopoulos, A.P. & Ormrod, D.P. (1990). Plant spacing effects on yield of the greenhouse tomato. *Canadian Journal of Plant Science*, 70; 565-573.
Plaisier, H. (2001). Cost or Profit – the question of energy screens. *Commercial Greenhouse Grower*, December 2001.
Reddy, V.R., Pachepsky, L.B. & Acock, B. (1994). Response of crop photosynthesis to carbon dioxide, temperature, and light: Experimentation and modeling. Hortscience, 29; 1415-1422.
Rogers, P. (2002). Shades of green. *Grower* 138 (36) (05.09.02); 16-19.
Rosenquist, E & Aaslyng, J.M. (2000). IntelliGrow – a new climate control concept. *Grøn Viden* No 122. Danish Institute of Agricultural Sciences, Tjele, Denmark, 8pp.
Salisbury, F.B. & Ross, C.W. (1985). *Plant Physiology* (Third Edition). pp 409-425.
Slack, G. & Hand, D.W. (1983). The effect of day and night temperature on the growth, development and yield of glasshouse cucumbers. *Journal of Horticultural Science*, 58; 567-573.
Slack, G. & Hand, D.W. (1985). The effect of winter and summer CO_2 enrichment on the growth and fruit yield of glasshouse cucumber. *Journal of Horticultural Science*, 60; 507-516.
Slack, G., Fenlon, J.S. & Hand, D.W. (1988). The effects of summer CO_2 enrichment and ventilation temperatures on the yield, quality and value of glasshouse tomatoes. *Journal of Horticultural Science*, 63; 119-129.
Spaargaren, J.J. (2001). *Supplemental Lighting for Greenhouse Crops.* Hortilux Schreder b.v. & P.L.Light Systems Inc.
Stanghellini, C. (1987). Transpiration of greenhouse crops. An aid to climate management. Dissertation, Agricultural University, Wageningen, The Netherlands, 150pp.
Stanghellini, C. & Van Meurs, W.T.M. (1992). Environmental control of greenhouse crop transpiration. *Journal of Agricultural Engineering Research* 51: 297-311.
Starkey, N.G. (1985). The effect of secondary glazing and fixed screens on greenhouse environment and crop response of tomatoes. *Acta Horticulturae* 174; 331-339.
Steekelenberg, N.A.M. van & Welles, G.W.H. (1988). Influence of day/night humidity and cation ratios and concentration in the nutrient solution on incidence *of Didymella bryoniae* in glasshouse cucumbers. *Netherlands Journal of Agricultural Science* 36; 225-230.

Thornley, J.H.M., Hand, D.W. & Warren Wilson, J. (1992). Modelling light absorption and canopy net photosynthesis of glasshouse row crops and application to cucumber. *Journal of Experimental Botany*, 43; 383-391.

Van Bavel, C.H.M., Takakura, T. & Bot, G.P.A. (1985). Global comparison of three greenhouse climate models. *Acta Horticulturae* 174; 21-33.

van den Berg, G.A. (2000). Belichten bij tomaten (Lighting of tomatoes*). Groenten en Fruit / Vkd Glasgroenten* 31; 15.

van den Berg, G.A., Buwalda, F. & Rijpsma, E.C. (2001). *Practical demonstration Multi-day Temperature Integration*. PPO 501. Praktijkonderzoek Plant & Omgeving, Wageningen, The Netherlands, 53pp.

Von Zabeltitz, C. Ed. (1988). Energy Conservation and Renewable Energies for Greenhouse Heating. FAO, Roma, Italy.

Warren Wilson, J., Hand, D.W. & Hannah, M.A. (1992). Light interception and photosynthetic efficiency in some glasshouse crops. *Journal of Experimental Botany*, 43; 363-373.

Winspear, K.W., Postlethwaite, J.D. & Cotton, R.F. (1970). The restriction of *Cladosporium fulvum* and *Botrytis cinerea,* attacking tomatoes, by automatic humidity control. *Annals of Applied Biology* 65; 75-83.