The Living Rainforest Sustainable Greenhouses

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Abstract

The Living Rainforest (www.livingrainforest.org) is an educational charity that uses rainforest ecology as a metaphor for communicating general sustainability issues to the public. Its greenhouses and office buildings are to be renovated using the most sustainable methods currently available. This will be realised through construction of a high insulating greenhouse covering with a k-value of less than 2 $Wm^{-2}K^{-1}$, passive seasonal storage of excess summer solar energy in the ground by a ground source heat exchanger and exploitation of this low grade solar energy for heating in winter by a heat pump. In winter the heat pump will produce cold water to cool the ground allowing a passive cooling function in summer via the GSHE. It will be demonstrated that a GSHE is an alternative for an open aquifer in regions with no aquifer availability. The heat pump will deliver the heating baseload, the peak load will be delivered by a biomass boiler, fired with locally-sourced low-cost wood chips. It is expected that the energy saving will be about 75%, resulting in a major cost reduction. The low k-value of the covering is linked to a light transmission of 75 %. This is high enough for the demands of the vegetation in The Living Rainforest. Because the inner greenhouse climate demands are comparable to that of ornamentals, the results will be applicable to commercial ornamental production. In future low k-value coverings will also be available with high light transmission, allowing wider application of the results. This paper focuses on the correlation between k-value, light transmission and energy demand in order to investigate the trade-off between light transmittance (a major energy gain) and heat loss. The effects of these design parameters on storage and harvesting capacity are also considered but appear to have a low sensitivity. The renovated greenhouse site at The Living Rainforest will show that new greenhouses and ecology can be linked to sustainability and this will be communicated and demonstrated to the public.

INTRODUCTION

The Living Rainforest offers a unique educational visit for people of all ages and abilities to learn how the future of tropical rainforests and other ecosytems is closely connected to human lives and lifestyles. It has developed substantially over a number of years. For many decades, the site was home to one of Europe's leading orchid nurseries, Wyld Court Orchids. In 1991 a conversion began and in 1993 Wyld Court Rainforest opened to the public, featuring plants and animals from the world's threatened rainforests. In 1996, the centre was donated to the World Land Trust and in July 2000, it was passed on to The Living Rainforest, an independent educational charity. The Living Rainforest is committed to creating a place for adults and children to explore modern issues of culture and ecology, ranging from the global to the local and from rainforests to other challenges of sustainability closer to home. It aims to reach the broadest possible audience in a friendly and engaging manner. The Living Rainforest has grown steadily since its establishment as an educational charity. However, it became a victim of its own success, with insufficient space, ageing buildings and an inefficient heating system urgently requiring renovation. Therefore a campaign was started to renew the buildings and ecosystem exhibits and this campaign obtained EULife support. The intention is to build the most sustainable greenhouse visitor centre in Europe to house The Living Rainforest's world class rainforest ecosystem display and to become a showcase for both ecology and sustainability. In the first phase the non-greenhouse visitor spaces have been rebuild using sustainable building materials and an ecologically appropriate, landscape sensitive design. In the second phase the greenhouses and offices will be renewed as a showcase for practical, sustainable solutions in construction and design, and for carbon-neutral renewable energy. Though crop production is not the goal of the renewed greenhouses, the climate conditioning is comparable to that in commercial ornamental production greenhouses in order to keep the tropical plant species and animals in optimal condition. Although the new sustainable Living Rainforest's greenhouses may not be feasible in the current economic climate, they will demonstrate how sustainable greenhouses are constructed and operated and therefore enlighten the path to a sustainable greenhouse industry facing rising energy costs.

GENERAL CONSIDERATIONS

The starting point for sustainable greenhouse design is reduction of energy consumption and therefore, CO_2 emission. Following the energy-efficient design, the generation of the remaining energy needs to be considered. The energy consumption is determined by separate aspects (Bot et al., 2005):

1. Heat loss of the greenhouse, determined by:
   a) Thermal properties of the greenhouse system: at given outdoor conditions and indoor climate settings the heat loss of the greenhouse system is determined by the thermal barrier between the greenhouse interior and the ambient. The thermal barrier can be improved by better insulation of the cover, e.g. by thermal screens, multilayer covering. In principle better insulation decreases light penetration into the greenhouse so energy saving competes with decreased production.
   b) Climate settings and control strategies: at given outdoor conditions and given thermal barrier, the indoor climate settings and the way they are changed by climate control strategies determine the heat loss of the greenhouse system. Growing at a lower temperature level decreases heat demand, humidity control e.g. by simultaneous heating and ventilation, increases heat demand while temperature integration control instead of temperature set point control decreases heat demand (delayed heating and ventilation). By greenhouse climate settings and control strategies the grower controls crop production (yield) and crop quality and affects heat demand (at the moment about 25% of his costs) in the greenhouse with given thermal properties.
2. Energy input to balance the heat loss. The energy input is determined by the conversion of primary energy input, maybe fossil or sustainable, to applicable energy in the greenhouse, which is heat. Better conversion efficiency, e.g. by application of a condenser, of a fuel cell or using a heat pump in combination with seasonal energy storage, decreases energy consumption.

These aspects interact: the lower amount of heat lost by the greenhouse system and the more energy friendly the greenhouse climate is controlled, the lower the amount of efficient conversed fossil or sustainable energy input is needed to compensate for this heat loss. The analogy with the energy consumption of a car is striking: aspect 1a is analogous to the aerodynamics, the weight and construction of the car as relevant for the system properties determining the energy demand at particular speed; aspect 1b is analogous to the driving style and decisions on the speed level of the driver as relevant for the systems control and aspect 2 is analogous to the type of engine in the car as relevant for conversion of fuel input (primary energy) to driving power (e.g. Diesel engine, Petrol engine or Hybrid).

In Figure 1 (Bot, 2007) the combination of the three given aspects 1 a, b and 2 is illustrated. With a reliable model (De Zwart, 1996), calibrated and validated extensively with data from actual (real life) greenhouses, the year round energy consumption is calculated for a greenhouse with varying thermal properties for a crop with climate control according to normal practice and heated conventionally with a boiler (upper line). Indeed the energy consumption decreases with decreasing k-value i.e. increasing insulation. The decrease is more or less linear but, if extrapolated, will not intersect the E-consumption axis in the origin due to the effect of humidity control on energy consumption. The effect of more optimal control strategies superimposes an additional energy saving of about 20%, indicated by the small vertical bars. This means that heating with a boiler in greenhouses with increased insulation will have an energy consumption within the given band width. For energy saving of about 50% the cover must be extremely insulated with k-value of about 1 $Wm^{-2}K^{-1}$, which could be realised using very expensive low emissivity vacuum glass panels. Replacing the boiler by an seasonal storage-heat pump system storing and exploiting excess summer solar heat (Bot, 2005), results in energy saving of about 30% for all thermal properties (lower line). So in this case the conversion from primary energy to heat input is changed (aspect 2). The calculations are with more energy friendly humidity control applying heat recovery on ventilated air. Again more optimal control may result in an extra energy saving of about 20%, showing the band width for this option. Energy saving of 50% is already realised at moderate k-value. The figure illustrates developments in energy saving. From the original situation, single glass and boiler heating (right upper point), the development is to better insulated greenhouses and exploitation of excess solar energy.

LIVING RAINFOREST GREENHOUSES

The current Living Rainforest (TLR) greenhouses are single pane glass covered with a high degree of leakage. The public accessible greenhouses are built partly as wide-span (ca 27x 27m) and Venlo- type (ca 22x10.3m) with total soil surface area of 960 m^2. In the new situation this will be extended to 1250 m^2. The climate control settings are dictated by the demands of the tropical crop, the (small) animals and of course the visitors. The day and night heating set point temperatures are 22 and 20°C respectively. Ventilation set point to prevent high temperatures is set at 25°C with band width 3°C. No control actions are needed to maximise humidity for the tropical crop, in the current single glass situation frequently water spraying is needed to maintain a minimal humidity of 80%. Heating is supplied with a 220 kW biomass boiler, fired with locally-sourced low-cost wood chips, installed recently to reduce the carbon foot print of TLR, and the original 440 kW oil fired boiler for back up and peak load. Permanent shading screens are installed preventing crop burning during summer. In winter these screens act as thermal screens. The energy consumption is very high, from the fuel bill before installation of the wood fired boiler an annual consumption of about 80 l oil per m^2 can be calculated.

From the general considerations a greenhouse with low energy consumption can be realised applying a combination of insulated cover and a heating system based on seasonal storage of excess summer solar energy and a heat pump for exploiting this stored low degree energy for heating. The wood fired boiler with day-night buffer can be used then for back up and peak demand. If the heat pump is driven with green electricity the energy supply will be completely carbon neutral. Another, even more sustainable option is to drive the heat pump by a bio-fuel driven gas motor, allowing the exploitation also of the reject heat connected to electricity production. However the TLR cogeneration unit would be too small for economical operation, so the choice is on green electricity driven heat pump.

For a practical greenhouse the insulation value and light transmission compete in the choice for an insulating cover. For TLR light transmission is not an important item since the tropical crop is adapted to grow under the tree canopy, so at relatively low light levels. Therefore an insulating cover with reduced light transmissivity can be applied here that may not be applicable in commercial greenhouses. The only drawback could be that low light transmittance would be the limiting factor for the entrance of excess summer heat to be extracted and stored for heating the greenhouse in winter using the heat pump.

The number of hours with excess solar energy is given by the local meteorological conditions and will be about 1200 hours a year. This number is only marginally affected by the insulation factor of the cover since cover heat losses are negligible compared to ventilation heat losses at high solar irradiation. During these hours the entrance of solar energy is about linearly proportional to the light transmission so indeed less solar energy is gained with lower light transmission. However the total amount of excess solar energy (about 1500 MJm^{-2}) is much higher than the energy to be extracted and stored for heating (about 500 MJm^{-2}), so light transmission is not the limiting factor. More crucial is the extracting capacity of the heat exchangers in the greenhouse.

The application of this type of cover opens the possibility to demonstrate and survey energy consumption in highly insulated greenhouses as a stimulus for the development of greenhouse covers that will combine high insulation and high light transmission. For domestic and office buildings reasonably priced high insulating glass panes (double, low emissivity glass with argon filled split between the panes) are available, having k-value of 1.5 $Wm^{-2}K^{-1}$ and light transmission of 70 % (Pilkington, 2004). From Figure 1 energy saving can be expected of 75 to 65 % for the combination of high insulating cover with heat pump and seasonal storage which is a challenge for the development of sustainable glasshouse horticulture.

As a result of high irradiation, greenhouse tends to heat up in summer. This excess summer solar energy can be stored on a seasonal base in the soil applying an aquifer (Bot, 2005) or via Ground Source Heat Exchangers (Van Gelder et al., 2006). Both seasonal storage options have different thermal characteristics. An aquifer delivers water with more or less constant temperature, the amount dependent on the aquifer capacity. One well delivers water at low (ca 10°C) and one well at high temperature (ca 18°C). An aquifer can only be exploited for heat storage when deep soil water (depth 20-100m) is available and stagnant. A Ground Source Heat Exchanger (GSHE) can be applied in virtually any geological setting, independent of presence of ground water. In a situation where there is a high movement of underground water around the aquifer or GSHE, it will work against attempts to store heat.

The main difference between the systems is that the flow temperature in a GSHE is not constant. A typical temperature bandwidth for a GSHE is from 2 to 22°C when free cooling is used and up to 35°C when mechanical cooling is used. TLR is located in a hilly region (Hampton Norris, Berkshire, UK) with deep ground water that can be expected to flow, so the aquifer option is not applicable for seasonal energy storage. Then GSHE is an attractive alternative.

GROUND SOURCE HEAT EXCHANGER

A Ground Source Heat Exchanger (GSHE) consists of a number of high strength polyethylene loops installed in boreholes drilled to a certain depth (typically 80-150 meters) as illustrated by Figure 2. Heat is exchanged between a fluid flowing through the pipes and the ground mainly through conduction and not by actively pumping ground water itself as in an aquifer system. The design question of a GSHE is how many heat exchangers, to what depth and how far apart need to be installed to be able to provide a certain amount of heating and/or cooling.

When the ground is used as an energy source for the heat pump it needs to be taken into account that the ground is a slowly reacting thermal system: the flow of energy is relatively slow and this means that the local soil temperature around the heat exchanger will fall when extracting heat as long as the heat pump is in operation. After a considerable time the global temperature gradient is such that the flow of energy from the surroundings exactly covers the energy extracted at the borehole. Especially for larger systems, where the borehole to borehole interaction plays an important role, the local temperature at which this equilibrium is reached is usually relatively low and therefore the performance of the system is low as well or a very large GSHE needs to be installed. However, when the ground can be used as a seasonal store the situation changes: after extracting heat in winter we can inject heat during summer and at the same time cool the greenhouse. A greenhouse is particularly suited as large amounts of thermal energy are "captured" during summer and available for harvesting. Moreover, this harvesting can be done by so-called "free cooling", without using the heat pump, and then only the electrical energy to drive the circulation pumps is needed. The resulting COP of this free cooling (definition of COP in next paragraph) is very high (around 20-50).

For a first evaluation the calculated heating and cooling demand pattern of the building (new greenhouses and offices) are linked to a thermal response model of the soil with GSHE, varying the number and depth of the bore holes. To supply the heat to the greenhouse a ground source heat pump system is considered. A heat pump is used to transfer low grade heat (generally somewhere between -3 and +7°C) to higher grade heat used for heating (generally between +35 and + 45°C). The heat pump has a very high efficiency, expressed as the Coefficient of Performance (the ratio between thermal energy delivered and electrical energy supplied), where for every kWh of electrical energy used to drive the compressor and circulation pumps between 4 and 5 kWh of thermal energy are transferred, where the remaining energy (3 to 4 kWh) is obtained "for free" from the environment. As the thermal energy from the environment (ground water, ground or even air) is in principle of solar origin the technology is considered sustainable.

When the emphasis is on energy saving, during the summer period more energy can be put in the ground than extracted in winter allowing the ground to gradually heat up. This is illustrated in Figure 3 together with balanced operation and the case where more energy is subtracted, so with emphasis on cooling. When the emphasis is on heating the heat pump evaporator is fed at higher temperature resulting in higher heat pump COP, so higher energy efficiency. After some years of operation the year round temperature curve will not change any more as illustrated by figure 4: the extra subtracted heat for heating is delivered by the surrounding soil. Therefore a GSHE-building combination has to be analysed for a multi-year period of about 25 years.

RESULTS AND DISCUSSION

For the Living Rainforest (TLR) a highly insulating cover (k = 1.5-2 $Wm^{-2}K^{-1}$) will be combined with seasonal storage applying the GSHE-heat pump combination. The base load heating will be provided by a 40 kW heat pump while the peak load will be topped up by a biomass boiler. With a 40 kW heat pump over 60% (188 MWh) of the total heat demand can be delivered to the system. During summer heat will be harvested by free cooling using the available fan coils. First the offices are cooled for optimal indoor summer climate, then heat is extracted from the greenhouses. Electrical energy is required only to run the circulation pumps and fans. It was calculated that, depending on the source temperature, the needed 130 - 160 MWh (380-460 MJm^{-2}) can be harvested during summer.

As the energy that can be harvested depends on the source temperature, and the source temperature in the GSHE depends on the amount of energy harvested, the solution to the design question is not straight forward but needs to be addressed by a dynamic model. To arrive at a feasible solution we first made a general design of the GSHE using an analytical model (Earth Energy Designer), using static load profile, for a deep (80 meters) and shallow (35 meters) GSHE system. For the complete refurbishment of 1250 m^2 TLR a shallow system of 48 GSHE to a depth of 35 meters or a deep system comprising 21 GSHE to a depth of 80 meters is indicated as a feasible system. These two systems are now being further analyzed using a dynamic model based on a TRNSYS code (Klein et al., 1976) to determine the thermal yield that can be harvested under actual operating conditions. This will also provide the Seasonal Performance Factors (average COP) and energy usage. Based on these parameters and cost estimates of the installation it can then be evaluated if the system will be economically applicable in future for various scenarios of rising energy costs.

CONCLUDING REMARKS

Considerable saving on fossil energy, and therefore on CO_2 emission, is possible through the application of high insulating covers and heating by the combination of seasonal stored surplus solar energy and a heat pump. When the heat pump is driven completely by sustainable energy the carbon foot print of the system is almost neutral. The TLR greenhouse will be a demonstration of sustainable greenhouse operation and show the bottlenecks in the developments for commercial greenhouse development still to be overcome. Ground Source heat exchangers (GSHE) can be applied as alternative for aquifers although their thermal characteristics differ completely. In this paper the focus was on heating, however GSHE can also be designed on cooling performance in summer. This opens the possibility of extending the growth season in regions where summer cooling is a major item.

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Figures

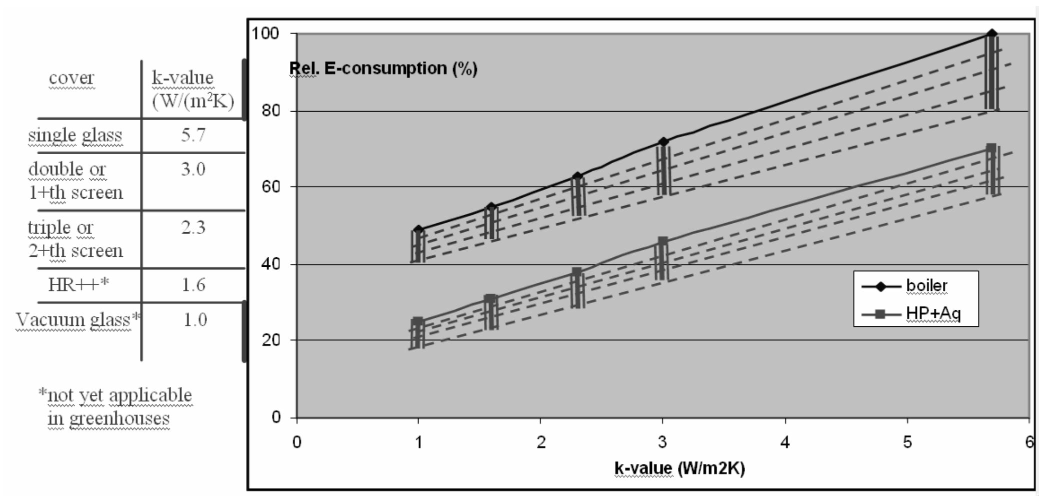

Fig. 1. Year round relative energy consumption for various covers with increasing insulation, heated with a boiler or via seasonal storage-heat pump (HP+Aq) system (from Bot, 2007).

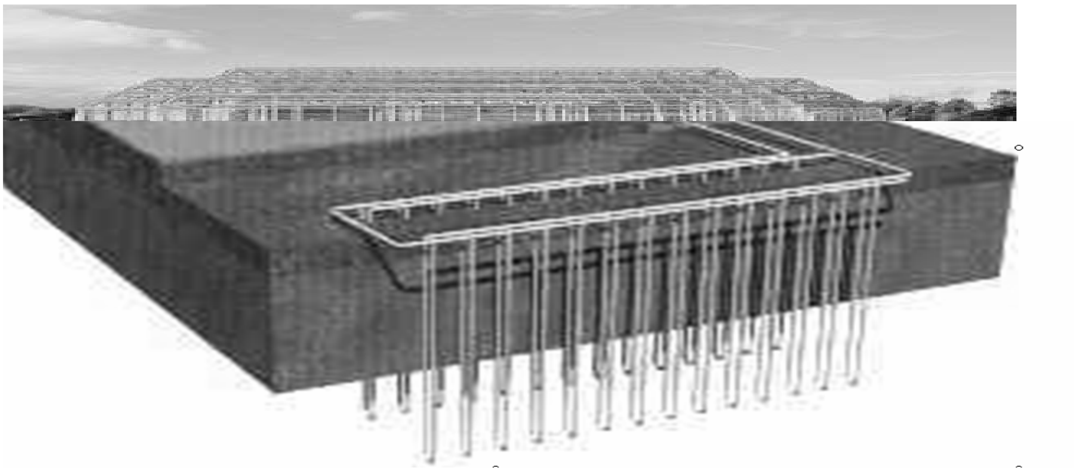

Fig. 2. Example of a ground Source heat Exchanger (GSHE) linked to a greenhouse.

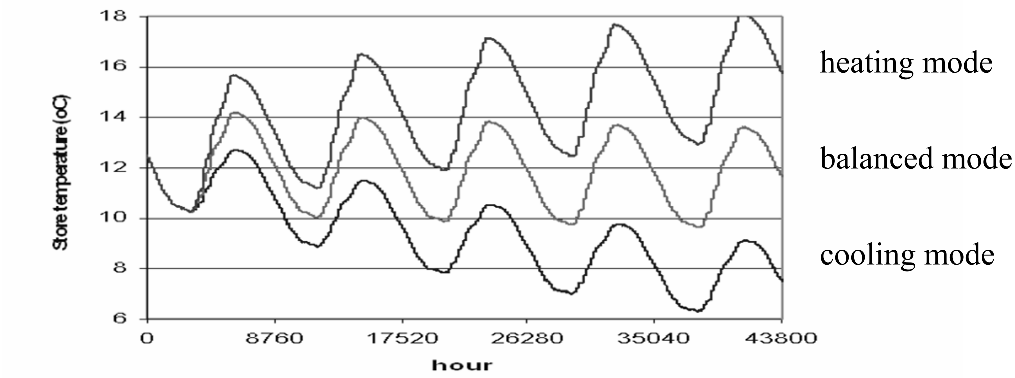

Fig. 3. Variations of average GSHE fluid temperature for year 1 to 5, for 3 different strategies: emphasis on heating (upper line), balanced (middle line) and emphasis on cooling (lower line).

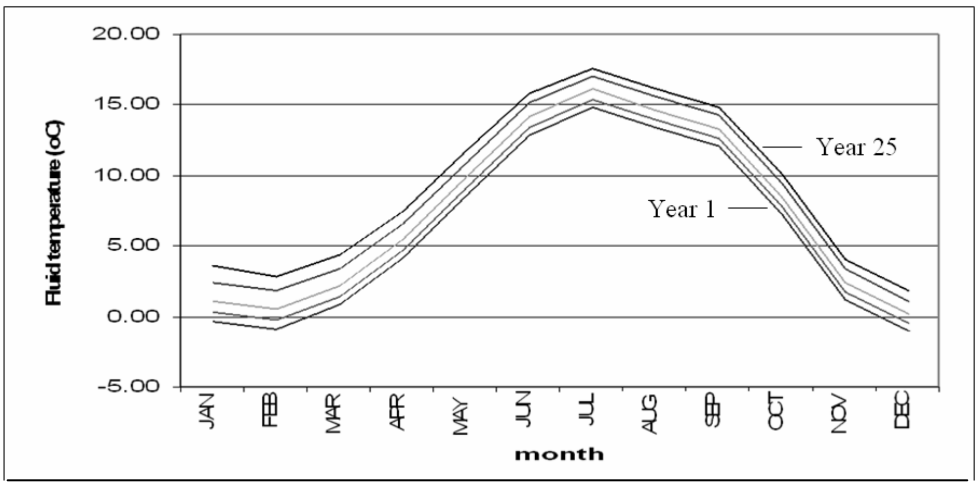

Fig. 4. Yearly variation of average GSHE fluid temperature with emphasis on heating for year 1 till the final situation (year 25).