The Sunergy Greenhouse - One Year of Measurements in a Next Generation Greenhouse

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Abstract

In summer, greenhouses have to deal with an excess of solar energy which is mostly discharged by ventilation. In moderate climates, on a yearly base this discharge of energy is comparable to the energy demand for heating. Thus, in times of growing awareness of the scarcity of fossil fuels, harvesting and storing of summertime heat excesses for application in winter seems to be a promising technique. Preferably the harvesting units are integrated in the greenhouse design because this enables the shared use of space and supporting constructions and the extraction of excess heat can improve the inside climate conditions, especially when one is trying to increase the inside CO_2-concentration to above outside levels. However, although the concept sounds easy, in practice a lot of difficulties have to be overcome since there are strong limits to the affordable expenses, giving the value of the energy harvested. Moreover, the harvesting of summertime excesses and the application of the (low thermal) heat results in an important electricity demand for driving ventilators and a heat pump. This means that the ratio between heat and electricity demand shifts to the latter, which is unfavourable because of the much higher value of electricity compared to heat. Nevertheless, with a carefully designed energy harvesting greenhouse, promising opportunities appear to be achievable, especially when smart choices are made around the greenhouse air temperatures and humidity control. This paper presents the reasoning of such a design called the Sunergy Greenhouse. The proposed design was built as a 550 m^2 demonstration object and has been in operation since June 2008. In this paper a number of results are presented and commented. Moreover, based on the observations, a simulation model was developed. With this model, amongst lots of other things, the impact of the prices of gas and electricity on the affordable costs of energy harvesting can be studied. The results, presented in this paper, help to understand business economical considerations.

INTRODUCTION

Although the current energy prices are lower than in 2008, it is to expect that the growing worldwide scarcity of oil, coal and gas, combined with the growing living standard of people will result in growing energy costs in the coming years. Since, for many nurseries, the energy consumption of greenhouse horticulture is a substantial factor on the business economical balance, reducing this energy consumption will gain relevance.

In general, the reduction of energy demands and/or energy costs can be achieved along three dimensions. In the first place the demands for heat and electricity can be diminished. This means a better insulation of the greenhouse, less lighting or lighting with an improved electricity to PAR conversion, lower greenhouse temperatures during heating and the acceptance of higher air humidity. The second possibility is to increase the contribution of sustainable energy sources like solar power to the energy requirement of the enterprise. The third possibility is to improve the conversion efficiency of non sustainable energy sources to the required energy manifestations (e.g., heat, electricity,

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light). These three dimensions are frequently referred to by the “Trias Energetica” (Lysen, 1996).

The Sunergy Greenhouse (Fig. 1), built as a part of the Innovation and Demonstration centre on low energy greenhouse operation, is an example of a next generation greenhouse that applies a well chosen set of elements of the Trias Energetica to realize a low energy demanding, but high productive greenhouse. This article discusses the key components and reasoning of the design and shows some results.

MATERIAL AND METHODS

The seasonal variation on higher latitudes means that there are warm periods with an abundance of solar energy followed by cold periods with a low solar energy supply and long nights. This makes that operating a greenhouse on predominantly solar energy requires a seasonal storage facility to carry the summertime surplus to winter. The large heat capacity of water, combined with its fluidity and its omnipresence makes water in an aquifer the most suitable low cost seasonal heat storage system (Aarssen, 2008). Currently, there are some hundred seasonal energy storage systems in operation in The Netherlands, from which around 25 at greenhouse sites. Thus the technical and practical experience has grown that much that, from a scientific and demonstration point of view, there is no need to include a real aquifer energy storage system on the Innovation and Demonstration centre. Moreover, it has been shown that a simple simulation model can closely describe the dynamic thermal behavior of such a storage system (Campen, 2005). A similar reasoning tells that a combined heat and power engine and a heat pump, which are key components as well, do not have to be included either in order to carry out relevant research and demonstration purposes on low energy greenhouses. Therefore, the experiments on the Sunergy Greenhouse are limited to a continuous measurement of the required heating and cooling power, the electricity demand to run pumps and ventilators, the water and CO_2 demand and the canopy development and production in the climate conditions achieved. Besides the heating and cooling power, the supply and return temperature that serves these commodities is recorded. This is important because the heating supply temperature affects the Coefficient of Performance (COP) with which the heat pump turns electric power into heat.

The Sunergy Greenhouse (Fig. 1) is a semi-closed greenhouse. It is closed during periods with high solar radiation in order to enable harvesting of solar energy on a relatively high temperature, but it lets in outside air during dull days and during the night for dehumidification purposes. This way of dehumidification lowers the investment costs of the air treatment unit and moreover lowers the electricity demand in comparison to a completely closed greenhouse with mechanical dehumidification (i.e., condensation on a cold heat exchanger and reheating the chilled air with a downstream second exchanger). This will be explained in more detail in the next section.

In order to be able to keep the greenhouse closed in high radiation periods, the greenhouse is equipped with overhead cooling units (one per 100 m^2). When on, the units circulate 40 m^3 per m^2 greenhouse per hour. This air flow cannot be varied so the cooling power is controlled by the flow of the cooling water. The temperature of the water supplied to the coolers is kept at 11°C. This because this temperature can be achieved in practical situations where the cold well is kept at 9°C, which is just below the deep soil temperature in the Netherlands (11°C). When assuring this temperature in the cold side of the pair of wells, the seasonal heat storage system can be kept thermally neutral on an annual base, which is currently obliged by Dutch legislation. In this way, the energy loss of the warm well to its environment can be compensated by a gain of energy into the cold well. The somewhat higher supply temperature to the cooler than the water temperature in the cold well (here set to 2°C) provides the temperature difference to transfer the energy via a heat exchanger which separates the aquifer water from the water in the greenhouse cooling system.

An important component of the Sunergy Greenhouse is the air treatment unit. This unit blows air via slurves beneath the gullies (Fig. 1) into the greenhouse with a controllable flow rate of 5 to 15 m^3 per m^2 per hour. The air can be obtained from the outside and from the inside of the greenhouse with a controllable ratio. Outside air is taken in when the greenhouse becomes too humid. When the air is taken from the inside, the air treatment unit can be used to improve the homogeneity. When outside air is let in for dehumidification, the heat exchangers in the air treatment unit (Fig. 2) provide that the air inflow is brought to greenhouse air temperature level. Thus, dehumidification with outside air does not affect the temperature distribution in the greenhouse.

To find a balance between high insulation and a high transmission of solar radiation, the greenhouse is cladded with single glass, but equipped with a double screen. During the night, both screens can be closed, reducing the overall heat loss coefficient to a value around 3.5 W/(m^2 K) and during cold days only the transparent, lower screen may be used.

Besides these innovative components for climate control, the Sunergy Greenhouse is equipped with common systems for watering, drainage and CO_2 dosing. The translation of the measured quantities to overall figures about gas and electricity consumption and the dynamic behavior of the aquifer system is performed by a simulation model that computes the aquifer charge and discharge flows, the on and off switching of a 200 kW per hectare combined heat and power engine, the electricity exchange with the public grid, and the charge and discharge of diurnal storage tanks. The model runs with the quarterly measured data and computes the dynamically changing COP, based on the measured temperature levels of supply and return water and the dynamically evolving temperatures in the aquifer storage system.

RESULTS AND DISCUSSION

In June 2009, the Sunergy Greenhouse has been in operation for one year. From June till November 2008 cucumbers were grown and starting halfway December, the greenhouse was tested by growing tomato. This period has given a large amount of data from which the detail performance of the components can be analyzed, but first the overall performance is presented.

Overall Performance

Despite the changes that were made along the run, the greenhouse has shown to be very productive. From August till November the cucumber production was 30 g of cucumber per MJ outside radiation. In summer (measured in June and expected to be continued till October), the tomato canopy produces with an efficiency of 20 g of tomato per MJ outside radiation. Both figures are high, especially when the modest energy consumption and CO_2-input is taken into account. Due to the intensive use of the thermal screens and the acceptance of a high humidity, the heat consumption of the greenhouse is only around 32 m^3 per m^2 per year, which is some 25% less than common practice in The Netherlands. Due to the fact that the greenhouse remains closed during sunny and warm days, the inside CO_2 concentration can be kept between 900 and 1000 ppm with a supply rate of only 100 kg/(ha h). This is around 40% of the supply rate used in the average vegetable greenhouse in the Netherlands.

Figure 3 shows the major quantities of the energy household in an almost year round period. Starting in June 2008, the greenhouse first accumulates energy in the aquifer by raising the temperature of 20 m^3 per m^2 from the original temperature of 11 to 18°C. This 18°C is a bit lower than the mean temperature of the water coming out of the coolers because 1 to 2°C is lost in the heat exchanger that separates the aquifer water from the water circulating in the greenhouse climate system.

By raising the temperature of the water in the aquifer, the greenhouse stores 460 MJ of solar heat per m^2 greenhouse in this first half summer period. In the following winter, 300 MJ per m^2 greenhouse was used to supply heat to the evaporator of the heat pump. Obviously, the greenhouse accumulates more solar heat than it uses for its own heating. When the curve of the accumulated heat in the aquifer (Fig. 3b) is extrapolated to June 2009, it can be expected that in one year, the greenhouse has stored an excess heat of

500 MJ per m^2 per year. This means that a Sunergy Greenhouse can provide solar heat to a non-closed greenhouse that uses a heat pump for heating. According to the results from this first measuring period, the surface ratio between the closed and the non-closed greenhouse would be about 1 to 1 to provide a long term thermally neutral seasonal storage system.

Figure 3c shows the primary energy consumption of the Sunergy Greenhouse. This is quite different than the heat demand because the heat demand is partly covered by solar heat from the aquifer. The figure shows a thick line, which is the net primary consumption, and a thin line, which is the gas consumption of the Sunergy Greenhouse. The difference between these lines comes from the import and export of electricity. In summer, the Sunergy Greenhouse is a net exporter of electricity. This results in a net energy consumption lower than the weekly consumed gas because some 20% of the consumed primary is exported as electricity to the public grid. In January and February the thick line exceeds the thin line. In these cold months, due to the bigger electricity demand of the heat pump than the production capacity of the combined heat and power unit, the greenhouse is a net importer of electricity.

The yearly mean gas consumption of the greenhouse (the thin line) is 0.54 m^3 per m^2 per week, resulting in a gross yearly consumption of 28 m^3 per m^2 per year. The thick line has a mean value of 0.485 m^3 per m^2 per week, resulting in a net yearly consumption of 25 m^3 per m^2 per year. From these figures it can be concluded that the greenhouse is a net exporter of electricity.

Experience with the Air Treatment Unit

Originally, besides for the distribution of outside air for dehumidification, the air treatment unit (Fig. 2) was meant to play an important role during periods of cooling and to play a major role when the greenhouse has to be heated.

However, during the first month of operation (August 2008) it appeared that the low temperatures around the roots and fruits, caused by the cold cooling air supplied from below, affected the ripening of the fruits in a negative way. Therefore, after a month, it was decided to block the cooling function of the air treatment unit for the sake of an improved vertical temperature gradient, meaning a higher temperature in the lower parts of the canopy. Thus, besides for the first weeks, all cooling of the greenhouse air in the Sunergy Greenhouse was performed by the overhead air conditioning units.

A similar change of operation during the first year of experiments was applied to the heating function of the air treatment unit and its distribution slurves. In the cold January month of 2009, it appeared that when the heat demand growed (f.i. $> 50\ W\ m^{-2}$) the temperature distribution along the depth of the path was very bad. The back side of the greenhouse was up to 4°C warmer than the front side at the end of the slurves. After a short attempt to improve the situation by reducing the air flow from the slurves at the back side of the path in favor of the air outlet at the front side, the conclusion had to be made that this lay out of slurves would not be able to combine an equal distribution of heating power and dehumidification capacity. This because the large surface of the slurve gives a substantial heating without any outlet of warm air, whereas the decreasing air temperature along the slurve demands an increasing airflow to balance the heat output along the slurve. However, suppose it would be possible to balance the total heat output per meter slurve by adjusting the air outlet to the heat release of the slurve surface. This would mean that at the beginning of the slurve the air outlet should be almost zero (because the slurve surface does the job), whereas at the end of the slurve high air outlet rates would be necessary to provide enough heating capacity with the air that has been cooled down along the slurve. However, this variation of air outlet rate would induce an equal variation of dehumidification capacity, meaning that an equal heat distribution of heating capacity conflicts with an equally distributed dehumidification capacity. Since an equal dehumidification capacity is of great importance to accept high humidity, which is necessary for a low heat demand, the choice was made to let the dehumidification function oft the air treatment unit prevail and to discard the heating function of the air treatment unit.

As a consequence of the strongly limited role of the heat exchangers in the air treatment unit, the relation between heating power and the required supply water temperature shifted upward (see Fig. 4). When using a heat pump as the major heating device, which is the case in the Sunergy Greenhouse concept, such an upward shift decreases the mean Coefficient of Performance of the heat pump. However, since not only the heat pump, but also the reject heat of the combined heat and power unit is used to generate the required temperature for heating, the heating system simulation model computes that the upward shift of the required temperatures is responsible for an increment of the primary energy demand of only 1 m^3 of natural gas equivalents.

Dehumidification

For some 4000 hours a year, during the night and on dull days, the input of vapor by evaporation of the canopy exceeds the withdrawal of moisture by leaking and condensation. In those hours, a greenhouse tends to become unfavorably humid. For about 2500 hours a year, the greenhouse has to be cooled which yields a large condensation flux on the coolers. The remaining hours, especially from December till February, the evaporation is only small and the condensation capacity at the cold cover is large. These factors result in an acceptable or even an unfavorably low humidity.

To avoid humidities too high during the 4000 potentially problematic hours, the Sunergy Greenhouse lets in outside air and does not apply mechanical dehumidification (comprising of a condensing heat exchanger followed by a reheating heat exchanger in an air treatment unit).

To show that this choice saves primary energy, let us suppose that a canopy evaporates 20 g of moisture per hour and that condensation and leakage removes 10 g of moisture from the air. Now suppose that that the 10 g of vapor excess is withdrawn from the greenhouse air by circulating 10 m^3 per m^2 per hour along a heat exchanger, kept at a mean temperature of 12°C. With a pressure drop of 100 Pa to circulate the air through the air treatment unit and slurves and an electricity to pressure conversion efficiency of 0.25, this air circulation requires 1 W/m^2 of electric power. In case the greenhouse air is 20°C with a relative humidity of 85%, a cold exchanger can remove these 10 g of moisture per hour, but, assuming a 50/50% sensible/latent ratio at the cooling surface, the 6.8 W of dehumidification is accompanied with 6.8 W of air cooling (6.8 W is the latent heat released when condensing 10 g of moisture per hour). When this cold surface is kept cold by a heat pump with a COP of 4, the electricity consumption for the 13.6 W sensible+latent heat extraction is 13.6/(4-1)=4.5 W. When adding the electricity consumption for the air circulation and expressing the dehumidification with a single performance figure, this way of dehumidification costs 0.55 W of electric energy per g/hour dehumidification.

In case the same amount of dehumidification is achieved by letting in outside air of 12°C and 90% RH, having an absolute moisture content of 9.5 g m^{-3}, the required amount of outside air is 12/(14.9-9.5)=2.2 m^3/h. In this formula 14.9 is the absolute moisture content of the greenhouse air. To heat this outside air to 20°C, a heating power of ((20-12)*2.2*1200/3600)=5.9 W is required. In case this heat is produced by a similar heat pump, the required amount of electric power to the heat pump is only 5.9/4=1.5 W. Thus, in these circumstances, the 10 g/h dehumidification can be realized with only 1.5 W for the heat pump and the same 1 W for the air circulation, giving a performance factor of 0.25 W of electric energy per g/h dehumidification.

When analyzing the outside and inside conditions in the 4000 potentially problematic hours it appears that the weather circumstances in the Netherlands are such that using outside air for dehumidification almost always requires the lowest amount of electricity per unit of dehumidification.

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Figures

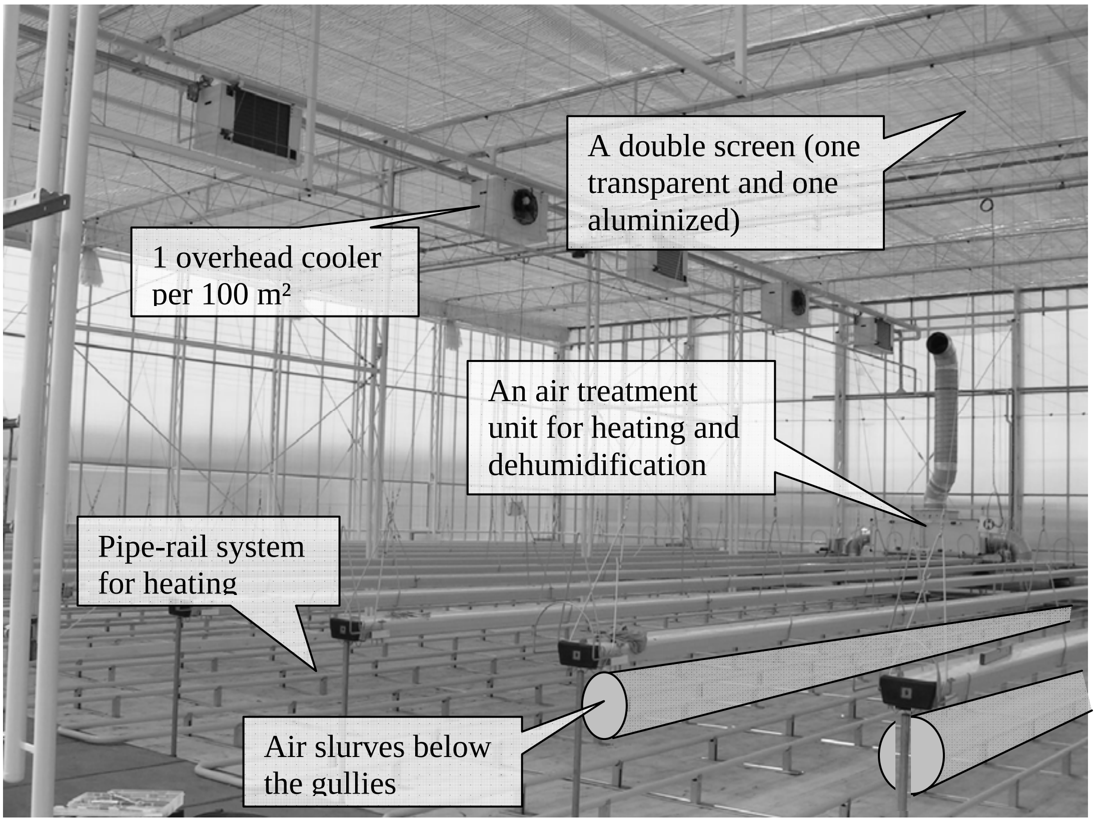

Fig. 1. A photo of the 550 m^2 Sunergy Greenhouse (the air slurves were not mounted yet at the time the picture was taken).

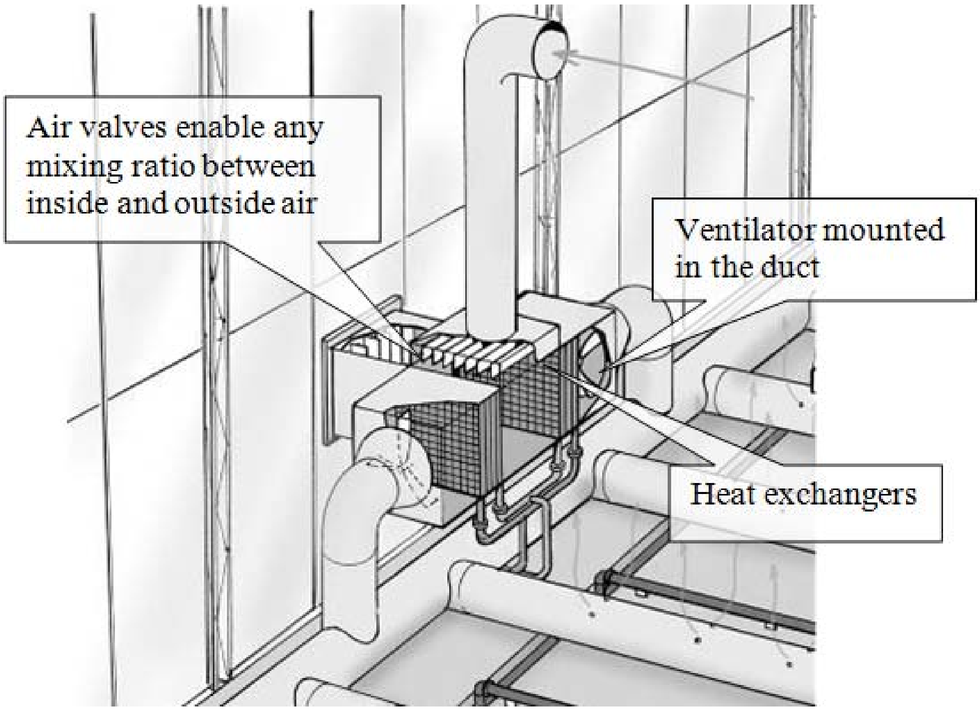

Fig. 2. A sketch of the interior of the air treatment unit.

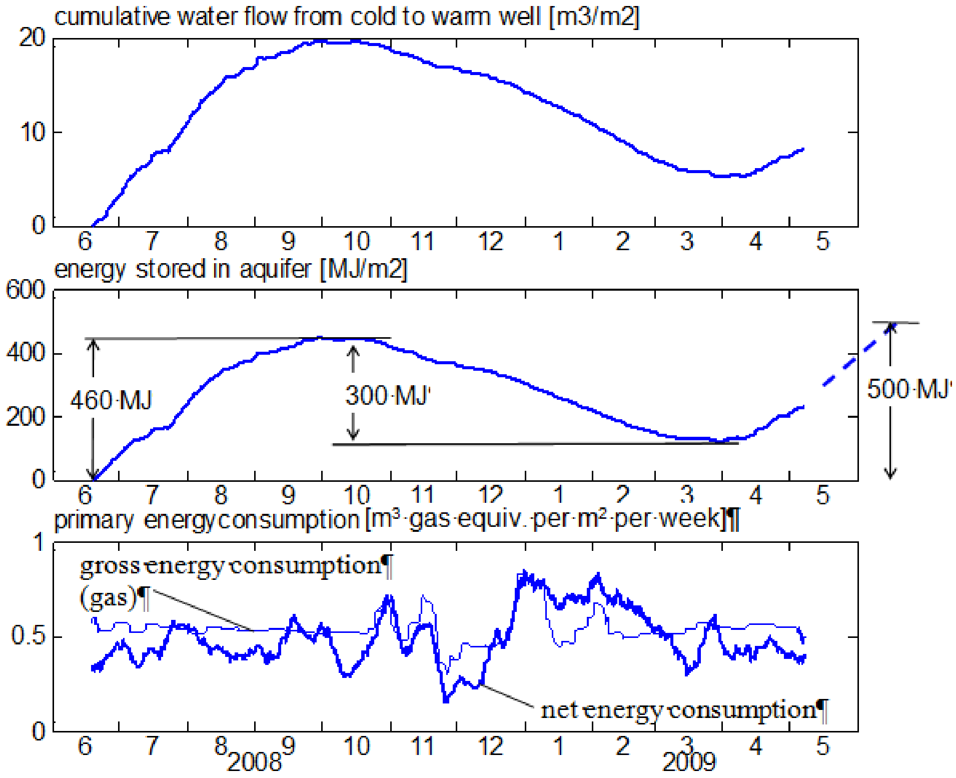

Fig. 3. Energy supply system performance figures of a nearly year round period of measurements on the Sunergy Greenhouse.

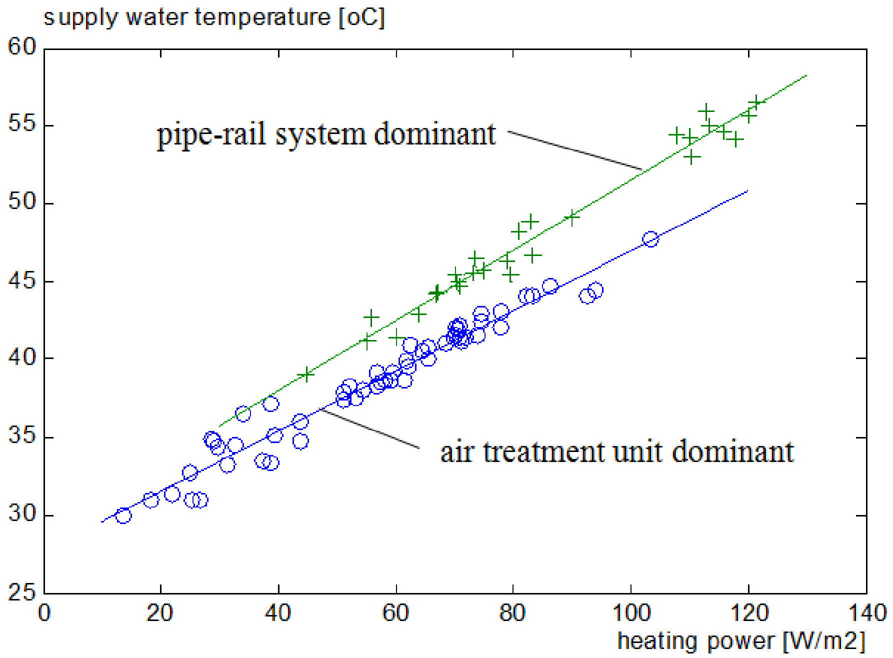

Fig. 4. Required supply water temperature to heat the Sunergy Greenhouse at 20°C as a function of the power demand with the air treatment unit as the dominant heating device or the pipe-rail system as the dominant heating device.