Concept for Water, Heat and Food Supply from a Closed Greenhouse -
the Watergy Project

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Keywords: desalination, solar collector, sustainable urban production, water recycling, CO₂ emission

Abstract
This paper describes the basic operation of a new type of closed greenhouse for solar thermal energy storage, water recycling, water desalination and advanced horticultural use. A system of constant air humidification enables the transfer of large amounts of energy via latent heat from the greenhouse to a thermal storage. To accomplish this, only little air velocity is required and can be provided by a buoyancy driven air circulation system. It is realised by a combination of a cooling tower and a secondary heat collector. In this heat collector the air is humidified to the maximum level before the process of heat exchange.

INTRODUCTION
Greenhouse production is a highly profitable technology for food production in Central and Southern Europe, but is facing growing challenges caused by increasing energy prices (for heating, transport) and limited water resources (for irrigation). Desalination is a technology used to supply future growing demands for water, but common technologies have a large demand for primary energy.

A widely discussed technological solution for these challenges is the idea of heat and water recovery from greenhouse exhaust air, or from the inside of closed greenhouses, aided by heat exchangers and heat accumulation systems (Warshall, 1996). The major challenges of such endeavours can be described as follows:
- Usually, a large amount of electric energy is needed for ventilation to reach a sufficient transport of hot air to a heat exchanger. The primary energy needed for this transport is close to the primary energy of the heat that can be captured. Because of this, such a system is only marginally effective. (Mackroth, 1982)
- Air has little heat capacity. Therefore, any transfer of heat from air to water or to any other storage media is little effective.
- Greenhouse temperatures are limited due to crop tolerances, a situation that leads to very low supply temperatures and therefore low efficiencies of heat exchangers and thermal storage systems.
- Placement of heat exchangers in the roof zone, representing the hottest area of a greenhouse, originates unwanted shading of the plants. Additionally, the heat transfer between the rising hot air and the falling cooled air from the roof zone results in insufficient cooling in the lower plant zone.

NEW GREENHOUSE ELEMENTS
The Watergy system (Buchholz, 2000) contains two innovative elements: a greenhouse cooling tower and a secondary collector element. These elements aim at working against the challenges mentioned above:

The cooling tower is used to overcome the need for electric fans by creating free, buoyancy driven ventilation. It consists of an air duct that drives heated air from the greenhouse to the top of the tower and an internal cooling duct with a large air-to-water heat exchanger made of plastic, which is connected to a heat accumulator. The air passes, driven by the buoyancy force, from the greenhouse into the chimney. After being cooled
by the heat exchanger, the air falls back to ground level. Vapour from the greenhouse condenses, releasing thermal energy and producing distilled water. The resulting cool dry air can circulate within the system. The cycling process can be used for greenhouse cooling, air dehumidification and energy transport to the heat exchanger. Using such a cooling duct, the produced cool air can be directed to the lower volume of the vegetation area without being mixed with the hotter air, which rises inside the greenhouse. The constant process of cooling and condensation along the whole duct also constitutes an effective means of dehumidification of the greenhouse air.

A secondary collector aims at further heating and humidification of the greenhouse air while on its way to the cooling tower, resulting in a higher efficiency of the heat transfer and storage processes. Higher temperatures result in higher heat exchanger supply temperatures and in a higher loading capacity of the storage system. A higher absolute humidity means a larger amount of thermal energy available, while it is transported with the same amount of air movement. In other words, less total air flow is needed for the transfer of solar energy from the secondary collector to the heat exchanger. Additionally, the higher humidity also results in a larger amount of energy that is released directly at the heat exchanger surface during the condensation process without thermal barriers of laminar air zones at the surface, and thus resulting in a higher total transfer rate of the heat exchanger.

Since the secondary collector is separated from the vegetation area, salty water can be used to feed the evaporation process of the secondary collector for desalination purposes. Through working with large amplitudes of salinity between the storage loading and de-loading phase, also endothermic and exothermic effects within the brine can be used as a part of the energy storing process.

**PLACEMENT OF THE SECONDARY COLLECTOR**

The placement of the secondary collector is dependent on the amount of irradiation. In areas with high irradiation, the collector can be placed above the vegetation zone and can be operated like a flexible shading system: Components of the greenhouse roof like a plastic layer and a water film can already filter a relevant part of the incoming radiation. If needed, additional shading can be provided by conventional shade curtains underneath the plastic film, or by mixing shading additives into the water film that can be added/removed mechanically in a controlled way. Both methods aim at using the solar radiation to heat up the water film for a consistent proportion of air heating and air humidification.

The secondary collector is limited to the basal surface and to a certain capacity, because of its position above the crop area and the need for as much radiation as possible for plant growth. On the other hand, the advantage of an installation above the plants is the possibility of having large, continuous greenhouse surfaces.

For areas with limited irradiation conditions (e.g., Central Europe), light is most of the time already a limiting factor for plant growth. Therefore, the secondary collector surface has to be placed outside the greenhouse. The resulting flexibility in the size of this collector surface allows for it to be sized in relation to the crop production area and to the desired crop production temperatures.

Since this area without plants is required in such a configuration, it is useful to think about an additional use of such a surface. A logical application can be integrating building facades and roofs in combination with greenhouses within an urban context.

In the Watergy project, both versions will be tested within two different prototypes. The first one is a single greenhouse for which the main focus is thermal control and water production. The thermal energy, that is stored during the day will be utilised for greenhouse heating at night during wintertime and for further water evaporation/condensation at night during summer, in particular evaporation of salty water for desalination purposes on the heat exchanger and condensation on the greenhouse cover. By unloading the storage at night, coolant for the next day is made available in both cases. (Saitoh, 2000)
The second prototype with an additional collector surface aims at producing heat that is used to load a seasonal thermal storage (Fisch, 1999; Saitoh, 1996) used during the summer for heating the building and during the winter for heating the greenhouse. In this prototype, the cooling duct is placed inside the building and the heat exchanger acts like a building radiation unit during the winter heating period. Waste air from the building will then be transported to the greenhouse for further space heating. The greenhouse cover has much less insulation capacity compared to the building walls, but this can be compensated for by a design with a larger building with slightly higher temperatures and a smaller greenhouse with lower temperatures requirements, so the air exchange rate of the greenhouse can be higher than in the building.

**IDEAL DESIGN OF THE WATERGY SYSTEM**

The non-variable factors of the system are as follows:
- The **evaporation of plants** in the greenhouse has to be as high as possible from the point of maximum cooling and maximum plant growth.
- The **possible maximum temperature** in the system is only dependent on the U-value of the transparent surface (insulation capacity at a given ambient temperature). It should be reached at maximum irradiation at a state of air saturation and can also be reached during lower radiation at decreased air velocity and/or by reduced air humidity.
- A **minimum temperature difference between the top and bottom of the tower** for a given height of the cooling tower and its corresponding air-resistance values needs to result in a sufficient pressure difference for an air flow that enables sufficient cooling in the vegetation zone.
- The **height of the cooling tower** (in relation to the size of a dependent greenhouse area), the **width of the cooling duct** (for optimised air flow at given air resistance, especially of the heat exchanger) and the **surface of the secondary collector** (to allow to reach the maximum possible air temperature) are the final design parameters that need to be set beforehand and can not be varied during the performance.

In relation to these static factors, there are only a few actuators that will be used to control the system.

**Operation Mode for Maximum Energy Input**

The main variable to be regulated is the **cooling duct outlet air temperature**. Having a maximum temperature at the top of the tower (that should always be as high as possible) and a given tower height and resistance in the air duct, the outlet temperature can be used to regulate the airflow in the system. If the temperature rises, the airflow diminishes. Both, an increase of the air temperature entering back to the greenhouse and a decrease of the air flow through the system result in an overall increase of the temperature in the system. This allows for an easy regulation of the system.

There are two limits important for temperature control:

1. The temperature in the crop area is limited by the tolerance of the plants.
2. To minimize the average temperature along the surface (in order to avoid thermal losses), the maximum possible temperature of the system should not be reached along the secondary collector, but only at the entrance of the cooling tower. Thus, it is also desirable that the temperature of the non-saturated air entering the secondary collector from the greenhouse is decreased first by being humidified and its temperature increased steadily to the possible maximum temperature near saturation.

These two limiting factors are leading to an ideal proportional size of the greenhouse light receiving surfaces (plant leaves and other exposed surfaces) and secondary collector surface (in terms of a variable shading system above the plant canopy or additional collector surface besides the greenhouse). An ideal proportion will enable both an optimum temperature in the vegetation zone for plant growth and the maximum possible temperature at state of air saturation at the cooling duct entry.
The minimum temperature in the cooling duct is limited by the coolest temperature of the water in the thermal storage and therefore is dependent on the coolest ambient temperatures during the de-loading phase of the system (if no further cooling device such as a heat pump is used). To control the outlet air temperature, it is possible to regulate the water flow through the heat exchanger (to minimise the energy needed for pumping) or to use a supply temperature higher than the minimum in the storage (to spare coolant if the capacity of the storage is limited).

The evaporation in the secondary collector must be as high as possible, but the 100% relative humidity of the air should only take place at the cooling duct entry, as during the loading phase, and there should be no condensation on the transparent greenhouse/collector walls to avoid thermal losses of the system. Only if the capacity of the heat exchanger is exceeded, evaporation on the outside surface of the cover would be acceptable to increase the heat transfer through the cover for sufficient cooling, but without losing water. Opening the system would be another alternative, but leads to water losses.

**Operation Mode for Below Maximum Irradiation**

The design considerations for the heat exchanger / heat storage are done for a maximum irradiation load. At days with less irradiation, the system is working below full capacity. There are again two options for operating the system:

- Generally, it is more efficient to run the system at lower temperatures and higher humidity, as thermal losses decrease and the yield of total thermal energy and recycled water increase.

If heat production at high temperatures is the preferred operation mode (e.g., for the continuous loading of a seasonal thermal storage), it is important to reach the maximum possible temperature. To achieve this, evaporation on the secondary collector should be diminished or even switched off.

This operation mode can also be suitable, if the temperature difference between the top and bottom of the tower is too low to initiate a sufficient airflow (e.g., for constant dehumidification of greenhouse air). Also, the temperature difference between the storage and the ambient temperature during de-loading state can sometimes be too low to initiate sufficient air flow for transporting the energy from the heat exchanger to the outer cover of the greenhouse. In both cases this operation mode is needed for a high storage temperature along the loading phase. This mode has to be designed according to the energy balance over the whole loading/de-loading phase.

**ROLE OF PLANTS IN THE SYSTEM**

The selection of crop species is one of the most important decisions in the design process. Especially, the specific tolerance to high temperatures (at high rates of humidity) and the ability to evaporate large amounts of water will affect the design process because of following reasons:

- A high evapotranspiration rate of the plants results in a stronger cooling effect. A stronger cooling allows decelerated air velocities in the greenhouse. The height of the cooling tower, designed to produce a certain air velocity, can therefore be reduced if the optimum crop species is grown constantly.

- A larger heat tolerance of the greenhouse crop can also result in a decrease of the air velocity, but in addition the secondary collector surface for the post-heating process can be smaller, since the temperature entering the collector is already closer to the maximum possible temperature in the system.

In a closed system, CO₂ can be added to the plant environment without having ventilation losses and set to an optimum value for plant growth. The possibility of space cooling throughout the day and heating through the night enables a more equal gradient of the greenhouse temperature, resulting in a temperature closer to the optimum growth temperature. Since a higher CO₂ concentration also leads to a higher optimum growth temperature, the total growth rate of the plants can be enhanced substantially.
The optimisation of all growth factors will benefit the efficient use of the energy balance, since plant activity becomes an important cooling factor in the crop area.

CONCLUSIONS
The proposed system enables the parallel production of water, energy and food. It has the potential to enhance plant productivity by more efficient supply of CO₂, enhanced biological pest control and its ability to balance ambient climatic conditions in the way of day/night temperature equalisation (summer cooling during daytime and winter heating during night).

The water recovery and desalination components could enable the regional growth of greenhouse production into dryer regions and decentralised applications closer to the customers with the ability of using and cleaning urban grey water. The method of solar heat capture enables applications for domestic heating, especially in regions with a large day/night temperature amplitude.

ACKNOWLEDGEMENTS
This research is funded by European Union’s 5th Framework Programme promoting Energy, Environment and Sustainable Development (Project Number NNE5-2001-683). Thanks to our other project partners from Wageningen University and Agrotechnology & Food Innovation (both Wageningen/the Netherlands) and Clina GmbH (Berlin/Germany).

Literature Cited


Figures

Fig. 1. (left). Watergy greenhouse, prototype 1 with cooling tower.
Fig. 2. (right). Evaporating surface of the secondary collector inside the greenhouse.

Fig. 3. Installation of a solar air collector for further heating of greenhouse air: Placement under the greenhouse roof with a transparent layer and underlying shading (left) or on an additional surface beside the greenhouse vegetation zone (right), dependent on given climatic conditions (amount of solar irradiation).
Fig. 4. Prototype 2 with a greenhouse attached to a building and the use of a façade and roof zone for post heating of the greenhouse air. Seasonal thermal storage is a central component of the building.

Fig. 5. Basic design to achieve efficient heat transfer from the greenhouse to the heat exchanger inside the cooling duct at maximum radiation load.
Fig. 6. Basic design to achieve efficient heat transfer to the heat exchanger and optimised water recovery at below maximum radiation levels.