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Watergy project: Towards a rational use of water in greenhouse agriculture and sustainable architecture

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Abstract

Watergy project is funded by the European Community's Vth Framework in its Energy, Environment and Sustainable Development programme. It consists of the development of a humid air solar collector system that follows the principle of a closed two phase thermosyphon. A combination of evaporation and condensation allows to use solar thermal energy in a much more efficient way. The main advantage is not only the reduction of costs in space cooling and heating, but the possibility of water purification, as the system can be fed with low quality water to obtain distilled water. The decentralization of heat and water supply opens the possibility of residential areas where greenhouses fed with low quality water (grey water and brackish water) could be used to produce distilled water as well as heat and fruits. The project contemplates the development of two prototypes: one application for arid climates in Southern Europe with an emphasis on water production in the context of greenhouse horticulture, and another for temperate Central European climate focused on heat and water production for sustainable architecture.

Keywords: Water treatment; Water management; Solar collector; Agriculture; Architecture

1. Introduction

The limited water resources are real challenges for the actual status of intensive greenhouse horticulture as a highly profitable technology of food production in Mediterranean areas. The intensive horticultural production system using greenhouses was shifted from Central to Southern Europe due to the increasing energy prices. The semi arid Mediterranean climate allows for a concept of passive greenhouse with considerably less addi-

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tional energy demand [1]. However, even though the greenhouse itself is a means of saving water (compared with outside growth, greenhouse horticulture demands a third less water consumption [2]), the water scarcity associated with the areas where the greenhouses are developing is a serious handicap for the sustainability of the actual production system.

Although modern technology proposes desalination as a source for this growing demand of water, common technologies are also strongly affected by their large demand for primary energy. Another technological solution is widely discussed: the idea of heat and water recovery from greenhouse air discharge or from the inside of closed greenhouse with the aid of heat exchangers and heat accumulation systems [3]. However, this solution faces with several problems: (i) the amount of energy needed for the transport of hot air to a heat exchanger, requiring forced ventilation; (ii) the reduced efficiency of the heat transfer from air to water due to the little heat capacity of air; (iii) the unwanted shading created on the plants by the heat exchangers, usually placed in the hottest area of the greenhouse, which is the roof zone; and (iv) the low temperature regime established by plant tolerance (usually no more than 35ºC).

The issue of sustainable architecture is a growing one, and energy efficient buildings are being promoted by governments and private organizations. However, although solar energy is slowly being introduced in the energy balance of the buildings with the use of standard solar collectors and even means for heat storage, the aspect of water supply and purification is still subject to centralization and dependent on an existing network.

2. A new concept of solar collector

Project Watergy proposes a new concept of solar collector based on a humid air circuit powered by thermal solar energy [4]. The collector is

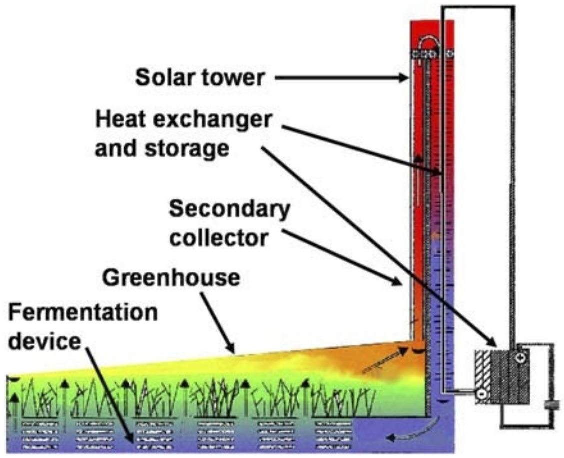

Fig. 1. Scheme of the new humid air solar collector proposed in project Watergy.

formed by a greenhouse connected with a solar chimney, inside of which a cooling duct contains an air-to-water heat exchanger connected to a heat accumulator (Fig. 1). The process starts with the heating of the air inside the greenhouse, which rises to the solar tower by natural buoyancy. The evapotranspiration of the plants and soil is added to the air, which becomes humid. Above the greenhouse, removed from the plant area, the rising air is further heated in a secondary solar collector until it reaches the maximum temperature at the top of the solar tower. In this secondary collector, in order to saturate the rising air while it is heating, a humidification system acts as an additional evaporation source. The aim is to have very hot and humid air at the top of the solar tower. Inside the tower, a feedback duct contains a heat exchanger which cools the air. On the surface of the heat exchanger, the cooling of the humid air creates condensation, releasing additional thermal energy and distilled water. The cold and dry air falls back to the greenhouse, where it is heated and humidified starting the cycle again. The final element of the closed system is a solid state fermentation device [5]. Greenhouse plants and fermentation micro-organisms supply each other with oxygen and carbon dioxide. Furthermore, metabolic waste heat can be added to the heat collection.

This concept has significant advantages compared with standard solar collectors. On one hand, the humid air allows to store more thermal energy at a given temperature, because of the use of latent heat in addition to the sensible heat. This higher energy density of humid air means that the same amount of energy can be transported by much lower air volume flow, which can be sustained by natural buoyancy. On the other hand, the evaporation and condensation processes increase the efficiency of the heat transfer. This allows for the heat exchanger to be smaller and made of cheaper materials (i.e., plastic). Also, the separation between the collector (greenhouse) and the heat exchanger (placed inside the solar tower) allows for more surface of both elements and further cost reduction. Additionally, the evaporation and condensation processes open the possibility of water purification as part of the solar energy collection system.

The energy collected in the heat exchanger is stored during the loading phase in external heat accumulators. During the deloading phase, the heat is released in the heat exchanger by the reversal of the circulation. The system allows several possibilities depending on the requirements. The heat collection can be done in a daily or a seasonal basis. In warmer climates, heat collected during the day can be released during the night, but in temperature climates the large difference between seasons suggests a summer heat collection for winter release. The project contemplates two versions of the collector, developed in two different prototypes, one for Mediterranean climate with day-night loading cycles and another for Central European climate with a seasonal storage of heat.

3. Watergy Prototype 1: a closed greenhouse

The first prototype (PT1) is a single closed greenhouse with the main focus on thermal control and water production [6]. It has been built in Almería (southeast of Spain), which is also the area with the highest concentration of greenhouses in the world. Fig. 2 shows an actual photograph of the prototype. It consists of a greenhouse of about 200 m^2, with a standard galvanized iron structure and polyethylene plastic cover. The solar tower is 10 m high, covered by polycarbonate, and the heat exchanger inside the cooling duct is built of polypropylene tubes. The secondary collector is a transparent plastic layer on top of the plant area with a water sprinkling system on it. Outside the greenhouse, the heat storage consists of three deposits of polyethylene which contain a total of about 15 m^3 water, connected to the heat exchanger. Both the heat exchanger and the heat storage are built in a modular way for testing different degrees of performance and capacity of the system [7]. The fermentation device has not been integrated in this prototype to avoid further complications, and the CO_2 necessary for plants is artificially supplied as in a normal commercial greenhouse. The prototype includes sophisticated measurement systems (temperature, air humidity and the flows of water, air and CO_2) to give comprehensive information about its physical behaviour. Sensors and actuators connected to low-level controllers activate a model-based optimal control system [8,9].

Fig. 2. Watergy prototype 1 built at the site of Estación Experimental de Cajamar, Almería, Spain.

In the closed greenhouse, the system acts as a climatization system powered by solar energy. Fig. 3 shows a scheme of the air circulation inside the greenhouse and through the heat exchanger during the day. Additionally, it establishes a water treatment cycle (see Fig. 4). The system can be fed with grey water in the irrigation. Also, saline water can be used in the evaporation on the secondary collector. The collection of distilled water in the condensation means that the system can act as a means of purifying dirty water. Alternatively, the water cycle can be closed and the collected water reused in irrigation. Therefore, the system allows a significant saving of energy and water. Also, from a horticultural point of view, the closed greenhouse means an improvement in production due to: (i) the extension of the productive period by climatization; (ii) the possibility of CO_2 enrichment of the air; (iii) the reduction in the use of pesticides.

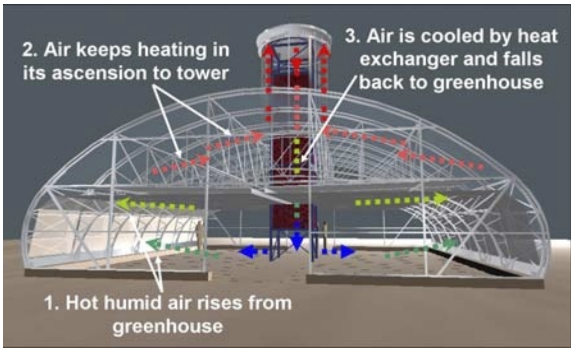

Fig. 3. Scheme of the air circulation inside Watergy PT1.

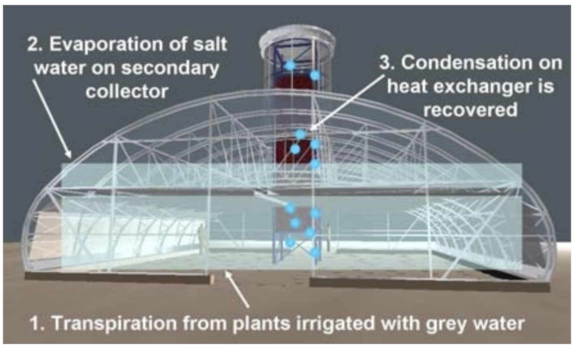

Fig. 4. Scheme of the water cycle in Watergy PT1.

Construction of Watergy PT1 ended at the end of the summer 2004. After that, a testing and adjustment phase of the operational system has been undertaken and the system is ready for operation since spring 2005. Summer 2005, however, was also devoted to test and adjustment of the heat deloading in extreme hot conditions. Fig. 5 shows the effect of the system on the temperatures inside the greenhouse, comparing two days with similar conditions but different operation. Five locations are indicated: 0 is the outside of the greenhouse, 1 corresponds to the top of the tower (input of cooling duct), 2 to the bottom of the tower (output of cooling duct), 3 represents the greenhouse temperature (average of several points in the plants area), and 4 the space above the inner roof. When the system is passive (no functioning of the heat exchanger, denoted by "p") there is a vertical gradient in the temperatures (2 and 3 are equal). When the system is active (cooling system operating, denoted by "a") a considerable decrease in the temperatures is observed, and most remarkable, the temperature of the point 2 (outlet of the cooling duct) is lower than 3, illustrating how the cool air dissipates through the plants and is heated by solar collection inside the greenhouse.

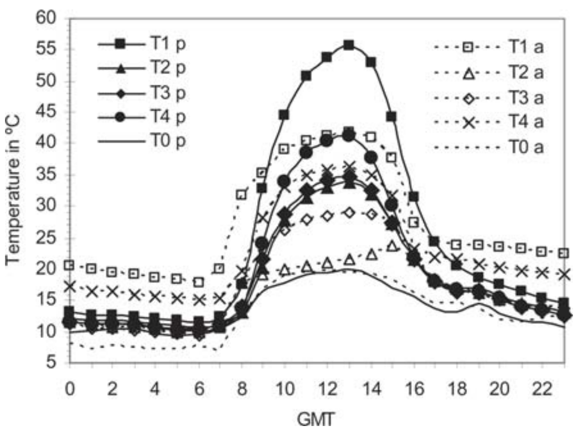

Fig. 5. Effect of the system on the temperatures of PT1.

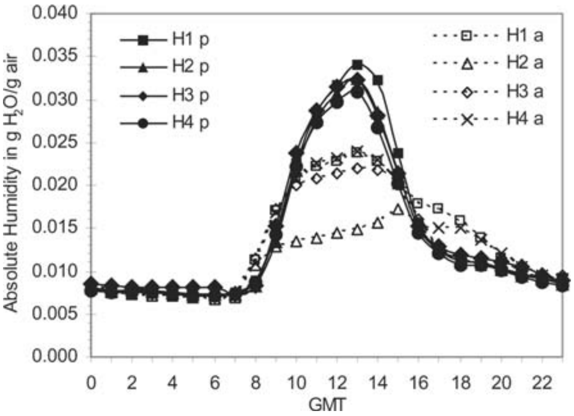

Fig. 6. Effect of the system on the air humidities of PT1.

Fig. 6 shows the effect of the heat exchanger on the absolute humidity of the air inside PT1. The decrease in the total amount of water vapour contained in the air is noticeable when the system is operating, manifesting the drying effect which is associated with the cooling of the air inside PT1. Especially, the difference of the water content of the air between the top (1) and the bottom (2) of the cooling duct is remarkable and evidences the condensation process that takes place as the air passes through the heat exchanger contained inside the duct.

During the testing phase, a whole crop cycle of French beans (about 13 weeks) was carried out, and the results were positive both in production (3 kg/m^2, a high value for such a winter cycle according to local production figures) and plant health (no chemical treatments were used and no diseases were observed). As many measuring and operation tests were carried out simultaneously, no reliable data about water production were obtained from this phase. The horticultural concept of the project contemplates values of the evapotranspiration as high as 400 l/m^2 for a 4 month summer cycle, which in principle could be fully recovered from the air in the normal functioning of the system. Recent figures oscillate between 300 and 400 l/d in springtime. Later data for the summer are not completely representative due to further tests of the system being performed simultaneously.

The periodical analysis of the collected water show a very good quality both chemically (residual chlorine less than 0.05 mg/l) and biologically (absence of legionella and undetectable presence of E. coli bacteria, i.e., less than 3 colonies forming in 100 ml). The high presence of aerobic bacteria (in occasions more than 30000/ml) recommends the adoption of a closed water cycle, where the collected water is reused for irrigation. So far, the recovery rate of the input water is about 75%. This figure is still subject to improvements with further technical adjustments, especially concerning the collection of the condensation which takes place at night on the inner side of the plastic cover, some of which leaks out.

4. Watergy Prototype 2: a sustainable building

The second prototype (PT2) has been constructed in the city of Berlin (Fig. 7). The test phase is undergoing for adjustment of the system. In this prototype, the Watergy concept is applied to building technology as a solar collector and water treatment mechanism. The greenhouse (40 m^2 surface, metallic structure covered with ETFE transparent foil) is attached to a two storey building (120 m^2, 6 m high, wood welted con-

Fig. 7. Watergy Prototype 2 built in Berlin, Germany.

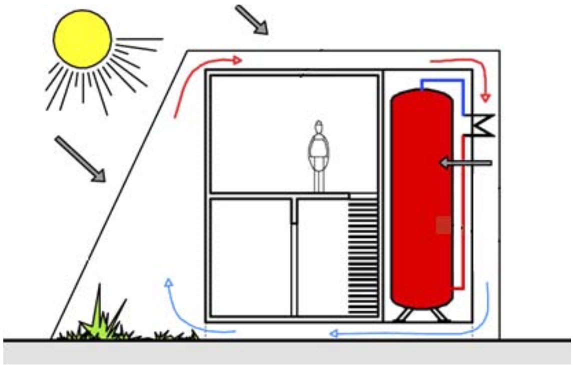

Fig. 8. Scheme of the heat collection in Watergy PT2.

struction). On the roof, a secondary collector with a humidificacion system helps the additional heating and saturation of the air before it reaches the heat exchanger. Fig. 8 shows the scheme of heat collection by Watergy PT2, with hot humid air (red lines) circulating from the greenhouse and roof area (secondary collector) to the heat exchanger, which extracts the heat to the storage and returns cold dry air (blue lines) to the greenhouse. In this process, condensation takes place on the surface of the heat exchanger as in PT1. The energy collected is used to load seasonal heat storage of about 35 m^3 capacity, with a 60 cm layer of cellulosics insulation. The heat stored during the warm part of the year is used for building and greenhouse heat supply during the cold part of the year. In this prototype the cooling duct is placed inside the building, and the heat exchanger acts like a building heat radiation unit during the cold period. Waste air from the building can be driven to the greenhouse for more efficient space heating.

Although it is based on the known concepts of standard passive house insulation and solar-based heating systems from seasonal heat storages, it is the first time that a so-called solar humid air collector is used for solar thermal heat generation. Additionally, the heat transfer from air to water as storage medium can assume the role of direct heating of water, sparing the use of conventional solar collectors.

Besides its function as a solar collector, the integration of the greenhouse in urban areas (see Fig. 9) is conceived as a method of recycling domestic grey water, generating clean water for human consumption as well as fruits. The greenhouse is fed with grey water, organic waste and even used air from the building, producing distilled water.

From an architectural point of view, the system proposes several challenges: (i) the concept of almost zero input energy in the climatization; (ii) the decentralization of supply, both of clear water and heat, and wastewater exhaust; (iii) the use of light materials in the building, as the heat accumulator allows reducing the thermal mass of the building.

4. Summary and conclusions

The Watergy project proposes two prototypes for application of a novel humid-air solar collector. The first is a closed greenhouse for solar ther-

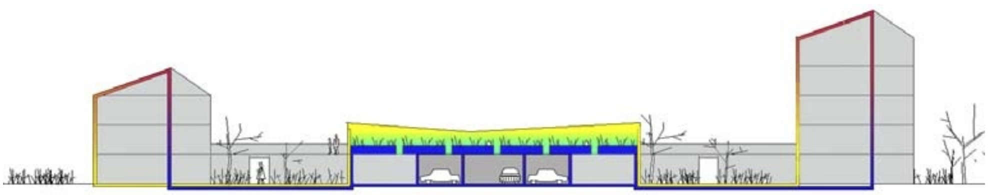

Fig. 9. Proposed solution for urban integration of the greenhouse as a solar collector. Empty surfaces as roofs of parking sites can be used for solar collection.

mal energy capture, water recycling, water desalination and advanced horticultural use. It is already constructed in Estación Experimental de Cajamar in Almería (Spain), and functioning since the fall of 2004. The system allows controlling the climate inside the closed greenhouse as well as closing the water cycle with the recovery of all the evapotranspiration from the plants. This opens a very interesting possibility for sustainable management of water in intensive horticulture, as the greenhouse irrigated with grey water becomes a means of producing not only of fruits but also clear water. Alternatively, if grey water is left out of the system, the greenhouse can reduce greatly its water consumption with the reuse of the recovered distilled water.

The second prototype is constructed in Berlin (Germany), and it is a building with an autonomous supply of heat and also of clear water. In this case, the closed greenhouse is connected to the building and purifies its residual grey water. Beside its main function as solar collector and water distiller, the greenhouse provides fruits and can be fed with residual air from the building. The more efficient collection of solar thermal energy in the system and its seasonal storage allow for a passive climatization of the building. In the context of sustainable architecture, the Watergy system means that this concept of zero energy is complemented with that of water autarchy.

The Watergy project proposes the integration of greenhouses in urban areas in symbiosis with houses. The greenhouse is incorporated as part of a new humid air solar collector system in which the heat collection process allows for grey water purification and edible biomass development. The system produces water of higher quality than standard biological treatment methods. The greenhouse is part of the collector surface, but offers further advantages as a supplementary living space and an integrated food production system.

The treatment of urban residual water in such an autonomous and local way opens two possibilities of great interest in the sustainable management of water. On one hand, the decentralization of water supply can be contemplated with self sufficient systems able to close their water cycle locally. Together with the collection of rain water, the system can be a basis for a complete autarky of water supply and wastewater treatment. On the other hand, intensive agriculture can be freed from its enormous water consumption, increasing the sustainability of greenhouses, which are able to produce distilled water as well as fruits. A closed greenhouse is also the means for an improvement in the quality of production, due to the isolation from insects and the possibility of CO_2 enrichment of the air to increase photosynthesis.

Of the two prototypes contemplated in the project, the closed greenhouse started to operate in spring 2005, subsequently generating data, while the sustainable building is still on the testing phase at the time of writing this paper.

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References

[1] G. Stanhill, The energy cost of protected cropping: a comparison of six systems of tomato production. J. Agric. Eng. Res., 25 (1980) 145–154.

[2] C. Stanghellini, F.L.K. Kempkes and P. Knies, Enhancing environmental quality in agricultural systems. Acta Horticulturae, 609 (2003) 277–283.

[3] E. Goto, K. Kurata, M. Hayashi and S. Sase, Plant Production in Closed Ecosystems: The International Symposium on Plant Production in Closed Ecosystems, Narita, Japan, August 26–29, 1996. Kluwer Academic Publishers, The Netherlands, 1997.

[4] M. Buchholz, Ein Feuchtluft Solarkollektor System zur kombinierten Raumklimatisierung und Wasser-

aufbereitung. In Der Gesundheitsingenieur, 124, Munich, 2003.

[5] M. Buchholz, Climate control in greenhouses and solid state fermentation systems as a source of water and energy. Proc. Word Renewable Energy Congress VI, Renewables — The Energy for the 21st Century, Brighton, July 1–7, 2000, A.A.M. Sayigh, de., Kidlington, Oxford, 2000.

[6] M. Buchholz and G. Zaragoza, A closed greenhouse for energy, water and food supply. Habitation, 9 3/4 (2004) 116.

[7] M. Buchholz, P. Jochum and G. Zaragoza, Basic water, heat and food supply from a closed greenhouse — The Watergy project. Acta Horticulturae, in press.

[8] P. Jochum and M. Buchholz, Simulation of thermal and fluid dynamical processes in closed greenhouses including water interactions between plants and air. Acta Horticulturae, in press.

[9] H.J.J. Janssen, Th.H. Gieling, S.L. Speetjens, J.D. Stigter and G. van Straten, Watergy, towards a closed greenhouse in semi-arid regions: infra structure for process control. Acta Horticulturae, in press.

[10] F. Orgaz, M.D. Fernández, S. Bonachela, M. Gallardo and E. Fereres, Evapotranspiration of horticultural crops in an unheated plastic greenhouse. Agric. Wat. Manage., 72 (2) (2005) 81–96.