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Closed Greenhouse Production Systems for Smart Plant Production in Urban Areas

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Abstract**—**The integration of agricultural production systems into urban areas is a challenge for the coming decades. Because of increasing greenhouse gas emission and rising resource consumption as well as costs in animal husbandry, the dietary habits of people in the 21st century have to focus on herbal foods. Intensive plant cultivation systems in large cities and megacities require a smart coupling of information, material and energy flow with the urban infrastructure in terms of Horticulture 4.0. In recent years, many puzzle pieces have been developed for these closed processes at the Humboldt University. To compile these for an urban plant production, it has to be optimized and networked with urban infrastructure systems. In the field of heat energy production, it was shown that with closed greenhouse technology and patented heat exchange and storage technology energy can be provided for heating and domestic hot water supply in the city. Closed water circuits can be drastically reducing the water requirements of plant production in urban areas. Ion sensitive sensors and new disinfection methods can help keep circulating nutrient solutions in the system for a longer time in urban plant production greenhouses.

Keywords**—**Semi closed, greenhouses, urban farming, solar heat collector, closed water cycles, aquaponics.

I. Introduction

THE cities of the world are growing. 54% of the world's population lives in urban areas and the most urbanized regions are Northern America (82%), Latin America (80%) and Europe (73%) [1]. The use of land by the urban spread limits the agricultural area. On the other hand, in order to secure food supply of an increasing urban population, agricultural production must be move closer to the settlements. Urban farming is a topic that has now been worked on worldwide. Prior the millennium urban food production estimates fifteen percent of the worldwide food production [2]. On one hand, questions about the ecology and economy of urban food production systems must be answered and on the other hand, the principles about technical integration of agricultural production plants into the urban infrastructure have to be developed.

Intensive vegetable production systems embedded in urban building structures leads to a consumer-oriented production of plant-based foodstuffs. Urban citizens can have a better relationship with the food production process and are able to learn more about process quality in the immediate vicinity of the market.

Plant cultivation in the city can only be established if a high areal production yield is generated and production systems are operating with high energy efficiency. The energy and material input as well as residual material remain should be minimized. Therefore, closed production systems, well known from intensive greenhouse horticulture, should be adapted to an urban application. The closed greenhouse concept provides a technology in which solar thermal energy can be produced with the help of technical cooled greenhouses [3], [4]. For more than 20 years, these systems have been technically developed and scientifically investigated. In these greenhouses, plants can be cultivated in hydroponic systems under low energy consumption [5]. Thus, vegetables can be produced with recyclable substrates (rockwool) or without substrates (aeroponics). With these closed production systems, agricultural production systems can also be combined to generate synergies through intensive use of the area, as well as energy and material exchange. An example of this is the combination of aquaculture and hydroponics (aquaponics) [6].

The essential prerequisite is a precise management of liquid fertilization and safe disinfection methods for the prevention of plant diseases in long time circulating nutrient solutions

II. Materials and Methods

Three innovative key technologies were developed to bring greenhouses into combined urban and closed production systems: A: A new cooling concept for a semi closed collector greenhouses (SCCG) to maximize energy harvest and water re condensation, B: new concept of heat storage in low-temperature water tanks and C: new sensors for analyzing the nutrient content of circulating nutrient solutions.

A. New Cooling Concept for SCCG

At the Humboldt University in Berlin, from 2010 to 2014, experiments with a SCCG-system took place with tomato production in hydroponics. Two experimental greenhouses, 307 m² each, were used for measuring the energy and water consumption. One greenhouse was constructed as a SCCG, the second greenhouse was operated as a reference greenhouse with conventional technical equipment. With the SCCG a heat pump integration and cooling concept to produce vegetables and thermal solar heat has been developed. At the same time the water consumption of the plant production can be lowered by high water vapor condensation from the cooling system and

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reuse of this water for irrigation purpose (Fig. 1).

New finned tube heat exchangers are located under the roof of the greenhouse to collect sensible and latent heat from the greenhouse air (Fig. 2). Cooling is performed without fans because the air movement is driven by density differences. Caused by re-condensation of the plant transpiration water vapor, the canopy itself is working as heat exchange surface and thus integrated into the cooling concept.

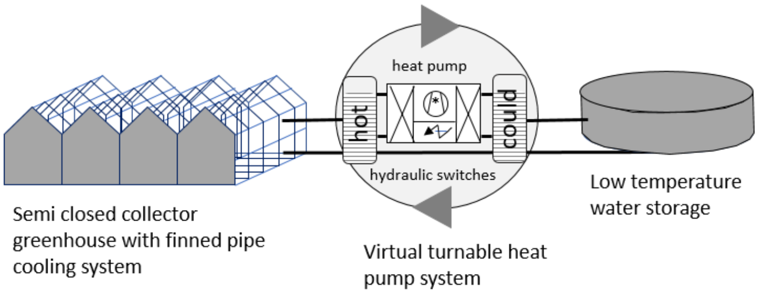

Fig. 1 Technical Setup of the semi closed collector greenhouse

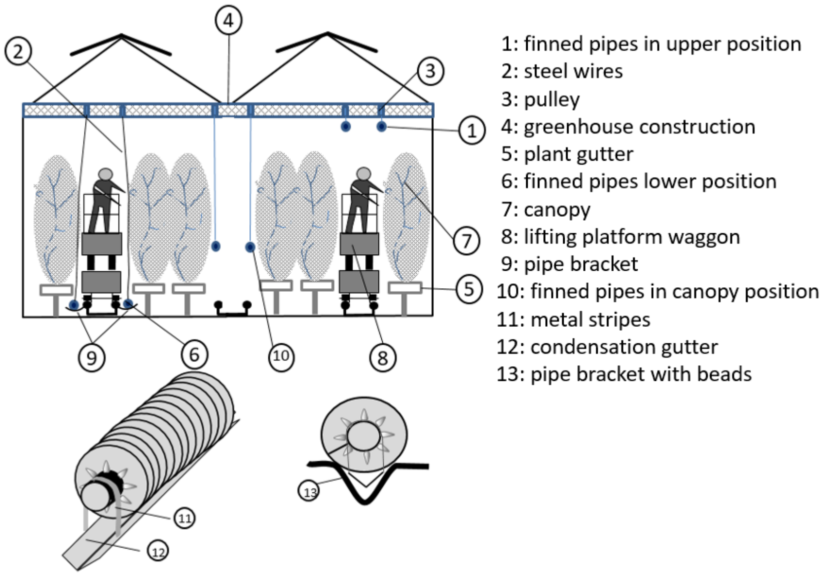

Fig. 2 New cooling technology for closed greenhouses using movable finned pipes (patented)

B. Concept of Heat Storage in Low-Temperature Water Tanks

A concept was developed with above-ground water reservoirs bivalent used for storage of rain water for irrigation purpose and storage of solar energy. A conventional rain water tank (1 m³ water per m² greenhouse ground area) with minimum isolation (500 mm expandable polystyrene on the surface) was operated in a temperature range from 5 °C to 45 °C to save the heat from the SCCG. Higher tank temperatures should be avoided in order to reduce the thermal losses and still make the water applicable for irrigation purposes.

C. Key Sensors, Automation and Disinfection Methods for Long Time Circulating Nutrient Solution in SCCG

Ion sensitive sensors have been developed for measuring the concentration of single ion groups like nitrate, ammonium, calcium, potassium and chloride. Because of compensation of the inevitably drift of these kind of membrane sensors, a calibration robot was developed. One time per day, the sensor parameters have been corrected by the help of defined calibration probes.

Software, hardware and precise pump technology are available to control the ion concentration in the circulating solution. With the micro injection of electrolytically produced potassium hyper chloride in the circulating solution, the activity of plant pathogens could be reduced (not shown).

III. Results

A. Water Savings and Solar Heat Extraction from Closed Greenhouses - Results from the Cooling Concept for SCCG

With the help of the SCCG-system consisting of the roof cooling system, the heat pump integration and the low-temperature storage, an energy yield of 1.76 GJ/m²a collector area could be measured in the closed greenhouse (Table I); that is half of the global radiation impinge on the greenhouse ground area.

While 0.53 GJ/m²a is used to heat the greenhouse, 1.39 GJ/m²a can be used for other thermal processes in the city (heating, hot water, drying)

TABLE I
HEAT ENERGY BALANCE FOR THE SEMI CLOSED COLLECTOR GREENHOUSE IN GJ/M² YEAR

Quantity	Value
Annual global radiation on the greenhouse surface	3.65
Overall stored heat energy	1.76
Electricity for heat pump cooling	0.32
Electricity for all electrical consumers for cooling	0.21
Electricity for heat pump heating	0.07
Electricity for all electrical consumers for heating	0.1
Electricity for the heat pump process	0.39
Thermal energy for greenhouse heating	0.53
Thermal energy for other thermal consumers	1.18

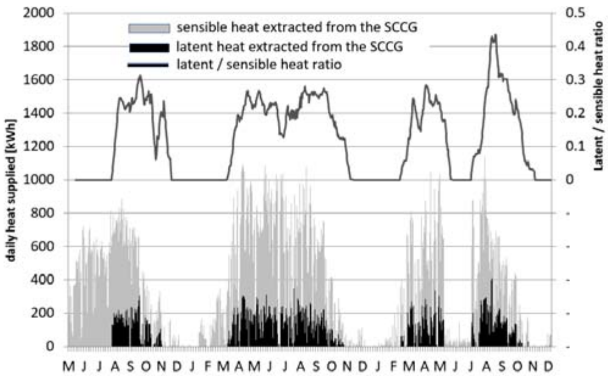

Fig. 3 Sensible and latent heat extraction from the semi closed collector greenhouse

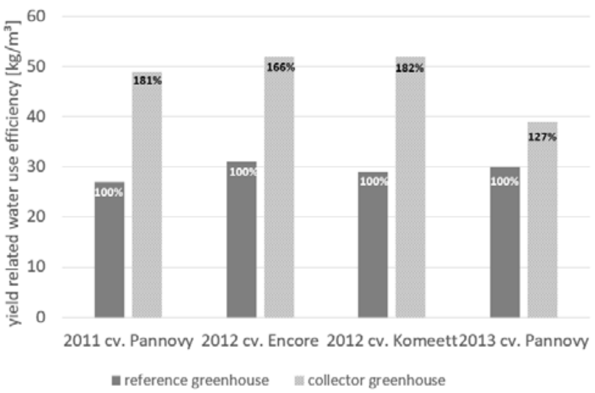

Fig. 4 Water use efficiency in different years with different tomato varieties

With a maximum electrical power of 133 W/m² for the heat pump, a maximum cooling capacity of 678 W/m² can be achieved with a working number for the cooling of 5.1, considering all electrical loads (COP = 3.6), the annual cooling output was 478 W/m². This means that roughly half of the global radiation input into the greenhouse can be withdrawn.

Due to operating the finned pipe cooling system below the dew point of the greenhouse air, a high amount of condensation water was collected. The part of the latent cooling by the canopy was about one third of the overall cooling performance (Fig. 3).

The water quality was high enough to reuse the condensate for the plant irrigation. Therefore, the water use efficiency was 27 to 82% higher compared to a conventional greenhouse tomato production (Fig. 4).

B. Thermal Heat Storage: Results from the Concept of Heat Storage in Low-Temperature Water Tanks

With the help of a water reservoir with a volume of 1 m³ of water per m² of SCCG base area, a heat quantity of 0.36 GJ can be stored at a temperature difference of 40 K. This means that the store is suitable to heat the greenhouse at temperatures outside of 5 °C for about two weeks without solar radiation. With the help of the storage, the collector greenhouse could be heated with solar energy from early March to late November (Fig. 5). From April to September more heat can be delivered than required for the greenhouse.

C. Analyzing Sensors for the Closed Recirculation Nutrient Supply Systems for Hydroponic Plant Production

With a sensor stability of about 6 months for membrane sensors, the daily slope of the ion concentration in the drain as an essential prerequisite for a time oriented nutrient supply strategy is now available. The first results had shown an increase in the calcium and potassium concentration while nitrogen concentration is decreasing (Fig. 6). Thus the micropumps have to inject different amounts of nutrient solution to work with a continuous ion concentration in the tank. With the help of a sophisticated software algorithm, the adapted amount of conventional nutrient solutions can be calculated. From the point of nutrient balance with these components a long-time circulation of the solution is now possible.

IV. DISCUSSION AND CONCLUSION

The results from the closed plant production system components had shown the ongoing progress in the key components of this technology. An essential prerequisite for system sustainability and a synergetic neighborhood of urban living systems and plant production is the autonomy of the plant production system. An additional added value may be generated by thermal heat production in the SCCG and absorption of gaseous urban CO_2-waste from other technical processes like heat production. With the ability and technology of thermal storage in aboveground, low temperature storage systems different possibilities for using reservoirs in the cities are available [7]. Excess heat from the SCCG can be used for service water heating or spa application in the cities.

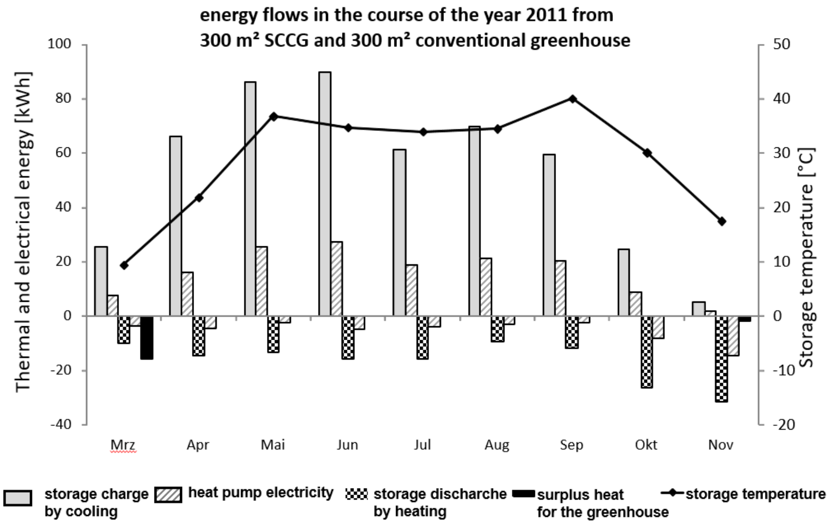

Fig. 5 Heat balance and temperature of the 300 m³ heat storage tank

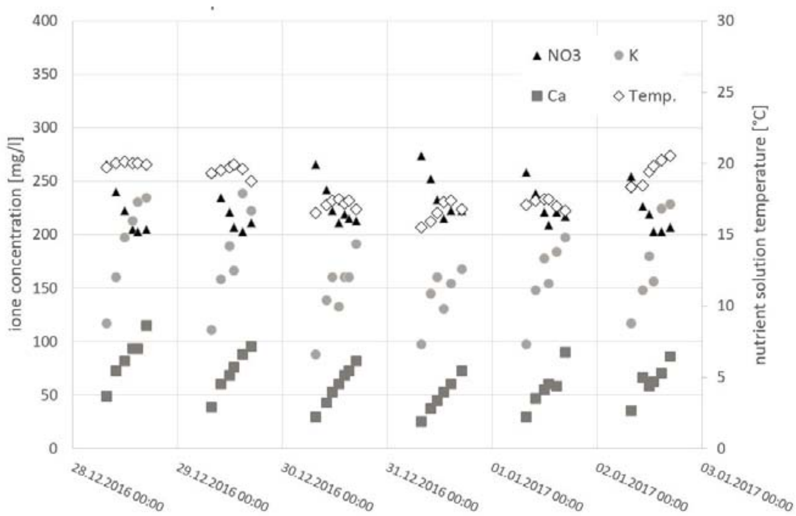

Fig. 6 Automatic 7 day measurement of temperature and ion concentration in the recirculating nutrient solution of the SCCG

The ion selective sensor technology is a key technology for analyzing and managing closed nutrient circles. Against ion-sensitive field-effect transistors (ISFET) [8] the developed membrane sensors are working stable for a period of about 12 months. It is also the basic for coupling production processes like vegetable and fish production (Aquaponics) or the recycling of grew waste water from urban systems. The question of the right location of plant production in the cities (roofs, facades) is less interesting than the question of the best interaction of plant production in an urban infrastructure. So far from the point of view of non-expensive light conditions, the production in high natural light transmitting greenhouses is the more economical way.

For the docking of the closed plant production systems on urban infrastructure more information about energy consumption and mass flows of city supply and disposal systems is required. Beside production purposes, plant production systems should be considered as education and social meeting center. Sustainability of plant production and production technology hereby play just as important role as production efficiency and costs.

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