Closed Greenhouse Concept Integrating Thermal Energy Storage (TES) applied to Aquaponics Systems

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***Abstract* - This paper focuses on the development of closed greenhouse concepts and application of that technology to aquaponics systems. At first, aquaponics systems and closed greenhouses with TES are described. Then, TES in abandoned mines are discussed. Finally, ongoing research on aquaponics systems at the South Westphalian University of Applied Sciences, Soest Campus, will be presented. The aim is to develop a concept for a prototype aquaponics system in the Ruhr-district in North Rhine-Westphalia at an abandoned coal mine in order to use mine water for heating the aquaponics system, improving the energy balance significantly.**

***Index Terms* -- renewable energy, mine water, energy efficient greenhouses, thermal energy storage, aquaponics**

I. Introduction

The term aquaponics is used for an agriculture system involving the simultaneous cultivation of plants and aquatic animals, such as fish, in a symbiotic environment. Aquaponics systems can be used in outdoor setups, mostly operating in warm areas (Asia, Australia, USA) or indoor aquaponics greenhouses, which are the favoured solution for mid-European climate conditions, such as present in Germany. Besides labour, energy usage (especially heating) is the largest cost factor for conventional greenhouses; however energy consumption varies largely with the layout and purpose of the greenhouse.

As a consequence, the significance of energy conservation and its management in the greenhouse is a crucial issue to enable cost efficient crop production. Ongoing research (especially in the Netherlands) is being carried out addressing the question of improved greenhouse performance by reducing energy inputs and conserving energy throughout the system. In this context so-called "Closed Greenhouse Concepts" combined with thermal energy storage (TES) have been proposed.

First prototypes are already operating in the Netherlands and have proven technical feasibility. However, applications are not wide spread, due to economic reasons. Recently, newly developed heat exchangers suitable for geothermal technology have been applied in order to increase efficiency of such systems: The drillings are still the main cost driver while the energy balance improves significantly and fossil fuels are substituted.

If the geothermal infrastructure already exists, e.g. by using former underground coal mine resources, energy costs might be lowered sufficiently by using mine water. Reduced heating costs are the main economic benefit of locating a greenhouse near a former coal mine. The annual savings from reduced heating costs might be high enough to drive a greenhouse project of this kind into the profit zone. The utilization of a seasonal thermal storage system might result in additional savings, which would make projects even more attractive.

II. Aquaponics System

Aquaponics is a food production system that combines conventional fish production with hydroponics (cultivating plants in water) in a symbiotic environment. Hydroponics is a subset of hydro culture and is a method of growing plants using mineral nutrient solutions, in water, without soil. Sustainability is achieved through the re-use of waste streams of water, nutrients and energy. In an aquaponics system, waste nutrients of the aquaculture effluent are used to produce plant crops. The effluent is treated by nitrogen-fixing bacteria (nitrification) transforming ammonia via nitrites into nitrates, which are utilized by the plants as nutrients. The water is then recirculated back to the aquaculture system.

The system needs electricity for lightning and pumps as well as heat for the fish tanks and plants. In addition, fishes need to be fed and fresh water is needed to make up for evaporation. The outputs are fish and produce. For the aquaculture part numerous cold-water and warm-water fish are available for cultivation. The selection of the species depends on the boundary conditions of the project. Warm water fish (e.g. tilapia, catfish) require higher temperatures in the water tanks (about 25-30°C) whereas the cold water fish (e.g. trout and carp) only need about 15-20°C temperature in the water tank. A rough sketch of the system is drawn in figure 1.

As existing hydroponic and aquaculture farming techniques form the basis for all aquaponics systems, the size, complexity, and types of foods grown in an aquaponics system can vary as much as any system found in either distinct farming discipline.

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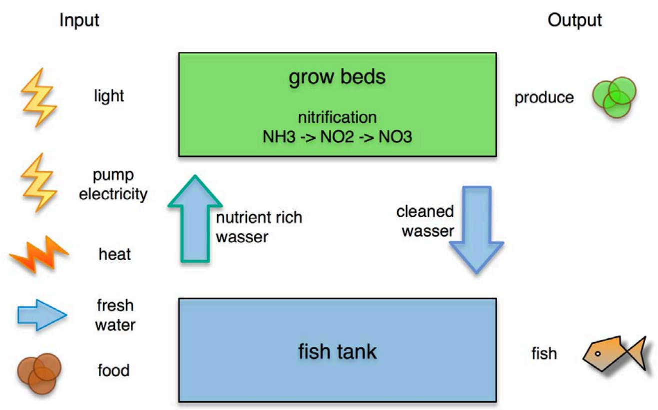

Fig. 1. Aquaponics system

The basic principle has already proven it's feasibility in many projects all over the world. In field applications, the principle of combined fish and plant production is already used about 2,000 years ago in tropical Asian countries with rice and carp. In the 1980s agricultural scientists used this innovative system in subtropical locations. However, the production in greenhouses or buildings in colder climates is quite young. In Europe only a few (mostly small) pilot plants exist at present.

From an ecological viewpoint, aquaponics systems provide many advantages:

- modular installation, flexible size;
- no need to use agriculture acreage;
- in contrast to conventional aquaculture production plants eliminating waste water, because of the cascade usage;
- allows waste heat utilization in close connection to the heat source (e.g. mine water, surplus heat from industrial processes, biomass reactor);
- independent from regional climate conditions.

Aquaponics systems are preferably operated in locations where surplus heat is available, e.g. in connection to biogas reactors or other sites with CHP plants. Also industrial waste heat from industrial sources can be used as input for the aquaponics system. The installation of aquaponics systems is especially interesting for urban areas with limited space availability as the modular systems can be operated even on polluted sites, e.g. abandoned coal mining locations. In addition, food is produced in proximity to the consumers resulting in a better balance concerning CO_2-emissions than conventional food production (transportation, distribution).

Research on one circuit and dual circuit aquaponics systems so far focused on general technical and economic feasibility and on the system dynamics of nutrient production and consumption and the achievable growth rates of both, the fish and the plants. The aspect of regarding the thermal properties of both subsystems and the possibility of leveraging those for root zone temperature management or short term thermal storage has yet been untapped.

The three basic grow bed systems of hydroponics, ebb and flow (E&F), nutrient film technology (NFT) and deep water culture (DWC), show different characteristics in their suitability for raising different crops. Low weight, good controllability of water and nutrient throughput and little risk of nutrient accumulation of the NFT system are the reason that this system is the preferred method in conventional under glass crop production. Yet in extended periods of high outside temperatures this system runs at the risk of overheating when used in long production lines, up to the point of drying up. E&F and DWC grow beds, which are significantly more expensive, have a higher thermal stability and might even be suitable for short term thermal storage in small temperature ranges. Systematic research with this focus has not yet been conducted

III. Closed Greenhouse Concept and Thermal Heat Storage

Recent research shows that a greenhouse, when viewed as a solar collector, captures about three times the energy that is necessary for yearly operation. The main share of this energy is generated in the form of heat. In classic conventional greenhouses this heat is lost or needs to be cooled down by using climate control. The closed greenhouse concept aims to harvest the excess solar energy which is passing through the green house and to store it in a thermal storage system (Thermal Energy Storage - TES) for utilization at a later time.

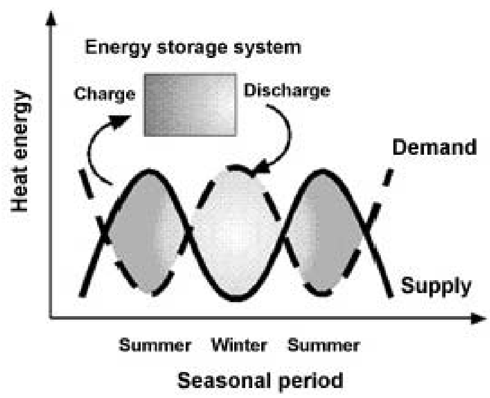

Fig. 2. Phase shift between supply and demand

Figure 2 shows the phase shift between the supplied energy, e.g. heated water from a solar collector, and the demand of energy for heating purposes for middle and northern European countries. In the summer period, when a lot of water is heated by the sun, the heating demand is low. But in the winter period during large heat demands the energy supply is not sufficient to satisfy demands. For those energy sources, such as solar energy, the lowest availability takes place exactly when there is a large amount of heating demand. Hence, it is necessary to use energy from a conventional power supply system. To make renewable energy more efficient, a device is needed, with which energy can be stored for an extended period. This can be achieved by a thermal heat storage system. The basic idea is to charge the storage system when solar energy is available and to discharge it when the stored heat can replace more expensive sources, which is also shown in figure 3. The balance of the energy supply and demand increases the efficiency of the whole energy supply system and decreases the operational costs.

Especially for long-term storage with regards to heating purposes, the size of the heat store must be large due to the large amount of energy. The significant size requirement can be met by utilizing the ground. Such a system is called ground heat store. Heat is stored in sensible form by raising the temperature of a body of rock, soil or water. The same body is cooled down during the period of heat extraction. A system for large-scale seasonal storage of heat can be used in many different ways. Three typical applications are shown in figure 3.

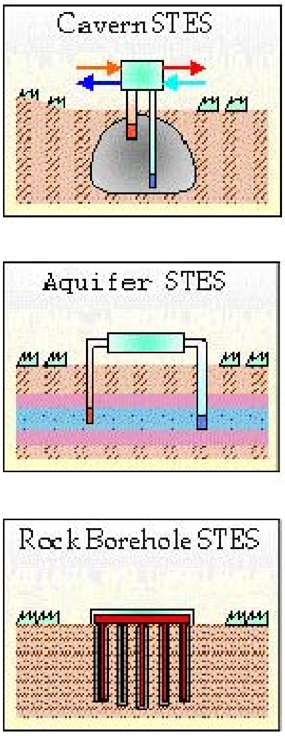

Fig. 3. Different types of Seasonal Thermal Energy Storage (STES). The Cavern STES and the Aquifer STES are usually operated with open systems (direct use of warm water) with a supply and injection well. The Rock Borehole STES is equipped with a number of geothermal U-type probes (closed system).

Which system can be applied usually depends on the available storage medium. With regard to the storage medium, three different basic types of heat stores in the ground can be distinguished. If water is used, it is contained in tanks, excavated pits, rock caverns or mines. In an aquifer heat store however, the combined volume of the ground, usually sand and water act as storage medium. In duct stores, heat is stored in the solid material, like soil, clays, sands or rocks [1].

In [1] the desirable characteristics of energy storage are summarized:

- The unit should be capable of receiving and discharging heat at the maximum rate without excessive temperature differences.
- The unit should have minimal losses, which includes heat losses out of the unit as well as degradation of thermal stratification within the unit.
- The unit should be inexpensive.

The first prototypes of greenhouses with TES have already been built and scientifically examined. In the vicinity of Venlo (Netherlands) a closed greenhouse complex with TES is in operation. The operation is therefore technically feasible, but not yet in broader application. The necessary boreholes are usually referred to as the main cost factor for systems of this type. If the utilization of existing infrastructure is possible costs can be reduced significantly.

IV. Thermal Energy Storage in abandoned Mines

Mine water sources in abandoned and flooded hard coal mines have significant potential for thermal usage and are suitable for storing heat or cold. Depending on the depth, the mine water has a temperature range of 20 to 35 °C. The heat can be easily used for heating purposes. However, for conventional heat utilization of mine water, heat pumps are required because of the low temperatures. In summer heat surplus produced in buildings (or greenhouses) can be stored underground. The usage of heat energy from mine water has already been successfully tested in several projects in central Europe, for example in Aachen (Germany) [2], Bochum (Germany) but also in Heerlen (Netherlands) [3].

A TES consists of two important components, the geological medium that provides the storage capacity and the ground heat exchanger. The borehole (or shaft in a mine) and the pipe installation, which direct the heat carrier through the boreholes, are the most important parts of every geothermal heat exchanger. The borehole (shaft) installation must achieve a good heat transfer. However it should also be cost effective. Therefore, a compromise between efficiency and costs has to be made. The heat carrier is circulated through boreholes in either open or closed loops, which represent the two basic circulation types. Boreholes may be connected either individually or in groups, in series or in parallel.

To extract the geothermal energy in hard coal mines, basically two different methods can be applied: the doublet system (open system) and the single probe (closed system). The single probe is a closed pipe system which is installed in the existing shaft of the coal mine. The heat is extracted from the mine water column in the shaft and the surrounding rock by a heat carrier medium (e.g. water). The closed pipe system works like a deep geothermal heat exchanger. The advantage is that no problems due to the mine water chemistry like corrosion or fouling occur in the heated system, because there is no direct interaction between the heat carrier and the rock (mine water). The heat transfer ensues through the pipe material and the mine water in the borehole (shaft). Consequently, the heat transfer is inferior compared with an open system. But it can be applied in many cases because it does not need special geological requirements like the open system does.

Single geothermal probes are suitable for applications when a relatively small amounts of heat needs to be recovered from a reservoir with sufficiently high temperatures. The characteristics of single probes for coil mine applications are:

- low cost system, but limited performance (10-100kW);
- only one shaft is needed for the heat exchanger;
- no direct use of the mine water (closed system), therefore less environmental impact;
- heat in the shaft and surrounding rocks are used.

The doublet system consists of a supply well (shaft 1) to pump the (warm) mine water to the ground surface (heat exchanger) and an injection well (shaft 2) to return the (cold) water back to the ground, see figure 4.

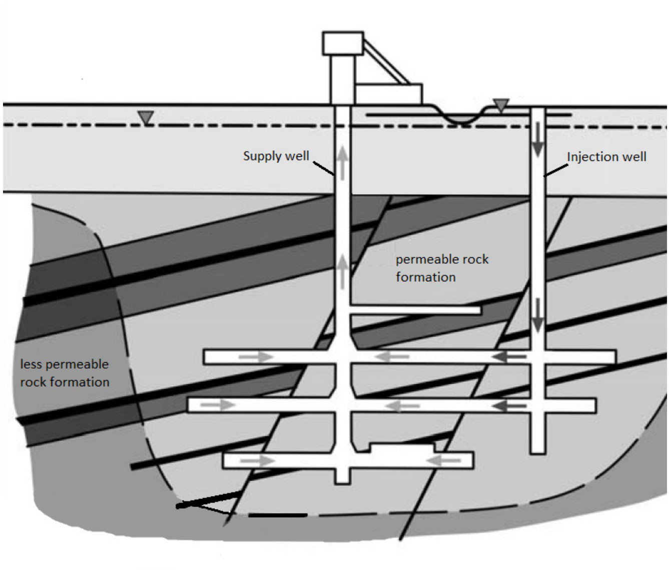

Fig. 4. Doublet system in abandoned coil mines with supply and injection well. The arrows display the water flow direction in heating mode (light arrow=warm water, dark arrow= cold water) [2].

As a result, an immense water circle is created which allows the extraction of much larger amounts of energy compared to the single probe system. As the mine water is directly used, the heat transfer is much better compared to the single probe. However, the complexity of the system is much higher either, as expenditures for the pipe system and the pumps have to be considered. Water chemistry problems could lead to scaling in heat exchangers and pipe systems.

The characteristics of the doublet system for coil mine applications are:

- separation of extraction and infiltration point (shaft);
- direct use of heat carrier (mine water);
- large continuous heat flow;
- high investment (pipe system, pumping);
- water chemistry could raise problems.

With the doublet system a larger amount of energy can be obtained continuously, whereas the single probe system, however, is less expensive. According to [2], despite the higher investment costs, the doublet system is the preferable option for long-term geothermal use. Usually, a flexible heat pump system is required independent from the type of system. If used as TES in combination with an aquaponics system, the mine water temperature would possibly be high enough for heating the fish tanks, as the required temperatures in the fish tank lies in a range of 25-35 ° C - depending on the fish species used.

V. Proposed Concept

North Rhine-Westphalia (NRW) has been the heart of the German coal mining industry for a long period. Coal mining starts in the mid ages near River Ruhr. Since 19th century the Industrial Revolution advanced with thousands of coal mines and steel works. Today "The Ruhr" is one of the densest populated areas in Europe with 7.3 million people on 4,435km² (1,645 per km²), see figure 5. More than 30,000 abandoned mine shafts and openings exist.

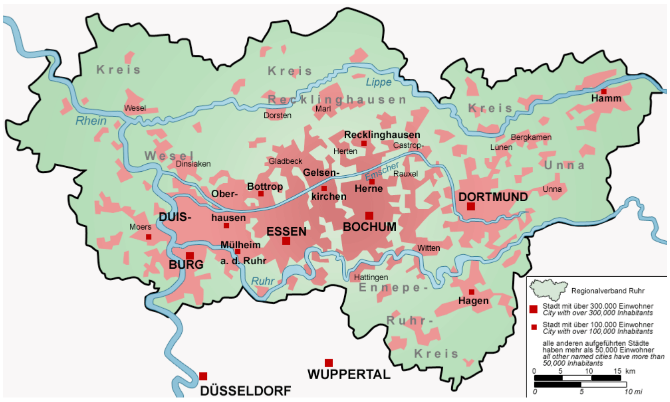

Fig. 5. The Ruhr area in North Rhine-Westphalia (Germany)

The majority of the mines are no longer in operation, in 2014 only three mines were still extracting coal. For safe operations of the hard coal mines in the Ruhr-area, a complex system of mine water drainage facilities in active and already abandoned coal mines is in use. Large quantities of mine water are pumped and deducted to the surface. Mine water levels at the central dewatering stations are kept between depths of 445-950 m. Since the mines were operating in depths of 1.500 m and more, warm mine water sources in abandoned mines of NRW have a significant potential for heating usage - an opportunity which is still to be tapped, especially since pumping of the water often has to continue long after mine closure to prevent contamination of groundwater and mining damages to the infrastructure above.

The German Government and the state government of NRW decided to stop state-subsidized coal mining in the Ruhr-area in 2018. The Ruhrkohle AG as the last remaining German hard coal mining company is working on concepts for the reuse of mining plants and sites. In this context a few pilot projects using mine water for heat recovery have already been realized. One example is the joint project "Robert Müser", conducted by the Stadtwerke Bochum and the RAG Aktiengesellschaft, which was successfully realized in order to generate heat from mine water. Here, the RAG annually pumps approximately 10 million cubic metres of mine water with a temperature of about 20° C. In theory, this heat potential is sufficient to supply the whole commercial centre at the Ruhr Park in Bochum with heat.

Based on these experiences, it is intended to install an aquaponics system on one of the former mining sites. This demonstration facility should be supplied with heat coming from mine water (until 2018). The greenhouse complex to be installed can be located very close to the supply well to avoid heat losses. Any contamination of the soil on the mining site is of little relevance, since the plants are growing in water, without soil. In this first stage of the project conventional greenhouse technology can be used as the mine water will be still pumped up.

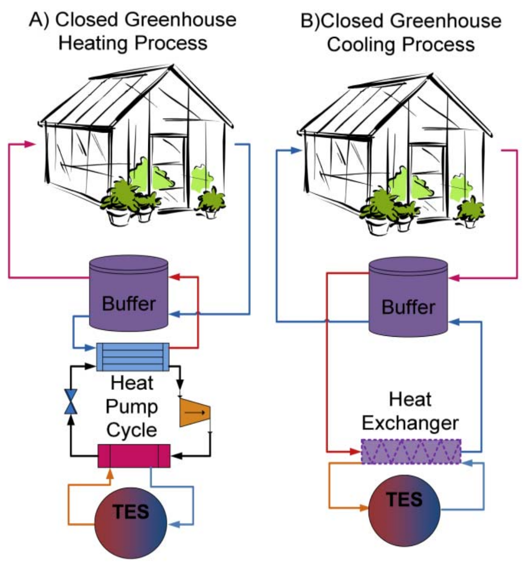

Fig. 6. Closed greenhouse concept with TES [4]: In a closed greenhouse, there is no ventilation, thus excess heat need to be removed. a) The heat can be stored using a seasonal TES (situated in coal mines) and used later in order to satisfy the heating demand (in combination with a heat pump) of the greenhouse. b) In the same way, the greenhouse will be cooled down by using the cold water from the ground.

In parallel a feasibility study should focus on the period after 2018 to answer the question how to use mine water if it no longer pumped up to the surface after the year 2018. Here, the combination of a closed (or semi-closed) greenhouse with a TES (coal mine shaft) should be investigated (see figure 6). Besides the advantages of energy efficiency, there are at least three more reasons to think about closed greenhouses:

- In an aquaponics system, fishes produce CO_2 which can be reused by the plants in a closed greenhouse only;
- food production in urban areas has to deal with an increased pollutant entry, different than the production in rural areas. Thus, to apply closed greenhouses should lower immission load considerably;
- Closed greenhouses are advantageous with regard to vermins and microbes. Defined interfaces to the outside world can be much more easily managed by hygienic accompanying measures.

First experiences concerning aquaponics have been made during the last two years with a small pilot plant (12m^2), running in Dortmund (hei-tro GmbH). As a next step, an aquaponics facility of about 80m^2 will be built at the South-Westphalia University to conduct research projects in close cooperation with the University of Rostock. The facility will start operation in autumn 2014 to acquire more knowledge and experience in the operation of an aquaponics system. The facility in Soest should act as a blueprint for the planned demonstration plant (1000m^2) to be built in Essen with combined heat utilization of the mine water. If the demonstration plant in Essen can prove feasibility, the concept could be applicable on other mining sites in Europe as well.

VI. CONCLUSIONS

Using mine water to heat and cool buildings is a proven concept – the innovative idea in this proposal is the combination of geothermal energy with food production in urban areas. Greenhouses with an associated aquaculture system exhibit a demand curve that is significantly different from district heating requirements and might offer a complementary combination. Compared to conventional greenhouse practice the larger water bodies in the fish tanks and if using deep water culture grow beds can be viewed as short circle thermal buffers which might allow for peak load management within the constraints of allowed root zone temperatures and maximum fish tank temperature gradients. Research is still required to understand many aspects of these systems and well developed demonstration projects are needed to showcase the technology and potential.

REFERENCES

[1] Nordell, Bo: Borehole heat store design optimisation, PhD Thesis; division of water resources engineering, Luleå University of Technology, Luleå, Sweden, 1994

[2] Schetelig, K., Richter, H.: Nutzung stillgelegter Bergwerke oder tiefliegender Grundwasservorkommen zur Wärme-/Kältegewinnung und -speicherung, 43. IWASA, Wasser als Energieträger, 10. und 11. Januar 2013, Internationales Wasserbau-Symposium, Aachen 2013.

[3] Verhoeven, R. et al.: Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling; 18th International Renewable Energy Storage Conference and Exhibition, IRES 2013.

[4] Vadiee, A: Energy Analysis of the Closed Greenhouse Concept - Toward one Sustainable Energy Pathway, KTH School of Industrial Engineering and Management, Department of Energy Technology, Division of Heat and Power Technology, SE-100 44 STOCKHOLM, 2011.