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Adaptive Aquaponics Design for Different Climate Regions with Geothermal Energy Potential

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ABSTRACT

The ongoing global push for sustainability has motivated both the greenhouse horticulture and aquaculture sectors to explore the potential of geothermal energy for heating as an alternative to fossil fuels. To improve heat use efficiency of geothermal wells these food production systems can be integrated into an aquaponic-based thermal treatment network. Within this network the fish farm utilizes residual geothermal heat supplied by the greenhouse and heat from the geothermal well directly at moments that greenhouse heat demand is low. The EU funded GEOFOOD project aims to analyze in detail how to optimize the design and operation of such aquaponic facilities that use geothermal energy.

To that end a predictive model was developed which simulates the heat balances present throughout the thermal treatment network. The model enables the user to compose a sequence of geothermal wells, greenhouses and aquaculture facilities for which different scenarios can be explored by selecting several types of greenhouse, different crops and fish species as well as climates.

Three different climate regions with potential for geothermal energy use for aquaponic production have been selected to perform a scenario study; The Netherlands, Iceland and Slovenia. The simulated aquaponic system consisted of a 5 ha Venlo type greenhouse for tomato production and an indoor pike-perch fish farm. It is found that for a greenhouse located in the Netherlands geothermal heat extraction can be increased with 31% by combining it with an indoor pike-perch fish farm of 6544 m^2, without the need of alternative energy sources during peak demands.

1. INTRODUCTION

GEOFOOD is a GEOTHERMICA research, innovation and demonstration project that aims to determine how and to what extent the economic feasibility of geothermal heat can be increased by means of circular food production systems. In such systems agricultural production, water treatment, nutrient recovery, as well as food processing are connected by the exchange of energy and mass flows (Thorarinsdottir and Unnthorsson 2018). Since these subsystems have a variety of heating (and cooling) requirements throughout the year, they can be operated as a thermal treatment network in order to optimize the heat extraction from a geothermal well.

Aquaponics is a farming system that combines hydroponic cultivation of vegetables with aquaculture, and has a high potential for circularity in terms of nutrients, water and energy is (Goddek, Delaide et al. 2015, Goddek and Vermeulen 2018). A predictive model was developed to simulate thermal treatment networks consisting of a geothermal well, greenhouse and recirculating aquaculture system (RAS). Within this network the RAS functions as a sink for the (low temperature) residual heat coming from the greenhouse, but also utilizes geothermal heat directly whenever greenhouse heat demand is low.

The model can be used to design and assess the potential benefits of geothermal aquaponic systems, thereby supporting the direct use of geothermal energy within the food sector. Potential use cases include: (1) evaluating geothermal energy use potential of transforming an existing greenhouse into a circular aquaponic system, (2) dimensioning the RAS and geothermal well to optimize geothermal energy use efficiency, (3) designing new geothermal aquaponic systems taking into account climate parameters, greenhouse/RAS construction and equipment, crop and fish species, and (4) identifying geothermal energy use potential for other food production and processing systems to be integrated into an aquaponic thermal treatment network.

2. MATERIALS AND METHODS

2.1 System overview

In Figure 1 a schematic overview is given of the modelled geothermal aquaponic system. It consists of a geothermal well, a greenhouse and RAS that are connected as a thermal treatment network. Within this network the RAS facility is modelled to function as a sink for residual heat coming from the greenhouse. The geothermal well can supply heat to the aquaponic system in three distinct ways: (1) to the greenhouse directly, (2) to the RAS facility directly or (3) to the RAS facility as a mixed flow with the residual heat from the greenhouse. The core model consists of two parts in order to calculate hourly values for the energy and mass flows: (1) the greenhouse model KASPRO and (2) a RAS model. The combined outputs are used to compute when and how much heat is extracted from the geothermal well.

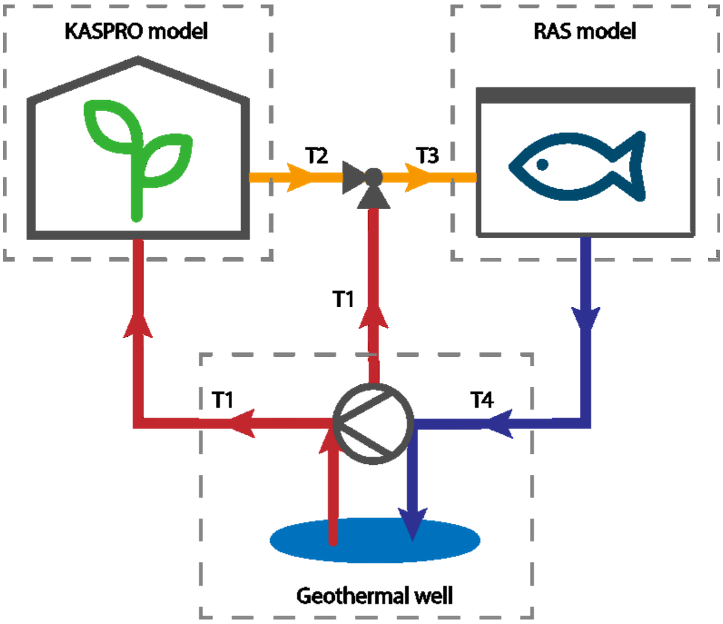

Figure 1: Schematic overview of the modelled geothermal aquaponic system.

2.2 Greenhouse simulation model

The model KASPRO (De Zwart 1996) has been used to simulate greenhouse heat demand as well as flow and temperature of the residual heat coming from the greenhouse. It is a physical greenhouse climate model coupled with a virtual climate controller, consisting of modules describing the energy and mass balances present within the greenhouse. The climate controller simulates commercially available greenhouse control equipment to enable climate management by means of heating, (mechanical) ventilation, (de)humidification, shading, artificial lighting and carbon dioxide enrichment, amongst others. KASPRO is continuously updated and validated in research projects to include innovations in greenhouse technology and crop management strategies (Luo, De Zwart et al. 2005, Kempkes, De Zwart et al. 2017, Graamans, Baeza et al. 2018).

2.3 RAS simulation model

The RAS energy model has been newly developed for the GEOFOOD project in order to predict the heat demand of RAS facilities. It is based on the energy balance for indoor aquaculture facilities as described by Timmons and Ebeling (2013). However, it is assumed that the building is an insulated, opaque structure for which heat gain by solar radiation does not play a significant role. The resulting energy balance is presented in Eq. (1). To calculate all heat flows several inputs are required that represent the outdoor climate (i.e. air temperature and humidity), design and management of the RAS facility (i.e. heat loss coefficient of the cover, water exchange rate, source water temperature, area of water surface, target indoor air temperature and humidity, and equipment characteristics) as well as the species of fish cultivated (i.e. target tank water temperature, feeding rate and feed to heat ratio).

$$Q_{demand} = Q_{building\ loss} + Q_{water\ exchange} + Q_{evaporation} + Q_{ventilation} - Q_{fish} - Q_{equipment} \qquad (1)$$

Q_{demand}	: overall heat demand of the RAS facility	[Wm^{-2}]
$Q_{building\ loss}$	: heat loss from the building	[Wm^{-2}]
$Q_{water\ exchange}$	: heat demand due to water exchange	[Wm^{-2}]
$Q_{evaporation}$	: heat loss due to evaporation	[Wm^{-2}]
$Q_{ventilation}$	: heat loss due to ventilation	[Wm^{-2}]
Q_{fish}	: heat produced by the fish	[Wm^{-2}]
$Q_{equipment}$	: heat produced by the equipment	[Wm^{-2}]

2.4 Computing performance of the thermal treatment network

In order to evaluate how efficient the thermal treatment network is at extracting heat from a geothermal well, a stepwise calculation is included that allows users to dimension system components and inspect performance. First, the greenhouse area and minimum temperature of the residual heat leaving the greenhouse are specified as well as the supply temperature of the geothermal heat and the percentage of yearly greenhouse heat demand that must be delivered by the geothermal well. Based on these inputs the maximum flow of the geothermal well is calculated with Eq. (2).

$$W_{geo} = \frac{A_{gh}\, Q_{req}}{\rho_{water}\, cp_{water}\, (T_{geo} - T_{res\,min.})} \qquad (2)$$

W_{geo}	: maximum flow of the geothermal well	[m^3s^{-1}]
A_{gh}	: greenhouse area	[m^2]
Q_{req}	: required heating capacity	[Wm^{-2}]
ρ_{water}	: density of water	[kgm^{-3}]
cp_{water}	: specific heat of water	[$J\ kg^{-1}K^{-1}$]
T_{geo}	: supply temperature geothermal well	[°C]
$T_{res\ min.}$	: minimum temperature residual heat	[°C]

Secondly, the temperature curve of the available heat for the RAS is obtained. This temperature varies over time depending on the heat demand of the greenhouse. However, it always ranges between the minimum temperature of the residual heat leaving the greenhouse and the supply temperature of the geothermal well. The available heat for the RAS, consisting of residual heat from the greenhouse and geothermal heat that is not used by the greenhouse, is subsequently calculated based on the available temperature.

In the final step the performance of the designed geothermal aquaponic system is computed for a range of RAS facility sizes. This is done by increasing the surface area incrementally between a minimum and maximum. The minimum size of the RAS facility is defined as the surface area that ensures no alternative heat source is needed to meet its heat demand other than the residual greenhouse heat or geothermal well. Though increasing the RAS facility further results in more heat extracted from the geothermal well, it also requires an alternative heat source to meet heat demand during peaks. The maximum size is therefore defined as the surface area for which an increase would no longer extract more heat from the geothermal well.

2.5 Scenario description

For the purpose of this paper a Venlo type tomato greenhouse combined with a RAS for pike-perch has been simulated to illustrate the functionality of the model. The objective of the simulation is to dimension the geothermal well and RAS for a greenhouse surface area of 5 ha under different climate conditions and availability of geothermal heating. To simulate the Dutch weather conditions, data from a typical meteorological year (i.e. SEL2000) available for De Bilt (The Netherlands) has been used (Breuer and Van de Braak 1988). The boundary conditions and inputs for the simulation of the greenhouse and RAS are presented in Table 1.

Table 1: Simulation parameters for the combined tomato greenhouse and pike-perch RAS.

Simulation parameters greenhouse		**Simulation parameters RAS**	
Area	5 ha	Heat loss coefficient cover	0.25 W/m^2K
Covering material	Single glass	Target indoor air temperature	26 °C
Lower pipe heating net Upper pipe heating net	Ø 51 mm, 5 per span Ø 32 mm, 2.5 per span	Target relative humidity of indoor air	85 %
Energy saving screen	SLS10 Ultra Plus	Target tank water temperature	26 °C
Growing cycle	Planting date 15-Dec Clean out date 20-Nov	Source water temperature	10 °C
Heating set point range	14 – 25 °C	Water exchange rate	3.85 $l/m^2/hr$
Humidity set point range	90 %	Feeding rate	0.25 $kg/m^2/day$
		Feed to oxygen ratio	0.6 kg/kg of feed
		Oxygen to heat ratio	13.6 x 10^6 J/kg of oxygen

The boundary conditions and inputs for the simulation of the geothermal well are based on the regional conditions. Within The Netherlands ground temperature ranges between 60 - 100 °C at a depth of 2000 meters (Veldkamp, van Wees et al. 2018). Geothermal greenhouse projects mostly aim for a supply temperature of 70 – 90 °C (Van den Bosch, Flipse et al. 2013). Therefore, the simulated supply temperature of the well has been set at 80 °C. Most greenhouses in the Netherlands use a pipe heating system that cools down the water to 35 °C. Further cooling can be achieved by increasing the surface of heat transfer (e.g. introducing more pipes). However, if the difference between pipe supply- and return temperature becomes too large, the homogeneity of the greenhouse climate can be affected (De Zwart 2013). Therefore, the minimum temperature of residual heat leaving the greenhouse has been set at 35 °C. Finally, to avoid over-dimensioning, it is assumed that 70 % of yearly greenhouse heat demand must be supplied by the geothermal well. This heating capacity will not be sufficient for peak demands of the greenhouse. However, investment costs for a geothermal well increase with higher capacity due to drilling depth and/or material (Lukawski, Anderson et al. 2014).

RESULTS AND DISCUSSION

The hourly mean heat demands of the tomato greenhouse and RAS facility within the Netherlands are presented in Figure 2a. The simulated RAS is more energy intensive per unit floor area (i.e. 2468 MJ/m2) than the simulated greenhouse production (i.e. 1438 MJ/m2). What attracts attention is the difference in consistency throughout the year. The RAS heat demand is rather constant, whereas the greenhouse shows a heat demand curve with peaks during the winter period and little to almost no heat demand during July, August and the crop change in November. From a perspective of circular food production, the heat demand curves indicate potential in terms of periods during which geothermal (or residual) heat is available for other food production or processing systems. For example, the period of tomato crop change in November can be used for an energy intensive process such as drying (Andrejevski and Armenski 1999).

The reason that the heat demand of the indoor aquaculture system does not fluctuate much is twofold: first, the climate within an opaque structure is less influenced by heat gain from solar radiation and, when properly insulated, is also less effected by outdoor temperature. Second, results show that water exchange is the major mode of heat loss for the simulated RAS facility, accounting for 61 %. Since the exchange of water is assumed to be constant throughout the year and it is assumed that the source water temperature is constant, so is the resulting heat demand. This indicates that the source water temperature greatly influences the heat demand of any RAS facility. Another determining factor is to which extent water can be recirculated in order to mitigate water exchange. This in turn depends on what equipment is installed within the RAS facility that can filter and treat effluents (e.g. mineralisation reactor) (Piedrahita 2003, Goddek, Delaide et al. 2018).

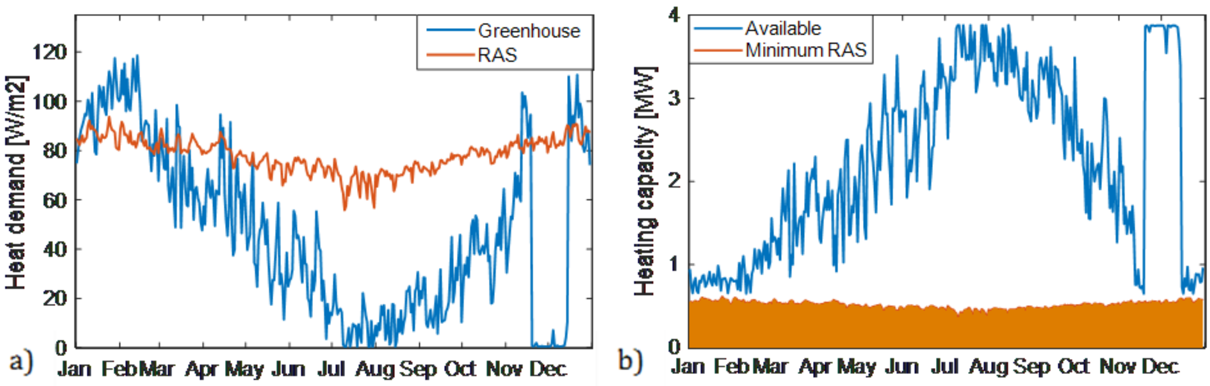

Figure 2: a) Heat demand of the simulated greenhouse and RAS. b) Heating capacity needed by the minimum size RAS and available heating capacity.

The flow of the Dutch geothermal well is computed at 62.3 m^3/hr. This flow ensures that the geothermal heat supply target of 70 % of yearly greenhouse heat demand is maintained. The available heat for other food production systems (in this case a RAS facility) consists of residual heat coming from the greenhouse and geothermal heat that is not needed by the greenhouse. The minimum RAS surface area, for which only the available heat is sufficient, is computed at 6544 m2. Combining the Dutch tomato greenhouse with the pike-perch RAS facility into a circular aquaponic system would increase geothermal heat extraction by 31 %. The mean hourly available heating capacity as well as the heating capacity needed by the minimum size RAS facility are presented in Figure 2b. The area below the heating demand of the RAS represents the amount of additional heat that can be extracted from the geothermal well.

From Figure 2b it can be observed that still a large part of the available heat remains unused. Therefore, the model also calculates what would happen if the RAS facility is increased in size. In order to optimize the direct use of geothermal energy for a given aquaponic project, the appropriate size of the RAS facility can be evaluated using graphs as presented in Figure 3. Figure 3a shows the additional heat extracted from the geothermal well and the heat demand from an alternative source for an increasing surface area of RAS. Figure 3b shows the increase in geothermal heat extracted as a percentage, as well as the percentage of heat that cannot be supplied to the RAS facility using only the thermal treatment network. The surface area for which further increase will cost more heat from an alternative source than is additionally extracted from the geothermal well, is indicated by the vertical dashed line (i.e. approximately 4.2 ha for the RAS in The Netherlands).

From Figure 3b it can be observed that if the Dutch RAS facility is increased from 6544 m^2 to 4.2 ha the heat extraction increases by another 87 %, thereby increasing overall heat extraction by 118 %. However, it also means that 42 % of the heat for the RAS will have to come from an alternative source. If, for example, only at peak demand an alternative heat source may be used, amounting to no more than 5 % of yearly RAS heat demand, the simulated results show that the RAS facility can be increased from 6544 m^2 to 8894 m^2 (i.e. an increase of 35.9 % in fish production capacity). In that case the simulated aquaponic system, consisting of a 5 ha tomato greenhouse and 8894 m^2 pike-perch RAS, could extract 40 % more heat from the geothermal well than a 5 ha tomato greenhouse.

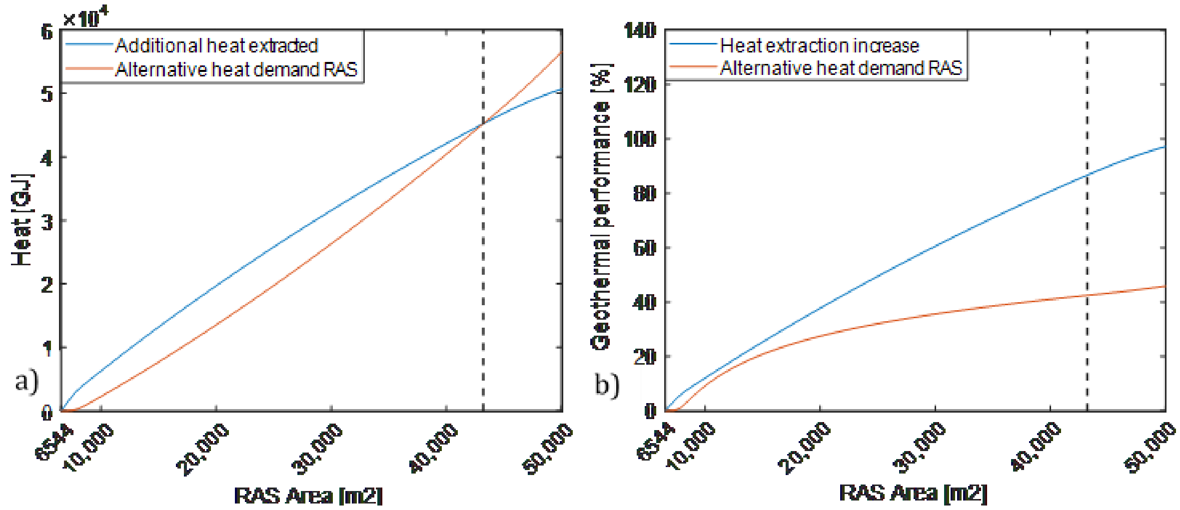

Figure 3: Graphs to evaluate an increase in RAS facility size. a) Additional geothermal heat extracted and alternative heat demand (GJ). b) Increase in geothermal heat extracted and alternative heat demand (%).

CONCLUSIONS

Integration of the newly developed RAS model and the greenhouse model KASPRO into a thermal treatment network enables assessment of geothermal energy use potential within circular food production systems, in particular aquaponics.

The model outcomes show that an integral part of designing geothermal aquaponic facilities is the trade-off between extracting additional geothermal heat and requiring heat from an alternative source during peak demand.

Furthermore, the simulated results indicate that the difference in minimum and maximum RAS facility size can be very large. At a given RAS size it may therefore be more valuable to consider other food production and processing systems to increase geothermal energy extraction than to further increase the size of the RAS facility.

In the specific case of the simulated tomato greenhouse within The Netherlands, the results suggest that integrating a RAS facility contributes positively to exploitation of geothermal heating infrastructure. However, a validated version of the model should first be coupled to an economic module before such geothermal projects can be assessed in terms of economic feasibility.

Finally, the next step is to validate the newly developed RAS model. Since there is a lack of available datasets on RAS heat demand, both from research facilities and commercial systems, a research RAS facility is being constructed for the GEOFOOD project in Bleiswijk, The Netherlands. This research facility will be used, among other purposes, to gather data on the energy and mass flows within RAS- and aquaponic systems.

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