GEOFOOD - Energy model of geothermal greenhouse aquaponic systems

Part I: Model description and applications

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Report WPR-968

Referaat

Dit rapport bevat een beschrijving van het aquaponics model dat is ontwikkeld binnen het EU-project GEOFOOD. Energiemodellen voor de productie in kassen en recirculerende aquacultuur systemen zijn gecombineerd om te evalueren hoe er optimaal gebruik kan worden gemaakt van een geothermische bron. Het model kan worden ingezet als een ontwikkelingstool om het directe gebruik van geothermische warmte binnen aquaponics, en daarmee de agri-food sector te stimuleren.

Abstract

This report contains a full description of the functionality and applicability of a geothermal greenhouse aquaponic model that has been developed for the EU project GEOFOOD. Energy models for greenhouse and aquaculture production have been combined to assess how heat extraction from a geothermal well can be optimised. The model can therefore be applied as a development tool to support the direct use of geothermal energy within the food sector by evaluating the potential of aquaponics as a thermal treatment network.

Report info

The GEOFOOD project is part of the GEOTHERMICA RD&D programme (Project no. 731117) subsidised by the ERA-NET Cofund. Participation within the Netherlands is subsidised by the Netherlands Enterprise Agency (RVO) and Topsector Tuinbouw & Uitgangsmaterialen. The consortium partners include Wageningen University & Research, Landing Aquaculture, Ammerlaan The Green Innovator (Netherlands), University of Iceland, Samraekt (Iceland), University of Maribor and the Municipality of Brezice (Slovenia).

Reportinfo

Report WPR-968

Projectnumber: 3742247400

BABS-code: BO-59-101-001-WPR

Doi-number: 10.18174/527778

Theme: Climate & Energy

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VAT no. NL 8065.11.618.B01

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1 Introduction

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

To investigate the potential of this principle one of the main research topics within the GEOFOOD project is the direct use of geothermal energy for aquaponics. Aquaponics is a farming system that connects hydroponic cultivation of crops with aquaculture by exchanging water- and nutrient flows. Building on this circular concept, a predictive model was developed to design and assess geothermal aquaponic systems consisting of a geothermal well, a greenhouse and a recirculating aquaculture system (RAS).

Geothermal energy use in the greenhouse horticulture sector has steadily increased over the past two decades. Lund & Boyd (2016) report that 9.56% of worldwide geothermal heating capacity is used to heat greenhouses in 31 different countries. In all three countries participating in the GEOFOOD project (i.e. Iceland, the Netherlands and Slovenia) commercial greenhouse production that utilizes geothermal energy has been established. In Iceland the practice of heating greenhouses using geothermal energy dates back to 1924. Currently the total geothermal energy used in Iceland's greenhouse sector is estimated to be 740 TJ per year (National Energy Authority Iceland, 2020). In 2019 a total of 21 geothermal doublets were operational in the Netherlands that supplied 5,600 TJ of heat, mostly for commercial greenhouse production (TNO, 2019). In Slovenia a total of 112 TJ is used annually by several greenhouse companies that drilled their own wells (Rajver *et al.* 2019).

The aquaculture sector also utilizes geothermal energy directly for heating; about 3.37% of the worldwide geothermal heating capacity (Lund & Boyd, 2016). However, most of the aquaculture production systems for which this heat is used are not RAS but outdoor ponds and raceways. Compared to pond- and raceway systems, (indoor) recirculating aquaculture offers a much higher degree of control over fish production processes. Using biological filtration principles and effluent treatment, RAS effectively reduce water- and land use as well as environmental impact such as eutrophication (Timmons *et al.* 2018). As Martins *et al.* (2010) indicate, there is no compiled dataset of RAS production in Europe but the available data suggests that aquaculture production in RAS is increasing.

In practice there is an increasing number of commercial greenhouses throughout Europe that use geothermal energy whereas geothermally heated RAS are virtually non-existent. The existing geothermal greenhouse companies are therefore an important group of stakeholders that can facilitate the advance of innovative circular food production systems such as RAS and aquaponics. To support such efforts a starting point for the model developed within the GEOFOOD project, is a geothermally heated greenhouse which utilizes a RAS as a sink for its residual heat. This report contains a full description of the functionality and applicability of the developed geothermal greenhouse aquaponics model.

2 Model overview

Figure 1 shows a schematic overview of the modelled geothermal aquaponic system. It consists of a geothermal well, a greenhouse and a recirculating aquaculture system (RAS) that are connected as a thermal treatment network. Within this network the RAS facility is modelled to function as a heat sink for the geothermally heated greenhouse. This means that the greenhouse heat demand has priority over RAS heat demand. The RAS is therefore supplied with heat in two distinct ways. First, whenever the greenhouse does not require the full heating capacity of the geothermal well, the remaining capacity can be utilized directly by the RAS. This energy flow going from the geothermal well to the RAS is indicated in Figure 1 as $Q_{\text{geo-ras}}$. The temperature of the geothermal water, T_{geo} , is determined by characteristics of the well such as geographical location and drilling depth. Second, the greenhouse can supply residual heat to the RAS ($Q_{\text{gh-ras}}$) when the temperature of the return water from the pipe heating system in the greenhouse (T_{gh}) exceeds the temperature of the fish rearing water.

Figure 1 Schematic overview of the modelled geothermal aquaponic system.

Though both modes of heat supply to the RAS can occur simultaneously, climate conditions will mainly determine how much and in which form the energy is available. For example, during the winter period when greenhouse heat demand is high, most if not all of the heating capacity of the geothermal well will be used by the greenhouse. Leaving only low-temperature residual heat from the greenhouse pipe heating system to be used by the RAS. The opposite occurs in summer when greenhouse heat demand is low and the primary source of heating for the RAS is the high-temperature output of the geothermal well.

In both examples the aquaponic system setup contributes to additional heat extraction from the geothermal well compared to a stand-alone greenhouse. Either by lowering the temperature of the water that is reinjected into the geothermal reservoir (i.e. $T_{\text{ras}} < T_{\text{gh}}$), or by utilizing the geothermal well for aquaculture production when greenhouse production has little to no heat demand.

The core model consists of two parts to calculate hourly values for the energy and mass flows: (1) the greenhouse climate and energy model KASPRO and (2) a newly developed RAS energy model. The combined outputs as well as geothermal well parameters are used to compute when and how much heat is extracted by the aquaponic thermal treatment network.

3 Greenhouse climate and energy model

The simulation software KASPRO is a greenhouse climate and energy model coupled with a virtual climate controller. It consists of modules describing the energy and mass balances present within the greenhouse including convective and radiative heat exchange as well as latent heat fluxes associated with (crop) evaporation. 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. In Figure 2 an overview is presented of the state variables and control parameters that are included in the model. The boundary conditions include outdoor climate and soil temperature. KASPRO is continuously updated and validated in research projects to include innovations in greenhouse technology and crop management strategies (Graamans *et al.* 2018; Katsoulas *et al.* 2015; Kempkes *et al.* 2017; Luo *et al.* 2005). An extensive description of KASPRO can be found in De Zwart, (1996).

Figure 2 State variables and controls of the greenhouse model KASPRO.

Within the GEOFOOD project, KASPRO is used to calculate greenhouse heat demand as well as flow and temperature of the outgoing residual heat in the water from the pipe heating system that can be utilized by the aquaculture facility. However, greenhouse energy consumption is greatly dependent on outdoor climate, type of greenhouse, available greenhouse equipment, climate management settings, crop and growing season. Therefore, a flexible setup of KASPRO has been integrated within the overall aquaponic model to allow for quick inspection of scenarios that represent locations with geothermal potential.

4 RAS energy model

The RAS energy model has been newly developed for the GEOFOOD project in order to predict the heat demand of RAS facilities. Project partner Landing Aquaculture provided Wageningen University & Research with input on energy and mass balances applied to indoor recirculating aquaculture. Some adaptations and improvements resulted in a model that was implemented in MATLAB to enable year-round simulations. The RAS energy model describes the heat balance as presented in equation 1.

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

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

To calculate all heat flows several inputs are required that represent the outdoor climate, design and management of the RAS facility as well as the species of fish cultivated. An overview of the inputs is presented in Table 1.

Table 1
Nomenclature of input variables RAS model.

Variable	Description	Unit
A_{cover}	area of cover	[m ²]
A_{floor}	area of RAS facility	[m ²]
A_{water}	area of water surface	[m ²]
P	power of equipment units	[W]
R_{FO}	feed to oxygen ratio	[kg/kg]
R_{OH}	oxygen to heat ratio	[J/kg]
RH_{in}	target relative humidity of indoor air	[%]
RH_{out}	relative humidity of outdoor air	[%]
T_{in}	target indoor air temperature	[°C]
T_{out}	outdoor air temperature	[°C]
T_{source}	source water temperature	[°C]
T_{tank}	target tank water temperature	[°C]
U_{cover}	heat loss coefficient cover	[W/m ² K]
W_{feed}	feeding rate	[kg/s]
$W_{infiltration}$	air infiltration rate	[m ³ /s]
W_{water}	water exchange rate	[m ³ /s]
η	efficiency of equipment units	[-]

Heat loss from the building consists of losses through the walls, roof, floor and due to infiltration. These are calculated using equations 2.A to 2.C respectively. Equation 2.B is based on heat loss through the floor along the building perimeter as described by Timmons *et al.* (2018). It is assumed that the building is an insulated, opaque structure where heat gain due to solar radiation does not play a significant role.

$$Q_{cover} = U_{cover} \left(\frac{A_{cover}}{A_{floor}} \right) (T_{in} - T_{out}) \quad (2.A)$$

Q_{cover}	: heat loss through walls and roof	[W/m ²]
U_{cover}	: cover heat loss coefficient	[W/m ² K]
A_{cover}	: cover area	[m ²]
A_{floor}	: RAS facility area	[m ²]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

$$Q_{floor} = U_{perimeter} \frac{L}{A_{floor}} (T_{in} - T_{out}) \quad (2.B)$$

Q_{floor}	: heat loss through floor	[W/m ²]
$U_{perimeter}$	: empirical constant for floor heat loss	[W/m K]
L	: building perimeter	[m]
A_{floor}	: RAS facility area	[m ²]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

$$Q_{infiltration} = W_{infiltration} \frac{\rho_{air} c_{p_{air}}}{A_{floor}} (T_{in} - T_{out}) \quad (2.C)$$

$Q_{infiltration}$	: heat loss due to infiltration	[W/m ²]
$W_{infiltration}$	: infiltration rate	[m ³ /s]
ρ_{air}	: density of air	[kg/m ³]
$c_{p_{air}}$	: specific heat of air	[J/kg K]
A_{floor}	: RAS facility area	[m ²]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

RAS facilities have an exchange of water with the environment that depends on requirements of the cultivated fish species, growing density and installed filter equipment. Some water leaves the system by means of evaporation and splashing. However, the main outflow consists of water that can no longer be recirculated due to quality constraints. The outgoing water has to be replenished with water from a suitable source (e.g. treated rainwater or ground water). The energy demand to heat up the inflow of source water to tank water temperature is calculated according to equation 3.

$$Q_{\text{water exchange}} = W_{\text{water}} \frac{\rho_{\text{water}} c_{p_{\text{water}}}}{A_{\text{floor}}} (T_{\text{tank}} - T_{\text{source}}) \quad (3)$$

$Q_{\text{water exchange}}$	: heat demand due to water exchange	[W/m ²]
W_{water}	: water exchange rate	[m ³ /s]
ρ_{water}	: density of water	[kg/m ³]
$c_{p_{\text{water}}}$	: specific heat of water	[J/kg K]
A_{floor}	: RAS facility area	[m ²]
T_{tank}	: tank water temperature	[°C]
T_{source}	: source water temperature	[°C]

The rate of evaporation from the fish tanks and filter tanks depends on the amount of open water surface and the indoor climate (i.e. temperature and humidity of air). The heat loss associated with evaporation is calculated with equation 4. This empirical equation from ASHRAE, (2004) has been applied within aquaculture to a shrimp RAS facility by Li *et al.* (2008).

$$Q_{\text{evaporation}} = \frac{A_{\text{water}}}{A_{\text{floor}}} (0.089 + 0.0782 v) (P_{\text{water}} - P_{\text{air}}) \quad (4)$$

$Q_{\text{evaporation}}$	: heat loss due to evaporation	[W/m ²]
A_{water}	: water surface area	[m ²]
A_{floor}	: RAS facility area	[m ²]
v	: air velocity over water surface	[m/s]
P_{water}	: saturation vapour pressure evaluated at tank water temperature	[Pa]
P_{air}	: saturation pressure evaluated at dew point temperature of indoor air	[Pa]

The units for the constants 0.089 and 0.0782 are in W/(m² Pa) and W s/(m³ Pa) respectively.

To avoid the accumulation of moisture and carbon dioxide within the facility, the indoor air must be exchanged with outside air by ventilation. Within the model it is assumed that the ventilation rate is driven by the rate of evaporation. The ventilation rate and resulting heat demand are calculated with equations 5.A and 5.B respectively.

$$W_{\text{ventilation}} = \frac{W_{\text{evaporation}}}{\rho_{\text{air}}(x_{\text{in}} - x_{\text{out}})} \quad (5.A)$$

$W_{\text{ventilation}}$	: ventilation rate	[m ³ /s]
$W_{\text{evaporation}}$	: evaporation rate	[kg/s]
ρ_{air}	: density of air	[kg/m ³]
x_{in}	: indoor humidity ratio	[kg/kg]
x_{out}	: outdoor humidity ratio	[kg/kg]

$$Q_{ventilation} = W_{ventilation} \frac{\rho_{air} c_{p_{air}}}{A_{floor}} (T_{in} - T_{out}) \quad (5.B)$$

$Q_{ventilation}$	: heat loss due to ventilation	[W/m ²]
$W_{ventilation}$	: ventilation rate	[m ³ /s]
ρ_{air}	: density of air	[kg/m ³]
$c_{p_{air}}$	: specific heat of air	[J/kg K]
A_{floor}	: RAS facility area	[m ²]
T_{in}	: indoor air temperature	[°C]
T_{out}	: outdoor air temperature	[°C]

The heat produced by fish is based on the feeding rate and metabolism of the fish. It is calculated using equation 6. Another input of energy is the significant amount of electrical equipment that RAS facilities contain to recirculate and treat water (e.g. pumps, drum filters, fans, UV systems and ozone generators). The heat produced by this equipment is calculated using equation 7.

$$Q_{fish} = W_{feed} \frac{R_{FO} R_{OH}}{A_{floor}} \quad (6)$$

Q_{fish}	: heat produced by fish	[W/m ²]
W_{feed}	: feeding rate	[kg/s]
R_{FO}	: feed to oxygen ratio	[kg/kg]
R_{OH}	: oxygen to heat ratio	[J/kg]
A_{floor}	: RAS facility area	[m ²]

$$Q_{equipment} = n P \frac{(1 - \eta)}{A_{floor}} \quad (7)$$

$Q_{equipment}$	: heat produced by equipment	[W/m ²]
n	: number of equipment units	[-]
P	: power of equipment	[W]
η	: efficiency	[-]
A_{floor}	: RAS facility area	[m ²]

5 Computing performance of the aquaponic thermal treatment network

In order to evaluate how efficient the aquaponic 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 indicators. The approach implemented within the model is as follows: first, the planned greenhouse area and minimum temperature of the residual heat leaving the greenhouse pipe heating system are specified. Second, the supply temperature of the geothermal heat is specified as well as the percentage of yearly greenhouse heat demand that must be delivered by the geothermal well. Based on these inputs the required heating capacity of the geothermal well is determined. The maximum flow of the geothermal well is calculated with equation 8.

$$\frac{A_{gh} Q_{req}}{\rho_{water} cp_{water} (T_{geo} - T_{res min.})} \quad (8)$$

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

After the required flow of the geothermal well has been established, the temperature profile of the available heat for the RAS facility is obtained using equation 9. 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 pipe heating system and the supply temperature of the geothermal well. The available heat for the RAS facility is subsequently calculated based on the available temperature. The available heat consists of residual heat from the greenhouse pipe heating system and geothermal heat that is not used by the greenhouse.

$$T_{available} = T_{geo} - \frac{A_{gh} Q_{gh}}{\rho_{water} cp_{water} W_{geo}} \quad (9)$$

$T_{available}$	: available temperature for the RAS facility	[°C]
T_{geo}	: supply temperature geothermal well	[°C]
A_{gh}	: greenhouse area	[m ²]
Q_{req}	: required heating capacity	[W/m ²]
ρ_{water}	: density of water	[kg/m ³]
cp_{water}	: specific heat of water	[J/kg K]
W_{geo}	: maximum flow of the geothermal well	[m ³ /s]

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 and/or geothermal well. Though increasing the RAS facility further results in more heat extracted from the geothermal well, it also creates the need for an alternative heat source to meet heat demand during peaks. The maximum RAS size is therefore defined as the surface area for which an increase would no longer extract more heat from the geothermal well.

The outcome of the model consists of a series of graphs, each illustrating one or more performance indicators. This allows users to investigate which combinations of geothermal wells, greenhouses and RAS facilities make up a geothermal aquaponic system that meets their requirements. Some key performance indicators are explained by equations 10 through 12.

$$P_1 = \frac{Q_{alt}}{Q_{add}} \quad (10)$$

Q_{alt} : additional heat needed by RAS facility from an alternative source [J]
 Q_{add} : additional heat extracted from geothermal well by RAS facility [J]

A first performance indicator (equation 10) is the ratio between additional heat needed by the RAS facility from an alternative source and the additional heat extracted from the geothermal well. When this curve exceeds the value 1, it means that an increase in surface area will cost more heat from an alternative source than is additionally extracted from the geothermal well (i.e. $Q_{alt} > Q_{add}$).

$$P_2 = \left(\frac{Q_{alt}}{Q_{RAS}} \right) 100 \quad (11)$$

Q_{alt} : additional heat needed by RAS facility from an alternative source [J]
 Q_{RAS} : total heat demand of RAS facility [J]

A second indicator (equation 11) is the percentage of heat that cannot be provided to the RAS facility by the geothermal well. Same as for dimensioning the geothermal well to meet a target percentage of greenhouse heat demand, the RAS facility can be dimensioned to take a target percentage of heat from the geothermal well.

$$P_3 = \left(\left(\frac{Q_{gh} + Q_{RAS} - Q_{alt}}{Q_{gh}} \right) - 1 \right) 100 \quad (12)$$

Q_{gh} : heat supplied by geothermal well to greenhouse [J]
 Q_{RAS} : total heat demand of RAS facility [J]
 Q_{alt} : additional heat needed by RAS facility from an alternative source [J]

A third indicator (equation 12) is the percentage of increase in heat extracted from the geothermal well. It is defined as the amount of heat extracted by an aquaponic system compared to that of a stand-alone greenhouse, considering the same geothermal well.

6 Model applications

As is described in chapters 1 through 4, the geothermal greenhouse aquaponics model that has been developed for the GEOFOOD project is composed of a greenhouse climate and energy model as well as a RAS energy model. Separately these models are suited to evaluate the energy demand of individual greenhouse and aquaculture production systems taking into account local climate parameters, equipment and crop or fish species.

However, it is the structure of the combined model that enables assessment of geothermal aquaponic systems. The model can be applied as a development tool to support the direct use of geothermal energy within the food sector as follows:

1. Evaluating the increase in geothermal energy use efficiency of transforming existing greenhouses that utilize a geothermal well into aquaponic systems by dimensioning a suitable RAS facility.
2. Designing new geothermal aquaponic facilities optimising for energy use efficiency taking into account local climate parameters, greenhouse/RAS construction and equipment, crop type, fish species, ratio of greenhouse to aquaculture area and the available capacity of the geothermal well.
3. Identifying geothermal energy use potential for other food production and processing systems to be integrated into an aquaponic thermal treatment network.

Besides these applications the model can be adapted to reverse its starting point of an existing geothermally heated greenhouse using a RAS as a heat sink, to an existing RAS facility that uses a greenhouse as a heat sink. Lastly, the model structure allows for expansions to take into account additional energy flows from other production and processing systems (e.g. (micro)algae production, nutrient recovery and agricultural drying).

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