GEOFOOD - Additional heat utilization processes for geothermal aquaponics

Alexander Boedijn[1], Alexander van Tuyll van Serooskerken[1], Esteban Baeza Romero[1], Eric Poot[1] and Carlos Espinal[2]
1. Wageningen University & Research, 2. Landing Aquaculture

Report WPR-1100

Referaat
Dit rapport bevat een verkennende studie naar aanvullende warmtebenuttingsprocessen die efficiënt warmtegebruik kunnen bevorderen van geothermische aquaponics. Elk warmtebenuttingsproces is geselecteerd op zijn potentiële bijdrage aan het opzetten van circulaire voedselproductiesystemen. De warmtebenuttingsprocessen zijn geëvalueerd op basis van hun warmtevraag en op de mate waarin ze geïntegreerd kunnen worden in een aardwarmtenetwerk. Deze studie en de verkregen inzichten in geothermische aquaponic systemen zijn ontwikkeld voor het EU-project GEOFOOD.

Abstract
This report contains an exploration towards additional heat utilization processes that can increase the heat use efficiency of geothermal aquaponics. Each heat use application is selected based on its potential contribution towards circular food production systems. The heat use applications are evaluated based on heat demand and on the extent to which they can be integrated into a geothermal treatment network. This study and the resulting insights into geothermal aquaponic treatment networks have been developed for the EU project GEOFOOD.

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Address

Wageningen University & Research, BU Greenhouse Horticulture
Violierenweg 1, 2665 MV Bleiswijk
P.O. Box 20, 2665 ZG Bleiswijk
The Netherlands
+31 (0) 317 - 48 56 06
glastuinbouw@wur.nl
www.wur.eu/greenhousehorticulture

Table of contents

1 Introduction

1.1 GEOFOOD

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.

1.2 Geothermal aquaponics

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) (Boedijn, Baeza, *et al.* 2019a).

The model can calculate heat demand patterns for greenhouse- and aquaculture production, based on the requirements of the crop and fish species, system design and local climate. Figure 1 shows an example of a simulated glasshouse growing tomato and a RAS that produces pike-perch, located in the Netherlands (Boedijn, Baeza, *et al.* 2019b).

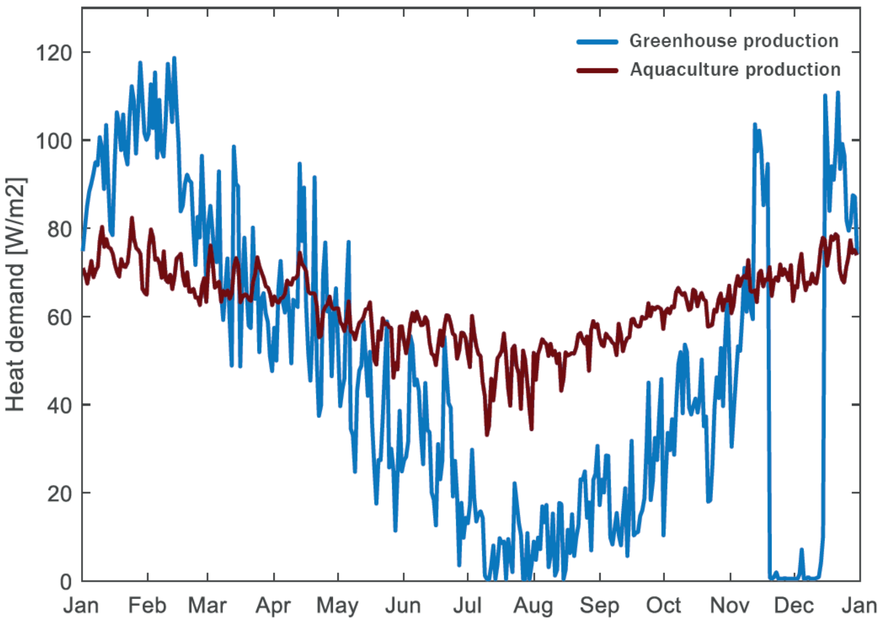

Figure 1 *Simulated heat demand of greenhouse- and aquaculture production in the Netherlands.*

Further output that the model provides can be used to determine when and how much geothermal heat remains unused by greenhouse- and/or aquaculture production. Figure 2 shows an example of how much heating capacity is 'left over' throughout the year, assuming that a geothermal well is principally used to heat a tomato greenhouse of 5 ha, located in the Netherlands.

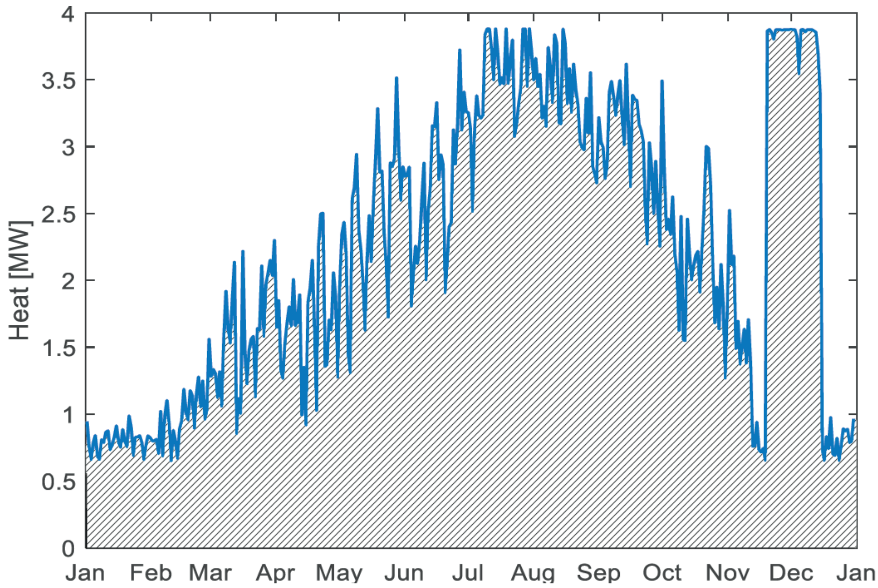

Figure 2 *Residual heating capacity of a 5 ha, geothermally heated tomato greenhouse in the Netherlands.*

The heating capacity in figure 2 is calculated based on the capacity of the geothermal well (62 m^3/h), available heating temperature (ranging between 80 and 35°C) and the minimum return temperature (26°C), which in this case is equal to the target water temperature for pike-perch production. As a result, the graph can be used to determine how big of a pike-perch RAS can be supported by the residual geothermal heat and how much additional heat would be utilized compared to a stand-alone greenhouse.

However, the total available residual heat (i.e. the shaded area in figure 2), doesn't have to be completely utilized by addition of only a pike-perch RAS. Other food production applications with a heat demand could also make use of the residual heating capacity. Which applications are most suitable depends on the required capacity, temperature as well as timing. For instance, the large heating capacity that is available in December (see figure 2) results from the need to clear and clean the greenhouse before the new crop arrives. During this time the maximum heating capacity and temperature supplied by the geothermal well could be used by an application that requires a higher temperature (in this example around 80°C). In this report we explore such opportunities and estimate the potential to increase overall heat extraction from a geothermal well by connecting additional heat utilization processes.

1.3 Extending an aquaponic geothermal treatment network

As previous studies have shown, cascaded use of geothermal energy can increase heat use efficiency and improve economic feasibility of geothermal wells (Ambriz-Díaz *et al.* 2017; John W. Lund & Chiasson, 2007; Rubio-Maya *et al.* 2015; Yousefi *et al.* 2019). Within the GEOFOOD project, results of a model study on geothermal aquaponics indicate that heat use efficiency can indeed be improved by connecting a RAS to a geothermally heated greenhouse. In the case of a Dutch tomato greenhouse of 5 ha, it was found that geothermal heat extraction could be increased by 31% if the residual heating capacity would be used for a 6,500 m^2 pike-perch farm (Boedijn, Baeza, *et al.* 2019b). Figure 3 shows a schematic overview of the simulated setup, in which the fish farm functions as a heat sink. This means that the greenhouse heat demand has priority over RAS heat demand. The fish farm 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. Second, the greenhouse can supply residual heat to the RAS when the temperature of the return water from the pipe heating system in the greenhouse is still high enough to heat the fish rearing water (i.e. cascading).

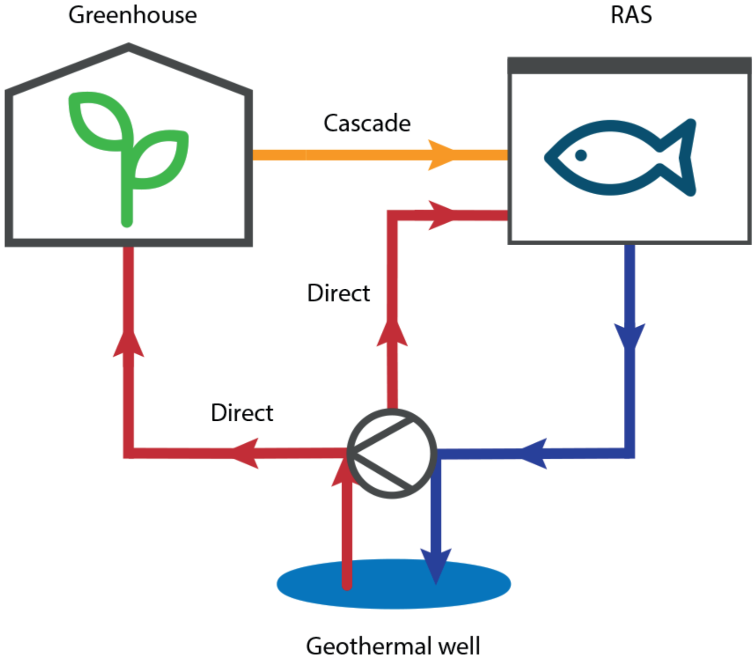

Figure 3 *Schematic overview of an aquaponic geothermal treatment network.*

Though the aquaponic system in figure 3 can extract more heat from a geothermal well than a stand-alone greenhouse, additional heat utilization processes could increase heat extraction even further. The Lindal diagram shown in figure 4 offers a broad overview of potential applications of geothermal energy within the food- and agriculture sectors (Nguyen *et al.* 2015). Though many of the applications in figure 4 could utilize residual heat within a geothermal aquaponic system, a selection is made in this report to support the following scope: additional heat utilization processes that can improve the overall circularity and sustainability of geothermal aquaponics.

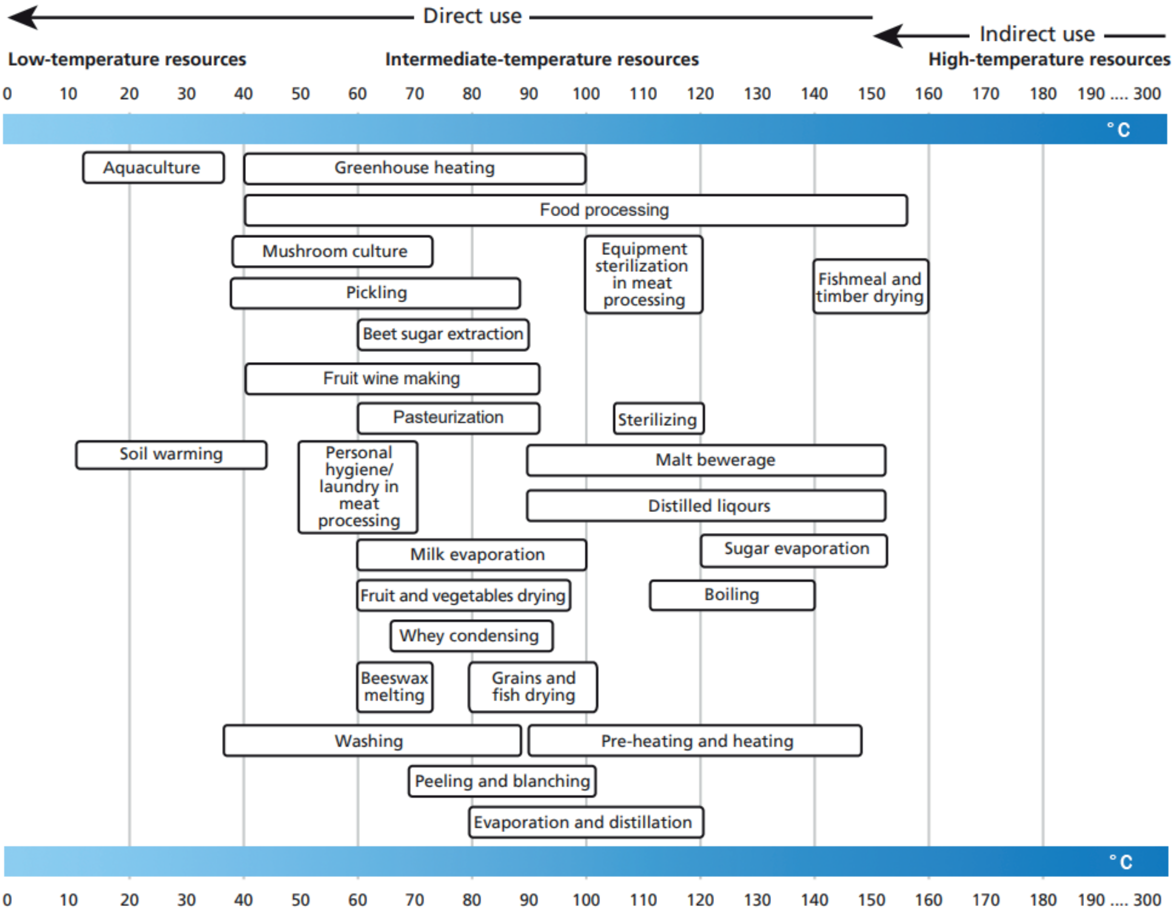

Figure 4 *Lindal diagram of potential applications of geothermal energy in the food- and agriculture sectors. Source: P.G. Pálsson (2013) in Nguyen et al. (2015).*

The following applications have been selected that connect to sustainability challenges in the greenhouse horticulture sector, aquaculture sector or in aquaponic systems:

- ***Drying vegetables and herbs*** – surplus production or produce that does not meet quality standards can be dried to reduce loss of food and avoid low-grade organic waste streams.
- ***Drying organic waste or used substrate*** – the water content of greenhouse waste flows can be decreased to reduce transport, preserve quality and improve (re)usability.
- ***Direct air capture (DAC)*** – CO_2 that is dosed in greenhouses to increase yields can be captured directly from the atmosphere in order to replace CO_2 obtained from fossil fuels and/or other industrial processes, thereby reducing greenhouse gas emissions.
- ***Drying fish and fish products*** – shelf life can be extended, and by-products can be dried to reduce food losses.
- ***Drying aquaculture sludge*** – the water content of sludge can be decreased to reduce transport and improve (re)useability for further processing (e.g. as a fertiliser).
- ***Microalgae production*** – microalgae can contribute to closed loops by utilizing nutrients in waste streams (e.g. sludge and discharge water) and by replacing ocean-derived fish meal and fish oil in feeds.
- ***Mesophilic and thermophilic biological filtration*** – optimising water quality management, water efficiency and valorising aquaculture effluents.

2 Additional heat utilization processes for greenhouse horticulture

2.1 Drying vegetables and herbs

Background
Geothermal energy can be used to dry a variety of agricultural products to increase shelf life and/or product value. In most installations hot water from a geothermal well is used in a water-to-air heat exchanger to heat up air to temperatures of 35-90°C, depending on the requirements of the product. Fans are used to move the heated air through a drying space that contains the product. The FAO commissioned report by Nguyen *et al.* (2015) provides a rich overview of example cases for geothermal drying of rice, grains, (coffee) beans, maize, garlic, onions, chili, tomatoes, cotton and fruits. J. W. Lund & Boyd (2016) report that 2,030 TJ of geothermal energy per year is used worldwide for agricultural drying, which is about 1% of total geothermal direct-use applications.

Reducing food loss and avoiding low-value organic waste
Geothermal drying could specifically be combined with greenhouse production to reduce food losses by focusing on two waste flows; 1) produce that is rejected based on cosmetic specifications (e.g. shape, size, colour) and 2) surplus production. Though data to quantify these waste flows is scarce, several institutes and initiatives provide estimates. For Europe, Porter *et al.* (2018) estimate that 51,500 million kg of fresh fruit and vegetables are lost every year due to so called 'on-farm cosmetic grade-outs'. Estimations vary widely between different countries, crops and cultivation systems but given the resources spent during any food production phase (e.g. water, fertilisers, energy, labour), it is clear that efforts to reduce this loss of food would contribute to a more sustainable food production system.

For Dutch greenhouses it is estimated that 5% of tomatoes and bell peppers are rejected on-farm based on cosmetic specifications (Galama *et al.* 2014; Ministry of Agriculture, Nature and Food Quality, 2018). Taking into consideration that tomato- and bell pepper production in the Netherlands amounts to 910 million kg and 415 million kg per year respectively (CBS, 2019), the estimated losses amount to nearly 48 million kg and 22 million kg. Not all of this produce goes to waste as there are initiatives that aim to set up innovative chains to buy, process and sell it (see for instance 'Verspilling is Verukkelijk'). Still, most of it ends up as biomass of lower value such as animal feed or compost. Drying certain rejected or surplus produce using (residual) geothermal heat would help to retain its value as a food product.

When prices are very low, legislation forces growers in many countries to eliminate this surplus fresh production from commercial chains, to decrease the offer and stabilize the market. The drying of this product allows for the long-term preservation of this product and later commercialization, while still making an impact on the stabilization of the market as the product goes from fresh to dry.

Example case – Drying tomatoes as additional heat utilization process
An example case is the geothermal drying installation at the Dutch tomato grower Duijvestijn Tomaten. Besides heating their 14.5 ha greenhouses using a geothermal well, they have developed and integrated a drying installation to process rejected- and surplus produce. Their estimated flow of rejected tomatoes is 50,000 kg per year out of a total production of 10 million kg. The drying installation dries the tomatoes at a temperature of about 60°C (Ten Voorde, 2016).

Andritos *et al.* (2003) report for their geothermal drying installation in Greece that moisture content of tomatoes is reduced from about 92% to 10% at air temperatures of 50-57°C. During the first year of operation about 4,000 kg of dried tomatoes were produced using 1 TJ of geothermal energy. Given that fresh tomatoes were reduced 10-12 times in weight, this translates to 21-25 MJ/kg. In experiments by Örvös *et al.* (2014) values around 13 MJ/kg fresh weight were found.

Drying tomatoes – Quantitative estimate & Qualitative considerations

As an example we consider a tomato greenhouse of 5 ha, located in the Netherlands, producing 70 kg/m^2 per year. Furthermore, we assume that drying tomatoes takes 19 MJ/kg. If 5% of total production would be dried, this would take about 3.3 TJ of geothermal energy. The yearly heating demand of the greenhouse ranges between 47-63 TJ, depending on how many energy saving measures a grower has implemented. Given the yearly heat demand of the greenhouse, the additional heat utilization provided by drying would be 5-7%. This number could be further increased if neighbouring greenhouses and/or farms would also dry their rejected- and surplus production.
In terms of system integration, drying requires a temperature of 35-90°C, depending on the product. For tomatoes temperatures ranging between 50-70°C are used in order to retain colour, aroma and vitamins (Azeez et al., 2019). Though a Dutch greenhouse produces tomatoes almost year-round, the main production months are May until September (Raaphorst & Benninga, 2019). During this time the flow of rejected or surplus production will be largest, which suits the required drying temperature and heat demand because in summer geothermal heat supply exceeds greenhouse heat demand. Of course, a business case has to be established taking into account the possible number of operational hours as well as opex versus capex, in order to justify any investment for equipment that utilizes the residual geothermal energy; in this case a drying installation.

2.2 Drying organic- and substrate waste flows

Background
Organic waste and used substrate are two residual material flows from greenhouse production that contain water. Organic waste is considered as all the plant material that is not part of the product (e.g. stems, leaves and roots of a tomato plant). Most organic waste comes from vegetable crops such as tomato, bell pepper, cucumber and eggplant. For Dutch tomato production Montero *et al.* 2011, assumes 100 ton/ha of fresh weight plant material. About 13% of this organic waste is dry matter (Heuvelink, 2018; LLorach Massana, 2017), and the remaining 87 ton/ha is water.

Substrates such as stone wool, coir and peat are used in soilless cultivation systems to grow the plants out of the soil. After a cultivation cycle the substrate is often replaced. For a greenhouse using stone wool, almost 9 ton/ha of the total 15 ton/ha substrate waste is water contained by the stone wool (Grodan, 2018).

Reducing transport and improving reusability
If (residual) geothermal heat is available, it could very well be used to dry the organic- and substrate waste flows to reduce transport. In the life cycle analyses (LCA) by Montero *et al.* (2011) the waste management stage for greenhouse production does not contribute majorly to overall environmental impact. Still, within the waste management stage, transport of organic waste is often the largest contributor across impact factors such as abiotic depletion, acidification, eutrophication, global warming, photochemical oxidation and energy use. Montero *et al.* (2011) assume 40% of the fresh organic weight must be transported as waste. Geothermal drying could bring that down to 13% of fresh weight, a three-fold reduction.

Within the context of transitioning towards a circular economy, organic- and substrate 'waste' flows are regarded more and more as potential resource flows. Organic waste from greenhouses is regarded as biomass that has a range of applications in addition of composting or burning (Greenport West-Holland & Green Chemistry Campus, 2019; Lemmens, 2020; SIGN, 2020). Geothermal heat could support these efforts because many of these applications require a drying step. Drying could also be of use for the recycling process of stone wool substrate. Stone wool substrate is converted into a granulate that is used for the production of bricks (Abbenhuijs, 2018).

Example case – Drying substrate plugs as additional heat utilization process
An example case is the drying space that Van der Knaap has set up to dry substrate plugs. The drying space is heated using the return water from their research greenhouse that uses geothermal heat. The return water is still warm enough to provide energy for the drying process. The water that returns to the geothermal well is cooled down further, thereby increasing heat use efficiency. The plugs are mainly dried to increase shelf life (Van der Knaap, 2020).

2.3 Direct air capture (DAC)

Background
Direct air capture (DAC) is a process developed to capture CO_2 directly from the atmosphere. Though a variety of methods of capture are currently explored, two major DAC technologies are categorised by Fasihi *et al.* (2019) as high temperature aqueous solutions and low temperature solid sorbent systems. For both systems the working principle is based on substances that bind CO_2 when they come into contact with the ambient air. Energy for heating is needed to release the CO_2 from the substance. Applications for DAC split into carbon storage solutions to mitigate climate change (Breyer *et al.* 2019), and utilization of the captured CO_2. For the food sector, Koytsoumpa *et al.* (2018) identify for instance beverage carbonation, coffee decaffeination and wine production as applications that have a considerable CO_2 demand. Horticulture is also mentioned since CO_2 is dosed in greenhouses to increase crop growth.

Fossil free CO_2 dosing for greenhouses
A common practice in (mid- to high-tech) greenhouses is to increase the CO_2 concentration of the air to increase crop growth. In the Netherlands this demand for CO_2 amounts to 2.6 million tonnes per year (Van Der Velden & Smit, 2019). Most of this CO_2 is produced by cogeneration plants (CHP) that run on natural gas. Besides CO_2, the CHP's are used by growers to provide heat and electricity to their greenhouses. In 2019 about 0.7 million tonnes of the total CO_2 demand was purchased from external sources (Van Der Velden & Smit, 2020). As the energy transition progresses, the greenhouse horticulture sector aims to reduce fossil fuel use and carbon emissions by replacing CHP's for sustainable energy sources. Geothermal heat is currently the main source of sustainable energy and a total of 21 doublets were operational in the Netherlands that supplied mostly to commercial greenhouse production (TNO, 2019).

As growers switch to sustainable energy sources that do not emit CO_2, their (own) supply for CO_2-enrichment in the greenhouse disappears. Van Der Velden & Smit (2019) estimate that by 2030 the demand of Dutch greenhouse growers for external CO_2 will increase to 1.8-3.0 million tonnes per year. CO_2 captured by DAC could become a part of the solution if the benefits from a higher crop yield outweigh the costs. Another driver to use DAC is that the CO_2 can be produced fossil free when sustainable energy is used for the process. In practice this could lead to (virtual) net-zero CO_2 emissions by greenhouse horticulture production.

Example case – DAC as additional heat utilization process
Several companies have started up that use DAC technology to sell CO_2 for a range of applications. One of the first commercial DAC installations, designed by Climeworks, opened in 2017. It is located in Hinwil, Switzerland, and supplies 900 tonnes of CO_2 per year to a nearby greenhouse of about 4 ha (Climeworks, 2021). The installation in Hinwal uses (residual) heat from a waste incineration plant, but the heat for a DAC plant could of course also be provided by a geothermal well.

Direct air capture – Quantitative estimate & Qualitative considerations

As an example we examine a greenhouse of 5 ha that doses 20 kg CO_2/m^2 per year. Total demand of the greenhouse is 1,000 tonnes per year. Based on the overview of low temperature solid sorbent technologies by Fasihi et al. (2019) we assume that the heat demand for 1 ton of CO_2 is 6.3 GJ. If the total CO_2 demand of the greenhouse would be supplied by DAC, total heat demand for that CO_2 is 6.3 TJ. The yearly heating demand of the greenhouse ranges between 47-63 TJ, depending on how many energy saving measures a grower has implemented. Given the yearly heat demand of the greenhouse, the additional heat utilization provided by DAC would be 10-13%.
Then again, since growers strive for a CO_2-concentration of 600-1000 ppm in the greenhouse, specific DAC technologies may be developed that maintain that target within a more closed-greenhouse design. Much less CO_2 would be needed if the CO_2-rich air leaving a greenhouse would be recirculated. In that case less heat would be needed to capture CO_2 but the economic feasibility of DAC for greenhouses may increase.
In terms of integration, low temperature solid sorbent DAC systems require 80°C or higher. High temperature systems require 900°C (Fasihi et al., 2019). As Chamorro et al. (2014) indicate, very few locations in Europe show geothermal potential of more than 100°C at 2,000 m depth. Therefore, geothermal heat seems most suitable for low temperature DAC technologies. Iceland could be an exception as there are much higher temperatures available. Timing wise, CO_2 is most needed (and dosed) in the greenhouse during summer when there is more sunlight available for photosynthesis. Zooming in, CO_2 is only dosed during the day since plants take in CO_2 and release oxygen through photosynthesis, and at night plants release part of that CO_2 through respiration. As can be seen in figure 1, greenhouses have a low heat demand during summer (especially during the day), which means that the unused geothermal heating capacity (see figure 2) coincides well with the periods of high CO_2 demand. On the other hand, the business case for a DAC installation also has to deal with the fluctuating CO_2 demand of a greenhouse. Multiple applications for heat- and CO_2 may therefore have to be clustered to achieve economic viability.

3 Additional heat utilization processes for recirculating aquaculture

3.1 Drying fish

Background
Drying is one of the oldest methods of preserving fish. By removing water from the fish, the growth of micro-organisms is inhibited (Parvathy, 2018). Traditionally, fish is dried outdoors or through solar drying systems. However, indoor mechanical systems allow for consistent, year-round drying. These advantages have led indoor drying to become the dominant technique in for instance Iceland, with drying tunnels and chambers being common designs. Air is heated and blown past the fish at a specific rate, leading to convection and evaporation of the water. In Iceland, geothermal energy has been used for this process for over 40 years (Ragnarsson, 2015).

Valorising fish by-products
For cod, 40-50% of fish weight does not go to the fillets (Fatykhov *et al.* 2020). Iceland exports dried fish heads, bones and chops to developing countries, with Nigeria being its biggest market for dried products, and about 5% of Iceland's aggregate seafood exports (Salaudeen *et al.* 2014). This is not only an important economic activity, but also a valorisation of nutritious parts of the fish that would not be kept otherwise after filleting. Geothermal energy plays a key role here and the same principle can be applied to aquaponic systems elsewhere.

Example case – Drying fish as additional heat utilization process
One of the largest producers of dried cod heads in Iceland is the company Haustak. Haustak dries 12,000 tonnes of raw material per year, to produce 2,500 tonnes of dried output. To do this, they buy 1.3 kg/s of steam (220°C at 18 bar) from a nearby geothermal plant, and use this steam to heat up water to 70°C (Ragnarsson, 2015). The hot water is subsequently used to heat the air that goes into the drying tunnels. Drying tunnels use air of 50-90°C for the drying process (Adeyeye, 2019). With the efficiency of tunnel driers, energy consumption is around 5.8 MJ per kg of water evaporated (Arason, 2003). This means that Haustak's geothermal energy consumption is roughly 55 TJ per year.

Drying fish – Quantitative estimate & Qualitative considerations

As an example we consider an aquaculture system that has been investigated within the GEOFOOD project by Landing Aquaculture (2020). It concerns a recirculating aquaculture system (RAS) of about 4500 m^2, producing 200 tonnes pike-perch per year. We assume that 50% of the fish must be dried, and that bones, heads etc. have a dry matter content of 30% (Toppe et al., 2007), and are dried until their water content is 15% (Nguyen et al., 2015). If 5.8 MJ is needed per kg of evaporated water, this equates to an energy requirement of 375 GJ on an annual basis. The yearly heating demand of the RAS ranges between 8-11 TJ, depending on the system (Boedijn, Baeza, et al., 2019b). Given the yearly heat demand of the RAS, the additional heat utilization provided by drying fish would be 3.4-4.7%.
However, in this report the focus is on a geothermal aquaponic system in which the geothermal well is dimensioned based on the heat demand of the greenhouse. Compared to the heating demand of a 5 ha greenhouse, the additional heat utilization of drying fish is less than 1%.
Timing must also be considered. The fish are harvested once a week, meaning a week's energy (7 GJ) would only be needed on the day of harvesting. Therefore, to make use of the (residual) available geothermal energy, the drying of fish should be done on days when other processes are not occurring. Especially during the summer period when greenhouse heat demand is low, drying offers a useful alternative to keep the geothermal well in production.

3.2 Drying aquaculture sludge

Background
Feed conversion is higher in recirculating aquaculture systems than in other types of aquaculture systems (Timmons *et al.* 2018). Still, in a RAS, solid waste or sludge – from faeces and bacterial films – must be removed periodically. This is because sludge can host pathogens and consume significant amounts of oxygen. Many techniques exist to filter out sludge, most of which are mechanical. Sludge is a considerable material flow. Depending on the species of fish, sludge production is 10-40% of the feeding rate, in terms of dry weight, with 25% being typical (Del Campo *et al.* 2010). In many cases, the sludge is disposed into surface water; a leakage (and loss) of nutrients that eventually leads to eutrophication (Global Seafood Alliance, 2021; Seymour & Bergheim, 1991).

Switching from mineral- to organic fertilisers
Switching from mineral- to organic fertilisers is a key pathway within the transition towards circular food production (Chojnacka *et al.* 2020). If nutrients are recovered from organic sources such as animal manure, sludge from sewage treatment plants and residual biomass flows, this would mitigate several major issues. First, less minerals would have to be mined, mitigating resource depletion. And second, less nutrients would be disposed into the environment, mitigating environmental impact and avoiding resource dispersion.
Aquaculture sludge is high in organic matter and nutrients. For example, 30-84% of phosphorus in the waste flows is contained in the sludge (Yogev *et al.* 2020). For manganese, that number is 86%; for iron, 24%; and for zinc, 47% (Zhanga *et al.* 2021). Because of this, sludge is a potential source of macro- and micronutrients. However, even after thickening, sludge is 90% water (Landing Aquaculture, 2020), which makes it inefficient and costly to transport. This is why, before aquaculture sludge is applied as a fertiliser, it can be dried and thereafter turned into pellets (Brod *et al.* 2017). Drying sludge therefore presents an opportunity where geothermal energy could be used.

Example case – Drying aquaculture sludge as additional heat utilization process
In 2013, Norway was the largest per capita aquaculture producer in the world. In Norway, fertiliser pellets made from fish sludge were studied as a way to close nutrient cycles. Compared to mineral fertiliser, the relative agronomic efficiency for nitrogen was 50-80% for barley (Brod *et al.* 2017). Other experiments have shown dried fish sludge to be a comparable source of phosphorus to dairy manure (Brod *et al.* 2016). In this experiment, sludge was dried at 105°C to 90% dry matter before being pelleted. Although these studies did not use geothermal energy, belt-convective driers to dry sewage sludge based on geothermal energy have been studied, with similar drying temperatures (Calise *et al.* 2018). Lower temperature dryers are also an option (Mäkelä *et al.* 2017; Zhang *et al.* 2021).

Drying aquaculture sludge – Quantitative estimate & Qualitative considerations

As an example we consider an aquaculture system that has been investigated within the GEOFOOD project by Landing Aquaculture (2020). It concerns a RAS of 4500 m^2, producing 200 tonnes pike-perch per year. It is assumed that the total suspended solids (TSS) produced is 25% of the feed given in terms of dry matter and the system takes in 744 kg of feed per day.
TSS dry matter production per day is therefore 186 kg. After thickening, the effluent has about 10% dry matter, meaning there is 1674 kg of water in the effluent. Typically, the resulting fertiliser pellets are about 10% water. Therefore, still 1653 kg of water would need to be evaporated every day. With an energy consumption of 3.6 MJ per kg of water (Tańczuk et al., 2016), this equates to almost 6 GJ per day. On an annual basis aquaculture sludge drying would require 2.2 TJ of geothermal heat. The yearly heating demand of the RAS ranges between 8-11 TJ, depending on the system (Boedijn, Baeza, et al., 2019b). Given the yearly heat demand of the RAS, the additional heat utilization provided by drying sludge would be 20-28%. However, in this report the focus is on a geothermal aquaponic system in which the geothermal well is dimensioned, based on the heat demand of the greenhouse. Compared to the heating demand of a 5 ha greenhouse, the additional heat utilization provided by drying aquaculture sludge is 3.5-4.7%.
Of course, like with drying fish, this does not necessarily have to be done daily. If the sludge can be kept for longer than a day, drying could be concentrated into only a few days per week. This would lead to the same energy demand on an annual basis, but would make the system more flexible, acting as a buffer to use up excess heat when it is available. Sludge is kept for around 14 days (Acierno et al., 2006), meaning that in theory the peak daily energy demand for drying could be increased by 14 times.

3.3 Algae production

Background

Pike-perch, a fish species studied in the GEOFOOD project, is carnivorous and requires a diet relatively high in protein (Nyina-wamwiza *et al.* 2005). Of the polyunsaturated fatty acids (PUFA's) present in pike-perch, the ratio of omega 3 to omega 6 is between 3:1 and 4:1 (Pyanov *et al.* 2014). Fishmeal is an excellent source of protein and omega 3 (Miles & Chapman, 2006) and up to 50% of the content of fish feed for aquaculture is fishmeal and -oil; raw materials that come from wild-caught fish or bycatch. This leads to overfishing, which is one of the reasons the production of fishmeal and -oil is forbidden in Europe. However, these products are still imported from Latin America, where it is still legal (Schafberg *et al.* 2018). Nevertheless, this remains an unsustainable process and is expected to become a limiting factor in aquaculture worldwide (Gasco *et al.* 2018).

A sustainable source of fish feed

Several studies have looked into substitutes for fishmeal as a source of protein, and especially omega 3 (Gasco *et al.* 2018; Naylor *et al.* 2009; Schafberg *et al.* 2018). The omega 3 in natural ecosystems comes from aquatic sources (Hixson *et al.* 2015), and its primary producer are algae (Ebm *et al.* 2021). This makes cultivated algae a natural alternative source of omega 3 for fish feed. To increase the sustainability and circularity of this algae, main inputs such as carbon dioxide, water and nutrients could be supplied by an aquaculture system or greenhouse (Sijtsma *et al.* 2021). Since this report focuses on geothermal energy and its utilisation, the energy consumption of algaculture is of interest. Algae grow under a wide range of temperatures, with 15-30°C being a normal range (Waller *et al.* 2012), but optimal temperatures range between 25-30°C (Dauta *et al.* 1990), depending on the cultivated species.

Example case – Growing algae as additional heat utilization process
An example of algae being produced in Iceland's challenging climate using geothermal energy is a facility at the Hellisheiði geothermal heat- and power plant, built by the company Vaxa (Finger *et al.* 2021; Novoveská *et al.* 2019). Hot- and cold water, as well as electricity and carbon dioxide from the power plant are used to grow algae (ON Power, 2019; Richter, 2020). Artificial lighting is used, which produces a lot of its own heat as a by-product (Tzachor, 2019). The algae is partially used for fish feed as a source of omega 3 (Vaxa, 2020).

Algae production – Quantitative estimate & Qualitative considerations

As an example we consider an aquaculture system that has been investigated within the GEOFOOD project by Landing Aquaculture (2020). It concerns a RAS of 4500 m^2, producing 200 tonnes pike-perch per year. Such a system takes in 744 kg of feed per day. In a study by Schafberg et al. (2018), about 26% of fish feed for pike-perch (dry weight) was replaced by a microorganism mix (i.e. cyanobacteria, yeast and microalgae). This constituted a 50% reduction in fishmeal and -oil. For the RAS considered in this example, it would mean that a daily microorganism production of 193 kg is needed.
Schafberg et al. (2018), indicate that the production of the microorganisms in an outdoor tubular photobioreactor required some heating (and lighting) to maintain (optimal) production conditions. Furthermore, the microbial biomasses were dried at 35-40°C for 16-18 h to accommodate the pelleting process. The overall heat demand for a kg of feed product is unfortunately not mentioned.
In a study by Hemming et al. (2014), algae were cultivated in a greenhouse achieving a yearly yield of 1.8 kg of dry matter per m^2, using 461 MJ/m^2. To meet the algae demand of the RAS a 4 ha greenhouse would be needed, consuming 18 TJ of heat per year. However, for other algae species and production systems, much higher productivities per m^2 are reported (Schultze et al., 2015; Sijtsma et al., 2021). Therefore, to implement algae production as an additional heat use application, the heat demand must first be determined based on the species of fish, species of algae and suitable production system.
Unlike the other two examples in this section, which involved drying products, the heat demand of algae production is not constant throughout the year. Especially when grown outdoors or inside a greenhouse, it follows a similar heat use pattern as greenhouse (tomato) production. Still, low temperature geothermal heat could be cascaded to a well-insulated (indoor) algae production to increase overall heat use.

3.4 Mesophilic and thermophilic biological filtration

Background
In recirculating aquaculture systems (RAS) several biological filtration processes are used to maintain water quality and treat effluents. Some of the main processes are nitrification, denitrification and mineralisation (Delaide *et al.* 2020; Rurangwa & Verdegem, 2015). All these processes depend on bacteria and each species has its own niche within a RAS. Like many biological processes, temperature is one of the main factors affecting the performance of filtration systems based on microorganisms.

Optimising biological water management in RAS and valorising aquaculture sludge
In RAS, water temperature is an important parameter in dimensioning of nitrifying biofilters connected to the fish tanks. In parts of the system where the water treatment loops are not part of the recirculation loop (e.g., end of pipe treatment), higher temperatures can be employed to either 1) increase the rate in which mesophilic bacteria process pollutants or 2) promote thermophilic bacterial communities which may increase reactor performance substantially. Increasing reactor performance results in smaller, more economical setups. To facilitate meso- and thermophilic bacterial communities (some) additional heating may be required that increases overall RAS heat demand.

For mesophilic applications, water must be warmed above 8-15°C and kept ideally between 20-30°C. Under these conditions, the performance of fixed film nitrifying biofilters increases by about 4% for each extra degree of temperature (Zhu & Chen, 2002). In denitrification reactors, nitrate removal rates can increase ten-fold when temperature is brought from 6°C to a more optimum 25°C. This has important consequences to the dimensioning of end of pipe nitrogen removal system which must meet a certain N concentration target. Examples of high(er) temperature applications include thermophilic anaerobic digesters (Gebreeyessus & Jenicek, 2016), thermophilic nitrogen removal systems (Lopez-Vazquez *et al.* 2014) and thermophilic membrane bioreactors (Collivignarelli *et al.* 2021). Reported performance increases when thermophilic systems are used over mesophilic reactors, is of 25-50%.

4 Aquaponic geothermal treatment network

4.1 Combining heat use applications

As described in section 1.2 of this report, a greenhouse alone cannot make full use of the capacity of a geothermal well since its demand for heat is not constant throughout the year or even throughout a day. To extract as much energy from a geothermal well as possible, it must 1) be used year-round close to its maximum capacity and 2) the reinjection temperature must be as low as possible. To increase geothermal energy extraction, multiple heat utilization processes can be connected in a network to achieve optimal heat use. Several applications have been discussed in this report that qualify for such a geothermal treatment network based on characteristics such as heat- and temperature demand as well as timing (i.e. when heat demand occurs relative to availability). Figure 5 shows a schematic overview of such a network.
The greenhouse, direct air capture, drying fish and drying vegetables are displayed in figure 5 as applications that require a higher temperature (>60°C) and therefore use geothermal heat directly. A RAS, algae production, drying sludge and drying organic waste are lower temperature applications that can utilize cascaded heat but may also use geothermal heat directly when the higher temperature applications have lower (or no) heat demand.

4.2 Utilizing existing geothermal infrastructure

The aquaponic geothermal treatment network in figure 5 may be approached as one system, but in this report additional heat use has consistently been compared to a geothermally heated greenhouse. That is because in practice there is an increasing number of commercial greenhouses throughout Europe that use geothermal energy. 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 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.
All the additional heat use processes in figure 5 have the potential to increase the heat use efficiency of a stand-alone geothermally heated greenhouse. Furthermore, each application also has potential to increase overall circularity and sustainability of an aquaponic food production system.

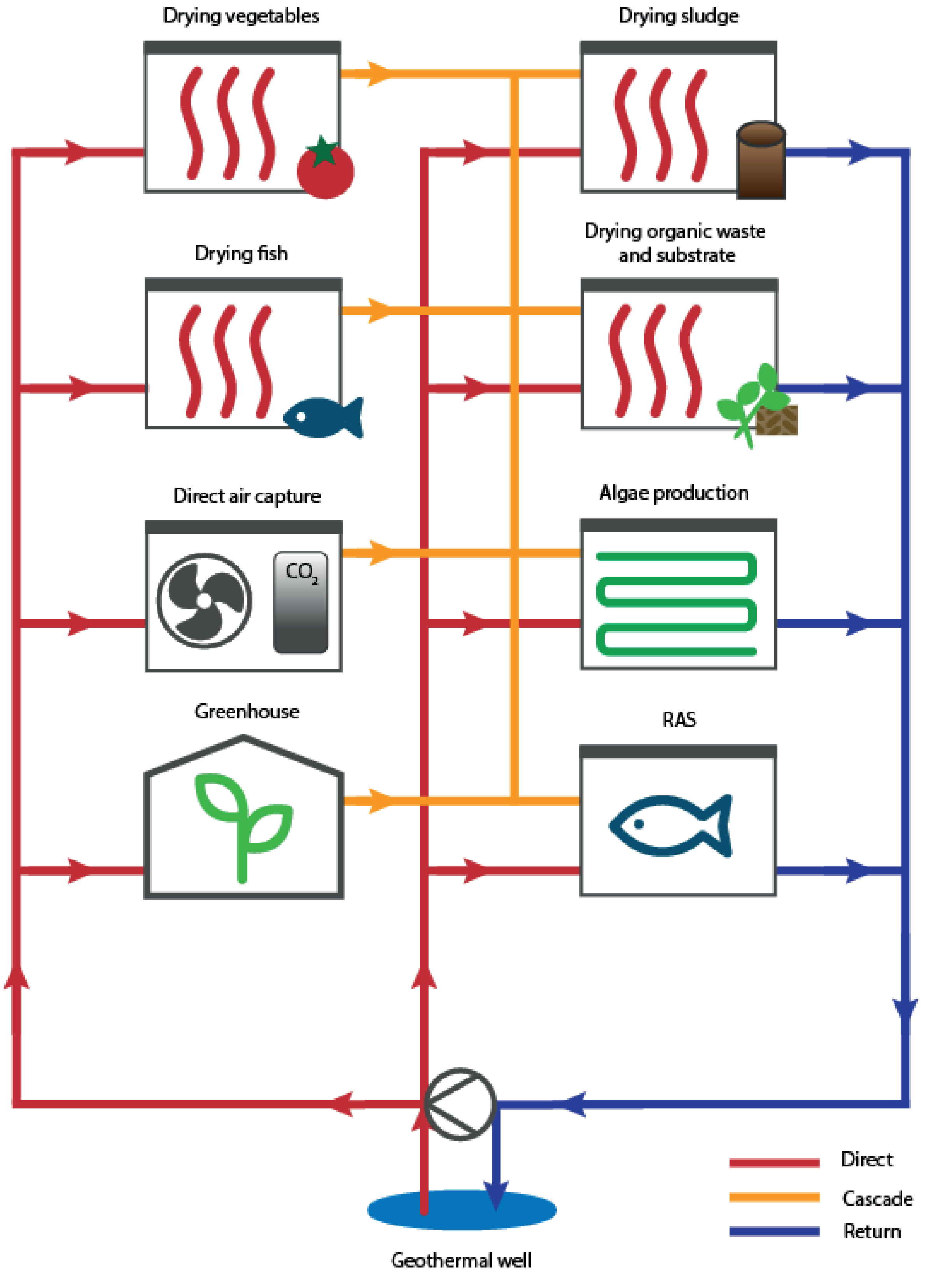

Figure 5 *Schematic overview of an aquaponic geothermal treatment network that has been extended with additional heat utilization processes.*

5 Conclusions

From this explorative study it becomes clear that there is a range of additional heat utilization processes that can increase the heat use efficiency of a geothermal greenhouse or -aquaponic system. Quantitative estimates in this report help to assess the potential of an application. However, system integration based on temperature demand as well as timing, proves to be an important aspect to consider. Finally, careful selection of applications does not only drive the energy transition but may also support the transition towards circular food production. This is because the availability of (residual) geothermal energy can provide the necessary heat to valorise waste- and by-products or utilize renewable resources.

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Wageningen University & Research,
BU Greenhouse Horticulture
P.O. Box 20
2665 ZG Bleiswijk
Violierenweg 1
2665 MV Bleiswijk
The Netherlands
T +31 (0)317 48 56 06
www.wur.nl/glastuinbouw

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