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Cross-industry exploration for external utilization of waste heat -

Tomato greenhouse, fish production, and insect production

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Abstract

This Memo is extending the investigation of low temperature waste heat users in Deliverable D6.4_2018.1. Based on the previous analysis, detailed investigations related to the production of tomatoes in greenhouses, different fish species in recirculating aquaculture systems, and insect production are conducted. Its aim is to show that low temperature waste heat can be used in food production and that there are potential business cases.

Simple energy calculations show that 100 GWh of waste heat can be utilized for both fish and tomato production. The size of the production facilities is in the range of existing production facilities. However, only a portion of this energy is actually used without seasonal energy storage due to variations in the outside and water temperatures.

The development of business cases requires further in-depth analyses and simulations of the production facilities. These analyses should take into account space requirements, and improved analysis regarding to heat loss and economic requirements within a production facility.

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1 Introduction

In Deliverable D6.4_2018.01, we investigated the availability of low temperature waste heat from aluminium plants and potential users of said waste heat. However, due to the approach of identifying many potential users, it was not possible to investigate the different cases in detail. This deliverable will therefore focus on three different cases with further analysis regarding market situation of potential users, how much waste heat can be utilized with how much space, and how the utilization of waste heat affects the environmental impact of the production.

To this end, we investigate:

1. tomato production and processing in a greenhouse heated by waste heat in Section 2;
2. warm-water fish production onshore utilizing recirculating aquaculture systems (RAS) in Section 3;
3. production of insects, both for feed and food proteins in Section 4.

Tomato production can be seen as an integration possibility achievable in a short-term, as the concept of utilizing waste heat for greenhouse heating is widely applied in Europe. As shown in D6.4_2018.01, waste heat from a dairy in Norway and a lignite thermal power plant in Germany is used in greenhouses. Warm-water fish production using waste heat has a medium-term perspective. Fish production in RAS with waste heat is not uncommon. However, the markets for warm-water fish is smaller in Europe compared to other continents. Hence, the production of warm-water fish will require a further development of the market in Europe. Insects production is a long-term alternative, as the utilization of insects as protein source is currently still in development. There are several projects related to the use of insects for both food and feed, and the compounded annual growth rate of insects is estimated to be large, albeit from a very small total market volume.

2 Tomato production and processing

We analyse the feasibility of using available waste heat for growing tomatoes in greenhouses. The use of thermal waste in greenhouses is a proven concept. In 1988 there were 34 ha of greenhouses, mostly commercial, which were using thermal waste from electric power plants in the European Economic Community (now the European Union) [1]. The interest in implementation has been influenced by fuel prices.

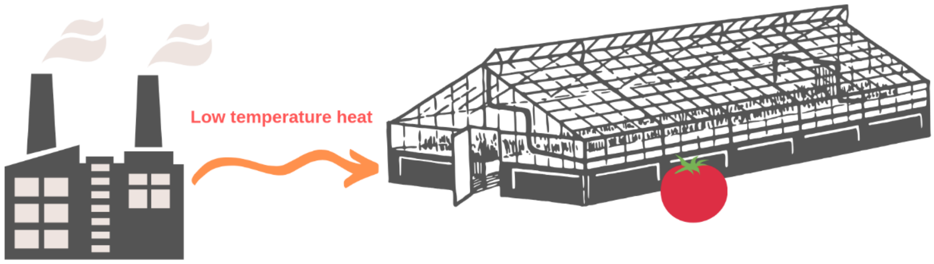

Figure 1: Use of waste heat for heating a greenhouse.

2.1 Consumption and production: market situation in Norway

2.1.1 Consumption of tomatoes in Norway

The annual consumption of tomato in Norway is of 7.3 kg per capita. Including tomato products (e.g. tomato sauce), annual per capita consumption increases to 16.3 kg; showing a slight increase since 2013, when it was of 15.5 kg [2], [3].[1] Considering turnover, tomato is the biggest segment of vegetables sold in Norwegian retail[2], with ~1.6 billion NOK in 2018, versus ~1 billion NOK for cucumber, which is the second biggest [4][3].

Figure 2 shows the average price of tomatoes in the last ten years [5]. Average listing price for Norwegian tomatoes the second half of 2018 was 17.24 NOK/kg [6] and in 2018 17.47 NOK/kg [5].

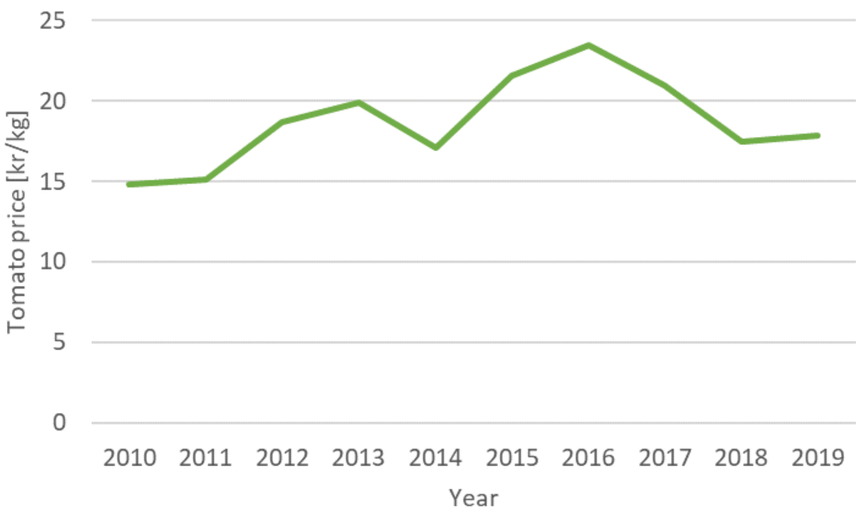

Figure 2: Listing price of tomato in Norway in the last decade (Data from [5]).

[1] To put those values in perspective; annual consumption in Italy and Spain is 94 and 85 kg per capita [3].
[2] Considering production, cucumber and cabbage production is higher, and until 2017 rutabaga (kålrot) was also higher [155].
[3] Values include 15 % mva (VAT); reported by [4], with original source Nielsen Scan Track Dagligvare.

2.1.2 Domestic production and imports of tomatoes in Norway.

In Norway, tomatoes are exclusively grown in greenhouses[4]. In 2016, tomatoes amounted to 37 % of the total production of greenhouse vegetables in Norway, only after cucumbers, which amounted to 53 % [7].

Rogaland produces more than 80 % of the tomato produced in Norway [8], [9]. About one third (33.3 %) of total consumption of tomatoes in Norway is from domestic production [4]. As shown in Figure 3 , since 2010, greenhouse tomato production in Norway has been relatively stable, between 10 500 and 12 900 t/a [10][5]. In this period, an average of 354 decares[6] have been dedicated to producing tomatoes in greenhouses [10][7].

In the high season, especially during May-June, there is a high supply of tomatoes, and Norwegian production has to compete in prices with imported products [4], [6][8]. In the last years, imports of tomatoes into Norway have also been relative constant, with an average of 24 122 t/a [11]. The two main import countries for tomatoes are Spain and the Netherlands, with 45 % and 40 % of total imports, respectively [12][9]. In 2018, the commercial sales of imported tomato to wholesalers had a value of 515 MNOK [12].

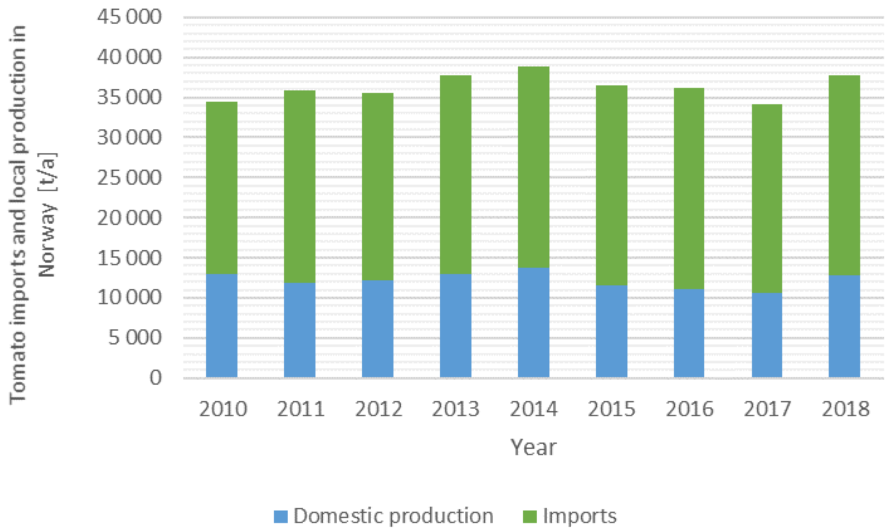

Figure 3: Annual Volume of tomatoes imported into Norway from 2010 to 2018 [4], [10], [11].

2.2 Growing tomatoes in greenhouses

2.2.1 Required growth conditions

Optimum mean daily temperature for growth is 20-25 °C, with night temperatures between 10-20 °C. Relatively dry climates are preferred and air humidity also needs to be controlled (<75 % RH) to maintain yield and reduce incidence of pests and fruit rotting [13], [14]. Crop performance is sensitive to irrigation frequency and technique. Tomatoes may be grown in greenhouses or in open field.

[4] Comparing total production values from [33] and greenhouse production values from [10].
[5] There is a small difference between the domestic production reported by [10] and [4]. The values used in Figure 2 are from [10].
[6] 1 decare = 1000 m²
[7] There is a mismatch in SSB. In [16] SSB reports 466 decares of greenhouse area for tomatoes in 2016. For the same year, they report 345 decares in [10]. This last figure is reported as preliminary. However, 466 decares reported in [16] is higher than any figure reported in the last years in [10].
[8] Tomato imports are reduced in June-July [12], [156].
[9] [156] reports 517 MNOK as the value of imported tomato in Norway in 2018.

Planting distance in greenhouse varies from 3 plants/m² [15] to 5 plants/m² [14], and 4 plants/m² can be considered to be standard [13], and was found to be optimal in a study in Norway [15].

Tomato's growing period is of 90-150 days, meaning that there can be up to three plantings per year, which may be done in production-intensive greenhouses. In open field, tomato is sometimes grown in a rotation with crops such as maize, cabbage, cowpea, to reduce pests and disease infestations [13]. In Norway, ~92 % of the tomato growing areas are treated with biological control agents, and ~13 % are treated with chemical pesticides [16].

2.2.2 Main characteristics of greenhouses in Norway, Spain and the Netherlands

In 2016, there were 78 holdings with greenhouses producing tomatoes with a total area of 466 000 m² in Norway [16]. Most holdings are in Rogaland, and in 2006 ~40 % were between 2000 and 4999 m² [17]. NIBIO Særheim has 2 research greenhouses; one of 1000 m² and one of 700m², with 8 departments, each of 70-100 m² [8]. These numbers contrast with the 77 000 m²- greenhouse of Miljøgartneriet, or the estimated minimum economical commercial greenhouse area for tomatoes in the Netherlands given by Peet and Welles of 15 000 m² [18], or the average 10 600 m² for greenhouses for vegetables in Ontario (Canada) [19][10].

As already mentioned, most imported tomatoes in Norway come from the Netherlands and Spain, which have competitive yields. While Norwegian and Dutch greenhouses are hydroponic, framed glass greenhouses, Spanish greenhouses are mostly plastic-film greenhouses ("parral") [18], [20], [21]. In Spain, the majority of the production that is sold as fresh tomatoes is produced in hydroponic greenhouses, although a large part is also grown in irrigated, open fields, while tomato destined for processing (e.g. sauces) is almost exclusively grown in open field [22][11].

Temperature control

As mentioned, optimum temperature is 20-25 °C, with night temperatures between 10-20 °C. Norwegian greenhouses are heated with electricity or natural gas [23]; the use of heating oil was discontinued almost a decade ago. Dutch greenhouses are commonly heated with natural gas, with combined heat and power technology (CHP) for larger greenhouses, producing ~10 % of the national electricity consumption [24]. Few greenhouses are heated using heat from geothermal aquifers [25]. Due to the structure of Spanish greenhouses as well as the availability of sunlight and warmer ambient temperatures, it is less common to find sophisticated climate control in Spanish greenhouses as in Dutch greenhouses [24]. However, in the high-producing areas, there are greenhouses with climate control [26]. There are also research efforts to increase energy efficiency or use renewable energies (e.g. [27], [28]).

Maximal temperatures are considered to limit summertime production in southern latitudes (e.g. Spain), where greenhouses use mechanical fan cooling, fog cooling or natural ventilation [29]. The use of these type of ventilation systems hinders the possibility of CO_2 enrichment [18].

Operating costs for tomato greenhouses

Energy in greenhouses, especially in northern latitudes, is used for heating and lighting. In 2006, 30-40 % of production costs of Norwegian greenhouses were related to energy, and the situation in the Netherlands and Denmark was similar [30].

In Canada, the main operating cost for greenhouse vegetables in 2005 was heating (28 %) [18]. However, with changing prizes and technology improvement, in 2018 labour accounted to the largest share (also 28 %), while fuel (heating) expenses were only 8.6 % of total operating expenses [31].

[10] Ontario is the largest producer in Canada and the average size in Canada was 6800 m² in 2008. There is no more recent data (see [157])
[11] In Spain, 10 520 ha were dedicated to grown tomato in greenhouses and 3 700 ha in open fields in 2018 [22].

High-tech greenhouses are less labour-intensive than low-tech greenhouses. However, as labour costs in Norway are high, this should be considered in an economic analysis. Miljøgartneriet, with 77 000 m² employs 70-85 workers in the high season [3]. Besides labour and energy, another relevant operating cost is the CO_2 for enrichment, which is usually bought liquefied. The cost of water, fertilizers, pest control, and eventual ethylene to accelerate ripening should also be considered when performing a detailed economic analysis.

2.2.3 Yield

Annual yield (production/area) depends on factors such as: plantings per year, plant density, irrigation system and patterns, ventilation, greenhouse structure, CO_2 enrichment, soil, and ambient (temperature, light, humidity) control [13], [15], [25], [32]. Worldwide, typical yield under irrigation is 4.5-6.5 kg/m² [13].

China is the leading producer worldwide (~30 % of total production), but most greenhouses are low-tech and national average yield is ~5.6 kg/m² [33]. There are research efforts to improve these numbers [34]. Mexico, where tomato was most probably domesticated, has appropriate light and soil conditions but production has varied degrees of technology and greenhouse tomato yields vary from ~12 to ~70 kg/m² [35], [36][12].

In Spain, the average yield is ~8.5 kg/m², and Almería, the province with the highest average yield, produces ~9.8 kg/m². With high-tech greenhouses, the Netherlands has the world's highest national average yield, ~51 kg/m² [25], [33], [37][13].

In the northern latitudes, high-tech greenhouses are required to grow tomatoes, and in 2017 all the Nordic countries were in the top 10 countries regarding yield[14]: Finland 4th (~36.5 kg/m²), Sweden 5th (~36 kg/m²), Iceland 6th (~33 kg/m²), Norway 7th (~32 kg/m²), Denmark 9th (~31 kg/m²). Average yield in Canada is ~7.8 kg/m², but top producers with good environment control and high-tech greenhouses may achieve yields of ~60-70 kg/m² [18], [38].

Research efforts to increase yield in Norway

In 2010-2018, average yield in Norwegian greenhouses was 32-38 kg/m² [10], [33]. The BIOFRESH project, with 35 participating greenhouses, coordinated by NIBIO Særheim (2016-2020)[15] and funded by the Norwegian Research Council [39], [40] aims to improve competence regarding production of greenhouse vegetables in (semi-)closed greenhouses in Norway. Preliminary results considering Norwegian conditions show that, with appropriate control of temperature regime, yield potential of cherry tomatoes in greenhouses is much higher than in the open land with larger fruits [41]. An optimized year-round cultivation system with three plantings and efficient temperature, light and water management, achieved over 100 kg/m² in a commercial setting in Norway. The authors of this report estimate a maximum potential of 125-140 kg/m² [15], [40], [42][16]. These values are three times the Norwegian average yield and two times the typical yields for high-tech greenhouses. The effect of artificial light in yield has been studied previously. A study in Japan, [43], observed "only" an increase of 24 % in winter and 12 % in summer using night-time LED inter-lighting.

[12] Mexican national average yield (greenhouse and open field production) is ~4.5 kg/m².
[13] Considering only the top 25 producers, the United States, Spain, Portugal and Morocco complete the top 5 countries with highest yield. Worldwide, Belgium has the second highest yield ~50 kg/m², and the top 10 is completed by the Nordic countries, the UK (~38.9 kg/m²) and Ireland (~31.6 kg/m²,) [25], [33]
[14] None of the Nordic countries is among the top 25 producers.
[15] The project finishes in July 2020 [40].
[16] In [42] it is claimed that these results were published in the Journal of Agricultural and Food Chemistry. Such publication was not found when searching in the Journal's website. In the profile of Michel Verheul from Nibio (https://www.nibio.no/ansatte/michel-verheul) the publications regarding this topic are: two articles in Acta Horticulturae [15], [158] of which only the abstract is available, and a poster with title "LED inter-lighting increases tomato yield due to higher photosynthetic light use efficiency of low-positioned leaves", for the 1st European Congress on Photosynthesis Research in Uppsala (2018).

2.2.4 Environmental impact of growing tomatoes

GHG emissions and carbon footprint

When looking at carbon footprint we should note that the values reported are highly dependent on the used methodology, available information and system boundaries. This is discussed, among others, in [44] and [45].

The main contribution to greenhouse gas (GHG) emissions comes from energy use for lighting and heating greenhouses [44], [46]. Theurl et al. [47] contrasted GHG emissions of tomatoes consumed in Austria, produced locally and in Spain or Italy. They concluded that greenhouse gas emissions from tomato production highly depend on the production system such as the prevalence or absence of heating. Due to heating, greenhouse tomatoes have a higher carbon footprint than open-field tomatoes. Pérez-Neira et al. [26] estimated that Spanish tomatoes produced in heated greenhouse had 2.75 times higher carbon footprint and 3.3 higher cumulative energy demand than unheated crops.

An environmental study comparing environmental impact of producing tomatoes in Swedish greenhouses with importing tomatoes from the Netherlands or Spain to Sweden concluded that greenhouse climate control and the transportation of produce are the most important contributors to the environmental impact. Specifically, that energy source for climate control of greenhouses, is more significant than transportation distances in a European context [24]. Stoessel et al. [48] arrived to similar conclusions when analysing production in Swiss greenhouses.

According to a 2012 report for the environmental impact of Norwegian agriculture [44], considering retail as the system boundary, Dutch tomatoes produce 1.7-2.8 kg CO_2eq/kg[17] when using natural gas and 1.1 kg CO_2eq/kg when using CHP. The carbon footprint for tomato imports from Spain to central Norway is between 0.4 to 1.8 CO_2eq/kg, depending on the methods of production. In 2017, Pérez-Neira et al. [26] estimated 0.92 kg CO_2eq/kg (on-farm) for Spanish tomatoes produced in heated greenhouses.

Verheul and Thorsen [49] analysed CO_2 emissions of six Norwegian greenhouses using natural gas as heat source and the farm gate as system boundary[18]. They estimate that ~93 % of CO_2 emissions from production of tomatoes in Norway comes from heating and ~1 % from electricity (light). Each plant required 42.3 kWh of electricity, 30.1 kWh of natural gas, and 0.083 m^2 per year. The CO_2 footprint was 3.8-4.25 CO_2eq/kg. The footprint is reduced to 0.770-1.07 kg CO_2eq/kg with biomass CHP[19] [44][20]. The Norwegian Gardeners Association (Norske Gartnerforbund) reports 0.62-1.83 kg CO_2eq/kg, and 0.81 kg CO_2eq/kg in an energy-intensive production that yielded 115 kg/m^2 [23], but there are no available details on the methodology. In 2006, Bævre et al. estimated that a 2 000 m^2 greenhouse in Norway requires in average 100 kW of heat (maximum of 200 kW), and in average 200 kW of electrical energy (maximum of 1100 kW) [30].

To put these values in perspective, open-field production of tomatoes in Spain produces ~0.37 kg CO_2eq/kg [50][21]. Therefore, using waste heat to grow tomatoes in Norwegian greenhouses, would result in an important reduction in CO_2 footprint of tomatoes consumed in Norway as it would substitute tomatoes from the Netherlands and potentially Spain with a higher CO_2 footprint.

[17] [44] reports 1.7 CO_2eq/kg and [50] report 2.8 kg CO_2eq/kg.

[18] In this study, all greenhouses were producing round tomatoes, with an average weight of 95 grams.

[19] CO_2 footprint of Norwegian greenhouse tomatoes may be smaller. [159] reports 2.3 CO_2eq/kg as a yearly average, but does not report methodology or source. In a press release, it is said that an Asplan Viak AS study calculated 2.3 CO_2eq/kg for Norwegian tomatoes and 0.3-0.6 CO_2eq/kg for Spanish tomatoes [160]. It is not specified whether the boundary for Spanish tomatoes is at farm gate or retail.

[20] [44] reports 5.31 kg CO_2eq/kg when using heating oil, but it is no longer used.

[21] Open field GHG emissions are highly variable, but consistently lower than emissions from greenhouse production. Values vary from ~0.03 to up to ~0.4 kg CO_2eq/kg [45].

Water footprint[22] and Virtual water content[23]

As with carbon footprint, the methodology and the system boundaries influence the value reported [51], [52]. It is important to note that there are three types of water footprint: green (evaporation), blue (surface or groundwater) and grey (pollution). The term "water footprint" sometimes does not consider grey water footprint.

The value for water footprint (l/kg) is directly related to yield. Thus, water requirements depend on the technology used. High-tech Dutch greenhouses require less than 10 l/kg and low-tech production in China requires 284 l/kg [25], [52].

In 2017 Hoekstra and van Heek estimated 214 l are required for each kg of tomato [53]. In 2004, an UNESCO-IHE study estimated that the global average for the virtual water content of tomatoes was 184 l/kg, while Dutch tomatoes required 8 l/kg; Norwegian, 10 l/kg[24]; and Spanish, 53 l/kg [54][25].

Almería (in Andalucía) and Badajoz (in Extremadura) [26] are the provinces in Spain with the highest production of tomatoes. Tomatoes in Badajoz are mostly used for processing and tomatoes from Almería are mostly sold fresh [51]. A study in 2002 estimated that greenhouses in Almería use 27 l/kg[27,28] [55]. A more recent study with a different methodology estimated 46.3 l/kg [51].

Water footprint in terms of l/kg in Andalucía and Extremadura is low with respect to the rest of Spain. However, due to the high production, the total water footprints for tomato production of these two provinces are the highest in Spain. In 2009, of the ~326 Mm³ of water that were consumed (evaporated, polluted or lost) for tomato production in Spain, ~90 Mm³ were consumed in Andalucía and ~125 Mm³ in Extremadura[29] [51], [56].

If we consider that ~95 % of tomatoes is water, exports of tomatoes can be considered water exports. Spain exported 81.4 Mm³/a of water during 2000-2004 [51]. In 2010, tomato exports represented 2.5 % of total Spanish water exports[30] [56]. This should be taken into account as production sites for tomatoes in Spain are the ones that have the most conflicts between agriculture and the conservation of rivers and water resources [51]. Moreover, drought periods are expected to become more frequent in the south (Andalucía) and south east of the Spanish peninsula [57].

Tomato production in Andalucía and Extremadura used to use groundwater almost exclusively. Despite water efficiency has improved dramatically, especially with the use of drip irrigation, the availability of renewable water is not enough. Irabien and Darton estimated that the Almería region receives 200 m³/m² of annual rainfall, but greenhouse production of tomato in Almería utilizes 800-1000 m³ water/m² per year. Most water bodies in these regions are at risk of no compliance with the European Water Framework Directive [56]. In

[22] The water footprint of an individual, business or nation is defined as the total volume of fresh water that is used to produce the foods and services consumed by the individual, business or nation. A water footprint is generally expressed in terms of the volume of water use per year [54]. Water footprint calculations differ in methodology [51].
[23] The virtual water content of a product is the volume of water used to produce the product, measured at the place where the product was actually produced [54].
[24] In a study of 6 greenhouses in Norway, average water consumption was 24.3 l/kg. However, part of this water is treated and recirculated and no life-cycle analysis (LCA) was performed [49].
[25] These numbers are national averages. Methods of production are not considered.
[26] Almería is the capital of the autonomous community of Andalucía. Badajoz is in the autonomous community of Extremadura.
[27] National average water footprint for Spanish tomato is 97 l/kg, open air uses 73 l/kg and open-air irrigated uses 331 l/kg and for greenhouses it is 74 l/kg [56]
[28] Open field production in Almería uses 50-60 l/kg according to [55].
[29] Irabien and Darton report 66 l/kg as blue, and 121 l/kg as grey footprints for greenhouses in Almería [58].
[30] Tomato exports represented 8 €/kg, while average exports represented 2.5 €/kg [56].

the most recent analysis (2017), only 43.4 % (29/67) of groundwater sources in Andalucía comply with environmental objectives [57].

Desalinization of brackish water or seawater is now necessary, and this requires additional energy [58]. To mitigate the exploitation of groundwater, there are 13 desalinization plants in the Spanish Mediterranean coast, three of which are in the Almería region [59]. Desalinated water is distributed to households and greenhouses. There are plans to duplicate desalinization capacity by 2020 and to analyse the technical feasibility of interconnecting desalinization plants in southern Spain [60].

It should be noted that there are efforts to increase efficiency of water use [57][31]. There is also some ongoing research to optimize water distribution in that region (e.g. [61]) and to reduce water consumption in greenhouses (e.g. [62])[32].

Norway is a water-rich country. In 2004, it was estimated that it had 382 Gm^3/a total renewable water sources and withdrawing 2.14 Gm^3/a (0.56 %). The values for Spain were 111.5 Gm^3/a and 35.77 Gm^3/a (32 %). The values for the Netherlands were 91 Gm^3/a and 7.9 Gm^3/a (8.6 %) [54]. Therefore, the overall effect of the water footprint of tomato production in Norway is lower than the overall effect of the water footprint of tomato production in Spain or the Netherlands.

Tomato waste from greenhouses (overproduction and sub-prime quality)

In greenhouses, there might be an occasional overproduction of tomatoes, and a fraction of the production is unsuited for fresh consumption sale due to aesthetic reasons (colour, shape, maturity or lesions). In Norway, waste due to overproduction and subprime quality (unacceptable colour, shape, maturity, lesions) corresponds to approximately 2 % of total production (~200 ton/a). There is an additional loss of up to 10 %, depending of the type of tomato, at the retailer's level (unsold tomato) and due to inadequate temperatures during transportation and retail. Total waste is estimated to be ~6 %. Previous efforts to produce tomato sauce of the surplus tomatoes in Norway has not been economically viable so far and subprime tomato is currently used as cattle feed [3].

Food security

The Norwegian government considers that "optimal, sustainable use of agricultural land, also in Norway, is of great importance for global food security" and that "in the future it is important that the land-based food production [in Norway] continues to increase, as will the demand from a growing population" [63].

2.3 Reliability of heat supply and heat storage for greenhouses

A greenhouse using waste heat from the industry will most probably still require a backup natural gas boiler. Although aluminium manufacturing is a constant process, it is probable there will be both planned and unplanned downtime during the year[33]. During this time, the backup boiler should provide the required energy. Alternatively, energy storage could provide heat during downtime in the aluminium plant. Considering seasonal heat storage in the initial design would enable a larger greenhouse area, but a more detailed study is required to determine feasibility.

Short-term storage could become relevant due to the daily variations in ambient temperature [30]. Seginer et al. [64] suggested an optimal control policy for day-to-night energy storage for a Dutch greenhouse for tomato production. Shukla et al. [65] reviewed different energy storage systems for solar greenhouses[34],

[31] It is expected that by 2021, 345 hm^3/a of groundwater in Andalucía are used for agricultural purposes, affecting 73 % (49) of the groundwater sources in the region [57]

[32] For a review on energy-for-water interconnections with focus on desalinization see [161].

[33] Swedish metal industries have an average downtime of 12 % [162].

[34] Only heated with solar energy.

including phase change materials, and thermal energy storage. Further analysis is required to determine the feasibility of heat storage for greenhouses in Norway.

2.4 Other possible synergies of greenhouses with the aluminium industry

Besides the use of low temperature heat, CO_2 capture and utilization could be another possibility of industrial symbiosis between aluminium plants and greenhouses [66], [67]. Utilization of low temperature heat is already implemented in the 77 000 m²-Miljøgarneriet greenhouse in Norway, which uses surplus CO_2 and warm wastewater from a nearby diary plant.

The aluminium industry accounts for ~1 % of global greenhouse emissions [68]. There are ongoing projects to directly utilize captured CO_2 in Dutch greenhouses (e.g. [69]). However, CO_2 used for enrichment would have to be treated so that it is suitable to be in contact with food. This would represent an additional capital investment, that would have to be compared to the operating costs of purchasing liquid CO_2 for enrichment. Even if this is the case, it is possible that competitiveness (consumer decisions) is affected by the perceived risk of using CO_2 from the metal industry [19].

2.5 Estimation of heating requirements and production

Here we calculate the size and potential tomato production of a greenhouse that can be heated with the available waste heat. The developed model is not "site-specific". We assume that we have 100 GWh/a available at an appropriate temperature (70 °C). The available heat is assumed to be the same independently of the season at outdoor temperature. Considering[35] 8760 h/a, this corresponds therefore to $\dot{Q} = 1.14 \times 10^7$ W.

This study is based on the methodology proposed by Andrews and Pearce [19]. The energy balance for a greenhouse is:

$$\dot{Q} = UA\left(T^{in} - T^{amb}\right) + C_{p,air}\Phi_{air}\rho_{air}\left(T^{in} - T^{amb}\right) - \beta S$$

Neglecting solar radiation, considering constant heat capacity ($C_{p,air}$) and air density (ρ_{air}), and expressing the energy balance in terms of a linear dimension (L), as in Figure 4.

$$\dot{Q} = \left(4Lh + \frac{L^2}{cos\theta}\right)U(T^{in} - T^{amb}) + 1800\left(h + \frac{G}{2}\right)L^2N\left(T^{in} - T^{amb}\right)$$

The parameters are described in Table 1; we use the values suggested by [19] [36]. This equation can be rearranged such that L is a quadratic function of $\dot{Q}$, T^{in}, T^{amb} with the parameters in Table 1. Radiative heat losses are not included in the calculation.

Table 1: Parameters used to calculate linear dimension of greenhouse.

Term	Value	Description
H	4 m	Height
θ	30°	Roof pitch angle
G	2 m	Length of a side of the pitched roof
U	W/m²	Heat transfer coefficient
N	2.1×10^{-4} s^{-1}	Ventilation rate

[35] As this is a rough estimation, no downtime is considered.

[36] The Excel spreadsheet was validated obtaining the same results as in original paper [19]. The analysis in the original paper is done for Canada, so we consider the heat transfer coefficients and ventilation rates to be appropriate for Norwegian conditions.

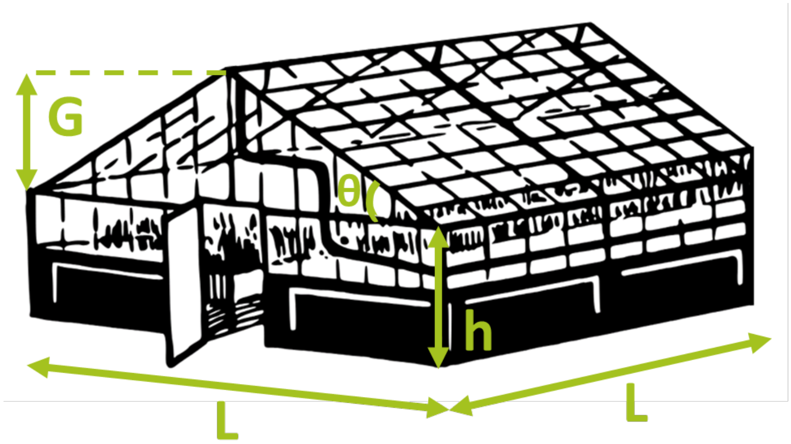

Figure 4 Dimensions of greenhouse in terms of linear dimension L

To calculate *L,* we use T^{in} = 21 °C, which is an appropriate temperature for growing tomatoes. Ambient temperature values were obtained from the Norwegian Meteorological Institute for the station in Haugesund Lufthavn [70] in Karmøy, considering the possibility of using the waste heat from the aluminium smelter. Moreover, Karmøy is in Rogaland, which concentrates most of the Norwegian tomato production [8]. In 2018, the minimum and maximum daily average temperatures were -8.8 °C and 24.9 °C. We size the greenhouse for the coldest day of the year in Karmøy, so T^{amb} = -8.8 °C.

With these values, the available heat is enough for a 56 517 m² greenhouse. Considering a yield of 32 kg/ m², which is a conservative value for Norway, we would produce 1809 t/a. If sold at 17.47 NOK/kg, the average price in 2018 [5], this represents 31.6 MNOK/a.

2.5.1 Monthly heat consumption

Actual energy requirements vary with ambient temperature. Table 2 and Figure 5 show the monthly average temperature values for Karmøy in 2018. Table 2 and Figure 6 show the estimated monthly energy consumption. With these considerations, annual consumption would be of 42.21 GWh/a out of the 100 GWh/a available. These estimations show that there is a good potential for analysing heat storage possibilities or optimizing temperature control.

Table 2: Monthly heat consumption considering actual ambient temperatures.

Month	Days/month	Average T [°C]	Energy [GWh]
Jan	31	2.98	5.14
Feb	28	0.44	5.29
Mar	31	0.87	5.74
Apr	30	6.99	3.86
May	31	12.63	2.44
Jun	30	13.00	2.22
Jul	31	15.66	1.60
Aug	31	15.09	1.69
Sep	30	12.88	2.24
Oct	31	9.27	3.34

Nov	30	6.55	3.98
Dec	31	4.61	4.67

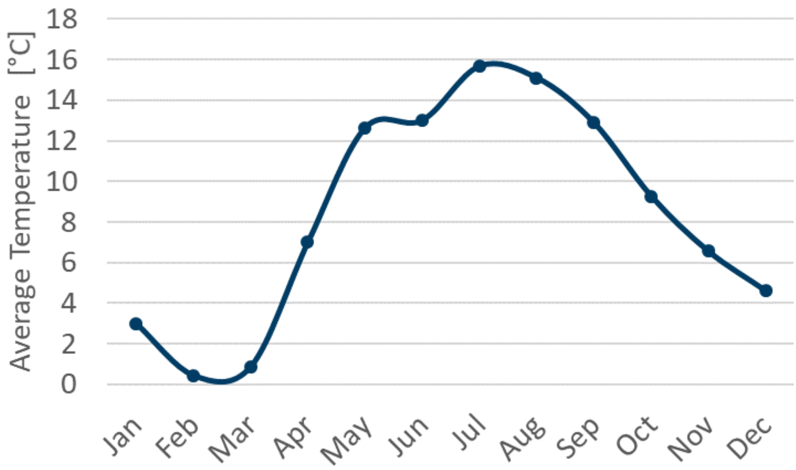

Figure 5: Average monthly temperature in Karmøy in 2018 [70].

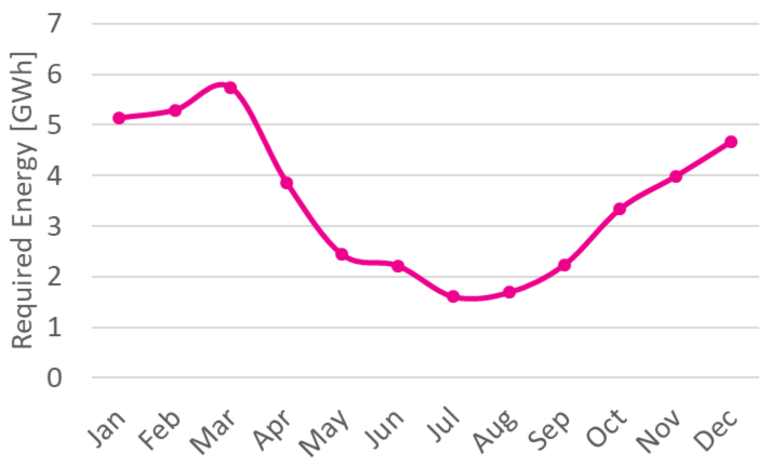

Figure 6: Estimated monthly energy consumption for a 56 500 m² greenhouse in Karmøy with temperatures in 2018.

2.5.2 Production potential

Figure 7 show the production potential as a function of available energy; showing typical greenhouse areas. Figure 7 was obtained using the parameters in Table 1 and the coldest temperature in Karmøy.

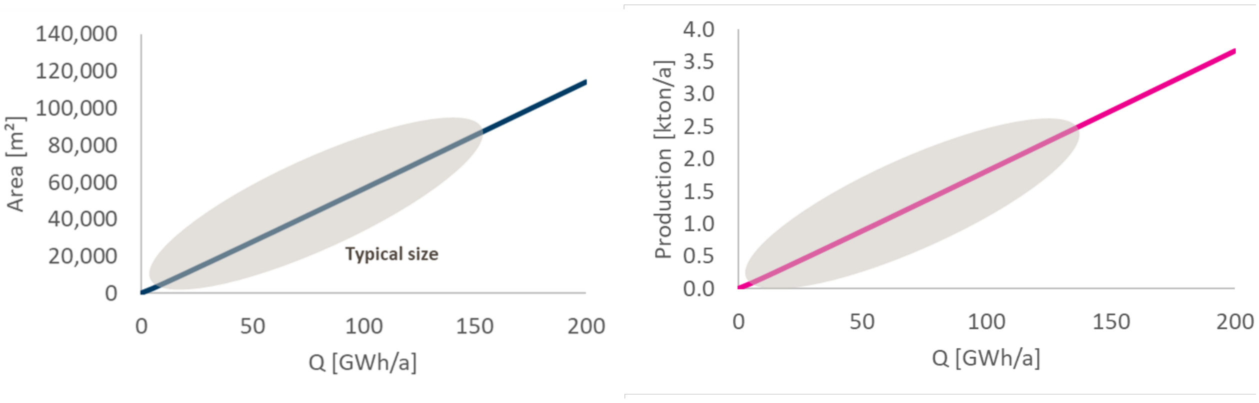

Figure 7: Production potential for available energy.

2.5.3 Sensitivity

Bævre et al. [30] reported in 2006 that for a 2 000 m² greenhouse in Norway, average heating requirements were 100 kW and maximum of 200 kW. For the same size, this calculation gives 510 kWh/a. Thus, ours is a conservative estimation.

For ventilation, we are considering constant ventilation rate, ρ_{air}, $C_{p,air}$. Additionally, the greenhouse temperature (T^{in}) is constant, but it is possible to vary. In the night, the greenhouse temperature could drop to 10 °C. In a more detailed analysis, we should consider heat losses in piping and heat exchangers.

We are using a conservative value for the heat transfer coefficient (U). Estimated energy requirements would decrease if we consider solar radiation and insulation. Hence, it is important to conduct sensitivity analysis related to the parameters. We use the same equation for the calculations. In this calculation, *U* is 4 W/m²; but it could be 2.5 W/m² with better insulation [19]; for example, using a thermal blanket. The dark green line in Figure 8 shows the effect of reducing *U*. On the other side, *U* increases linearly with wind [67] and the dark blue line in Figure 8 shows the estimated consumption if we consider the wind velocity in Karmøy[37] at 10 m height. Solar radiation would decrease energy requirements. The yellow line in Figure 8 shows the estimated energy requirements, considering solar radiation in Bergen and wind in Karmøy[38].

[37] There are no available values at 4 m or less, which would be more relevant for this study.
[38] There are no available values for solar radiation in Karmøy. The closest are in Bergen.

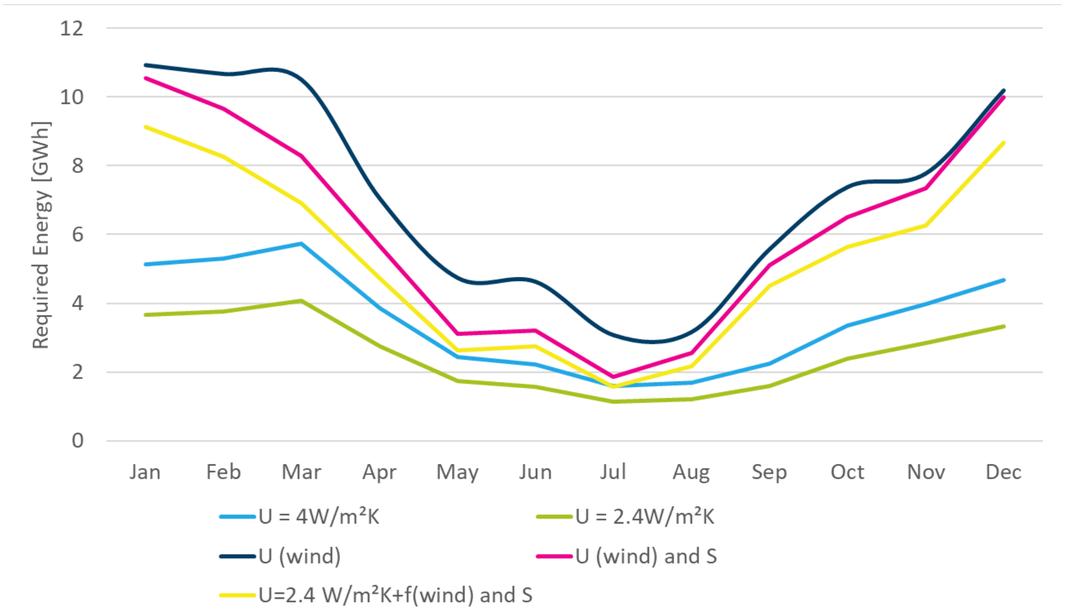

Figure 8: Effect of heat transfer coefficient in calculation of required monthly energy.

2.6 Processing of tomatoes

A combined plant for drying of tomatoes exploits the potential of valorisation of crop biomass in the vegetable supply chain. In this report, we analyse two possibilities: drying to produce powder (e.g. for tomato soup) and production of juice, paste or smoothies. Drying is more energy intensive, and could be done during the summer months, when heating requirements for the greenhouse are lower. In the winter, when "waste heat" is required to maintain an adequate inside temperature in the greenhouse, production could be shifted to liquid products (juice, paste or smoothies). The production of liquid products also requires thermal energy (see Paste and juice production) and a techno-economic assessment is required.

There is some market potential. A 2018 report forecasted that the global packed dehydrated food market would grow at a compound annual growth rate (CAGR) of 5.67 % during 2018-2022 [71]. In 2016, Norway imported 11 497 ton of tomato paste, equivalent to ~13.2 MUSD [72]. In 2018, tomato sauce accounted to at least 30 % of sauce imports, and most sauce imports come from Sweden, the Netherlands, and Italy [6].

In countries like Spain or Poland that produce greenhouse and open-field tomatoes, it is common that greenhouse tomatoes are for fresh consumption, and open-field tomatoes are for processing [3], [51].

The SUNNIVA project, funded under the framework of the Era-Net SusFood Call (2014-2017), investigated possibilities of valorisation of vegetable products in several countries, including Norway [73][39]. SUNNIVA aimed at the development of a sustainable food system from production to consumption, addressing the entire food supply chain for the vegetables tomato and *Brassica* (cabbages, cauliflower and broccoli). It was coordinated by NOFIMA and other Norwegian participants were NIBIO, Fjordland AS and Fjordkjøkken AS. It gave priority to the stabilization of wet products over using drying technologies because of the comparatively higher energy requirements.

2.6.1 Quality of processed product

Tomato contains well-known antioxidants such as vitamin C, carotenoids, flavonoids, and hydroxycinnamic acids. Lycopene is a carotenoid and the antioxidant which gives the characteristic red hue of tomatoes. Methods for valorisation of tomato should preserve as much as possible (or concentrate) these components [3],

[39] Reference[3] is a product of the SUNNIVA project [73].

[73]. Light, pH and temperature during storage and processing may affect lycopene concentration. Løvdal et al. [3] did a survey on the effect of processing on lycopene concentration and quality of processed tomatoes. Lycopene is relatively stable when tomato treated thermally [74]. Thermal treating, such as boiling, may decrease total concentration[40] but increases bioavailability (*cis-lycopene* is absorbed better than *trans-lycopene*) [75]. Other antioxidants, such as vitamin C and tocopherols, are less heat-stable [76]. Mechanical treatment does not affect lycopene, but exposure to oxygen affects other nutrients. To conserve critical bioactive compounds, the processing method should: minimize exposure to light, oxidation and heat [75].

In the next sections, we present two possibilities for valorisation: drying to produce powder (e.g. for soups) and production of liquid products (juices, purees or smoothies).

2.6.2 Drying of tomatoes

Available methods for removing moisture are: freeze, vacuum, osmotic, cabinet or tray, fluidized bed, solar, sonic, electromagnetic and microwave drying, and combinations thereof [75], [77], [78]. Freeze and vacuum drying are considered costly alternatives [77]. Freezing is done with liquid nitrogen, and the frozen tomatoes are then milled. Microwave drying is fast, but there are concerns about product quality. Osmotic drying may remove around 75 % of water and the solute is "added" to the product (e.g. salted tomatoes) [75].

Low-tech methods, such as sun-drying, are traditionally used in the Mediterranean countries. Even with convenient sun and ambient temperature conditions, drying times are usually long [79]. Reinoso et al. [80] left the tomatoes at the same conditions of low humidity and high temperature of standard greenhouses, with no additional heat source or artificial air circulation[41]. In a period of 15-20 days, tomato moisture was reduced from 80-90 % to 10-60 %, depending on ambient conditions.

Convective drying

Convective drying is possibly the most common process to dehydrate food and ~85 % of industrial applications use a variation of this technology[42] ([81] in [82]). In this case study, this is a relevant method due to the availability of waste heat. Drying may be done with temperatures between 40-110 °C (usually 50-80 °C). Reported drying periods are highly variable (2-35h), but they typically are 5-6h [77], [83], [84]. Most convective drying is done in trays; industrially, it is done in tunnels of conveyor dryers. Air velocities may be in the range of 1.5-2.0 m/s [84].

There are different reported times, from 5 to 28h for drying non-treated tomatoes with air at 60 °C [77]. Tomatoes are usually dried in slices or in halves. As expected, the size (thickness) of the pieces and the layout affects drying kinetics [77]. To preserve quality, systems with shorter drying times at relatively high temperatures (~70 °C) are preferred [75].

Examples of studies to find drying curves of tomatoes (moisture ratio with respect to time) are found in [77], [79], [85]. The drying phenomenon of biological products during the falling rate period is controlled by the mechanism of liquid and/or vapor diffusion [84]. The models used are usually derived from Fick's second law or a simplified version of it. They have a general form of $MR = a\ exp(-ktn)$. A model found frequently is the Page model. In the characterization of drying behaviour, activation energy for moisture diffusion is usually a reported parameter [79], [83], [85].

Equipment for convective drying

Belt-through conveyor driers are used for diced fruits and vegetables and they have higher drying rates than tunnel driers. They usually dry in two stages: 50-60 % and then 15-20 % moisture. For powder, pneumatic

[40] Some researchers report an increase in concentration of flavonoids and lycopene [76]

[41] The experiments were done in Almería, southeastern Spain.

[42] For food in general, not exclusively for tomatoes.

ring dryers are used. These dryers have a capacity of 10-25 ton wet food/h and may evaporate 16 ton water/h. Foods are metered into meal ducting and suspended in high-velocity hot air. It may be integrated with a disintegrator mill, enabling control of particle size and residence time [86].

Labour intensity is low for both technologies [86]. It should be noted that this equipment is not usually compact, and if it was to be used on-site and seasonally this might increase labour requirements (assembly/disassembly).

Energy required for convective drying

Tomatoes contain 90-95 weight % of water. Drying is considered to be energy intensive due to the latent heat of evaporation of water. A tomato is considered "dry" with <15 weight % of water [77].

Bosona and Gebresenbet [46] estimated an energy consumption of 3 600 kJ/kg of water removed. Durance et al. [87] reported 29 900 kJ/kg of water removed, including the air fans[43].

In practice, actual energy requirements for convective drying are calculated with the energy balance on the air side (e.g. [82], [88]). This calculation requires measurements for air humidity, required air flow, air temperature, and drying time ("tomato mass flow").

When doing this investigation, we did not find any research using the energy balance on the tomato side, which is given by:

$$Q_{dry} = m_{tom,dry} C_{p,tom}\left(T^{out} - T^{in}\right) + m_{H_2O}\left[C_{p,H_2O}\left(T^{out} - T^{in}\right) + \Delta\widehat{H}_{H_2O}^{vap}\right]$$

Where $m_{tom,dry}$ is the mass of the dry tomato and m_{H_2O} is the mass of water in the tomatoes. To estimate the energy requirements for drying the tomatoes using this formula, we consider $T^{in} = 21$ °C; $T^{out} = 70$ °C; tomato heat capacity $C_{p,tom} = 1.9$ kJ/(kg K), water heat capacity $C_{p,H_2O} = 4.2$ kJ/(kg K), and enthalpy of vaporization $\Delta\widehat{H}_{H_2O}^{vap}(70\,°\mathrm{C}) = 2333$ kJ/kg, and 90-95 % water content (m_{H_2O} [0.9-0.95]). Then, we would require 2294-2416 kJ/kg wet tomato, or equivalently 2544-2549 kJ/kg water to completely dry the tomatoes. The resulting values are lower than those reported by Bosona and Gebresenbet [46]. This was expected because in this calculation we do not consider energy losses.

Considering 100 GWh/a of available heat at 70 °C and a tomato production of 1800 ton/a (the hypothetical production obtained in Estimation of heating requirements and production) less than 2 GWh/a would be required for drying the production of a year. With this rough estimation and looking at Figure 6, it seems feasible that waste heat that is not used to heat-up the greenhouse during the summer months can be used to dry tomatoes.

As discussed before in this report, actual energy requirements (drying efficiency) will depend on the configuration of the system. Additionally, we would have to consider electric consumption of fans and conveyors (besides lighting for personnel).

Possibilities for reducing energy required for drying

Fellows [86] lists some possibilities to reduce energy consumption (and in some cases the capital cost of the dryer). Insulation, heat integration and the use of heat pumps are mentioned. Another option could be to preconcentrate the tomato using evaporators[44]. No research was found for tomatoes, and the effect on the quality of the product should be considered.

[43] This value is the sum of the energy from the required natural gas and the power input to two fans. Air was at 70 °C, 12 %RH and 1.5 m³/s. Drying time was 14.75 h

[44] Energy use per unit mass of water removed in evaporators is lower than that for dehydration [86].

Combined drying methods

As mentioned previously, convective drying rates are in general quite low. To overcome this limitation, hybrid methods may be used. Depending on the configuration, energy consumption may be reduced. Bantle and Eikevik [89] studied a convective drying system with ultrasound for clipfish. Another option to reduce time is to combine convective drying with microwave [87], [90]. Vadivambal and Jayas [91] made a review of both methods for drying agricultural products, and they concluded that ultrasonic drying seems to be better for heat sensitive materials because it does not require significant temperature rise in the product. Hosainpur et al. [92] found that when using ohmic pre-drying of tomato paste, the specific energy consumption and drying efficiency varied respectively from 3.72 to 2.29 MJ/kg water and 67.8 to 83.8 %.

Pre-treatment for drying

Tomatoes have a waxy skin, which affects drying dynamics and pre-treatment methods have been used to facilitate drying. However, pre-treatment methods may deteriorate flavour and nutritive value. Pre-treatments can be divided into [75]:

- Mechanical: cutting in halves, perforating with needles [75]
- Chemical: dipping in a solution (e.g., $CaCl_2$, NaCl, metabisulphite, H_2O_2) [75], [79], [83]
- Thermal: freezing [75]

Depending on the solution used, chemical treatment can affect, both positively or negatively, the nutrient content, aspect (browning) and storage life of the produced powder [93].

2.6.3 Paste and juice production

As in the case of drying, maintaining the native constitution of tomato is preferred for quality. Figure 9 depicts the main steps for producing tomato. Heat is required for "break", (sometimes) concentration, pasteurization and hot filling.

Figure 9: Typical processing for tomato juice [94].

Cold and hot break

There are two conditions that are commercially used for chopping the tomatoes before extracting the juice [94]–[96]: cold break and hot break. "Hot" break refers to chopping at 75-100 °C [95], typically 85-90 °C [96], while "cold" refers to temperatures below 70 °C [96], typically <66 °C [95].

Chopping temperature has an effect on microbial deactivation and product flavour. Cold maintains colour and taste but decreases consistency, while hot break maintains consistency but at the expense of colour and taste. Commercially, both methods are used. High pressure processing (HPP) or a combination of HPP with a thermal treatment can also be used with purees. Cold break would be preferred for a premium flavoured juice [94].

Extraction and concentration

This is usually done using some press technology. The spiral-press filter technology can produce tomato juice and puree, with low exposure to oxygen, preserving, for example, ascorbic acid content[45] [97].

[45] Storage and thermal processing of the juice affects concentration of nutrients during consumption [97].

In the SUNNIVA project, this spiral-filter press technology was combined with the microwave-based pasteurization technology of Enbiojet to produce tomato, carrot and apple juice. Refractance Window Drying (RWD), a novel thin-film drying method featured by short processing time, low energy cost, and good product quality was initially considered, but it was not further investigated in SUNNIVA [73].

This technology is commercialized under Vaculiq trademark. Modules are now sold in different sizes, with processing capacities from 1 to 3 ton/h. The same system can process different vegetables and fruits [98]. In the available information it is not clear if modifications are required. It was developed by the Hochschule Geisenheim University in Germany. The two latest publications are about strawberry puree [99]. It is now owned by GEA Mechanical Equipment GmbH [100].

Pasteurization

The juice or pastes it should be treated to inactivate microbial activity (sterilization) [95]. Any treatment should also maintain the paste consistency, especially for purees. Juice is typically treated thermally.

Post-extraction, there are LTL (low-temperature, long time) and HTST (high-temperature, short time) treatments [101]. An example of a HTST treatment is UHT, (90-110 °C), for about 30s [97]. Jayathunge et al. [94] also report 75 °C for 23 s. It should be analysed if LTL is technically feasible using low temperature waste heat and if the quality of the product is adequate.

An alternative is to use HPP at ambient temperature– at ~700 MPa, or HPP in combination with a thermal treatment [95], [102]. Jayathunge et al. [94] reviewed several treatments for processing tomato products such as microwave heating [103], ratio-frequency heating, ohmic heating, pulsed electric fields.

Hot filling (canning)

Tomato juice and sauces are filled into cans at high temperature (e.g. 104 °C for 20 min) [96].

2.6.4 Additional considerations for processing of tomatoes

Tomatoes are produced in 1-3 plantings (and harvesting periods) in the year ("batch" production). Processing technologies are usually semi-batch or continuous. Therefore, storage facilities for fresh tomatoes, possibly with refrigeration, would probably be required. If grown in greenhouses, with the possibility of controlling greenhouse (light and temperature) conditions, there could be a possibility of designing the greenhouse in such a way that it is possible to have a more "continuous" production of tomatoes by "staggering" plantings. This would reduce storage requirements (and costs).

In the case of liquid products, the product is usually be cooled to ~4 °C to minimize flavour loss during storage [96]. Therefore, refrigerating facilities are also needed.

Labour includes, among others, removing stems and transferring the tomatoes from washing, to shredding, to press.

2.6.5 Environmental impact of processing tomatoes

Regardless of the process, tomatoes should be washed for further processing. Stoessel et al [48] estimated about 400 kg of water per ton of fresh tomato.

Bosona and Gebrensenbet [46] performed a life cycle analysis of organic tomato production and supply in Sweden and concluded that the drying process increased the energy demand while it reduced climate change impact due to the reduction of product losses and increase of the product shelf life. It also reduces the weight and volume, reducing packing, storage and transportation costs [104]. This could improve the sustainability of locally produced organic tomato value chains, especially if integrated with renewable energy sources.

Production of tomato waste from processing

Processing of tomato usually produces waste. As reference, in Poland, 8.5 % of processed tomato is wasted (1-3 % seed, 2.8-3.5 % skin, and up to 2 % whole fruit) and in Turkey 10-18 % of the total processing raw material is wasted [3]. The spiral-filter technology to produce juice has a yield of ~88 % [97].

Alternative uses for tomatoes and waste

The press cake resulting from tomato juice and sauce consumption consists of skin and seeds [105]. Seeds account for 10 % of the fruit and 60 % of the total waste and are a source of protein (35 %) and fat (25 %). These may be used to produce tomato seed oil [106].

Lycopene may be extracted from this tomato waste, and may be used in the manufacture of functional foods and nutraceuticals [75]. Lycopene is associated with the water-insoluble fraction of skin, and thus, skin waste is rich in lycopene. Extraction of lycopene is traditionally done using solvents. It can also be done using supercritical CO_2 or ultrasound/microwave assisted extraction. It costs 2000€/kg, but in average, tomatoes contain only <1 mg of lycopene per 10 g of tomato[46]; requiring at least 10 ton of tomato to produce 1 kg of lycopene, considering 100 % yield[47] [3]. Tomato pomace can also be used to extract vitamin B_{12} [106].

Reinoso et al. [80] dried greenhouse vegetables with the intention of using them as fuel for direct combustion to generate CO_2 for greenhouse enrichment. To be used as biomass for combustion, tomatoes should have <25 % moisture.

2.7 Final comments and recommendations

From a global perspective, the main advantage of producing greenhouse tomatoes in Norway instead of southern Europe is the reduction of the overall water footprint. When using waste heat, there also a good potential of reducing the CO_2 footprint.

An advantage that has not been discussed of using waste heat to increase local production of tomatoes is that when the produce is grown close to their final markets they can be allowed to ripen on the vine, improving their flavour compared to imported produce which must ripen in transit [19].

As the greenhouse is designed for the coldest day of the year, the size of the greenhouse would be increased if we consider heat storage [64], [65], [107].

Two processing options are described: production of powder (e.g. for soups) and production of liquid products (e.g. juice). Both options require use of heat, either for drying or for sterilization. On-site processing of tomato would increase the requirements for space and labour. A more in-depth analysis, with actual information of the site location, (waste) energy availability and market potential is required to make a more specific recommendation.

Some aspects not covered in this report that can be topics for a future analysis are:

- Economic evaluation; calculation of investment and operational costs
  - Electricity consumption in greenhouses (lighting) varies seasonally
  - CO_2 enrichment, usually with liquid CO_2
  - Electricity consumption for processing could be relevant
- Steady-state improvements for greenhouse model
  - Inclusion of CO_2 enrichment
  - Inclusion of solar radiation and wind data for actual location
  - Detailed calculation of heat transfer coefficients [67]
  - Inclusion of evo-transpiration rate of the crop [108]

[46] Reported concentrations of lycopene in raw tomato range from 2.5 mg to 670 mg 100 g^{-1} [97]
[47] Experimental techniques, such as ultrasound/microwave assisted extraction may achieve 97.4 % yield[3].

- Dynamic greenhouse model
    - Heat storage analysis
    - Control of inside conditions (e.g. temperature, humidity [109])
        - Day-night and seasonal variations in temperature setpoint
        - Variations in ventilation rate
- Heat integration of (aluminium) plant, greenhouse and processing facilities. The potential challenge is the integration of continuous, batch and semi-batch processes, along with (aluminium) plant downtime.
    - Heating back-up boiler requirements
- Analysis of produced waste (disposal) and wastewater treatment
- Processing
    - Analysis of environmental footprint of processing.
    - Detailed evaluation of energy requirements for processing options
    - Detailed evaluation of available technologies
    - Economic evaluation of processing options
    - Availability of heat (possible use of heat pumps) for pasteurization of juices (or use of alternative technologies)
    - Evaluation of required additional area for on-site processing (processing, packing, storage, logistics).

3 Fish farming in recirculating aquaculture systems (RAS)

This section analyses the feasibility of using low-temperature waste heat from aluminium plants for the production of warm-water fishes in recirculating aquaculture systems. To date, there exist several applications of waste heat for onshore fish production. This does not necessarily correspond to recirculation aquaculture systems but may be also once-through aquaculture systems.

These cases are:

- Mo Industri Park[48]:
  Ranfjord Fiskeprodukter AS receives waste heat from the process industry at Mo Industri Park and utilizes it for smolt production.
- Eramet in Kvinesdal[49]:
  Waste heat from silicomanganese is used for the production of turbot by Stolt sea farm.
- Stolt sea farm in Iceland[50]:
  Sole production with water provided from a geothermal power plant. This industry park also includes other companies which take in electricity and warm water from the geothermal powerplant.

3.1 Recirculating aquaculture systems

The main aim of recirculating aquaculture systems is to reduce water consumption. A further benefit is a reduced feed consumption due to reduced losses and a better control over the water quality as the systems have a high degree of monitoring and control possibilities. The reduced water consumption also reduces the impact of the aquaculture on the surrounding water bodies.

3.1.1 General layout of recirculating aquaculture systems

The general layout of a RAS is shown in Figure 10. The effluent from the fish tanks is first treated in mechanical filters to remove the organic waste products, and subsequently biofilters to oxidize the free ammonia to nitrate. The biofilters utilize bacteria for this process.

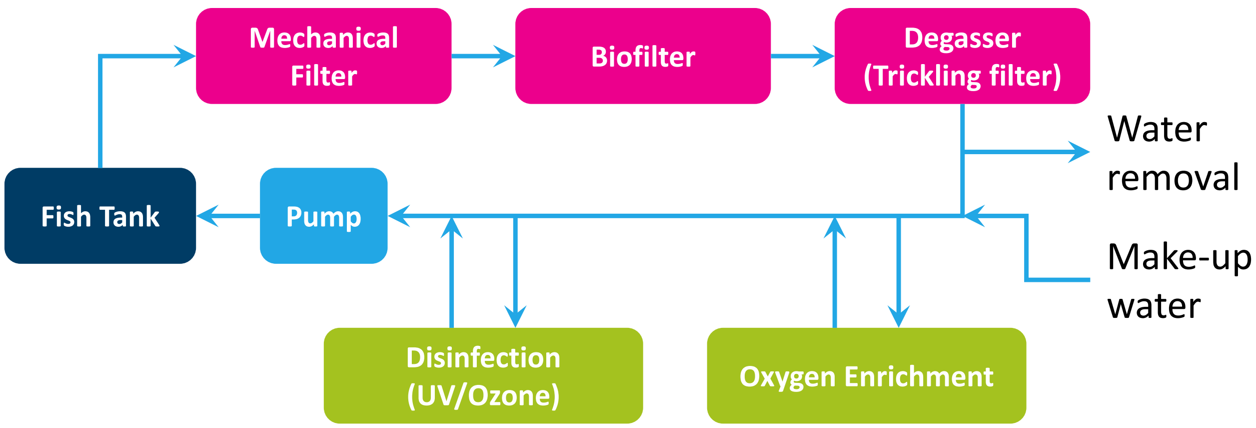

Figure 10: General layout of a recirculation system, adopted from [110].

The nitrate has to be removed from the system. This is general achieved using a purge stream for water removal. Consequently, fresh water, so-called make-up water, has to be added to maintain a common volume.

48 http://www.mip.no/mo-industripark/bedrifter-i-mo-industripark/#havbruk
49 http://eramet.no/var-virksomhet/kvinesdal/
50 https://www.resourcepark.is/companies/

To reduce the make-up flow, it is possible to utilize denitrifying bacteria like *Pseudomonas denitrificans* and a source of carbon like wood methanol. A degasser is then located downstream of the two filter units. Its function is to remove CO_2 from the water. Depending on the configuration, it is furthermore possible to use an oxygenation unit to increase the oxygen dissolved in water for a higher productivity and an ultraviolet light or ozone treatment to destroy unwanted bacteria in the water. The outline above is given for a single module. In general, an aquafarm consists of several modules for each of the life stages of the produced fish. One advantage is that only parts of the production is affected by diseases in the water, compared to a centralized approach for water treatment.

3.1.2 Ecological assessment of recirculating aquaculture systems

The ecological impact of RAS in comparison with open net pen, that is production in the sea in nets, or flow-through aquacultures received significant attention in the last decade. The investigated fishes included mostly trout, salmonids (cold water fishes), and tilapia (warm-water fish). Due to the different methodologies, it is not possible to directly compare these results and translate them for a Norwegian application. However, these studies give an indication of the potential environmental impact of fish production in RAS.

Ayer and Tyedmers [111] assessed four different culture systems for salmonid production. RAS is according to the study the environmentally worst alternative except for eutrophication. However, the study utilized coal power for RAS instead of hydro power and a different fish species, reducing the usefulness of the results as the power production was responsible for the largest share in all indicators. D'Orbcastel et al. [112] compared flow through and recirculating aquaculture farms for trout production utilizing the French power mix (high in nuclear power). The reduced feed conversion ratio for RAS resulted in a lower feed demand. As the feed has a major impact on all indicators, RAS performed superior to flow-through aquaculture with respect to the indicators. The results are more reliable compared as nuclear power was used for power generation in both cases. Production in Norway with 97 % renewable power will reduce the impact of increased power demand on environmental indicators further. Similarly, Samuel-Fetwi [113] utilized life cycle analysis for comparing different production systems for rainbow trout. Again, electricity consumption was responsible for the bad performance of RAS. However, a sensitivity analysis showed that utilizing wind power as power source improved the performance of RAS drastically. Due to a reduced feed consumption, it was eventually superior to the two alternatives. As a last study, Liu et al. [114] compared the production costs and the greenhouse gas intensity of salmon from open net pen and RAS. RAS is more expensive and has slightly increased CO_2 emissions. The study highlighted again the importance of the power source and the impact of the feed production on the global warming potential of aquaculture.

Based on above's life cycle analysis, it can be concluded that RAS results in reduced feed demand while the energy demand and the costs of production are increased. The power grid intensity is therefore crucial in assessing the ecological potential of RAS. RAS production in Norway with low emission hydro power and the potential of utilizing waste heat from industrial sites can therefore result in a lower environmental impact than production of the fishes in countries with either reduced available fresh water or less stringent environmental constraints.

3.1.3 Heating demand in recirculating aquaculture systems

None of the mentioned studies investigated specifically the heat demand in RAS. Instead, energy was considered as a cost factor, but it was not distinguished between the different energy vectors. There is however most likely no demand for heat as the studies investigated production of local fish. As the aim is to farm water fish in Norway, it is important to analyse in which process parts heat is required and/or lost.

Heat is required in RAS for heating the make-up water and compensating for energy losses from the tanks or the hall in which the RAS is located. The heat demand is therefore varying over the year, similar to the heat demand of a greenhouse. RAS produces a portion of the required heat through losses in the pumps and the motion of the fish. Furthermore, it is possible to utilize heat exchangers for recovery of the heat in the discharge streams. The total heat demand of an aquaculture farm requires therefore careful analysis of all parameters.

The following analysis will be conducted for the RAS aquafarm developed in the publication by Liu et al. [114] for a 3 300 t heat-on gutted salmon. Due to the limited available time, it is not possible to conduct similar analysis regarding other fishes within this work package. It shall only serve as example for the energy demand of a large-scale RAS fish farm. The fish farm consists of the full production from fry to grow-out. Table 3 shows the required modules, number of units (tanks) per module and the respective flowrates. The total power requirement of the farm is given by 2.458 MW, of which 2.079 MW corresponds to the power requirement of the pump. This power can be directly translated into heating of the water.

Table 3: Size of the different units and modules for the production of 3 300 t HOG salmon from the analysis of Liu et al.

	Modules [#]	Units/module [#]	Unit diameter [m^2]	Total flowrate [t/h]	Total make-up flowrate [t/h]
Fry	1	18	2	90	4.80
Smolt	2	4	9	1 362	11.40
Pre-grow-out	3	4	10	3 960	34.20
Grow-out	8	5	16	45 420	345.00
Final purging	1	2	16	2 280	66.00
Combined				53 112	461.40

Make-up water heating

Despite high circulation rates, large amounts of make-up water may be required for a large-scale farm. The following analysis for heat requirement is based on the publication of Liu et al. [114]. The heating demand for the make-up water is depending on both the required water temperature T_{oper} and the water temperature of the water-source T_{source}. Using these two values, it is possible to calculate the heating demand for the make-up water as

$$\dot{Q} = (T_{oper} - T_{source})c_p\dot{m}$$

Considering a water source temperature of $T_{source} = 5$ °C, the groundwater temperature of Norway, and an operation temperature of $T_{oper} = 15$ °C, the total heating demand for heating the make-up water would correspond to $\dot{Q} = 5.34$ MW, more than double than the heating provided by the pumps. Note, the higher the recirculation rate, the higher the ratio of heat provided by the make-up water pumps due to a reduced freshwater consumption.

The make-up water heating is depending on both the water source and the required operation temperature. Ground water has an almost constant temperature over the course of a year [115]. Norwegian ground water has a temperature between 3 and 6 °C, depending on the location. Norway satisfies however around 85 % of the water demand from surface waterbodies. The temperature of the surface water bodies fluctuates over the course of the year and can reach temperatures of 15 °C in the summer, but also close to the freezing point temperature in winter. Hence, the heating demand is increased in the winter and reduced in the summer if normal, tapped water is used as make-up water instead of groundwater. The required operation temperature is depending on the farmed fish. Salmon, as used in the example above, requires in general a low temperature compared to other aquaculture fishes [110]. Hence, we can observe a direct relationship between the required temperature of the produced fish (or alternatively the temperature difference ΔT) and heat.

Room heating

RAS can be either constructed as free-standing tanks or alternatively in large halls in which the tanks and the required additional equipment is located. The advantage of using a hall is the ability to control the exterior as well. Both approaches lead however to heat losses to the environment, similar to the greenhouse example in the previous section. The heat losses through the hall can be similarly qualified as:

$$\dot{Q} = UA\left(T^{in} - T^{amb}\right) + C_{p,air}\Phi_{air}\rho_{air}\left(T^{in} - T^{amb}\right) - \beta S$$

The total area *A* of the 3 300 t salmon aquafarm example can only be estimated due to different potential layouts of a RAS hall. Based on the number of units and the area of a circle, this corresponds to 9 953 m^2. Note, that this area only corresponds to the tank area. Depending on the packing, more space is required for the tanks (10 % for the densest packing, 27 % for square packing). Furthermore, the filters and pumps require additional space. The area exposed to nature furthermore includes the walls of the hall. The total area to the outside using a wall height of 6 m, square packing of the individual units and close connection of each module is then given by 18 062 m^2. Using the same numbers of the greenhouse example, this would correspond to a heating demand of 1.71 MW, 32 % of the heating demand of the make-up water. Utilizing an improved heat transfer coefficient of 2 W/m^{2}K, the value is reduced to 0.86 MW. It is furthermore possible that not the whole hall is heated to the required temperature level. For example, the temperature in the hall could be 10 °C while the temperature in the tanks is 15 °C. In this situation, losses may first occur from the tanks to the hall and then from the hall to the outside environment.

The solar irradiance and ventilation terms are slightly more complicated in the estimation of the heat loss from fish farms. It is for example possible to utilize heat recovery ventilation to reduce the heat loss through ventilation. The exact ventilation rate is hard to estimate without a properly sized plant. As a guiding figure, if we consider the same values as in the greenhouse example, we obtain a heat loss of 0.68 MW which can be obviously reduced through a lower ventilation rate and the utilization of heat recovery.

This simple analysis shows that it is important to consider the space occupied by the recirculating aquaculture system. If no hall is used, the heat transfer from the water tanks is more difficult to estimate. The main reason is the difficulty of estimating how the tanks are packed and what intermediate temperatures may be present.

3.2 Fish species for warm-water recirculating aquaculture systems

The chosen fish species are important both for the commercial viability of RAS production, the difficulty in rearing the fish in RAS, and the required energy demand as outlined in Section 3.1.2. Bregnballe [110] differentiates fishes with good biological performance and acceptable market conditions (simpler to develop a business case), fishes with lower market prices (good to rear, but difficult to obtain a profitable business case), and very challenging due to difficulties in growing or tough market conditions. In the following market analysis for the production of tilapia, pangasius, and barramundi are presented in combination with the required temperature ranges of the respective fish. The energy demand is based on the studies for the salmon farm.

3.2.1 Tilapia

Tilapia is one of the most produced fish in aquaculture. In 2016, Tilapia accounted for 8 % of the produced fish with a produced mass of 4 200 kt [116]. As comparison, salmon corresponded to 4 % and 2 248 kt (of which 1 233 kt where produced in Norway[51]). Tilapia is a white fish. The largest producer of Tilapia is China. The total tilapia import to Europe corresponded to 96 million € in 2017, falling from 118 million € in 2013 [117]. The significance of Tilapia as food is projected to grow in the upcoming years despite reduced consumption in Europe and the USA [118]. Although it is easy to grow in RAS, its low price requires both large

[51] Salg av slaktet mat - https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett/aar

scale production and a high degree of automatization for being economically competitive. Blue Ridge Aquaculture as example produces 2 kt tilapia each year in Virginia utilizing RAS as one of the few profitable producers in the USA [119].

The optimal temperature for tilapia is 28 °C [120] requiring the heating of the pond during the whole year, even if surface water is utilized. Utilizing ground water at 5 °C and assuming the same water demand as it is the case for salmon production outlined in Table 3, this would correspond to a total energy requirement of 98 GWh. The main driver for the energy demand is the heating of ground water to the required temperature of 28 °C. Hence, the monthly energy demand varies only slightly over the course of the year. If, on the other hand, surface water would be used, then the heating demand would be reduced over the summer months while potentially increased in the winter. Assuming an overall inlet water temperature of 15 °C, the overall energy demand is reduced to 51 GWh, highlighting the importance of the water source for calculating the energy demand of a RAS.

3.2.2 Pangasius

Similar to tilapia, pangasius is a low-priced fish with a large market volume. In 2016, 1 741 kt of pangasius were produced in aquacultures. The largest producer of pangasius is Vietnam, accounting for 70 % of the total production[52]. Ngoc et al. [121] compared the feasibility of RAS for pangasius farming in Vietnam. According to their study, RAS is more profitable than open pond farms with an economy of scale for larger systems. European imports of pangasius corresponded to 245 million € in 2017, a decline from 331 million € in 2013 [122]. The current market and price outlook for pangasius is due to an increased supply volume and a reduced demand in the important markets USA and China challenging.

Pangasius requires the same temperature as tilapia, that is 28 °C. Hence, the analysis above related to the energy consumption still holds.

3.2.3 Barramundi

Barramundi, also called Asian sea bass is a fish originating from Southeast Asia and Australia. The overall production volume of Barramundi is with 82 kt production in 2017 smaller than the one of pangasius and tilapia. However, barramundi is able to reach a premium price compared to the other two species. Hence, it can be economical to produce barramundi in RAS. Barramundi production in RAS has existed in Virginia for more than 20 years, showing the viability for both the production of barramundi in RAS and as a premium whitefish [123]. The market for barramundi is expected to grow in the next decade and may be "the next biggest premium whitefish" according to panellist at the Global Seafood Market Conference in 2017 [124].

Barramundi requires the same temperature as tilapia, that is 28 °C. Hence, the analysis above related to the energy consumption still holds. Contrary to both pangasius and tilapia, barramundi requires fish proteins and oil in its diet. This increases the pressure on forage fish.

3.3 Conclusion

All three investigated species require a water temperature of about 28 °C. The exact heat demand of producing the species in Norway using waste heat is not possible to estimate, as their production requires different steps and the grow-out of the species is different compared to the utilized example from salmon production. However, the analysis shows that the available heat allows the development of a large-scale fish farm with warmwater fish. The scale of the fish farm is similar to developed onshore fish farms.

[52] Data obtained from FishStatJ 4.00.1, a software developed by FAO with the database *FAO Global Fishery and Aquaculture Production Statistics.* Downloaded from http://www.fao.org/fishery/statistics/software/fishstatj/en

Each of the mentioned fish has a different market situation. While barramundi requires the development of a European market or export from Europe, both pangasius and tilapia are faced by the problem of a tough market situation and low prices for the fish.

The utilization of recirculating aquaculture systems has the advantage of reducing the environmental impact compared to traditional sea-pen and flow through aquaculture, if renewable electricity is utilized. Especially eutrophication is less problematic due to the high recirculation rate. Producing warmwater fish in Norway has furthermore the advantage of producing close to the European market and avoiding the risk of introducing an invasive species through escapes, as none of the species investigated can survive at normal Norwegian seawater temperatures.

4 Insects production

This section summarizes the findings about the potential of having facilities for rearing and processing of insects as users of waste heat from aluminium production plants. Human consumption of insects has been occurring for hundreds of years in certain parts of the world, and insects are a part of the regular diet even today for approximately 2.5 billion people in Africa, Asia and Latin America [125]. The number of people eating insects is set to increase, as population growth and increased global prosperity, among others, will put pressure on the prices for animal protein and the feed that livestock consumes.

Insects can serve to convert low-grade biowaste to high-grade protein that can be consumed by people and livestock. Organic waste that is used to feed insects emits less CO_2 than if it were to naturally decompose, and so it is environmentally beneficial to include insects in our food chains; both because it traps more greenhouse gases that would otherwise be emitted, but also because the protein is produced with much lower greenhouse gas emission than conventional livestock.

Some insects, such as the black soldier fly (*Hermetia illucens*) and the yellow mealworm (*Tenebrio molitor*), are more efficient in terms of growth per unit of feed at converting organic waste to high-grade protein compared to other species. These are prime candidates to investigate for commercial production, as they require less feed during rearing. The focus in this work has therefore been on these two insect species.

4.1 The rearing of the insects

Today, the most common way to collect edible insects is to find them in the wild [126]. Commercial ventures that produce and process insects for human and livestock consumption do exist, but the details of their methods for raising insects are not publicly available and are most likely trade secrets that each company holds. Some public documents give some details on how the insects can be produced, and these are summarized here.

Common for all the methods is how the heat is used. Based on research papers, it is clear that the growth rates of both the black soldier fly and the yellow mealworm are sensitive to the temperature and humidity in the growth sites. A significant amount of recovered heat will therefore be used to maintain these parameters close to the optimum of the species.

The overarching development of these two insects is fairly similar. Small worms hatch from eggs laid by an adult female insect, and these begin feeding on the available organic material. Following a period in the larval stage – which varies depending on the insect species – the insect enters the pupal stage, at which point it matures to an adult insect. When the yellow mealworm emerges from the pupa stage, it will be a beetle. This beetle will continue to feed and lay eggs. The black soldier fly on the other hand, will stop feeding when it reaches the pupal stage and will not continue to consume organic material as an adult fly.

Another difference between the yellow mealworm and the black soldier fly is the lifecycle of the two insects. There is a large difference in the total life expectancy of the two species, where the yellow mealworm lives for much longer than the black soldier fly. The total time from when the egg is laid to when the insect dies varies depending on the growth conditions, because this has a strong influence on the time it takes for the insect to reach the pupa stage in its life cycle. Nevertheless, it is possible to compare the lifecycle of these two insects by looking at the range of possible developmental times, and the times to maturity at optimal conditions.

The yellow mealworm is reported to have a total lifetime of 280 to 630 days [127]. The eggs take between 10 and 12 days to hatch, after which a larval stage of three to four months takes place. It has been reported that the larval stage can take up to 18 months, but this is presumably due to particularly poor growing conditions. After the larval stage, the pupal stage begins and this can last between seven and nine days at 25°C, or up to 20 days at lower temperatures. The adult stage follows the pupal stage, and the yellow meal worm can live for two to three months as an adult [127].

The uptake of heavy metals has been studied by van der Fels-Klerx et al. [137]. It is reported that the yellow mealworm larvae accumulated high levels of arsenic, intermediate levels of cadmium and low levels of lead when fed with food contaminated with these heavy metals. The arsenic was excreted slowly when the larvae were transferred to a noncontaminated diet. These contaminations had no effect on the growth rates of the larvae, and so they will be undetected unless the insects themselves are tested. Therefore, the feed for the larvae should be checked for contaminants, and the larvae themselves should routinely be checked for heavy metals.

The black soldier fly typically takes around four days to hatch [128], [129], but incidents where the hatch time reached 14 days have also been reported [130]. Under optimal conditions with regards to climate and quantity and quality of food, the black soldier fly larva will grow for 14-16 days [128], [129]. The black soldier fly only feeds during its larval stage, and it is vital that it is able to consume enough proteins and fats to successfully metamorphosize into a fly, find mates and lay eggs. Therefore, it is able to extend the length of the larval stage under less than ideal conditions. Following the larval stage, the black soldier fly enters its pupation stage, where it becomes immobile and stiff. This stage lasts two to three weeks, after which an adult fly exits the pupa shell. The adult then lives between one and two weeks [128], [129].

Heavy metal uptake of black soldier flies was also studied by van der Felx-Klerx et al. [137]. It was found that when black soldier flies were fed organic material contaminated with cadmium at the limit of EU regulations, then the concentration in the black soldier fly larvae would exceed the limit. Unlike the yellow mealworm, the black soldier fly cannot excrete the cadmium, and so it is particularly important that the black soldier flies are not fed with contaminated feed.

4.1.1 Condition of growing environment

Yellow mealworm

It has been reported that yellow mealworm larvae have been reared at 28 ± 2 °C, with a relative humidity of 60-70 % [131]. Another study states that the optimal temperature range for rearing yellow mealworms is between 25 and 27.5 °C, and that the total developmental time for these conditions is 80.0-83.7 days [132]. Another study reports the optimal temperature for mealworm growth to be at 31 °C, but the total development time is not reported here. Park et al. reported that when the temperature was 25 °C, then a decrease in humidity was found to not affect the adults, larvae or pupae [132]. For the relatively low temperature of 10 °C, it was reported that the mortality of young larvae increased when the relative humidity was low [133]. The reverse was true for older larvae. Low humidity was harmful to the eggs regardless of the temperature, as it caused the eggs to dry out.

In addition to setting the proper temperature and humidity, it is also important to find the correct larval density in the feeding sections. It has been reported that for a given system, increasing the larval density from 12 to 96 larvae per square meter reduced the biomass produced per gram of feed by approximately 22 % [134].

Black soldier fly

The larvae of the black soldier fly have an optimum temperature range of 24 to 30 °C [128] and the larvae are reported to have been raised at 25-30 °C [135]. The larvae need a shaded area where they can feed, and if they cannot locate this then they will bury themselves in the feed. Since the larvae have no chewing mouthparts, it is important that the feed is provided in small pieces. Furthermore, it is important that the water content of the feed is between 60 and 90 % [128]. It has been found that the optimal temperature and developmental time for larval development can vary depending on the feed stock used, and that the optimal temperature may reach as high as 35 °C [136].

Following the larval stage, the black soldier fly evolves to its prepupal stage. At this point it seeks a warm, shaded and dry area whereupon it begins the process of pupation. At this point it is best that the conditions are as constant as possible. There exists a temperature at which the pre-pupae cannot evolve into pupae, and Chia et al. found that this temperature was 40 °C [136].

The adult flies require a warm area (25-32 °C) that has an abundant amount of natural light. During this time the fly will search for a partner that it can copulate with. It has been observed that mating activity is elevated in the light of the morning. A humid environment has been found to increase the lifespan of the adult flies, and this in turn increases the chance of a successful reproduction [128]. Chia et al. found that the population growth rate was highest at 30 °C [136].

4.1.2 Processing

Yellow mealworm

Tran et al. mentions several drying techniques that have been used in studies [127]. These are drying at 50 °C for 3 days, at 100 °C for 200 minutes, boiling in water for 3 minutes followed up with oven drying at 60-100 °C and sun drying for 2 days. From this point, one can serve the worms whole or grind them to be used in some form of insect meal.

Black soldier fly

Kawasaki et al. report having dried black soldier fly prepupae and larvae at 60 °C for 48 hours before feeding it to poultry [135]. Another sterilization process that has been documented is to cook the prepupae in boiling water for one minute, before drying them on a table in the sunlight [128]. From here, the authors recommend further processing for the intended use; for long-term storage, the larvae can be frozen or further dried using different process.

4.2 The market for insect products

There exists a market for insects and products that are made from them and this subsection will summarize the findings on the market for products derived from insects.

4.2.1 Uses of insect products

Food

Insects can be included in the regular diet of people. As the global population continues to grow and climate change strains existing meat production facilities, substituting insects for traditional proteins may become necessary for people to have a nutritional diet. People in Asia and South America already have insects as part of their normal diet [125], [138], showing how eating insects is commonplace in these regions. In Europe, the USA and Canada, insects are typically seen as repulsive and entomophagy (human consumption of insects) is very rare. It is therefore important that either governments or potential commercial suppliers make a significant effort to advance the public acceptance of insects as a food source.

It appears that mealworms have entered the commercial food market in Europe in a small scale. A company called Little Hero is an example of a company that occupies this niche market[53]. Founded in 2019, they now offer snacks and pasta-substitutes that are based on mealworms and crickets through Lidl in the Netherlands [139]. There is also the company called Essento[54], which sells products based on mealworms and other insects through Coop shops and various restaurants in Switzerland. For North America, several suppliers of mealworms were found, but no examples could be found of restaurants or grocery stores adopting mealworm products.

[53] https://www.golittlehero.com/our-products

[54] https://essento.ch/en/

No examples of products made out of black soldier flies that were intended for human consumption could be found.

Livestock and fish feed

Another way to introduce insects into the food chain of people is to use insects as feed for livestock, poultry and fish. The primary role that the insect feed would play in these diets is as a substitute for other protein sources, which may be for example soy or fish meal. Given a certain area at which you can plant soy or raise livestock, it has been shown that the protein yield from black soldier flies is much higher than the alternatives, yielding for example over a 100 times more protein compared to soy [129]. Considering how insects are a much more efficient way of producing protein than conventional protein sources, this may present an opportunity for future livestock, poultry and fish feed. van Huis et al. specifically comment that the black soldier fly should be considered as animal feed because of their reduced environmental footprint as well as their favourable macronutrient composition [126].

In the case of the black soldier fly, using its larvae as feed has shown to have other advantages than just efficient production. Lee et al. showed that using the larvae of the black soldier fly as feed for poultry may enhance the immune system's defence against *Salmonella Gallinarum*, thereby increasing the survivability of the chickens [140]. The black soldier fly larvae also increased the body weight gain of the chickens. Cullere et al. studied including black soldier fly larvae meal in the diet of broiler quails and concluded that it was a promising insect protein source for quails [141]. They noted however that a potential drawback could be the fatty acid profile of the meat, and that further research should be conducted on how to improve the fatty acid profile of the black soldier fly. Kawasaki et al. studied using black soldier fly larvae as feed for broiler chickens and found that the egg weight and eggshell thickness increased in the group fed with black soldier fly pre-pupae [135]. Makkar et al. summarized the use of insects as animal feed, and they have found that poultry fed with black soldier fly larvae meal consumed less feed but gained similar weight, suggesting a higher feed conversion when some of the soy feed is substituted with black soldier fly larvae [142].

The black soldier fly has also been evaluated as a potential feed for fish. It has been shown that black soldier fly larvae meal can replace the soy meal content of fish feed for Atlantic salmon, both partially [143] and completely [144], [145]. It has been noted that when substituting fish meal with black soldier fly larvae meal, one has to be careful with feeding the fish with enough omega-3 fatty acids, which the black soldier fly larvae typically do not have. However, it has been shown that for the black soldier fly larvae, using a feed stock high in omega-3 fatty acids will also increase the concentration of these in the larvae meal. Thus, feeding fish offal to the black soldier fly larvae can be a measure to increase the omega-3 fatty acid content of the larvae to suitable levels [146].

Yellow mealworms have also been considered for animal feed, as Makkar et al. show [142]. For broilers, it was found that up to 25% of the base diet for the broilers could be replaced with dried mealworm without negative effects. Furthermore, dried and ground mealworms could replace the fish meal in the diets of laying hens, and this was found to also increase the productivity of the hens. Mealworms are also suitable for poultry diets, but mealworms contain low levels of calcium which may be an issue for poultry. This may be mitigated by feeding the mealworms with calcium-fortified diets.

Pet food

Mealworms have not only been evaluated as feed for livestock and fish, but also as pet food. The traditional market for commercially raised mealworms is food for exotic pets, such as reptiles and birds [142]. Several producers of black soldier fly larvae meal also advertise food for more conventional pets that includes larvae meals, but the market adoption of these is unclear. Regardless, in the future, the market for pet food based on insect meals may increase and replace more traditional pet food sources.

4.2.2 Existing producers

Several commercial actors have established themselves in the insect market. All the commercial actors that the author could find have focused on the black soldier fly. In Europe, companies such as Protix[55], Entocycle[56] and Innovafeed[57] have been formed that produce black soldier flies. Entocycle has recently opened a pilot facility in London, and it seems that their focus will be to target the animal feed market. Protix will compete in this market segment, but also advertises products for humans as well as pet food and fertilizers based on insect by-products. Innovafeed specifically targets the aquaculture and young mammal feed sectors.

In the US, we find Enterra[58] and Enviroflight[59]. Similar to the European counterparts, they target the poultry and aquaculture feed markets, but also offer products for conventional household pets and exotic animals. Like Protix, Enviroflight also offers fertilizers.

In China, there is a company called EVO Conversion Systems[60], that uses black soldier flies as a waste management measure. It is unclear to the authors whether the focus of this company is to produce black soldier fly products or to reduce landfill waste. Regardless of whether they currently offer commercial products based on black soldier flies, as a producer of black soldier flies they are able to either partner with a company that processes the flies into products, or develop this knowledge themselves to offer products similar to those listed earlier to the Chinese or Asian markets.

Similarly, we find companies like Ynsect[61] for mealworms. They raise mealworms which they process into feed for aquaculture and pets as well as a fertilizer product.

4.2.3 Market forecasts

Several market forecasts have been made on the insect market. The ones that have been found have not focussed on a specific insect species, but rather the insect feed market or the insect protein market as a whole. From these, it is difficult to discern how much of the expected growth will be in the markets for black soldier flies and mealworms, but it is reasonable to expect that the black soldier fly at least will perform well considering the popularity of the species in commercial ventures and research.

A market research report by Meticulous Research released in 2018 predicts that the edible insect market will increase at a compounded annual growth rate (CAGR) of 23.8% from 2018 to 2023, reaching a market value of 1.2 billion US dollars in 2023 [147]. They report that the largest market today for insect foods are in Asia, but that the North American market is expected to grow the fastest in the aforementioned period. The same institution released another market forecast in 2019, where they predict that from 2019 to 2030, the edible insect market will grow at a CAGR of 24.4% to reach a valuation of 7.96 billion [148]. Here too, they point out North America as the market that is expected to grow the fastest.

The market for insect feed has also garnered attention for market forecasters. A forecast released in 2017 predicted that the feed market would exceed $1 billion in 2022 [149], which would mean a CAGR of 102.5% from 2017, which is the year it was published. This growth primarily originates from expected increased consumption of traditional proteins such as fish and livestock, where these will be fed with insect products. Another forecast from 2019 into the insect feed market predicts that the insect feed market will grow at a CAGR of 23.0% to reach a market value of $178.3 million in 2023 [150]. In this analysis, Europe is pointed as the largest growing market, and the authors comment that the market for the mealworm in particular is growing at a high CAGR of 24.0%.

[55] https://protix.eu
[56] https://www.entocycle.com
[57] https://innovafeed.com
[58] http://enterrafeed.com
[59] https://www.enviroflight.net
[60] https://www.evoconsys.com/
[61] http://www.ynsect.com/en/

4.2.4 Regulations

The regulations regarding the intake of insects is very restrictive in Europe and North America. In Asia, where entomophagy is common, local laws are no issue for the production of insects for the consumption by humans or animals [151], [152]. This same positive attitude towards insect consumptions is absent in the West, and so regulatory bodies in these markets must be convinced that the production of insects can be done in a safe manner and that introducing insects to the food chain will not introduce new diseases or ailments.

In 2017 it was decided to allow for insect proteins to be used as fish feed in the EU [152]. The insects raised for this purpose must adhere to the conventional livestock regulations, meaning that they cannot be fed any waste products. This will reduce the environmental benefit of using insects as feed, which has been discussed earlier. In the US, the black soldier fly was recently approved by the US Food and Drug Administration (FDA) for use as feed in fish [153] and poultry diets [154]. The Washington Post notes that Enviroflight and Enterra in North America and Protix in Europe are working towards regulatory approval for using insect meal in the diets of other animals, such as swine and household pets [129].

The regulations regarding human consumption of insects are not clear but are presumed to be restrictive except for specific insect products. In the EU, insect products for human consumption are categorized as a "novel food," and these products had to be submitted to the European Food Safety Authority (EFSA) for approval by 2018. The outcome of this evaluation is unknown. Similarly, any insect product that wants to be launched in North America must be approved by the FDA, the Canadian Food Inspection Agency and Health Canada

4.3 Conclusion

In this chapter, information about the production of the black soldier fly and the yellow mealworm has been presented together with their market uses and their market opportunities and restrictions. This has been done for the purpose of evaluating the rearing of these insects as a potential high value uses of waste heat from the aluminium industry.

From a technical standpoint, the rearing of the insects requires stable conditions at a little over ambient temperatures and high humidity. The aluminium industry is able to deliver the required heat to uphold the humidity and temperatures, and due to the continuous nature of aluminium production, this heat will also be delivered in a stable fashion. No calculations have been made to estimate the heat demand of such a plant, but it is assumed that upholding the humidity will require the most heat.

The market of insect products seems very small today, but several commercial actors that target the fish and poultry market have been established recently. Research has shown that insect meals can substitute current use of soy and fish meal, but it is unclear to what degree the market has adapted insect meal as fish and poultry feed. These actors cannot currently sell their insect meals as feed for other animals, but they are working together with their respective regulatory bodies to expand the list of animals that can be fed with their insect meals. Market forecasts estimate that the use of insects as human food and animal feed will expand rapidly the next few years, suggesting that the forecasters expect regulatory approval for such insect products.

5 Overall conclusions

This report investigated three different cases for the utilization of waste heat. Greenhouse heating is potentially the most mature use of waste heat as the application was already proven, and markets are existing both in Norway and on a European level. Knowledge related greenhouse heating from external sources are existing as well. A problem with greenhouse production is the seasonal need for heat. Assuming available waste heat of in total 100 GWh evenly spread out over the year will result in utilization of only 42 % of the waste heat. In fact, this may be even worse as there is more waste heat available in the summer due to the higher outside temperature. A second advantage of greenhouse production is given by the possibility to utilize CO_2 from the aluminium production if it is captured. At the moment, this is not economical, but may be in the future. The required amount of CO_2 in a greenhouse is by far lower than the available CO_2 from the aluminium production but it may be still beneficial to utilize it on site instead of transporting it for storage. The benefits of producing in Norway are among others a reduced CO_2 intensity, reduction in water consumption in regions with limited water resources, and a reduction in dependence on foreign food production.

Due to the large variety in potential fish species, it is difficult to conduct a thorough analysis of the heat demand of aquaculture. Each fish species requires different stacking densities and rearing times. Fish production using waste heat is also a proven technology and utilized already for a long period. The utilization of recirculating aquaculture requires less waste heat than flow-through aquaculture. The amount is depending if it is possible to utilize surface or ground water as makeup water source. The heat demand is more or less constant in the different seasons if ground water is used. Otherwise, similar conclusions as it is the case for greenhouse heating can be drawn. An additional problem in estimating the heat demand is the plant layout. If the tanks are in the open, it is difficult to calculate an exact energy balance. Alternatively, if the fish tanks are in a hall, the total space requirement is uncertain and depending on the exact layout and placement of the different tanks. Due to the large amount of waste heat available, it is beneficial to produce warmwater fish. There exists already profitable warmwater fish production in RAS, but it may be necessary to develop a market in Europe or focus on the export for a profitable business case. Due to the higher cost of RAS, it is more beneficial to produce premium fishes like barramundi although the world-market is very small compared to the market of fishes like tilapia or pangasius.

Insect production as a last case is currently still in a developing stage. Large insect producers are located in Southeast Asia, and hence, do not require heating. Production of insect in Europe is on a very small scale and currently hindered by regulations related to use as food and feed. The current market is correspondingly small. Large scale insect rearing is not conducted within Europe. Hence, it is difficult to estimate the exact heat demand. At the current stage, large scale production of insects in Europe seems to be unprofitable due to the niche market. However, insects can potentially disrupt the feed production sector and acquiring knowledge related to large scale insect production from waste heat may become an economic advantage in the potential market.

All cases use waste heat for room/water heating and not directly for chemical reactions or physical changes. This results in a large uncertainty related to the total heat demand, as insulation of the space/tanks may reduce the heat demand drastically at the costs of increased investment costs. This may lead to a wide variety of actual heat demands. The estimates made in this deliverable can therefore serve as guidelines on how much waste heat can be utilized and how much products can be produced. However, these cannot be generalized and a careful analysis with specific data is required for a more accurate estimate of the actual energy demand. It is therefore also difficult to obtain correct heat balances and estimates for energy efficiency as all of the heating is discharged into the environment eventually. However, food production from waste heat can be seen as improved utilization of the waste heat compared to the current practice of releasing it to the air.

6 References

[1] Commission of the European Communities, "Thermal waste recovery at electric power plants in the European Economic Community," Paris, EUR 11660, 1988.

[2] FAO, "Food Supply - Crops Primary Equivalent," *FAOSTAT*, 2013. .

[3] Løvdal *et al.*, "Valorization of Tomato Surplus and Waste Fractions: A Case Study Using Norway, Belgium, Poland, and Turkey as Examples," *Foods*, vol. 8, no. 7, p. 229, Jun. 2019.

[4] OFG, "Totaloversikten 2018 - Opplysningskontoret for frukt og grønt," Langhus, Norway, 2019.

[5] NIBIO, "Tomat," *Totalkalkylen - statistikk*, 2019. .

[6] Landbruksdirektoratet, "Markedsrapport 2018. Vurdering av markedene for norske landbruksvarer.," 2019.

[7] SSB, "Increased vegetable production," *Agriculture, forestry, hunting and fishing*, 2017. .

[8] A. Sæbø, "Særheim," *NIBIO*, 2019. .

[9] J. Wølstad, "GH Rogaland," *Gartnerhallen*, 2019. .

[10] SSB, "Yield of various horticultural crops, by horticultural crop, contents and year," *Horticultural production*, 2018. .

[11] M. Ridder, "Annual volume of tomatoes imported into Norway from 2010 to 2018," *Statista*, 2019. .

[12] B. Åsbø, "Import tomater 2018," *GrøntProdusentenes Samarbeidsråd*, 2018. .

[13] FAO, "Tomato," *Crop Information*, 2019. .

[14] SIAP, "Tomate rojo," *Monografías de productos agroalimentarios mexicanos*, 2019. .

[15] M. J. Verheul, H. F. R. Maessen, and S. O. Grimstad, "Optimizing a year-round cultivation system of tomato under artificial light," *Acta Hortic.*, no. 956, pp. 389–394, Oct. 2012.

[16] SSB, "Use of biological control agents and chemical pesticides in greenhouses," *Agriculture, forestry, hunting and fishing*, 2016. .

[17] SSB, "Holdings with greenhouses and area of greenhouses, by size of greenhouse area per holding," *Census of greenhouses and nurseries*, 2006. .

[18] M. M. Peet and G. W. H. Welles, "Greenhouse tomato production," in *Tomatoes (Crop production science in horticulture)*, E. P. Heuvelink, Ed. Wageningen University, 2005.

[19] R. Andrews and J. M. Pearce, "Environmental and economic assessment of a greenhouse waste heat exchange," *J. Clean. Prod.*, vol. 19, no. 13, pp. 1446–1454, Sep. 2011.

[20] W. E. de León-Sifuentes, "Evaluación ambiental de la producción de tomate bajo condiciones protegidas en las Palmas de Gran Canaria, España, mediante la utilización de la metodología del análisis del ciclo de vida (ACV)," Universidad Autónoma de Barcelona, 2009.

[21] "Tomater med dårlig rykte," *Norges Matfat*. .

[22] MAPA, "Resumen de resultados España y Comunidades Autónomas 2018," *Encuesta sobre Superficies y Rendimientos Cultivos (ESYRCE)*, 2018. .

[23] NGF, "Norske tomater,- bedre enn sitt rykte ?," *Norsk Gartnerforbunds energiside*. .

[24] H. Karlsson, "Seasonal vegetables; an environmental assessment of seasonal food," Norwegian University of Life Sciences, 2012.

[25] F. Viviano, "This tiny country feeds the world," *National Geographic*, 2017. .

[26] D. Pérez Neira, M. Soler Montiel, M. Delgado Cabeza, and A. Reigada, "Energy use and carbon footprint of the tomato production in heated multi-tunnel greenhouses in Almeria within an exporting agri-food system context," *Sci. Total Environ.*, vol. 628–629, pp. 1627–1636, Jul. 2018.

[27] R. Ureña-Sánchez, Á. J. Callejón-Ferre, J. Pérez-Alonso, and Á. Carreño-Ortega, "Greenhouse tomato

production with electricity generation by roof-mounted flexible solar panels," *Sci. Agric.*, vol. 69, no. 4, pp. 233–239, 2012.

[28] J. K. Gruber, J. L. Guzman, F. Rodriguez, C. Bordons, and M. Berenguel, "Nonlinear model predictive control of greenhouse temperature using a Volterra model," in *2009 European Control Conference (ECC)*, 2009, pp. 1299–1304.

[29] A. Franco, D. L. Valera, and A. Peña, "Energy Efficiency in Greenhouse Evaporative Cooling Techniques: Cooling Boxes versus Cellulose Pads," *Energies*, vol. 7, no. 3, pp. 1–21, 2014.

[30] O. A. Bævre, L. Ø. Bø, R. Jelsa, E. Randeberg, and M. Verheul, "Energi til norsk veksthusnæring - bruk av naturgass som energibærer og CO_2-kilde," 119/06, 2006.

[31] Statistics Canada, "Greenhouse, sod and nursery industries, 2018," 2018. .

[32] Y. Li, W. Niu, M. Dyck, J. Wang, and X. Zou, "Yields and Nutritional of Greenhouse Tomato in Response to Different Soil Aeration Volume at two depths of Subsurface drip irrigation," *Sci. Rep.*, vol. 6, no. 1, Dec. 2016.

[33] FAO, "Crops Statistics," *FAOSTAT*, 2019. .

[34] Wageningen, "Growing tomatoes in a Chinese Solar Greenhouse, in the Netherlands and in China," *Wageningen University & Research News*, 2017. .

[35] SIAP, "Anuario Estadístico de la Producción Agrícola," *Servicio de Información Agroalimentaria y Pesquera*, 2019. .

[36] P. Ponce-Cruz, "Producción de tomates en invernadero en México," *Hortalizas*, 2013. .

[37] Hortoinfo, "Informe Tomate," 2017. .

[38] Government of Alberta, "Commercial greenhouse tomato production," *Greenhouses*, 2019. .

[39] NIBIO, "BioFresh," *Bioeconomic production of fresh greenhouse vegetables in Norway*, 2019. .

[40] D. I. Danielsen, "Norge har større avlinger av tomat og agurk enn Spania og Nederland," *forsking.no*, 2019. .

[41] M. Meland, F. M. Maas, and Å. Jørgensen, "Sweet cherry production in controlled environment," *Acta Hortic.*, no. 1235, pp. 353–358, Feb. 2019.

[42] Gartnerforbundet, "Myter om veksthusproduksjon i Norge," 2019. .

[43] F. T. Tewolde *et al.*, "Nighttime Supplemental LED Inter-lighting Improves Growth and Yield of Single-Truss Tomatoes by Enhancing Photosynthesis in Both Winter and Summer," *Front. Plant Sci.*, vol. 7, Apr. 2016.

[44] J. Hille, C. Solli, K. Refsgaard, K. Krokann, and H. Berglann, "Environmental and climate analysis for the Norwegian agriculture and food sector and assessment of actions," 2012–1, 2012.

[45] W. Y. Lam *et al.*, "Variability of Greenhouse Gas Footprints of Field Tomatoes Grown for Processing: Interyear and Intercountry Assessment," *Environ. Sci. Technol.*, vol. 52, no. 1, pp. 135–144, Jan. 2018.

[46] T. Bosona and G. Gebresenbet, "Life cycle analysis of organic tomato production and supply in Sweden," *J. Clean. Prod.*, vol. 196, pp. 635–643, Sep. 2018.

[47] M. C. Theurl, H. Haberl, K.-H. Erb, and T. Lindenthal, "Contrasted greenhouse gas emissions from local versus long-range tomato production," *Agron. Sustain. Dev.*, vol. 34, no. 3, pp. 593–602, Jul. 2014.

[48] F. Stoessel, R. Juraske, S. Pfister, and S. Hellweg, "Life Cycle Inventory and Carbon and Water FoodPrint of Fruits and Vegetables: Application to a Swiss Retailer," *Environ. Sci. Technol.*, vol. 46, no. 6, pp. 3253–3262, Mar. 2012.

[49] M. J. Verheul and S. M. Thorsen, "Klimagassregnskap for norske veksthusprodukter," 2010.

[50] A. D. González, B. Frostell, and A. Carlsson-Kanyama, "Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation," *Food*

Policy, vol. 36, no. 5, pp. 562–570, Oct. 2011.

[51] A. K. Chapagain and S. Orr, “An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes,” *J. Environ. Manage.*, vol. 90, no. 2, pp. 1219–1228, Feb. 2009.

[52] M. M. Mekonnen and A. Y. Hoekstra, “The green, blue and grey water footprint of crops and derived crop products,” *Hydrol. Earth Syst. Sci.*, vol. 15, no. 5, pp. 1577–1600, May 2011.

[53] A. Hoekstra and Mi. van Heek, “Tomato,” *Water footprint network*, 2017. .

[54] A. K. Chapagain and A. Y. Hoekstra, “Water Footprints of Nations,” Delft, 16, 2004.

[55] J. Pérez-Parra, M. D. Fernández, and J. C. López-Hernández, “Situación actual y tendencias de las estructuras de producción en la horticultura almeriense,” 2002.

[56] D. Chico, G. Salmoral, M. R. Llamas, A. Garrido, and M. M. Aldaya, “The water footprint and virtual water exports of Spanish tomatoes,” Santander, 2010.

[57] Junta de Andalucía, “Demarcación Hidrográfica de las Cuencas Mediterráneas Andaluzas - Revisión del tercer ciclo (2021-2027),” *Programa, calendario, estudio general sobre la demarcación y fórmulas de consulta.*, 2019. .

[58] A. Irabien and R. C. Darton, “Energy–water–food nexus in the Spanish greenhouse tomato production,” *Clean Technol. Environ. Policy*, vol. 18, no. 5, pp. 1307–1316, Jun. 2016.

[59] Aquae Fundación, “Plantas desaladoras en España,” 2019. .

[60] T. Jiménez, “España duplicará en 2020 la producción de agua desalada,” *El Economista*, 2019. .

[61] J. D. Gil, M. Munoz, L. Roca, F. Rodriguez, and M. Berenguel, “An IoT based Control System for a Solar Membrane Distillation Plant used for Greenhouse Irrigation*,” in *2019 Global IoT Summit (GIoTS)*, 2019, pp. 1–6.

[62] A. Pawlowski, J. A. Sanchez, J. L. Guzman, F. Rodriguez, M. Berenguel, and S. Dormido, “Event-based control for a greenhouse irrigation system,” in *2016 Second International Conference on Event-based Control, Communication, and Signal Processing (EBCCSP)*, 2016, pp. 1–8.

[63] Regjeringen, “Food security,” *Ministry of Agriculture and Food*, 2015. .

[64] I. Seginer, G. van Straten, and P. J. M. van Beveren, “Day-to-night heat storage in greenhouses: 1 Optimisation for periodic weather,” *Biosyst. Eng.*, vol. 161, pp. 174–187, Sep. 2017.

[65] A. Shukla, A. Sharma, and K. Kant, “Solar Greenhouse With Thermal Energy Storage: a Review,” *Curr. Sustain. Energy Reports*, vol. 3, no. 3–4, pp. 58–66, Dec. 2016.

[66] B. Marchi, S. Zanoni, and M. Pasetti, “Industrial Symbiosis for Greener Horticulture Practices: The CO_2 Enrichment from Energy Intensive Industrial Processes,” *Procedia CIRP*, vol. 69, pp. 562–567, 2018.

[67] Z. S. Chalabi, A. Biro, B. J. Bailey, D. P. Aikman, and K. E. Cockshull, “Optimal Control Strategies for Carbon Dioxide Enrichment in Greenhouse Tomato Crops Part 1: Using Pure Carbon Dioxide,” *Biosyst. Eng.*, vol. 81, no. 4, pp. 421–431, Apr. 2002.

[68] M. Gautam, B. Pandey, and M. Agrawal, “Carbon Footprint of Aluminum Production,” in *Environmental Carbon Footprints*, Elsevier, 2018, pp. 197–228.

[69] Aker Solutions, “Aker Solutions Signs Carbon Capture Contract With Twence in the Netherlands,” 2019. .

[70] MET Norway, “eKlima,” *Observations*. Norwegian Meteorological Institute, 2019.

[71] TechNavio, “Global Packaged Dehydrated Food Market 2018-2022,” *Research and Markets*, 2018. .

[72] FAO, “Crops and livestock products,” *FAOSTAT*, 2016. .

[73] D. Løvdal, Trond; Vågen, Ingunn Molund; Agati, Giovanni; Tuccio, Lorenza; Kaniszewski, Stanislaw; Gregorowska, Maria; Kosson, Ryszard; Bartoszek, Agnieszka; Erdogdu, Ferruh; Tutar, Mustafa; van

Droogenbroeck, Bart; Vos, Christine; Hanssen, Inge; Larbat, Roma, "SUNNIVA - Final report," ISSN 1890-579X, 2018.

[74] I. Colle, L. Lemmens, S. Van Buggenhout, A. Van Loey, and M. Hendrickx, "Effect of Thermal Processing on the Degradation, Isomerization, and Bioaccessibility of Lycopene in Tomato Pulp," *J. Food Sci.*, vol. 75, no. 9, pp. C753–C759, Nov. 2010.

[75] S. . St. George, S. Cenkowski, and W. E. Muir, "A review of drying technologies for the preservation of nutritional compounds in waxy skinned fruit," *Soc. Eng. Agric. food, bilogical Syst.*, 2004.

[76] C.-H. Chang, H.-Y. Lin, C.-Y. Chang, and Y.-C. Liu, "Comparisons on the antioxidant properties of fresh, freeze-dried and hot-air-dried tomatoes," *J. Food Eng.*, vol. 77, no. 3, pp. 478–485, Dec. 2006.

[77] J. Khazaei, G.-R. Chegini, and M. Bakhshiani, "A Novel Alternative Method for Modeling the Effects of Air Temperature and Slice Thickness on Quality and Drying Kinetics of Tomato Slices: Superposition Technique," *Dry. Technol.*, vol. 26, no. 6, pp. 759–775, May 2008.

[78] G. S. V. Raghavan, T. J. Rennie, P. S. Sunjka, V. Orsat, W. Phaphuangwittayakul, and P. Terdtoon, "Overview of new techniques for drying biological materials with emphasis on energy aspects," *Brazilian J. Chem. Eng.*, vol. 22, no. 2, pp. 195–201, Jun. 2005.

[79] İ. Doymaz, "Air-drying characteristics of tomatoes," *J. Food Eng.*, vol. 78, no. 4, pp. 1291–1297, Feb. 2007.

[80] J. V. Reinoso Moreno *et al.*, "Optimal processing of greenhouse crop residues to use as energy and CO_2 sources," *Ind. Crops Prod.*, vol. 137, pp. 662–671, Oct. 2019.

[81] A. S. Mujumdar, "Principles, classification and selection of dryers," in *Handbook of Industrial Drying*, 2007.

[82] J. C. Atuonwu, X. Jin, G. van Straten, H. C. van Deventer Antonius, and J. B. van Boxtel, "Reducing energy consumption in food drying: Opportunities in desiccant adsorption and other dehumidification strategies," *Procedia Food Sci.*, vol. 1, pp. 1799–1805, 2011.

[83] M. Das Purkayastha, A. Nath, B. C. Deka, and C. L. Mahanta, "Thin layer drying of tomato slices," *J. Food Sci. Technol.*, vol. 50, no. 4, pp. 642–653, Aug. 2013.

[84] R. Queiroz, A. L. Gabas, and V. R. N. Telis, "Drying Kinetics of Tomato by Using Electric Resistance and Heat Pump Dryers," *Dry. Technol.*, vol. 22, no. 7, pp. 1603–1620, Dec. 2004.

[85] İ. Doymaz, "Mathematical Modeling of Drying of Tomato Slices Using Infrared Radiation," *J. Food Process. Preserv.*, vol. 38, no. 1, pp. 389–396, Feb. 2014.

[86] P. J. Fellows, "Dehydration," in *Food Processing Technology*, Woodhead Publishing Series in Food Science, Technology and Nutrition, 2009, pp. 481–524.

[87] T. D. Durance and J. H. Wang, "Energy Consumption, Density, and Rehydration Rate of Vacuum Microwave- and Hot-Air Convection- Dehydrated Tomatoes," *J. Food Sci.*, vol. 67, no. 6, pp. 2212–2216, Aug. 2002.

[88] R. A. Chayjan, J. A. Parian, and M. Esna-Ashari, "Modeling of moisture diffusivity, activation energy and specific energy consumption of high moisture corn in a fixed and fluidized bed convective dryer," *Spanish J. Agric. Res.*, vol. 9, no. 1, pp. 28–40, 2011.

[89] M. Bantle and T. M. Eikevik, "A study of the energy efficiency of convective drying systems assisted by ultrasound in the production of clipfish," *J. Clean. Prod.*, vol. 65, pp. 217–223, Feb. 2014.

[90] M. Zhang, J. Tang, A. S. Mujumdar, and S. Wang, "Trends in microwave-related drying of fruits and vegetables," *Trends Food Sci. Technol.*, vol. 17, no. 10, pp. 524–534, Oct. 2006.

[91] R Vadivambal and DS Jayas, "Comparison of ultrasound- and microwave-assisted drying of agricultural products – a review," *Stewart Postharvest Rev.*, vol. 5, no. 5, pp. 1–6, 2009.

[92] A. Hosainpour, H. Darvishi, F. Nargesi, and A. Fadavi, "Ohmic pre-drying of tomato paste," *Food Sci.*

Technol. Int., vol. 20, no. 3, pp. 193–204, Apr. 2014.

[93] W. A. Baloch, S. Khan, and A. K. Baloch, "Influence of chemical additives on the stability of dried tomato powder," *Int. J. Food Sci. Technol.*, vol. 32, pp. 117–120, 1997.

[94] K. G. L. R. Jayathunge, A. C. Stratakos, G. Delgado-Pando, and A. Koidis, "Thermal and non-thermal processing technologies on intrinsic and extrinsic quality factors of tomato products: A review," *J. Food Process. Preserv.*, vol. 43, no. 3, p. e13901, Mar. 2019.

[95] B. Krebbers, A. M. Matser, S. W. Hoogerwerf, R. Moezelaar, M. M. M. Tomassen, and R. W. van den Berg, "Combined high-pressure and thermal treatments for processing of tomato puree: evaluation of microbial inactivation and quality parameters," *Innov. Food Sci. Emerg. Technol.*, vol. 4, pp. 377–385, 2003.

[96] C. L. Goodman, S. Fawcett, and S. A. Barringer, "Flavor, Viscosity, and Color Analyses of Hot and Cold Break Tomato Juices," *J. Food Sci.*, vol. 67, no. 1, pp. 404–408, Jan. 2002.

[97] L. Kips *et al.*, "A novel spiral-filter press for tomato processing: process impact on phenolic compounds, carotenoids and ascorbic acid content," *J. Food Eng.*, vol. 213, pp. 27–37, Nov. 2017.

[98] N. Siewert, "VACULIQ - The system for juice, smoothie and puree?," *Fruit Processing*, Hamminkeln, Germany, 2013.

[99] HS Geisenheim, "No Title," *Publikationen der Profesur für Analytik & Technologie Pflanzl.Lebensmittel-Schwerpunkt Getränke*, 2019. .

[100] GEA, "New products and innovations," 2019. .

[101] M. Anese, P. Falcone, V. Fogliano, M. C. Nicoli, and R. Massini, "Effect of Equivalent Thermal Treatments on the Color and the Antioxidant Activity of Tomato Purees," *J. Food Sci.*, vol. 67, no. 9, pp. 3442–3446, 2002.

[102] C. Morris, A. L. Brody, and L. Wicker, "Non-thermal food processing/preservation technologies: a review with packaging implications," *Packag. Technol. Sci.*, vol. 20, no. 4, pp. 275–286, Jul. 2007.

[103] A. C. Stratakos, G. Delgado-Pando, M. Linton, M. F. Patterson, and A. Koidis, "Industrial scale microwave processing of tomato juice using a novel continuous microwave system," *Food Chem.*, vol. 190, pp. 622–628, Jan. 2016.

[104] A. C. Okos, M. R., Narsimhan, G., Singh, R. K., & Witnauer, "Food dehydration," in *Handbook of food engineering*, New York: Marcel Dekker, 1992.

[105] A. Avelino, "Saccharification of tomato pomace for the production of biomass," *Bioresour. Technol.*, vol. 61, no. 2, pp. 159–162, Aug. 1997.

[106] A. Schieber, F. . Stintzing, and R. Carle, "By-products of plant food processing as a source of functional compounds — recent developments," *Trends Food Sci. Technol.*, vol. 12, no. 11, pp. 401–413, Nov. 2001.

[107] H. H. Öztürk, "Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating," *Energy Convers. Manag.*, vol. 46, no. 9–10, pp. 1523–1542, Jun. 2005.

[108] S. Gavrila and A. Gontean, "Greenhouse Energy Balance Modeling Review and Perspectives," *IFAC Proc. Vol.*, vol. 43, no. 24, pp. 162–166, 2010.

[109] K. Maslak and S. Nimmermark, "Thermal energy use for dehumidification of a tomato greenhouse by natural ventilation and a system with an air-to-air heat exchanger," *Agric. Food Sci.*, vol. 26, no. 1, p. 56, Apr. 2017.

[110] J. Bregnballe, "A Guide to Recirculation Aquaculture," 2015.

[111] N. W. Ayer and P. H. Tyedmers, "Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada," *J. Clean. Prod.*, vol. 17, no. 3, pp. 362–373, Feb. 2009.

[112] E. R. d'Orbcastel, J.-P. Blancheton, and J. Aubin, "Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment," *Aquac. Eng.*, vol. 40, no. 3, pp. 113–119, May 2009.

[113] B. Samuel-Fitwi, F. Nagel, S. Meyer, J. P. Schroeder, and C. Schulz, "Comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems," *Aquac. Eng.*, vol. 54, pp. 85–92, May 2013.

[114] Y. Liu, T. W. Rosten, K. Henriksen, E. S. Hognes, S. Summerfelt, and B. Vinci, "Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater," *Aquac. Eng.*, vol. 71, pp. 1–12, Mar. 2016.

[115] J. Stene, K. Midttömme, H. Skarphagen, and B. G. Borgnes, "Design and operation of ground-source heat pump systems for heating and cooling of non-residential buildings," in *9th International Energy Agency Heat Pump Conference*, 2008.

[116] FAO, "The State of World Fisheries and Aquaculture - Meeting the sustainable development goals," Rome, 2018.

[117] "Exporting tilapia to Europe | CBI - Centre for the Promotion of Imports from developing countries." [Online]. Available: https://www.cbi.eu/market-information/fish-seafood/tilapia/. [Accessed: 22-Oct-2019].

[118] "Lower tilapia sales to the United States of America expected for 2019 | GLOBEFISH | Food and Agriculture Organization of the United Nations." [Online]. Available: http://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/1189929/. [Accessed: 22-Oct-2019].

[119] "Largest indoor fishery - Blue Ridge Aquaculture, Inc." [Online]. Available: http://www.blueridgeaquaculture.com/aboutus.cfm. [Accessed: 22-Oct-2019].

[120] A.-F. M. El-Sayed and M. Kawanna, "Optimum water temperature boosts the growth performance of Nile tilapia (Oreochromis niloticus) fry reared in a recycling system," *Aquac. Res.*, vol. 39, no. 6, pp. 670–672, Apr. 2008.

[121] P. T. A. Ngoc, M. P. M. Meuwissen, L. Cong Tru, R. H. Bosma, J. Verreth, and A. O. Lansink, "Economic feasibility of recirculating aquaculture systems in pangasius farming," *Aquac. Econ. Manag.*, vol. 20, no. 2, pp. 185–200, Apr. 2016.

[122] "Exporting pangasius to Europe | CBI - Centre for the Promotion of Imports from developing countries." [Online]. Available: https://www.cbi.eu/market-information/fish-seafood/pangasius/europe/. [Accessed: 22-Oct-2019].

[123] "Sustainability - Great Falls Aquaculture." [Online]. Available: http://www.greatfallsaquaculture.com/sustainability.html. [Accessed: 22-Oct-2019].

[124] "Barramundi poised to become the world's next biggest premium whitefish." [Online]. Available: https://www.seafoodsource.com/news/supply-trade/barramundi-poised-to-become-the-world-s-next-biggest-premium-whitefish. [Accessed: 22-Oct-2019].

[125] F. C. C. F. Asia, "Comments of LAO PDR: Development of regional standard for Edible Crickets and their products," 2010.

[126] A. van Huis *et al.*, "Edible insects: future prospects for food and feed security," Food and Agriculture Organization of the United Nations, Rome, 2013.

[127] G. Tran, C. Gnaedinger, and C. Mélin, "Mealworm (Tenebrio molitor)," vol. 2019. Feedipedia, a programme by INRA, CIRAD, AFZ and FAO, 2019.

[128] B. Dortmans, S. Diener, B. Verstappen, and C. Zurbrügg, *Black Soldier Fly Biowaste Processing - A Step-by-Step Guide*. Dübendorf, Switzerland: Eawag – Swiss Federal Institute of Aquatic Science and Technology, Department of Sanitation, Water and Solid Waste for Development (Sandec), 2017.

[129] C. Ingraham, “Maggots: A taste of food’s future,” vol. 2019. The Washington Post, 2019.

[130] D. C. Sheppard, J. K. Tomberlin, J. A. Joyce, B. C. Kiser, and S. M. Sumner, “Rearing Methods for the Black Soldier Fly (Diptera: Stratiomyidae),” *J. Med. Entomol.*, vol. 39, no. 4, pp. 695–698, Nov. 2002.

[131] J. Ramos-Elorduy, E. A. González, A. R. Hernández, and J. M. Pino, “Use of Tenebrio molitor (Coleoptera: Tenebrionidae) to Recycle Organic Wastes and as Feed for Broiler Chickens,” *J. Econ. Entomol.*, vol. 95, no. 1, pp. 214–220, 2002.

[132] J. Bin Park *et al.*, “Developmental characteristics of Tenebrio molitor larvae (Coleoptera: Tenebrionidae) in different instars TT - Developmental characteristics of Tenebrio molitor larvae (Coleoptera: Tenebrionidae) in different instars,” *Int. J. Ind. Entomol.*, vol. 28, 2014.

[133] F. Punzo and J. A. Mutchmor, “Effects of temperature, relative humidity and period of exposure on the survival capacity of Tenebrio molitor (Coleoptera: Tenebrionidae),” *J. Kansas Entomol. Soc.*, vol. 53, no. 2, pp. 260–270, 1980.

[134] T. Grau, A. Vilcinskas, and G. Joop, “Sustainable farming of the mealworm Tenebrio molitor for the production of food and feed,” *Zeitschrift fur Naturforsch. C*, vol. 72, 2017.

[135] K. Kawasaki *et al.*, “Evaluation of Black Soldier Fly (Hermetia illucens) Larvae and Pre-Pupae Raised on Household Organic Waste, as Potential Ingredients for Poultry Feed,” *Animals*, vol. 9, p. 98, 2019.

[136] S. Y. Chia *et al.*, “Threshold temperatures and thermal requirements of black soldier fly Hermetia illucens: Implications for mass production,” *PLoS One*, vol. 13, no. 11, p. e0206097, 2018.

[137] H. J. van der Fels-Klerx, L. Camenzuli, M. K. van der Lee, and D. G. A. B. Oonincx, “Uptake of Cadmium, Lead and Arsenic by Tenebrio molitor and Hermetia illucens from Contaminated Substrates,” *PLoS One*, vol. 11, no. 11, p. e0166186, 2016.

[138] P. B. Durst, D. V Johnson, R. N. Leslie, and S. Kenichi, “Forest insects as food: humans bite back,” *Proc. a Work. Asia-Pacific Resour. their potential Dev.*, 2010.

[139] K. Durrell, “Bühler to expand bug portfolio with yellow mealworm plant,” vol. 2019. FoodIngredientsFirst, 2019.

[140] J. Lee, Y.-M. Kim, Y.-K. Park, Y.-C. Yang, B.-G. Jung, and B.-J. Lee, “Black soldier fly (Hermetia illucens) larvae enhances immune activities and increases survivability of broiler chicks against experimental infection of Salmonella Gallinarum,” *J. Vet. Med. Sci.*, vol. 80, no. 5, pp. 736–740, 2018.

[141] M. Cullere, G. Tasoniero, V. Giaccone, G. Acuti, A. Marangon, and A. Dalle Zotte, “Black soldier fly as dietary protein source for broiler quails: Meat proximate composition, fatty acid and amino acid profile, oxidative status and sensory traits,” *animal*, vol. 12, pp. 1–8, 2017.

[142] H. P. S. Makkar, G. Tran, V. Heuzé, and P. Ankers, “State-of-the-art on use of insects as animal feed,” *Anim. Feed Sci. Technol.*, vol. 197, pp. 1–33, 2014.

[143] I. Belghit *et al.*, “Potential of insect-based diets for Atlantic salmon (Salmo salar),” *Aquaculture*, vol. 491, pp. 72–81, 2018.

[144] I. Belghit *et al.*, “Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (Salmo salar),” *Aquaculture*, vol. 503, pp. 609–619, 2019.

[145] E. R. Lock, T. Arsiwalla, and R. Waagbø, “Insect larvae meal as an alternative source of nutrients in the diet of Atlantic salmon (Salmo salar) postsmolt,” *Aquac. Nutr.*, vol. 22, no. 6, pp. 1202–1213, Oct. 2016.

[146] S. St-Hilaire *et al.*, “Fish Offal Recycling by the Black Soldier Fly Produces a Foodstuff High in Omega-3 Fatty Acids,” *J. World Aquac. Soc.*, vol. 38, no. 2, pp. 309–313, Oct. 2007.

[147] V. Shrivastava, “Global Edible Insects Market Will Reach USD 1,181.6 Million by 2023: Exclusive Market Research Report,” vol. 2019. Meticulous Research, 2018.

[148] M. Research, “Edible Insects Market by Product Type (Whole Insect, Insect Powder, Insect Meal, Insect

Type (Crickets, Black Soldier Fly, Mealworms), Application (Animal Feed, Protein Bar and Shakes, Bakery, Confectionery, Beverages) - Global Forecast to 2030," vol. 2019. Meticulous Research, 2019.

[149] S. Smith, "Worldwide Insect Feed Market is expected to exceed $1 billion in 2022," vol. 2019. Reportbuyer.com, 2017.

[150] A. Sawant, "Insect Protein Market is Anticipated to Grow at a CAGR of 23.00% During Forecast Period 2019 to 2023," vol. 2019. Market Research Future, 2019.

[151] L. Wood, "$7.95 Billion Edible Insects Market - Global Forecast to 2030," vol. 2019. Research and Markets, 2019.

[152] D. Dobermann, J. A. Swift, and L. M. Field, "Opportunities and hurdles of edible insects for food and feed," *Nutr. Bull.*, vol. 42, no. 4, pp. 293–308, Oct. 2017.

[153] R. Fletcher, "Insect meal gains US fish feed approval," vol. 2019. The Fish Site, 2018.

[154] Enviroflight, "Black Soldier Fly Larvae Ingredients Receive FDA Recommendation for Poultry Diets," vol. 2019. 2018.

[155] SSB, "Fakta om Jordbruk," *Jordbruk*, 2019. .

[156] OFG, "Digital plattoform for statisktikk," *Opplysningskontoret for frukt og grønt - Grønnsaker*, 2019. .

[157] Statistics Canada, "Estimates of specialized greenhouse operations, greenhouse area, and months of operation," *Table 32-10-0019-01*, 2018. .

[158] M. J. Verheul, "Effects of plant density, leaf removal and light intensity on tomato quality and yield.," *Acta Hortic.*, no. 956, pp. 365–372, Oct. 2012.

[159] L. L. Nymoen and J. Hille, "Klimavennlig mat i sykehjem," Tingvoll, 1/2012, 2012.

[160] C. Veløy, "Spanske tomater mer klimavennlige enn norske," *NRK*, 2016. .

[161] E. J. Sullivan Graham *et al.*, "Energy for Water and Desalination," *Curr. Sustain. Energy Reports*, vol. 4, no. 3, pp. 109–116, Sep. 2017.

[162] M. Tabikh, "Downtime cost and Reduction analysis: Survey results," Mälardalen University, 2014.