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Estimating the Water and Carbon Footprints of Growing Avocados in the Munich Metropolitan Region Using Waste Heat as a Water-Energy-Food Nexus Potential

*Lukas Becker and Daphne Gondhalekar**

Department of Civil, Geo and Environmental Engineering, Urban Water Systems Engineering, Technical University of Munich, Munich, Germany

Avocados, which have been labeled a superfood and are very popular around the world, are often grown in areas with water scarcity and have long-distance transports to their end consumer. Water and carbon footprints could be reduced by using greenhouse farming, waste heat and rainwater. This study aims to determine whether avocados and other exotic fruits could be locally or regionally grown in greenhouse systems in Bavaria heated using waste heat and examines whether this approach decreases the resulting water and carbon footprints. To test these hypotheses, the waste heat potential is estimated by analyzing a database provided by the Bavarian Environment Agency. Data on water and carbon footprints are extracted from databases by The Water Footprint Network and FAOSTAT. As a local case study, a greenhouse system using waste heat of a nearby glass factory in Upper Franconia is considered. The results show a tremendous waste heat potential for Bavaria and Munich with reduced carbon, but similar water footprints compared to international avocado production. The required area for these avocado farms would only amount to 0.016% of Bavaria's or 0.02% of Munich's total area. With more uncomplicated handling and earlier fruit bearing, fruits like papaya, guava, or carambola seem to be better suited for greenhouse farming than avocados. Waste heat supported farming in controlled environments can require significantly less water through modern irrigation techniques and should be considered when designing new food security concepts for urban or rural areas.

Keywords: WEF Nexus, waste heat potential, tropical greenhouse, food security, water resource management, water and carbon footprint, urban farming

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La Zhuo, Northwest A&F University, China

***Correspondence:**
Daphne Gondhalekar
d.gondhalekar@tum.de

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INTRODUCTION

Since the introduction of SDGs, worldwide food security has not improved, although the total number of people affected by food insecurity was re-evaluated and claimed to be significantly lower than previously estimated. Over two billion people suffered from moderate or severe food insecurity in 2019 and every year there are around 60 million more people worldwide suffering from hunger (FAO, 2020a; United Nations, 2021).

In 2006 the World Health Organization estimated that over 40% of people around the world will be affected by water stress or water scarcity during the next 50 years (World Health Organization, 2006). By now, these numbers have nearly been reached, with over three billion people living in agricultural areas with high water shortages or scarcity (FAO, 2020b; United Nations, 2021). Although the global access to electricity improved from 83% in 2010 to 90% in 2019, this declared "SDG Seven" has still not been achieved yet. There may still be over 600 million people worldwide with no access to electricity by the year 2030. Additionally, the global renewable energy share increased only slightly and will have to be focused much stronger in order to achieve this goal by 2030 (United Nations, 2021).

The complex interlinkages between the fields water, energy and food security represent the core of the specific research field "Water-Energy-Food Nexus" and are a central part of this study. The concept of Water-Energy-Food (WEF) Nexus was introduced 2011 during the Bonn Nexus Conference in Germany. It showed first insights about the benefits of the WEF Nexus concept and how it could improve water, energy and food security through e.g., trade-off reduction, building of synergies and the improvement of governance (Hoff, 2011).

A good example for the implementation of the WEF Nexus in an agricultural context is the field of avocado production. While avocados provide many people with their healthy nutrients, growing these fruits can lead to water, land use and, often as a consequence, also social conflicts (Madslien, 2020; Sommaruga and Eldridge, 2020; Cho et al., 2021; Henkin, 2021; Denvir et al., 2022). What would happen if avocados were instead locally grown in countries normally importing them, e.g., in Germany? With 67% of people living in cities by the year 2050, it is utterly important to ensure the future food security for urban areas (Brockerhoff and Nations, 1998). Assuming a meat reduced diet, regionally produced organic food has the potential to feed large regions of Germany as a case study for Hamburg and the surrounding regions showed (Joseph et al., 2019). A study conducted in Munich came to similar results regarding the potential of enhancing food security by urban farming (Gondhalekar and Ramsauer, 2017). During the last 2 years, the Covid-19 pandemic showed the fragility of international supply chains and can be seen as another reason why local food security should be enhanced. This project aimed to evaluate whether it is possible to improve urban food security in Bavaria and Munich by locally producing avocados in heated greenhouses. The temperature in these greenhouse systems is kept stable using waste heat. This study estimated the theoretical waste heat potential and avocado yield for Bavaria and Munich as well as the differences in carbon and water footprints between a potential Bavarian avocado production and the standard global avocado supply.

As a local case study an innovative greenhouse project from Upper Franconia in the north of Bavaria was used, as global examples data from Mexico, Chile and Peru were considered. The first section examines the used materials and methods of this work, while the second section looks at the specific results that were found. These results are then discussed, and conclusions are drawn in the last two sections of this paper.

Research Gap and Hypotheses

There is no sufficient research data available on greenhouse farming with avocados in Central Europe or the use of waste heat to ensure stable temperatures in greenhouses systems. The combination of these two issues brought up the idea for this project and the following hypotheses were made:

- It is possible to produce tropical or subtropical fruits, especially avocados, in Bavaria and the Munich Metropolitan Region with the use of waste heat.
- There is a significant potential to reduce ecological impacts (water and carbon footprint) considering the WEF Nexus.

MATERIALS AND METHODS

Waste Heat Farming Case Study

General

This study uses an existing Bavarian initiative as case study for successful greenhouse farming of tropical and exotic fruit products in Central Europe. The project is called "Tropenhaus Kleineden" (Eng.: "Palm House Little Eden") and can be found in the village Kleintettau, which is in the very north of Bavaria near the border between Bavaria and Thuringia. The region around Kleintettau, located in the district of Upper Franconia, is known for its colder climate compared to the rest of Bavaria (Lueers and Foken, 2004). On a total area of around 3,500 m^2 two greenhouses, one for visitors and one for research and production, were built between 2011 and late 2013. Besides tropical and subtropical fruits and vegetables another useful co-product of the greenhouse system is created by breeding fish in indoor tanks. For this, the tropical fish species of Tilapia is used. A relatively robust and frugal species, which is why it is often seen as the future of sustainable tank aquaculture (Yue et al., 2016). One of Tilapia's few downsides is its weakness against low temperatures. Ensuring stable temperatures suited for tropical fish and fruits is one of the main challenges for a greenhouse located in Central Europe.

Irrigation

Irrigating the plants in "Kleineden" is executed in a circular matter and only with the use of rainwater. Two tanks outside the greenhouse store the accumulating rainwater, before it gets pumped into the fish tanks inside the greenhouse system. This happens with the intention to build a circular system, where the fish are naturally adding fertilizer to the water with their feces. This fertilized water is then used to irrigate the plants. The remaining water in the fish tanks is circulated through a biological filter system of water plants and a small trickle bed reactor. Remains of harvested plants can later be used as fish food again, which closes the circle in this irrigation and fertilization system.

Heating

The challenge to sustainably heat the greenhouse, especially during winter, is overcome by using the industrial waste heat of a glass manufacturing company called "Heinz-Glas GmbH," which had the idea to further use its excess process heat in a productive matter (Heinz Glas GmbH, 2021). A small part of its unused heat

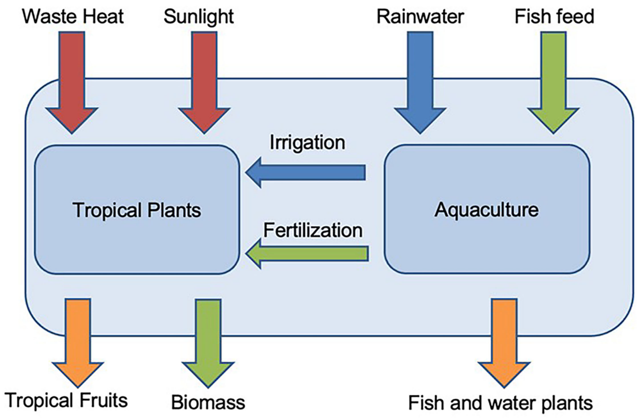

FIGURE 1 | Process streams greenhouse system "Kleineden" (adapted from Schmitt, 2013).

is transferred through a 550 m pipe connection to the greenhouse system, where it supplies the rooms, the greenhouses, and the fish tanks with warm temperatures. The power and heating supply in the glass manufacturing company, which creates the excess heat, is generated completely by renewable energies (Heinz Glas GmbH, 2021).

Figure 1 shows a simplified scheme of the different process streams going in and out of the greenhouse system. Additional technical characteristics of avocado farming are covered in the next chapter.

Further Technical Considerations for Avocado Farming

Irrigation in Avocado Orchards

Traditional avocado orchards have a high water demand for irrigation. The annual water use for Hass avocados ranges from 6,680 $m^3 * hectare^{-1} * year^{-1}$ in Israel to 7,875 $m^3 * hectare^{-1} * year^{-1}$ in California and 8,900 $m^3 * hectare^{-1} * year^{-1}$ in South Africa (Kalmar and Lahav, 1977; Gustafson et al., 1979; Hoffman and Du Plessis, 1999). Since greenhouses are controlled systems, and technology is easier to implement than on wide avocado orchards, it could be possible to use much less water than the traditional avocado agriculture. Promising results were found testing drip irrigation and micro sprinkler technique and the combination of both on several test avocado trees. The combination of both techniques resulted in the highest avocado yield compared to using only one of the respective irrigation methods (Darwish and Elmetwalli, 2019). During avocado irrigation, constant water stress through decreased irrigation volume is better adapted by the plants than short water stress during the growth period in summer. It is assumed that the plants adapt to constant water stress by reducing their vegetative part and lowering their evapotranspiration (Silber et al., 2019).

Precipitation in Bavaria

Since the case study's greenhouse is using only rainwater for irrigation the annual precipitation in Bavaria plays a key role in the possible implementation of rainwater as only irrigation source of greenhouse systems. The average annual precipitation for Bavaria amounts to 941 mm, which almost equals the value of 944 mm for the city of Munich (Munich Statistical Office, 2020a; Bavarian State Office for the Environment, 2021a).

Lighting

Due to other lighting conditions in Bavaria than in South America, avocado plants tend to struggle during the short winter days in Bavaria (R. Schmitt, personal communication, 18.06.2021). A solution to this problem could be found in artificial lighting, which is already standard in many innovative greenhouse systems like e.g., vertical farming systems (Orsini et al., 2020). A modern lighting structure with LEDs instead of high-pressure sodium (HPS) lamps can save 40% of the greenhouse's lighting demand. This LED lighting doesn't produce as much heat for the greenhouse system as the HPS lamps (Katzin et al., 2021). Regarding the vast waste heat availability for the case study's greenhouse, this fact has no big impact.

Pollination

Most relevant studies regarding the topic of pollination finds that insect pollinators have a great impact on pollination, fruit set and yield. The most important pollinating insects are managed honeybees. Wild pollinators are found on most avocado orchards around the world. Changes in land use or land management can negatively affect wild pollinators and therefore the successful avocado production (Dymond et al., 2021). Regarding the case study greenhouse system, it occurred to be difficult pollinating the avocado plants. The responsible general manager assumed it is connected to the different blooming times of male and female avocado plants and possibly less wild pollinators available in the greenhouse system than in a standard outdoor avocado orchard (R. Schmitt, personal communication, 18.06.2021).

Yield

The average yield of avocado orchards differs around the world. For this work, the FAOSTAT yield database of Mexico, Chile, and Peru from the year 2019 was compared and the maximum yield value considered as theoretical yield for the case study's greenhouse system. The chosen yield was the Peruvian yield with a yield value of 12,524.9 kg per hectare (FAO, 2021).

Waste Heat Potential and Avocado Consume

Data on waste heat potential in Bavaria was extracted from the web service "Energie-Atlas Bayern." This web service is provided by the Bavarian State Government. It has several tools regarding the evaluation of potential waste heat, such as a map or the possibility to download the specifically generated data matching chosen criteria. The number of avocados consumed in Bavaria were assumed using an avocado import database provided by the Federal Statistical Office of Germany (Federal Statistical Office of Germany, 2021).

Water and Carbon Footprint

Relevant data on the blue and gray water footprint of avocados was extracted from "The Water Footprint Assessment Tool" webpage, provided by the "Water Footprint Network" (Water Footprint Assessment Tool, 2021a,b). To predict the avocados' Carbon Footprint research is done on the emissions of supply chain logistics in this field of agriculture. Looking at the globally exporting avocado industry a product carbon footprint suggestion by Reinhardt et al. (2020) was considered. These tested global values do not consider the precise carbon footprint of avocado farming, but rather try to approximate the footprint using ratios of fruits with relatively similar ways of transportation and cultivation. The carbon footprint of the potentially local avocado industry in Bavaria will take occurring transport emissions and the footprint of materials needed to build a greenhouse into consideration. The assumed values of global and local avocado industries are tested and then compared to see what amount of carbon emissions could be avoided by producing avocados in Germany.

Calculation Steps

Step 1: Estimate Theoretical Waste Heat Potential for Bavaria

To calculate the theoretical waste heat potential for Bavaria and Munich a dataset from the Bavarian Ministry for Environment is used and filtered by specific parameters. The minimal necessary heating time is estimated with 6,500 h per year. This covers heating of the greenhouse for fall, winter, and spring. Because the case study greenhouse system used only about 4% of its annual waste heat consumption from June to August, the summertime will not be included into estimating the minimal annual heating time. The data of waste heat consumption only refers to the year 2013, since then the summers have been increasingly hotter and this trend is likely to continue, which is why the summer months are neglected. The sum of all applicable sites is formed and used as foundation for the calculations to follow. It is assumed that the sources producing waste heat are completely powered by renewable energy.

Step 2: Calculate Number of "Kleineden" Greenhouse Systems Heated by Theoretical Waste Heat Potential

The theoretical waste heat totals for Bavaria and Munich are then used to calculate how many "Kleineden" greenhouse systems could possibly be heated by this amount of waste heat. For this, the totals are divided by the area needed for one greenhouse system.

$$\begin{aligned} &Number\ of\ \text{“}Kleineden''\ greenhouses \\ &\quad = Total\ waste\ heat\ potential/1.2\ GWh \end{aligned} \tag{1}$$

Step 3: Calculate the Total Yield for Bavaria and Munich

Calculating the theoretical avocado yield is done by assuming a certain yield per area, which is done by using the agricultural value of kg per hectare. In this work, the yield in kg per hectare is estimated by considering the highest yield of the compared global avocado exporting countries Chile, Mexico and Peru while neglecting the yield variation between on-crop and off-crop seasons. Yield data is extracted from the FAOSTAT database supplied by the UN Food and Agricultural Organization (FAO). The results from the first calculation (1) are then used to calculate the total theoretical avocado yield.

Step 4: Calculate Water Footprints

The water footprints were calculated by multiplying the blue and gray water footprints of several avocado producing countries with the total theoretical avocado yield for Bavaria and Munich. These water demands were then compared to the also calculated water demand of the local greenhouse case study.

Step 5: Calculate Carbon Footprints of Global Avocado Industry and Two Local Scenarios

Calculating the carbon footprint was done with the help of numbers provided by the study of Reinhardt et al. (2020). With these, there could be assumed three different global scenario product carbon footprints as well as two scenarios for the product carbon footprint of the local greenhouse case study. One scenario applies the same ratio of carbon footprints between apple from New Zealand and regional and seasonal apple from Germany onto avocados from Peru and theoretically regional avocados from Bavaria. The other scenario uses the carbon footprint of tomatoes grown in heated greenhouses. The amount of heating accounting to this carbon footprint is then subtracted since the case study's waste heat is completely produced by renewable energy.

RESULTS

Theoretical Waste Heat Potential in Bavaria and Munich

With data provided by the Bavarian State Government this work comes to the following results:

- Total theoretical waste heat potential for Bavaria amounts to 5,973 GWh
- Total theoretical waste heat potential for Munich amounts to 33 GWh

Table 1 shows the sites with suitable waste heat potential in the city of Munich. All the potential sites have a maximum annual

TABLE 1 | Waste heat sites Munich (Source: Bavarian State Office for the Environment, 2021b).

Name	Amount of waste heat (GWh)	Temperature range (°C)	Operating time (h/a)
BMW Plant 01.50 (FIZ)	1.2	120	7,700
Paulaner Brauerei Gruppe GmbH & Co. KGaA Site Langwied	2	100–140	1,050–7,100
Renolit SE Branch Office Munich	6.5	80–262	2,000–8,760
RF360 Europe GmbH	3.7	85	8,700
Wastewater Treatment Plant Munich I Gut Großlappen	19.2	335–466	50–7,750

TABLE 2 | Number of possible greenhouse systems.

	Theoretical waste heat potential (GWh)	Number of sites	Potential number of greenhouse systems
Bavaria	5,973	680	4,978
Munich	33	5	27

operating time over 6,500 h and a temperature high enough to heat up a greenhouse system. The smallest waste heat potential occurs at a BMW plant with 1.2 GWh, the highest potential can be found at the WWTP Gut Grosslappen with 19.2 GWh. Four out of the five waste heat sites are industrial companies while one is a municipal facility.

The annual heat demand of the greenhouse case study "Kleineden" accounts for 1.2 GWh. Based on this waste heat demand the possible number of heated greenhouse systems similar to the chosen case study "Kleineden" was estimated and can be seen in **Table 2**. For Bavaria, the 680 waste heat sites could provide heat for 4978 "Kleineden" greenhouse systems. Munich could provide enough waste heat to supply 27 case study greenhouses with a total number of five sites producing waste heat.

Required Area

With a useable area of 2,300 m^2 per case study greenhouse system the total needed area for the calculated number of possible greenhouses can be estimated. The following areas (in hectare) are needed:

- In Bavaria a total useable area of 1,144.8 ha would be needed
- In Munich a total useable area of 6.2 ha would be needed

Bavaria has a total area of 70,542 km^2, the city of Munich a total area of 310.71 km^2 (City of Munich, 2021; Statista, 2021). The previously calculated required areas amount to the following percentages of the total areas of Bavaria and the city of Munich:

- Required Bavarian area as percentage of the total Bavarian area: 0.016%
- Required Munich area as percentage of the total Munich area: 0.02%

Avocado Yield

Looking at the theoretical avocado yield per hectare, the Mexican, Chilean, and Peruvian yields were compared, and the maximum yield chosen as final parameter. The maximum current yield per hectare was the Peruvian avocado yield in 2019, with an amount of 12,524.8 kg per hectare (FAOSTAT Visualizations, 2021). Using these numbers, the total theoretical avocado yield for Bavaria and Munich could be estimated as the following:

- Bavaria could produce a theoretical avocado yield of 14,339 t
- Munich could produce a theoretical avocado yield of 78 t

Putting these yield numbers into perspective, the import data for avocados into Bavaria were inspected. To estimate the possible avocado import, respectively, consumption for the city of Munich, the population of Munich and of the state of Bavaria were put into a ratio. As of September 2020, the population of Bavaria accounts to 13.14 million people and the population of Munich to 1.56 million people (Bavarian State Office for Statistics, 2020; Munich Statistical Office, 2020b). This results in a rounded percentage of Munich to Bavarian population of 11.86%.

Neglecting different age groups and an eventual higher avocado popularity and therefore consumption in urban areas, the avocado import numbers for the city of Munich for 2019 can be estimated with 1,665 t. With these results it can be seen which percentage of avocado imports to Bavaria and Munich could be reached by the yield of local avocado greenhouse systems.

The following results were found:

- Bavarian avocado imports could be fulfilled to 102% by Bavarian avocados
- Munich avocado imports could be fulfilled to 4.7% by Munich avocados

TABLE 3 | Water footprint comparison (Source: The Water Footprint Network, 2021).

Country	Green-blue water footprint (m^3/t)	Gray water footprint (m^3/t)	Total water footprint (m^3/t)
Chile	1,600	200	1,800
Mexico	1,000	99	1,099
Peru	970	81	1,051
Case Study "Kleineden"	1,900	0	1,900

Water Fooprints

The different water footprints of the chosen producer countries and the local case study can be seen in **Table 3**.

Chile has by far the most severe impact considering its green-blue water footprint of 1,600 m^3 per ton and its gray water footprint of over 200 m^3 per ton. The Chilean gray water footprint covers the combined footprints of Mexico and Peru. Looking at the local case study, the "Kleineden" greenhouse project only uses organic fertilizers and no pesticides. Hence, there is no impact by a gray water footprint. Of the global avocado exporting countries Chile by far has the highest total water footprint with 1,800 m^3 per ton. The second highest total water footprint is produced in Mexico with 1,099 m^3 per ton, followed by the total water footprint of the Peruvian avocado production with 1,051 m^3 per ton. The local case study greenhouse system would create a total water footprint of 1,900 m^3 per ton, surpassing even the highest footprint of the global total water footprint examples.

Putting the mentioned water footprints into a more comprehensive perspective the following section shows the comparison between the water footprint of the local case study and the global avocado production examples:

- Local total water footprint compared to Chilean water footprint: 106%
- Local total water footprint compared to Mexican water footprint: 173%

- Local total water footprint compared to Peruvian water footprint: 181%

Carbon Footprints

The assumptions of avocado carbon footprints for global avocado production were extracted from the current work of Reinhardt et al. (2020). They calculated carbon footprints for Peruvian avocados (organic and conventional production have the same footprint) as well as for a global average avocado. With these two different carbon footprint assumptions the following results of total carbon footprints with the respective theoretical avocado yield were achieved:

- Bavaria: Peruvian avocados would create a footprint of 11,471 t CO_2 equ., the global average avocados one of 8,603 t CO_2 equ.
- Munich: Peruvian avocados would create a footprint of 63 t CO_2 equ., the global average avocados one of 47 t CO_2 equ.

Regarding the carbon footprint of a potentially local greenhouse system, there were created two separate scenarios, which were then applied on the calculated findings. The following section explains the different scenario setups and shows the application results of both scenarios.

Scenario 1: Footprint ratio between apples imported from New Zealand and regional as well as seasonal apples from Germany

Reinhardt et al. (2020) estimated the product carbon footprints of apples imported from New Zealand with 0.8 kg CO_2 equ. per kg apples and the carbon footprint of regional and seasonal apples with 0.3 kg CO_2 equ. per kg apples. Using the same ratio as for these two footprints and including the comparison to Peruvian avocados, the footprint of a theoretical avocado production in Bavarian greenhouses would amount to 0.3 kg CO_2 equ. per kg avocados. Comparing local and global production with the carbon footprint for local production of this scenario came to the following results:

Local carbon footprint compared to Peruvian footprint: 38%
Local carbon footprint compared to global average footprint: 50%

Scenario 2: Modified footprint of tomatoes grown in heated greenhouses in Germany

The second scenario estimated the local avocado carbon footprint with the help of two studies. Reinhardt et al. (2020) calculated the product carbon footprint for tomatoes grown in heated greenhouses in Germany with 2.9 kg CO_2 equ. per kg tomatoes. Since the case study greenhouse is heated by waste heat that is produced using only renewable energies, the impact of heating was completely neglected. Rendon Velasquez and Franco Pereira (2020) assumed that heating makes up for 84.27% of the carbon footprint for a greenhouse building, if it was heated by a 100% renewable energy source (Rendon Velasquez and Franco Pereira, 2020). Combining the mentioned findings of both studies results in an estimated carbon footprint of 0.456 kg CO_2 equ. per kg avocados grown in a greenhouse heated by renewable energy fueled waste heat.

With this parameter the comparison between local and global carbon footprints came to the following results:

Local carbon footprint compared to Peruvian footprint: 57%
Local carbon footprint compared to global average footprint: 76%

Outcome of Hypotheses

This section shows the overall results and outcomes of the hypotheses previously mentioned in this work.

Hypothesis 1: It is possible to produce tropical or subtropical fruits, especially Avocados, in Bavaria and the Munich Metropolitan Region with the use of waste heat.
Outcome: This hypothesis was predominately fulfilled. There is a tremendous waste heat potential for Bavaria and the city of Munich. Tropical and subtropical fruits can be successfully grown in greenhouses, although avocado plants have a complex pollination procedure and can have difficulties growing in a standard greenhouse system.
Hypothesis 2: There is a significant potential to reduce ecological impacts (water or carbon footprint) considering the WEF Nexus.
Outcome: This hypothesis was partly fulfilled. Whereas, the product carbon footprints of a potentially local avocado industry would be significantly lower than the footprints the global avocado industry creates, this cannot be claimed for the water footprints. With the current data on the water demand of the local case study's greenhouse, the local water footprint would be slightly higher than the highest global avocado industry water footprint, namely higher than the one from Chile.

DISCUSSION

Waste Heat Potential

The chosen waste heat sources are part of a database provided by the Bavarian State Government. This database is built from voluntary data and probably only represents a fraction of the actual waste heat potential in Bavaria. The chosen maximum operating time of 6,500 h only looks at the total time but ignores the continuity of these hours. The potential could be lower if 6,500 h were not considered as the maximum operating time but as minimum operating time from the operating time ranges provided by the waste heat potential database. A continuous supply of waste heat must be ensured to keep the temperature inside the greenhouse on a constant level. This problem especially addresses the winter months and should be an exclusion criterion to choosing possible waste heat potential sites in further research projects.

Avocado Yield

The theoretical yield of greenhouse-grown avocados from Bavaria could cover more than the current avocado import numbers for the whole state of Bavaria. There were not made any calculations on the achievement of different yields. With denser tree spacing like e.g., 4 × 1.5 m rather than the conventional 3 × 3 m (Peru) a much higher total avocado yield could be reached

(Stassen et al., 1999). The assumption of Munich's avocado import/consumption numbers is rather rough due to the lack of data or surveys on this topic. The Statistical Office of Munich had no relevant data and there weren't found any useful data in public research publications either. Therefore, the numbers were interpolated by relating the avocado import numbers of Bavaria to its number of inhabitants. With this and the number of Munich citizens a possible consume amount for Munich was estimated. The real amount could be significantly higher. This assumption is based on the fact that the percentage of people following a vegetarian diet is higher in cities than in rural areas. Higher educated citizens are more likely to live by a vegetarian diet. On top of that, young people between 18 and 29 years represent the greatest share among different age groups living vegetarian (Mensink et al., 2016). Since Munich is a city with high numbers of student citizens, it can be assumed that avocado consume could be much higher than the amount this project was working with.

Water Footprints

Looking at the global water footprint examples from Chile, Mexico and Peru, there can be noticed that Chile has much higher footprints, green-blue as well as gray, than the two other countries.

Regarding the calculated total water footprints, the local case study has an even higher footprint than any of the three global examples. The reason behind this is a rather high estimation of water demand for the case study system of 950 liters of water per two fruits. This estimation was part of the personal communication with the case study's general manager (R. Schmitt, personal communication, 18.06.2021). The real water demand wasn't measured and is probably much lower. Due to the controlled environment of a greenhouse, the evaporated water is kept in the system and will recirculate by entering the soil again after dripping down the greenhouse's walls. The establishment of a modern drip or micro sprinkler irrigation system could further reduce the water demand too (Moreno-Ortega et al., 2019).

Carbon Footprints

Inspecting the carbon footprints of global avocado production, there weren't used footprint estimations for all of the three example countries Chile, Mexico, and Peru. The footprints solely considered Peruvian avocado production and a global average. This was due to working with one specific study's data to ensure consistency for global and local carbon footprints. The first scenario used probably represents the more unrealistic scenario compared to scenario two. The emission impact "greenhouse building" is completely neglected in this scenario. Additionally, it must be questioned whether the carbon footprints of highly technological greenhouse systems can be compared to conventional outdoor avocado orchards. This question represents the main limitation of the carbon footprint results. With the modified carbon footprint and the subtraction of the heating impact, the second scenario seemed to be better suited. Regarding future improvements of greenhouse buildings' carbon footprint the use of sustainable materials like bamboo or recycled glass could be a valuable approach.

Urban WEF Nexus Implications

Water – Energy: Water demand is closely interlinked to energy use since there is often the need of pumps to transport the irrigation water from the storage tank/groundwater well to the farming area. Higher water demand therefore means higher energy demand. This interlinkage could be reduced by irrigation systems working with gravity driven pipe systems.

Water – Food: Water use strongly interferes with agricultural food production and therefore food security. As mentioned in the introduction, agriculture is causing almost 70 % of worldwide water use. Reducing the irrigation volume directly impacts the yield volume (Silber et al., 2019).

Modern irrigation systems can reduce the needed water volume since the irrigation is precisely located near the plants and therefore less water is wasted. Rainwater use for irrigation would lower the blue water footprint of urban food production significantly. Intensive agriculture can also have negative effects on water security through soil degradation and impacts on groundwater aquifer with pesticides, nitrate, or high salinity.

Energy – Food: Energy and food security are correlated. Large industrial food production sites need energy in the form of fuel or electricity to irrigate the crops. Greenhouse systems need heating during winter, which consumes a tremendous amount of energy. This could be strongly reduced by using waste heat in agricultural controlled environments. Local food production produces less CO_2 emissions than food transported around the world.

Required Area and Urban Farming Ideas

The required useable greenhouse system area ranged between 0.016% of the respective total area in Bavaria and 0.02% of area in Munich. These values are marginal and could easily be achieved. On the other hand, Bavaria is a state with a quite high land use and decreasing untouched natural habitats. The risks and benefits of this development and potentially further increased land usage should be carefully considered. The municipalities of innovative cities could think about engaging into public-private partnerships by offering unused areas to private urban farming initiatives. A possible alternative to further land use changes would be the usage of existing structures. For urban areas, the idea to use rooftops, walls and green areas could be an interesting option and is backed up by several studies (Thomaier et al., 2015; Gondhalekar and Ramsauer, 2017; Orsini et al., 2020).

A possible combination of public areas and the use of waste heat could be the rooftops of public swimming pools. With the help of arial analysis, seven out of the 10 public swimming pools of Munich seem to have useable flat roofs. Regarding the use of private rooftop or wall areas it would be interesting to examine the possible use of gray water from sink or shower water for irrigation or heating.

Another idea to practice waste heat supported farming without putting more pressure on the densely populated Munich area, could be the involvement of the city's wastewater treatment plants. Reasons for this are:

- WWTPs are often located outside the city with enough space around possibly suited for farming areas.

- The fouling towers as well as the wastewater itself carry a high waste heat potential.
- Treated sewage sludge ash could be a fertilizer option for urban farming areas nearby.

Possible Alternative Agricultural Products

According to the general manager of the used greenhouse case study, Mr. Ralf Schmitt, avocado plants have difficulties growing in Bavarian greenhouse systems (R. Schmitt, personal communication, 18.06.2021). In Germany, avocado trees can take years until the first fruit bearing. After 3 years trying to improve the pollination rate and bringing the avocado plants through the short winter days, the avocados still had not bloomed in the "Kleineden" case study greenhouse. This was the reason why Mr. Schmitt decided to stop the experiment of growing avocados in the greenhouse project "Kleineden" in the fourth year of growing the avocado plants. These results could possibly be improved by more advanced greenhouse settings such as ultraviolet lighting, automated irrigation and a more intensive and complex pollination scheme. Despite the unfortunate ending of the avocado experiment, there was made good progress with several other fruits. Promising yield results were achieved with papaya, guava and carambola (R. Schmitt, personal communication, 18.06.2021). Experiments with other plants such as cocoa or coffee plants were botanically successful but failed from an economical perspective. The price of a cup of coffee produced in the Kleineden greenhouse system would amount to roughly 29 Euro (R. Schmitt, personal communication, 18.06.2021).

Climate Change in Bavaria

Water scarcity is not only already a problem in avocado producing countries but affects Bavaria too and it will probably increase due to climate change. The region in Franconia where the greenhouse case study is located, already suffers from increasing droughts since several years. Mr. Schmitt reported about 10–15% less rainfall over the last 5 years in this region (R. Schmitt, personal communication, 18.06.2021). His observations are backed by the Climate Report 2021 of the Bavarian State Ministry of the Environment and Consumer Protection. According to the report's prognosis average rainfall will decrease during summer, while extreme weather events like thunderstorms with the potential to bringing dangerous, punctual flashfloods will occur more often in the future (Bavarian State Office for the Environment, 2021a). While climate change will increase the dangers of agricultural production it will also enable new business paths. This trend will bring the possibility to grow new types of plants on Bavarian soil.

Climate Goals and Rising CO_2 Pricing

To achieve the climate goals resolved during the Climate Conference in Paris 2015 there must be undertaken greater effort. After promoting the energy transition for the last decade, the German government should promote the heat transition as one of the next important goals. The introduction of higher CO_2 pricing is a disputed topic in Germany during the summertime before the next federal election in September 2021.

The higher the price is for a ton of CO_2, the more expensive will the global food transport via ships and airplanes become. This can be seen as a chance for local urban food systems trying to increase food security of urban areas without relying on global food trade. Resource efficiency and the use of unavoidable waste heat will become more important by the further development and application of these measures.

Ethical Concerns

An ethical concern of this work occurs with the theoretical loss of jobs and prosperity for people working in avocado producing countries supplying the Bavarian market. Through the domestic production, Bavaria would reduce its import quantities for avocados. This could negatively impact the global avocado producers and enhance social conflicts in these countries. Contemplating this problem from a utilitarian perspective international avocado production brings benefits and happiness to more people than it harms. Examined under a deontological view, it is just the avocado farmers' duty to farm their orchards without thinking about the potential consequences of their doing. Seen from an ecocentric perspective, putting the nature's "well-being" into focus, industrial avocado production harms nature in several ways and should not be further proceeded. Soil degradation, groundwater pollution, deforestation, reduction of biodiversity, increased nitrate inputs to the ground or excessive fire clearance are enough reasons to condemn industrial agriculture from an ecocentric perspective. Regarding water use, there comes up the question whether the access to clean water is a human right given to everyone or a consumable good that can be sold. An example of this problem is the water supply in Chile, where water is handled as a privatized, consumable good (Prieto et al., 2019). Improving avocado farmers' lifes by engaging in international unions and demanding fair pricing and food labeling, better work safety and clear governmental guidance on agricultural businesses would be a starting point that could help. This should be the minimal condition for pursuing the plan to grow avocados or other exotic fruits in Central Europe.

CONCLUSIONS

This research aimed to identify the possibility of growing subtropical or tropical fruits, here especially avocados, in greenhouse systems in Central Europe. The results indicate that there is a tremendous waste heat potential that could cover greenhouse grown avocado yields in volumes similar to the current import numbers of avocados to Bavaria. Unused waste heat occurs all around the world and could be used to ensure food production in normally unsuited places. Due to complicated pollination procedures and unsure fruit bearing, avocados would not be suggested as preferable exotic crop type for greenhouse farming in Bavaria. There are other exotic fruits like papaya, guava or carambola with promising yield results made in a case study project in Upper Franconia. Water footprint results indicate a similar water footprint of local avocados compared to avocados grown in Chile. This could be significantly improved by introducing modern drip or micro sprinkler irrigation systems. Results for carbon footprints show that local avocados would be tremendously lower than global production with percentages between 38 and 50% or, respectively, 57 and 76% of global avocado production footprints, depending on the two different scenarios created. An unexpected insight of this research was the finding that land transport via trucks from and to the ports accounts to similarly high CO_2 emissions as ocean-crossing transport via container vessel. This work clearly illustrates the tremendous potential urban farming has in combination with waste heat utilization in Bavaria and Munich, but also raises the question whether the used local and global carbon footprints should be directly compared to each other. Another limitation of local avocado production would be the question whether this could be done without having any ethical concerns toward the prosperity and work of current avocado farmers. As recommendation, the potential of gray water use for irrigation of urban farming areas and possible public-private partnerships between municipalities and farming initiatives could be further examined. Further research on detailed waste heat potentials in Bavaria but also worldwide potentials should be undertaken while the existing waste heat potential in Bavaria and Munich should be exploited with stronger effort. The research topic of heat transition application as tool to reach the proclaimed climate goals would be worth to further pursuit. This research backs the assumption that the carbon footprint of local food production produces much lower CO_2 emissions than international food production with global supply chains. Avocado farming in Central Europe is more difficult than with other exotic fruits, which explains the low number of relevant data or existing avocado farming projects in these European regions. The findings of this work confirm the usability of the WEF Nexus concept and show possible use cases to ensure food security in urban areas around the world while reusing unavoidable waste heat.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LB and DG contributed to conception and design of the study. LB organized the database and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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