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Symbiosis opportunities between food and energy system: the potential of manure-based biogas as heating source for greenhouse production

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Abstract

The concept of symbiosis, a mutually beneficial relationship, can be applied to food and energy systems. Greenhouse systems and biogas plants are interesting technologies for food-energy symbiosis, as both are usually based in rural areas and offer opportunities for the exchange of materials (e.g. biomass waste from the greenhouse as input to biogas plants) and energy (heat from biogas co-generation for heating greenhouses). In this paper, the focus lies on manure resources for biogas in Switzerland, as manure amounts are high and currently largely underused. We provide a spatial analysis of the availability of manure as feedstock to biogas plants and heat source for greenhouses. In this feasibility study, we coupled the potential waste heat supply from manure-based biogas and the greenhouse peak heat demand. We quantified the area-based greenhouse heating demand for year-around tomato production (from 0.98 to 2.67 MW ha^{-1} where the farms are located) and the available heat supply from manure-based biogas (up to 3200 GJ a^{-1} km^{-2}). A total maximum greenhouse area of 104 ha could be sustained with manure-based biogas heat, producing 20,800 tonnes a^{-1} tomatoes. This amounts to 11% of the total domestic tomato demand. While the results are specific to Switzerland, our method can be adapted and also applied to other regions.

1. Introduction

Industrial symbiosis, based on the idea of the mutually beneficial relationship between two different species in biology, is defined as engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products" (Chertow 2000). The concept of symbiosis can also be applied to agri-food chains ("agroecological symbiosis" (Koppelmäki et al. 2019; University of Helsinki 2016) and energy systems, which have to be improved to pursue the Sustainable Development Goals of the UN Agenda 2030 (UN 2019; FAO 2014). In this paper, we focus on manure-based biogas as a heat source for greenhouses representing a symbiosis opportunity between energy and food systems.

Greenhouse systems offer a variety of benefits compared to open-field agriculture, including supply chain reliability and high crop yields. In Switzerland, they covered 471 ha in 2018 (SZG 2019). However, they also need the energy to provide appropriate conditions for plant growth, and nowadays, fossil fuels are the main energy resources used in greenhouse systems, contributing to climate change impacts. For example, vegetable production in Swiss greenhouses with fossil energy has larger environmental impacts than importing vegetables from Spain or Italy in winter and spring (Stoessel et al. 2012). Indeed, a study in 2018 showed that 225 ha of greenhouses consumed more than 350 GWh heat, mostly generated using natural gas (DM Energieberatung AG 2020). This has been recognized by Swiss retailers, which are aiming to extend local greenhouse production with waste heat (Myclimate 2019).

Several studies have investigated the supply of greenhouse heating demand with waste heat from waste incinerator plants (Marton et al. 2010), industrial processes (Andrews and Pearce 2011), district heating systems (Togawa et al. 2014; Dou et al. 2018), and power plants (Lee et al. 2016; Yu and Nam 2016). Similar to these examples, biogas plants and greenhouse cultivation systems can be integrated to close the cycle of material and energy flows. Alexandersson and Tran (2017) evaluated a case of integrated biogas plant - greenhouse system in Sweden and showed that combined biogas production and greenhouse cultivation is feasible. Hence the utilization of heat from biogas plants in greenhouses could decrease fossil energy use (Gruda et al. 2019; Flisch et al. 2009; Markou et al. 2017) and strengthen the position of Swiss agriculture by making local greenhouse vegetable production environmentally competitive with vegetable imports from warmer locations.

Manure currently represents an underused source of biogas energy in Switzerland. Animal manure refers to all by-products (both liquid and solid) generated by animal husbandry to produce food and other agricultural products. It mainly consists of animal feces, urine, and bedding materials. Only approximately 6% of the available manure is currently used for energy. In 2017, 106 agricultural biogas installations produced more than 448 TJ electricity and 83 TJ recovered heat per year (BFE 2017). However, it was estimated in a previous farm-level study, based on surveyed animal count, species and stabling system, that almost 10 times more manure can be mobilized in a sustainable way for biogas production (Burg et al. 2018a; Thees et al. 2017) (see SI for more details). The average size of the installed biogas systems is approximately 200 kW_{el} with almost no facility below 10 kW_{el} (BFE 2019).

The advantages of producing biogas from manure include a high climate benefit due to direct and indirect emissions savings (Burg et al. 2018b; Chadwick et al. 2011; Gerber et al. 2013) and the contribution to a more diversified energy mix. Indeed, biogas is less fluctuating and more controllable in comparison to solar and wind power. Therefore, biogas has an important role to play as a local source of renewable energy, and the biogas volume produced in agricultural areas can be expected to continue rising in the future (BFE 2017). This is in line with Switzerland's aim to increase the use of its domestic renewable energy resources (SFOE 2018).

For a long time, electricity generation from biogas has been the major focus, mainly due to the subsidy scheme in Switzerland (BFE 2015). In recent years, heat recovery and utilization have gained in importance, as a by-product of combined heat and power (CHP) biogas systems (Biomasse Suisse 2019; Genossenschaft Ökostrom

Schweiz 2018). Currently, only 65% of the gross heat production of biogas plants is used on average in Switzerland - 40% internally and 60% externally (Genossenschaft Ökostrom Schweiz 2018). Internal heat considers the utilization by the farmer itself e.g. for private housing or professional needs. External heat needs longer distance infrastructure to e.g. neighboring housing or industry, which are often far away from the farms. Especially when no heat consumers are close by, the unused heat could be used to supply the heating demand of greenhouses.

Land-use scenarios can geographically restrict symbiosis opportunities. Locations and distances of supply/demand points and land cover classification are considered as main constraints in the determination of strategic decisions. To be able to process sufficient feedstock, biogas facilities are generally using additional manure of surrounding farmers. However, the low energy density of manure (high water content, relatively low biogas yield) makes transportation challenging (Pöschl et al. 2010; Walla and Schneeberger 2008).

Here, we perform a feasibility study regarding the use of heat from agricultural biogas installations to produce food in greenhouses. We (1) present the analyses of available manure resources for biogas production, (2) use a model to analyze the energy demand of possible new greenhouses across the country and (3) couple the potential energy production and energy demand to quantify the feasibility of producing food from greenhouses heated with agricultural biogas in Switzerland. Furthermore, (4) a sensitivity analysis is carried out to evaluate the impacts of several parameters on the greenhouse peak heat demand and potential area of greenhouses supported by manure-based biogas. Although our results refer to a specific country, our method can also be applied to other regions.

2. Material and methods

2.1. Available manure resources for biogas production

In this study, we focused on the locally available manure resources. The following livestock types were considered: cattle, pigs, horses, sheep, goats, and poultry. Reference values were applied to calculate the quantity of slurry and/or manure per animal depending on species and stable systems (Flisch et al. 2009). In Switzerland, farms are relatively small with on average 27 reference livestock units (LSU) per holding (1 LSU = equivalent to one adult dairy cow) (FSO 2017). The spatial distribution is mostly scattered, with higher densities in the Swiss Central Plateau and along the mountain valleys. Farm density is relatively high (10 to 14 farms per 1 km radius) (Burg et al. 2018b). In practice, manure is only collected when generated on-farm. Hence, manure losses from excreta returned directly to pastures during grazing are not available for biogas production and have to be subtracted (see details in Burg et al. 2018a; Thees et al. 2017). Manure can be used as a substrate in agricultural biogas plants. Biogas is formed in reactors (fermenter) by anaerobic decomposition of organic substances.

The potential biogas production from the collected manure was then calculated with specific manure characteristics and methane production values from the literature in accordance with common practices (Flisch et al. 2009; KTBL 2013). As a basis for the further calculations, local biogas potential is aggregated up to a 1 x 1 km^2 grid for the whole of Switzerland. The potential additional biogas production from co-substrates was not taken into account (only animal manure). Afterward, in Switzerland biogas is usually converted into electricity and heat through combustion in a CHP engine (Dou et al. 2018; Togawa et al. 2014; Lee et al. 2016; Yu and Nam 2016).

2.2. Greenhouse energy demand and yield production

In order to calculate greenhouse energy demand, the energy balance of the greenhouse was established (equation 1) (Golzar et al. 2018):

$$\dot{q}_g(x,y,t) = \dot{q}_{con}(x,y,t) + \dot{q}_{trans}(x,y,t) + \dot{q}_l(x,y,t) + \dot{q}_{vent}(x,y,t) - \dot{q}_{solar}(x,y,t) \quad (1)$$

$$x = 1,2,\ldots,110 \quad j = 1,2,\ldots,30 \quad t = 1,2,\ldots,8760$$

Where (x,y,t) is x^{th} cell of Swiss longitude, y^{th} cell of Swiss latitude and t^{th} hour of the year, $\dot{q}_g$ is the heat flow rate required to maintain the desired temperature in the greenhouse (W), $\dot{q}_{solar}$ is the energy transfer of incoming solar radiation (W) in the interior, $\dot{q}_{con}$ is the convective and conductive heat transfer (W), $\dot{q}_{trans}$ is the heat flow rate due to crop transpiration (W), $\dot{q}_l$ is the energy exchange with the exterior due to long-wave and short-wave radiation (W), and $\dot{q}_{vent}$ is the heat transfer due to mass transfer by means of ventilation (W).

ASAE (2008) simplified this equation for the purposes of sizing a heating system: The solar irradiation term is removed and $\dot{q}_{con}$, $\dot{q}_{trans}$ as well as $\dot{q}_l$ are summarized as the total heat transfer between indoor and outdoor conditions. Therefore, the heating demand for greenhouses in different regions of Swiss is calculated based on equation 2:

$$\dot{q}_g(x,y,t) = UA\big(T_i - T_0(x,y,t)\big) + C_{air}\varphi\rho_{air}\big(T_i - T_0(x,y,t)\big) \qquad (2)$$

$$x = 1,2,\ldots,110 \quad j = 1,2,\ldots,30 \quad t = 1,2,\ldots,8760$$

Where A is the total surface area of the structure (m^2), U is the total heat loss coefficient of the structure ($W\ m^{-2}\ K^{-1}$), C_{air} is the specific heat of the air ($J\ kg^{-1}\ K^{-1}$), φ is the ventilation rate ($m^3\ s^{-1}$), ρ_{air} is the density of the air ($kg\ m^{-3}$). T_i and T_o are the internal and external temperatures (K) respectively.

In this study, we consider the Venlo glass greenhouse since this is the most common glass greenhouse structure (Antón et al. 2014). This type of greenhouse structure is widely used in central European countries such as Netherland and Germany (von Elsner et al. 2000).

$$\dot{q}_g(x,y) = \left(4Lh + \frac{L^2}{\cos(\Theta)}\right) U \left(T_i - T_{0,min}(x,y)\right) + 1800\left(h + \frac{G}{2}\right) L^2 N \left(T_i - T_{0,min}(x,y)\right) \qquad (3)$$

$$x = 1,2,\ldots,110 \quad y = 1,2,\ldots,30$$

Where L is the greenhouse length/width (m), whereby it is assumed that the greenhouse has a square footprint based on Andrews and Pearce (2011). h is the height of the greenhouse, θ the roof pitch angle, and G is the length of a side of the pitched roof. N is the ventilation rate (s^{-1}), determined by Andrews and Pearce (2011) and the ASABE (2008). For the comparison of peak heat demand, we assumed a reference greenhouse with the following dimensions: L = 100 m (following Andrews and Pearce (2011), h = 4 m, θ = 30° , G = 2 m, and N = 2.1×10^{-4} s^{-1}, which is an acceptable value for a new glass or plastic installation).

In order to calculate the total supported area by available biogas, equation 3 is rearranged to equation 4:

$$L(x,y)^2 = \left(\frac{-4hU\Delta T + \sqrt{(4hU\Delta T)^2 - 4\left\{\left(h+\frac{G}{2}\right)1800N\Delta T + \frac{U\Delta T}{\cos(\theta)}\right\}\left(-\dot{q}_b(x,y)\right)}}{2\left\{\left(h+\frac{G}{2}\right)1800N\Delta T + \frac{U\Delta T}{\cos(\theta)}\right\}}\right)^2 \quad (4)$$

$$\Delta T = \left(T_i - T_{o,min}(x,y)\right)$$

Where $\dot{q}_b(x,y)$ is the amount of heat produced by potential manure-driven biogas plant considering combined heat and power (CHP) systems (W) in 1×1 km^2 area.

Yield production in greenhouses depends on a wide variety of factors such as providing suitable indoor microclimate, CO_2 enrichment, and using artificial lighting. It could vary between 12 kg m^{-2} a^{-1} tomato as in low tech greenhouses in Spain and more than 60 kg m^{-2} a^{-1} tomato in high tech Dutch greenhouses (Cantliffe and Vansickle 2009; Hendricks 2012). In this study, we make a conservative assumption and consider 20 kg m^{-2} a^{-1} tomato, 22 kg m^{-2} a^{-1} cucumber, and 30 kg m^{-2} a^{-1} lettuce (Cantliff and Vansickle 2012; Keskitalo 2009) for all potential greenhouses in Switzerland. Indoor microclimate conditions required for achieving the aforementioned yield production are 20 ºC temperature, 450 ppm CO_2 concentration, 25 mol m^{-2} d^{-1} lighting for tomato (Golzar et al. 2018), 18 ºC temperature, 450 ppm CO_2 concentration, 20 mol m^{-2} d^{-1} lighting for cucumber (Mattson 2015) and 15 ºC temperature, 450 ppm CO_2 concentration, 17 mol m^{-2} d^{-1} lighting for lettuce (Mattson 2015).

2.3. Coupling potential energy supply and demand

We calculated the greenhouse potential area regarding energy demand and available manure. For each 1 x 1 km^2 grid, the amount of heat produced by potential manure-driven biogas plants considering combined heat and power (CHP) systems is estimated (Scarlat et al. 2018), as it is the most commonly used technology today in Switzerland. Due to the integrated biogas buffer tank in biogas facilities, the annual steady flow of biogas is assumed. This is not long term storage but serves as a buffer for the supply variation. Finally, we quantified the potential greenhouse area based on available heat from biogas and greenhouse properties in each grid (Figure 1).

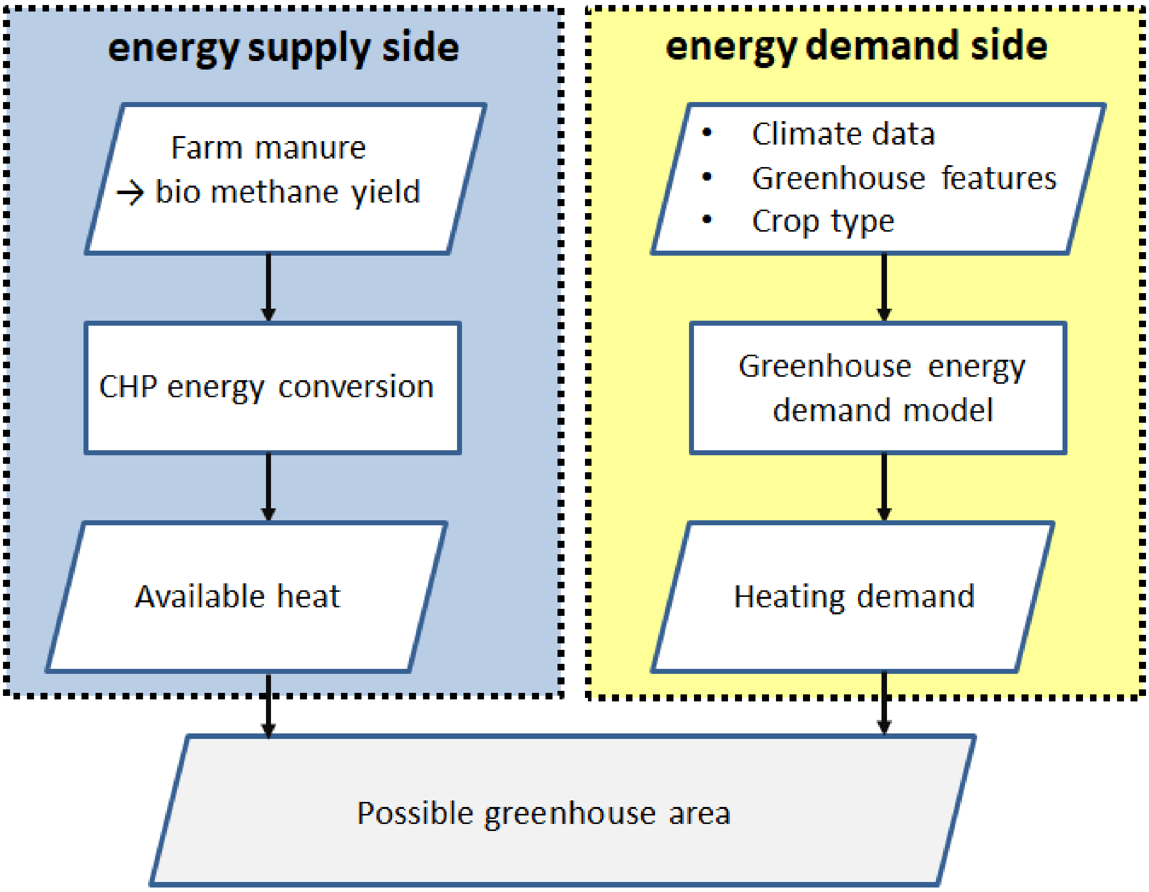

Figure 1: General algorithm for calculating the greenhouse potential area.

2.4. Hotspots of available manure

Based on the grid of the biogas potential from available manure (1 x 1 km^2; as calculated under 2.1) we conducted a hotspot analysis. Hotspot analysis seeks to identify groupings within an area, which may either represent high ("hot") or low ("cold") values of a given variable. Hotspots analysis is a helpful and effective tool that assists in the identification of areas to be prioritized for action. The visualization enables policy-makers, businesses, and other stakeholders to identify opportunities and develop targeted action plans (Barthel et al. 2015). To make efficient use of spatially dispersed resources, in our case manure, it is helpful to visualize not only cells with high resource potential but also areas with a statistically significant grouping of high-potential cells (Mohr et al. 2019).

Hot spot analysis was conducted based on the Getis-Ord Gi* Statistic (Getis and Ord 1992) in ArcGIS. Its use has been widely documented in the literature (Sánchez-Martín et al. 2019; Rodriguez et al. 2015; Graves et al. 2016). This method provides a visual clustering of high, low, and not significant values. To be a statistically significant hot spot, a cell (here 1 x 1 km^2 biogas potential from available manure) will have a high value and be surrounded by other cells with high values as well. To perform the analysis, a neighborhood distance of 12.2 km has been defined using the Optimized Hotspot Analysis tool. This distance is slightly below the maximum legal transport distance for manure in Switzerland (15 km) and is therefore appropriate. After the distance has been defined, the neighborhood is compared to the entire study area. If the neighborhood values are significantly higher than the study area, the cell is marked as a hotspot. Thus, each cell is assigned as a hotspot, coldspot, or not significant (Sánchez-Martín et al. 2019; Rodriguez et al. 2015; Graves et al. 2016).

2.5. Base case description

In this work, glass greenhouses with an overall heat transfer coefficient of 4 W m^{-2} K^{-1} are considered as the base case (Chau et al. 2009; Tantau 2013). No minimum size was set for greenhouse size. We considered the optimal internal temperature (T_i) for growing tomatoes, which is 20 ºC (Golzar et al. 2018; Jones et al. 1999), as an average value for the day and night temperatures. For external temperature, we considered the temperatures of all meteorological data points (6 km resolution) in Switzerland (Bollmeyer et al. 2015). The external temperature was determined based on the minimum temperature in 2015 (as the reference year) for each grid. However, the minimum temperature of each grid all around the year could lead to an extremely conservative design of the energy system with poor exploitation of the overall biogas heat potential when temperatures are not at the minimum. Therefore, because the plants can sustain also lower temperatures temporarily, we neglected 10% of the coldest hours of the year in the base case. Biogas facilities were assumed to have an efficiency of 35% for electricity production, and up to 45% for heat production (this already includes the own energy demand of the installation itself) and an annual operation time of 7500 h (Scarlat et al. 2018). The 45% efficiency is higher than today's average heat production but we expect new biogas plants to be built using the most recent technology and heat optimization measures (Biomasse Suisse 2019).

2.6. **Sensitivity analysis**

Nevertheless, there are some uncertainties associated with the values mentioned in the base case. To investigate the impact of these uncertainties on key outputs, a sensitivity analysis was conducted, taking into account weather data from 1995 to 2015:

- In order to evaluate the impact of cover material on greenhouse peak heat demand, plastic with a thermal coefficient of 6 W m^{-2} K^{-1} has been considered.
- To estimate the impact of indoor temperature, we analyzed the possibilities of growing cucumbers (18 °C) and lettuces (15 °C).
- The impact of neglecting 5% and 1% or none of the coldest hours of the year has been investigated.
- Moreover, some greenhouse holders do not cultivate anything during the cold months of the year (November to February). Therefore, the effect of considering

the minimum temperatures from March to October in 2015 on the greenhouse peak heat demand is also investigated. In other words, we consider the coldest hour of these months and recalculate the peak heat demand. As the coldest months are already excluded, we do not remove any of the coldest hours.

- In the base case, we assumed an optimistic value for CHP thermal efficiency of 45%. However, examples from already installed biogas plants in Switzerland have shown lower efficiencies (e.g. 32% final heat efficiency (BiEAG 2018)). This could be due to e.g. lower-performing technology, fermenter size, climatic conditions. Therefore, the impact of CHP with a thermal efficiency of 30% is compared with the base case.
- In addition, relying on fossil-based heating technologies as a back-up system to the biogas CHP is investigated. This is done by adding 20% to the manure resources in each grid cell.
- Finally, the impacts of different limitations on the size of the biogas plants, 10 kW_{el}, and 40 kW_{el} and the minimum greenhouse size (50 to 200 m^2) on the total potential area are analyzed.

3. Results

3.1. Available manure resources for biogas production

The resource distribution gives a first indication that greenhouses are only a viable option in the flatter and more temperate parts of Switzerland i.e the Swiss lowlands (Figure 2). This represents a total of 16 PJ biogas at the country level.

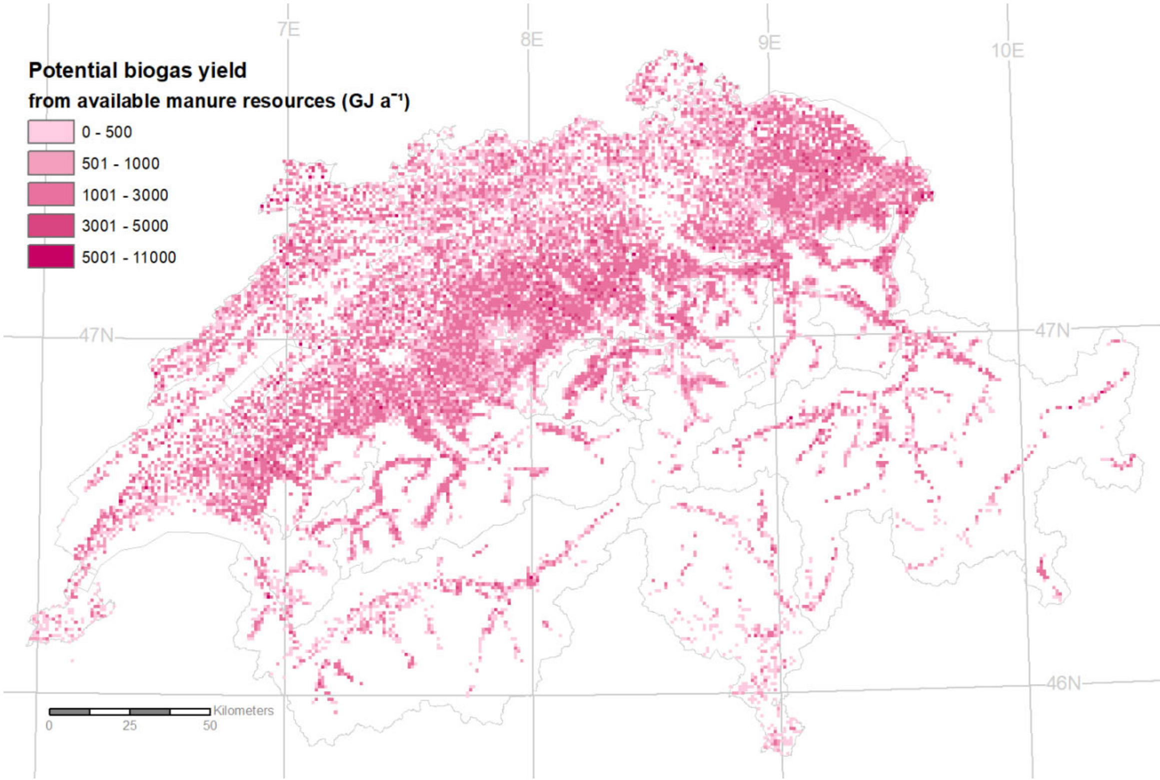

Figure 2: Spatial density of potential biogas yield from available manure resources in Switzerland, aggregated over 1 ×1 km^2 cells. Underlying data used to create this figure can be found in the Supporting Information.

The total average potential biogas yield from available manure per area of the hot spots is 1366 GJ km^{-2} compared to 741 GJ km^{-2} in the cold spots (Figure 3). The hot spots are found mostly in the Central Plateau, in areas where intensive agriculture is practiced whereas the cold spots lie almost entirely in the Alps.

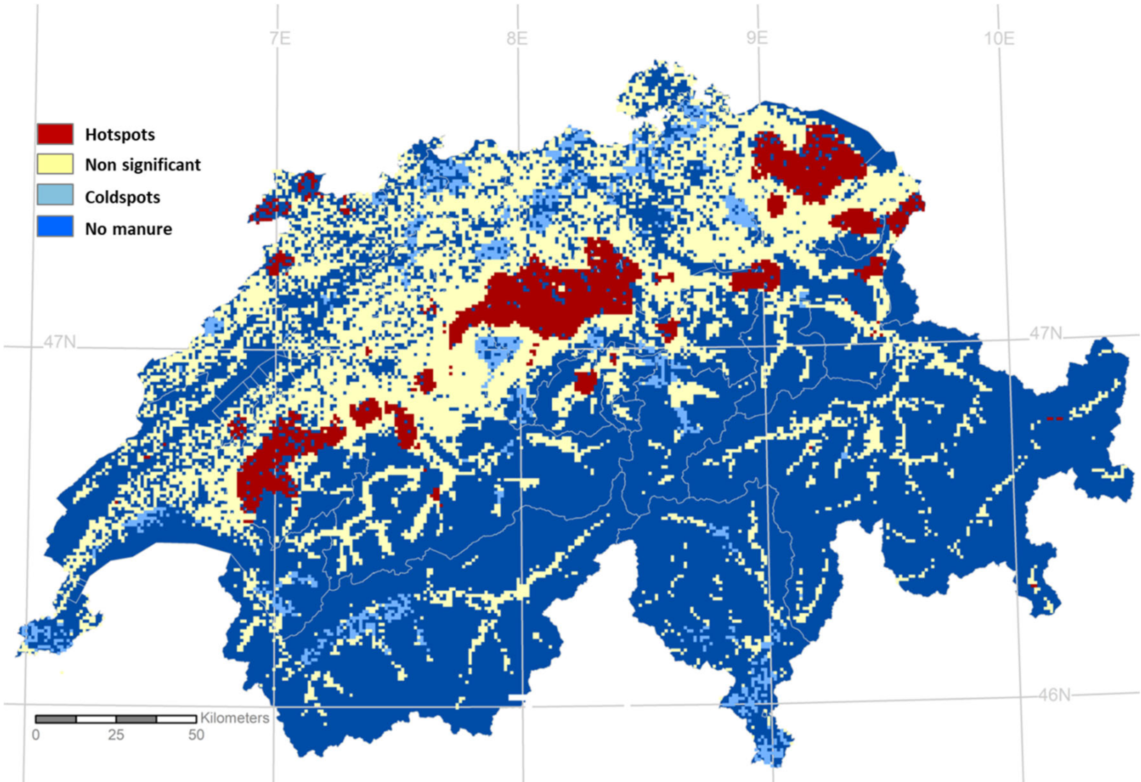

Figure 3: The hot spots and cold spots of potential biogas yield from available manure in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.

Moreover, figure SI 1 demonstrates the potential electricity production from manure in Switzerland. It shows that installing CHPs with an electrical efficiency of 35% would lead to producing a total amount of 5386 TJ electricity, thus partly or even fully covering the electricity demand of the greenhouses (lightning).

3.2. Greenhouse energy demand

As can be expected, energy demand has a direct relation with climate conditions particularly air temperature. Therefore, the energy demand in Alpine areas is higher than elsewhere (Figure 4). In addition to high-energy demand, the farm numbers in the Alpine area are smaller than in Swiss lowlands. Greenhouse peak heat demand is in the range of 1.25 to 2.94 MW ha^{-1}. This shows the variation of heating demand for possible greenhouses on farms in Switzerland.

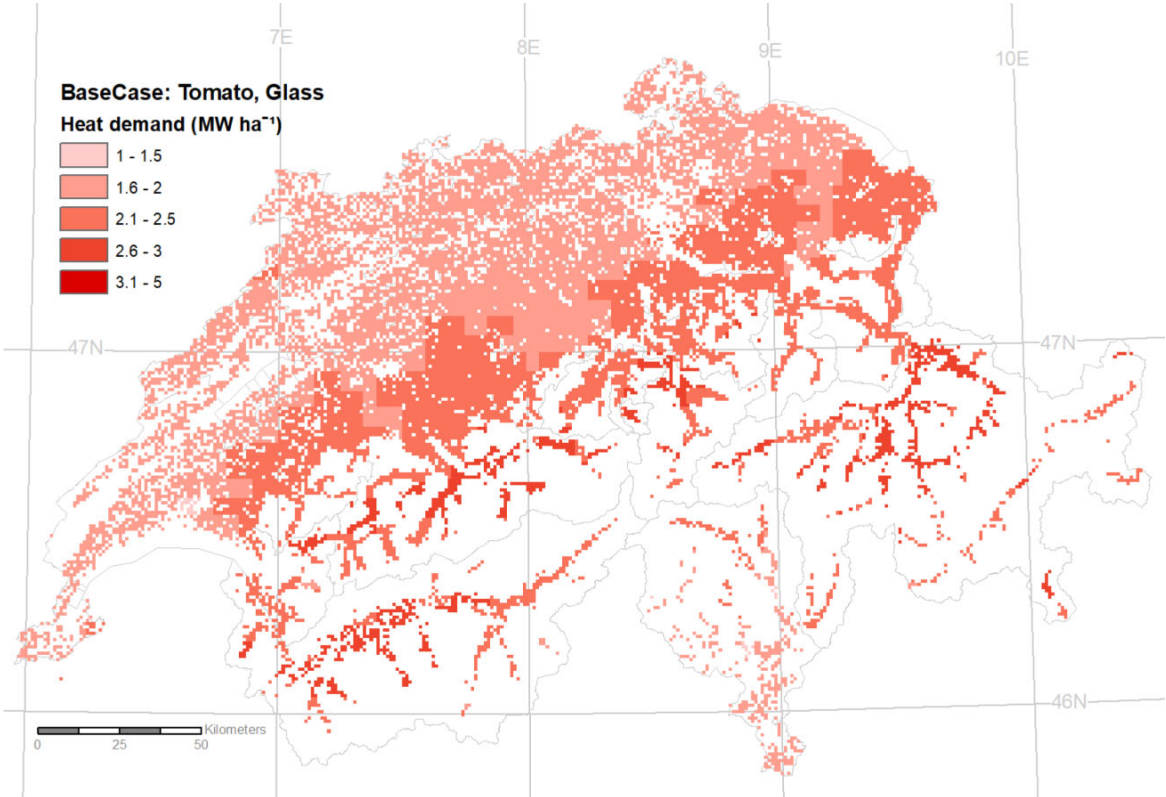

Figure 4: Peak heat demand for greenhouse with glass cover material in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.

3.3. Coupling potential energy supply and demand

The interaction between available manure as the heat supply and energy demand results in the potential area of greenhouses. Figure 5 depicts the potential area of glass greenhouses which of their heating demand (Figure 4) could be supplied by the available manure around existing farms (Figure 2). It shows that available manure could fulfill the heating demand of 104 ha greenhouse with glass cover material (base case scenario, no minimum greenhouse size). As a result, apart from Alpine areas, there are geographically good potential to create new symbiosis schemes between biogas plans and greenhouse systems.

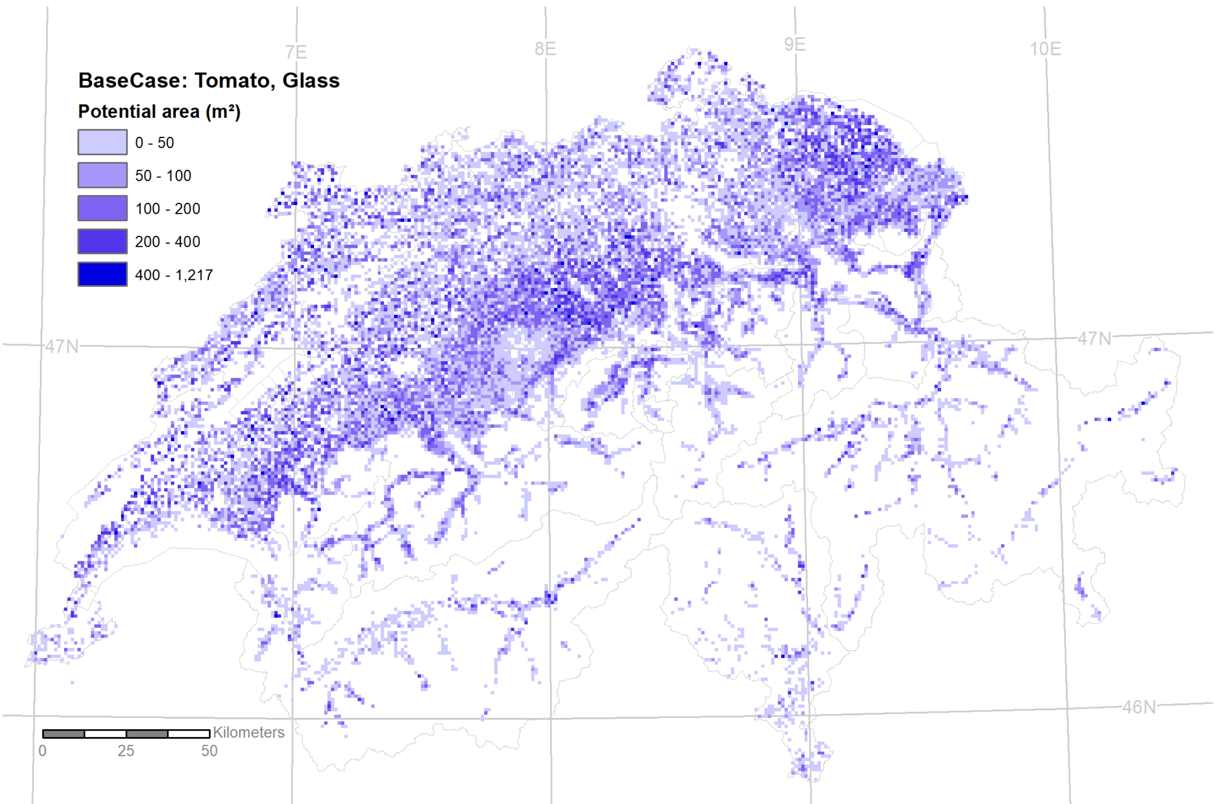

Figure 5: Potential area for greenhouse per km^2 with glass cover material and CHP system with a thermal efficiency of 45% in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.

3.4. Sensitivity analysis

The application of plastic covers increases heat loss from greenhouse surfaces by 33% (Figure SI 3). Indeed, greenhouse peak heat demand in the case of plastic cover material would be in the range of 1.87 to 4.40 MW ha^{-1}. Therefore, the area of greenhouses that could be supplied will decrease from 104 ha to 56 ha. In addition to the cover material, the indoor temperature has a large impact on the greenhouse peak heat demand (Figures SI 7 and 9). In cold places, growing plants like lettuce with lower indoor temperatures are more suitable than tomatoes.

The total potential area ranges from 118 ha in 2014 to 83 ha in 2010 (Figure 6). This indicates a 29% reduction in the potential area in the coldest year during the last 20 years in Switzerland compared to the warmest year. For plastic greenhouses, the potential area varies between 64 ha in 2014 to 44 ha in 2010. In addition, neglecting only 5% or 1% of coldest hours of the year decreases the total potential area (Figure SI 14 and 15), even for the March to October scenario (Figures SI 16).

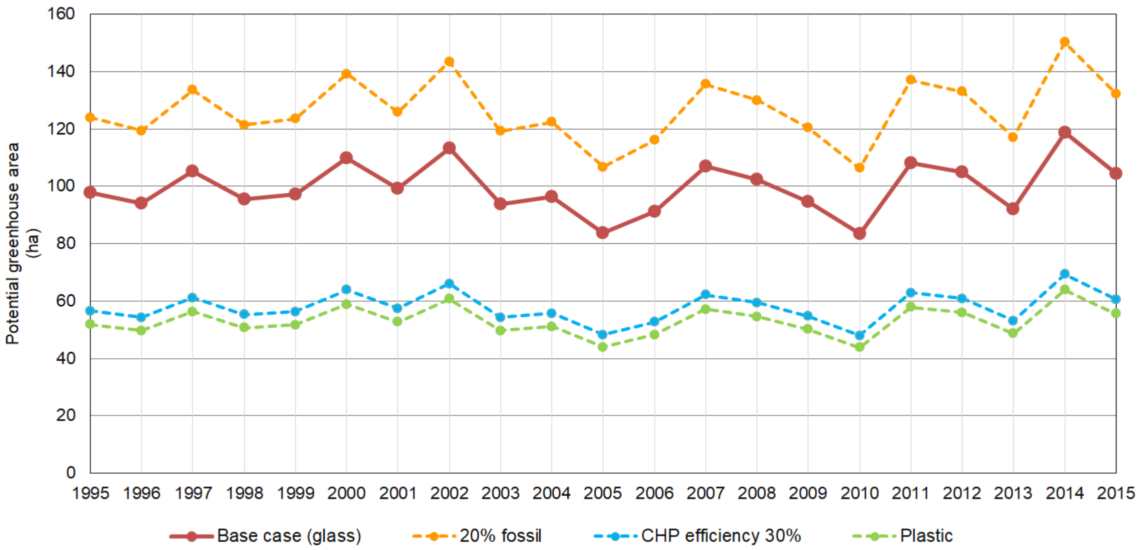

Figure 6: The impact of climate in different years on area potential for greenhouse with glass cover material in Switzerland (average=97, SD=7). Underlying data used to create this figure can be found in the Supporting Information.

If farmers cultivated all year round, January would be the coldest month of the year and the peak heat demand in Switzerland would vary between 1.25 MW ha^{-1} to 2.94 MW ha^{-1} (Figure 7). However, if farmers cultivated crops inside the greenhouse only from March to October, March would be the coldest month and peak heat demand would be in the range of 0.34 to 2.2 MW ha^{-1} (see Figure SI 11). On the other hand, the greenhouse potential area would be increased from 104 ha to 177 ha in the base scenario and from 61 to 88 ha if the coldest hour is considered (see Figure SI 10).

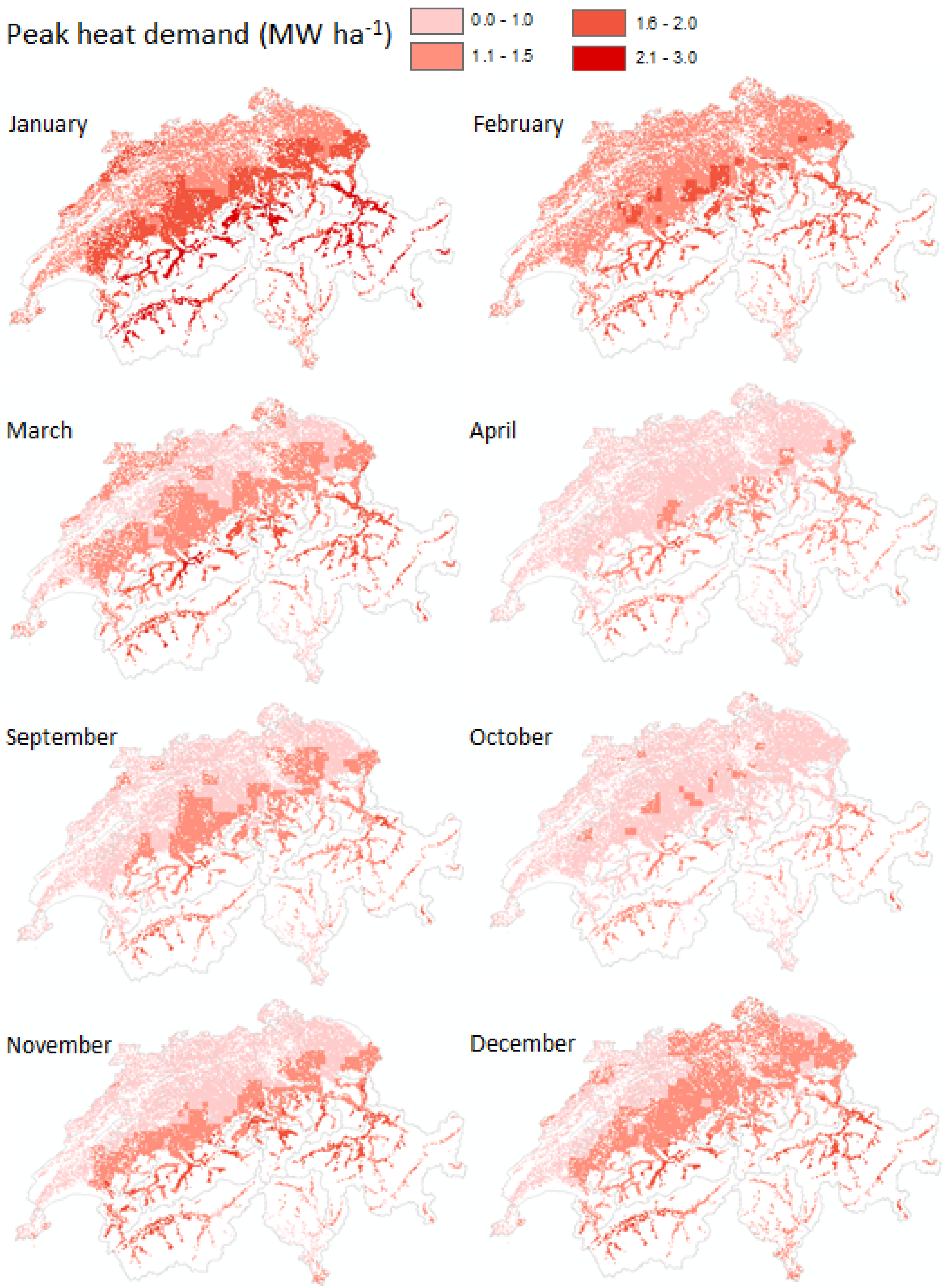

Figure 7: The impact of considering the minimum temperatures (coldest hours) of different months on the greenhouse peak heating demand. Months between May and August are not shown as no heating is required. Underlying data used to create this figure can be found in the Supporting Information.

By decreasing CHP heat efficiency from 45% (Figure 4) to 30% (Figure SI 4), the total potential greenhouses with glass cover material in Switzerland decreases from 104 ha to 60 ha based on climate conditions in 2015. It confirms that both parameters related to the greenhouse energy demand (e.g. cover material and indoor temperature) and energy supply (energy conversion technology efficiency) affect the total potential area to a similar extent. In addition, if a fossil-based back-up technology fulfilled 20% of the peak heat demand, the greenhouse potential area in Switzerland would be increased from 104 ha to 148 ha (see Figure SI 12). Figure 8 shows that the total area of potential small greenhouses is higher than of larger greenhouses. The total area of greenhouses of 50 m^2 or more is 88 ha while this is 27 ha if greenhouses minimal size is 200 m^2. This shows great potential for symbiosis opportunities for small greenhouses with limited transport of the resources.

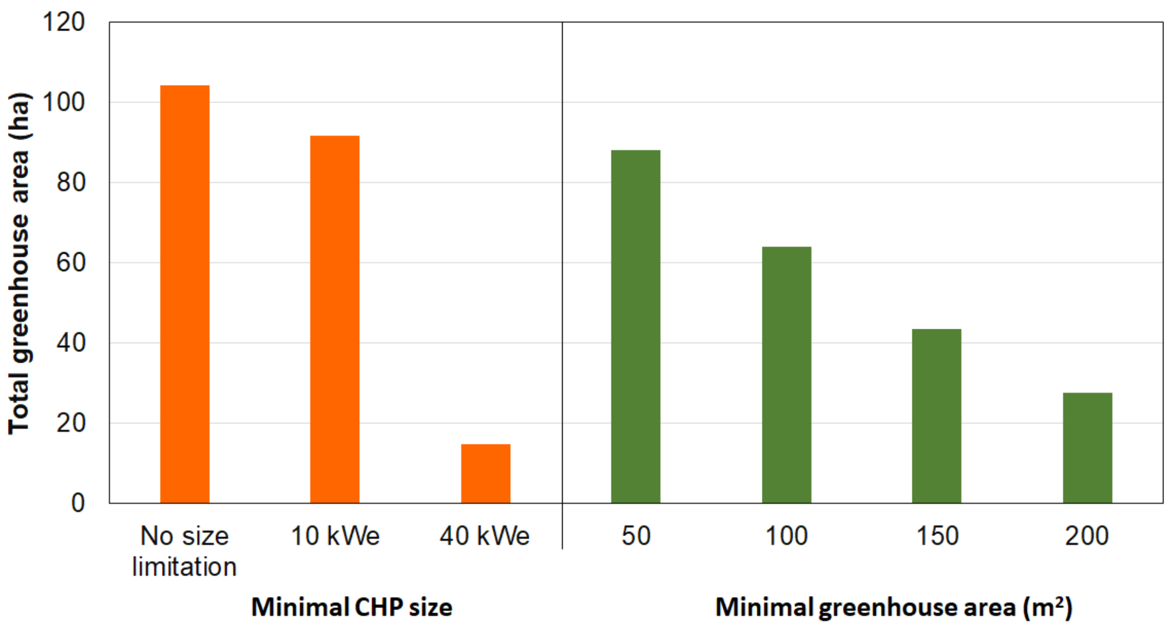

Figure 8: The total potential greenhouse area in Switzerland considering different minimal sizes of available combined heat and power (CHP) systems in $kW_{electric}$ and greenhouse areas. Underlying data used to create this figure can be found in the Supporting Information.

4. Discussion

We analyzed the available manure resources for biogas production and the energy demand of greenhouses across Switzerland. We then coupled the potential energy production and energy demand to quantify the feasibility of producing food from greenhouses heated with agricultural biogas from farm manure in Switzerland. Anaerobic digestion of manure allows to i) generate biogas for energy, ii) reduce the greenhouse gas (GHG) emissions, and iii) produce a valuable fertilizer (digestate).

Due to the distribution of manure availability in Switzerland, the analyzed greenhouse concept should only be considered in the lowland with a more temperate climate. The hotspots show where to look for the most promising locations. This visualization can be used to assist stakeholders in the identification of areas to be prioritized for action. Although the overall potential to produce heat and electricity for greenhouses is limited, it is by no means negligible. While the resulting greenhouses in Switzerland would be rather small and probably run as a side-business, other countries with larger farms should be able to develop this symbiosis on a larger scale. Moreover, the technology is steadily improving (SCCER biosweet 2014) and it can be expected that in the future for a similar amount of resources (Burg et al. 2019), more energy can be produced.

It can be expected that the quantity available to produce energy in agricultural biogas and heat greenhouses is actually higher than presented here, as manure is often co-digested with up to 20% of other substrates in order to maximize the biogas yield. Such plants still profit from the agricultural extra subsidies for manure-based plants (BFE 2015).

Regarding temporal variations, an advantage of the symbiosis is that manure availability and greenhouse peak heat demand follow the same general pattern along the seasons: heat demand is maximum during the coldest months when cows are mostly in the stables and the manure therefore fully available. Less manure is collected when the animals spend more time outside in spring and summer, which is also when the greenhouse heat demand is at the lowest. The heat surplus could still be used for additional purposes, such as drying hay or wood (Biomasse Suisse 2019; Rutz et al. 2015; Mergner et al. 2013). However missing demand for surplus heat is seen as a challenge by many (Lybæk and Kjær 2015), and the possibilities to use heat in summer in Switzerland are more limited than in winter (Buffat and Raubal 2019). Due to decomposition, manure storage from summer to winter would cause high biogas losses, leading to high GHG emissions and lower energy recovery (Burg et al. 2018b) and hence is not recommended.

Our sensitivity analyses showed the importance of factors such as energy efficiency, greenhouse material, or indoor temperature chosen for the greenhouse. Although a constant value is assumed for the indoor temperature to calculate peak heat demand in this work, indoor temperature variations could influence both heat demand and yield production. For instance, there is a linear relationship between energy demand and tomato production in the range of 17 ºC to 26 ºC (Golzar et al. 2018). Besides, outdoor temperature remarkably varies during the year which considerably affects greenhouse heat demand. Therefore, not cultivating tomatoes during cold months of the year like January and February could increase the energy performance of the greenhouse and the area that can be cultivated. All these characteristics vary depending on the location of the system. Also, the choice of the crop has a strong effect on the heat demand and potential greenhouse cultivation area, whereby crops such as lettuce do not have as high demands on temperature as tomatoes (see SI). This choice should be done according to local conditions and local consumer demand. The chosen crops in the present case, namely tomatoes, lettuce, and cucumber, are the second, third and sixth most eaten vegetables in Switzerland (UMS 2015) and hence it can be expected that demand for them is high.

If used all year round for tomatoes, the total manure-biogas heated greenhouse surface of up to 104 ha and the total vegetable production seems rather small. However, in relation to the total existing greenhouse production of only 471 ha in 2018 (increasing from 385 ha in 2008) (UMS 2015; SZG 2019), it is a rather substantial increase. In our case, we are considering greenhouses, with glass or plastic covering material without CO_2 enrichment and supplementary lighting. The typical yield for these types of greenhouses (heated plastic film tunnels) is 20 to 30 kg m^{-2} (Hemming 2010), giving a production of 20,800 tonnes a^{-1} tomatoes for the lower estimation. The investment cost of plastic greenhouses is relatively low which makes them more economic, particularly for small greenhouses.

Moreover, we can expect farmers to plant their crops according to the local conditions, e.g. by not producing crops during the coldest month(s) or alternating crops depending on the season (salad in winter, tomatoes, and cucumbers in spring/summer). For instance, if farmers only cultivate tomato from March to October, the total greenhouse surface would be increased by 40 - 70%. The optimal scheduling of crops could improve the overall quantity produced per square meter. A different strategy would imply using a fossil fuel back-up for the heating system to cover the coldest times of the year and thus allowing a larger surface to be cultivated. We calculated a likely scenario where the back-up would cover 20% of the peak load. However, the optimization of different aspects is needed at the business scale depending on local conditions (e.g. neighborhood, crop preferences, costs). The symbiosis opportunity between greenhouse and biogas plants could be extended in several ways. First, the electricity produced by CHP could be used for artificial lighting in greenhouses. To increase yield and improve product quality, supplementary lighting strategies can be followed to provide sufficient light for crops. As a rule of thumb, the one percent rule indicates that a 1% light increment results in a 1% yield increase (Marcelis et al. 2006). Different strategies for supplementary lighting for tomato, cucumber, lettuce, and sweet pepper consider 1700-3000 h a^{-1} with PPFD (photosynthesis photon flux density) of 33-210 µmol m^{-2} s^{-1} (Heuvelink et al. 2005). Nowadays, the efficacy of an efficient LED lighting system is 10.7 mol kWh^{-1} (Philips). Considering a total greenhouse area of 104 ha, the total electricity demand for supplementary lighting could be up to 15% of the total electricity production of the agricultural biogas plants in Switzerland. This not only increases expected yield production in the greenhouse but also increases cultivation season especially when the natural light is not enough for crop growth (Tremblay and Gosselin 1998). In addition, CO_2 off-gases from burning the biogas in the CHP plant can be injected into greenhouses to enrich CO_2 concentration (Oreggioni et al. 2019) and fertilize crops inside the greenhouse. Nederhoff and Vegter (1994) estimate that 10 kg m^{-2} a^{-1} CO_2, increase yield production by 10%. However, both of the mentioned symbiosis strategies will increase the investment cost and the complexity of the system.

Detailed techno-economic investigations are also needed for better decision making. Indeed, important limiting factors for implementing anaerobic digestion are the large investment expenditure and limited economic efficiency (Bauer et al. 2017; Scarlat et al. 2015; Akella et al. 2009; Lovarelli et al. 2019). Business models will have to improve in the future (Theuerl et al. 2019). Complementing the biogas installations with a greenhouse can increase the financial benefits expected (Markou et al. 2017) although it has to be assessed at the business scale (Gruda et al. 2019).

Also, the residues of the greenhouse crops can be used as a substrate for the biogas facility, thus increasing the heat and energy production of the system. This forms a bilateral relation between the biogas facility and the greenhouse system. Nowadays, the local resources (manure, agricultural by-products) are usually used on the farm anyway. Farmers consider manure as a valuable resource for the fertilization of their crops. The anaerobic digestion provides the same amount of nutrients, concentrated in a lower amount of digestate to spread (Arthurson 2009). These aspects make the symbiosis between the biogas plant and the greenhouse very strong and intricate both ways, as the farm supplies the manure feedstock and receives the nutrients back in the form of the digestate. This digestate can be also used in the greenhouse to fertilize the crops. Further nutrient flow assessment would be required to quantify this benefit.

The system also allows a reduction in GHG emissions as it improves the management of manure (Chadwick et al. 2011; Gerber et al. 2013), substitutes the energy sources to produce the heat (Gruda et al. 2019), and reduces imports of both fossil fuel and food. Regarding the latter, domestic production of tomatoes could be increased by almost 50% and would cover 11% of domestic demand (Zhiyenbek et al. 2019), thus reducing the need for import, particularly before and after the main field crop season. However, it should not be forgotten than the risks linked to the energy system would also be transferred to the food system.

The local conditions will also need to be taken into account. Land suitability is very important, as relatively flat areas close to the stable where the manure is produced are needed to build the greenhouse. As preliminary tests, we had checked before running the simulations that such surfaces with slopes less than 10 º were available in each grid cell to make sure that our proposed solutions would be feasible regarding the terrain. The analysis showed that bigger farms are located in the lowlands anyway and not in steep terrain. However, only business cases will tell for which farm such a system can be put in place. Not only land availability but also legal context can influence if and where biogas plants and greenhouses can be built. Due to the lack of space, Swiss laws are fairly strict regarding what can be built on agricultural land (Swiss Federal Law on Spatial Planning), while being more flexible for industrial land. Moreover, local acceptance is also needed: while small greenhouses may not be a major concern for close neighbors, larger ones might face opposition for landscape conservation reasons. Also, the support of the local municipality will facilitate the procedure for obtaining a building permit. Finally, the farmers themselves need to show an interest to integrate the here proposed symbiosis concept of manure-based biogas as a heat source for greenhouses into their daily practices. All these aspects need to be integrated when moving to the business case and implementation level.

5. Conclusions

In this paper, a case of symbiosis between manure-based biogas plants and greenhouse systems in Switzerland was investigated. It was concluded that systems with combined agricultural biogas production and greenhouse cultivation are technically feasible and symbiosis should be strived to promote low-carbon agriculture. The other main conclusions of the present study can be expressed as follows:

- There is a heterogeneous distribution of manure resources and consequently the available heat to supply greenhouse peak heat demand in Switzerland. Our results show that the hot spots are mostly located in the Swiss lowlands while the cold spots lie almost entirely in the Alps. Also, the peak heat demand of a potential greenhouse ranges from 0.98 to 2.67 MW ha^{-1}, depending on where farms are located. These outcomes highlight the importance of spatial analysis to reveal the hot spots for symbiosis relations.
- Our combined supply-demand analysis indicates that the total greenhouse potential area based on manure within 1 x 1 km^2 grid and greenhouse peak heat demand is 109 ha. Thus, implementation of symbiosis between biogas facilities and greenhouses could be considered as a strategic plan to provide the energy needed and to reduce environmental impacts of greenhouse production which consequently strengthen local food production and shorten the food supply chain. However, detailed economic analysis considering investment/operation costs is necessary to evaluate the economic feasibility and justification of our proposed symbiosis relation.
- Sensitivity analysis shows the importance of heat utilization efficiency (the higher the CHP efficiency, the larger the greenhouse area that can be sustained), greenhouse covering materials (glass greenhouses have better insulation properties than plastic ones), as well as greenhouse crop type (greenhouses for lettuce need less heating than for tomatoes) on greenhouse potential area.

- It is not yet clear what the optimal sizes of biogas CHP are, as there is a tradeoff between transporting low-energy-density resources (manure) and efficiency gains by larger sizes. This needs to be investigated economically and environmentally in more detail.
- More studies will be needed to assess further important aspects of this possible symbiosis such as environmental benefits, nutrient cycles, and carbon balance in Switzerland and other regions of the world.

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Supporting information

The supplementary information gives additional details regarding background and details as well as additional results (maps) showing differences between greenhouse types (glass vs plastic), CHP heat efficiency 30 to 45 %, different seasons and months, and temperature (14 to 16°C).

Figure Legends

- Figure 1: General algorithm for calculating the greenhouse potential area.
- Figure 2: Spatial density of potential biogas yield from available manure resources in Switzerland, aggregated over 1 ×1 km^2 cells. Underlying data used to create this figure can be found in the Supporting Information.
- Figure 3: The hot spots and cold spots of potential biogas yield from available manure in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.
- Figure 4: Peak heat demand for greenhouse with glass cover material in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.
- Figure 5: Potential area for greenhouse per km^2 with glass cover material and CHP system with a thermal efficiency of 45% in Switzerland. Underlying data used to create this figure can be found in the Supporting Information.
- Figure 6: The impact of climate in different years on area potential for greenhouse with glass cover material in Switzerland (average=97, SD=7). Underlying data used to create this figure can be found in the Supporting Information.
- Figure 7: The impact of considering the minimum temperatures (coldest hours) of different months on the greenhouse peak heating demand. Months between May and August are not shown as no heating is required. Underlying data used to create this figure can be found in the Supporting Information.
- Figure 8: The total potential greenhouse area in Switzerland considering different minimal sizes of available combined heat and power (CHP) systems in $kW_{electric}$ and greenhouse areas. Underlying data used to create this figure can be found in the Supporting Information.

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