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Linking Solar and Biomass Resources to Generate Renewable Energy: Can We Find Local Complementarities in the Agricultural Setting?

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Highlights:

What are the main findings?

- Agricultural potential ~15 PJ/a biogas yield and ~10 TWh/a (36 PJ) solar electricity.
- Several technologies have been identified as possibilities for local complementarities.

What is the implication of the main findings?

- Temporal complementarity at the farm scale can only lead to partial autarchy.
- Larger scales are more relevant for complementarities between solar and biomass resources.

Abstract: Today, an energy transition is underway to tackle the problems of climate change and energy sufficiency. For this transition to succeed, it is essential to use all available renewable energy resources most efficiently. However, renewable energies often bring a high level of volatility that needs to be balanced. One solution is combining the use of different renewable sources to increase the overall energy output or reduce its environmental impact. Here, we estimate the agricultural solar and biomass resources at the local level in Switzerland, considering their spatial and temporal variability using geographic information systems. We then identify the technologies that could allow for synergies or complementarities. Overall, the technical agricultural resources potential is a ~15 PJ/annum biogas yield from residual biomass and ~10 TWh/a in terms of electricity from solar photovoltaic tiles installed on roofs (the equivalent to ~36 PJ/a). Biomethane upgrading, power to X, electrolysis, cooling or photovoltaic roofing on biogas facilities are among the examples that could foster complementarity in the system if resources are pooled within the agricultural setting. Temporal complementarity at the farm scale can only lead to partial autarchy. The possible benefits of these complementarities should be further investigated, looking in particular at the economic viability of such systems.

Keywords: bioenergy; complementarity; decentralized; biomethane; photovoltaic; Switzerland; synergies; GIS

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1. Introduction

Today, an energy transition is underway which has to tackle the problems of climate change and energy sufficiency in a fast-paced, changing world. However, renewable energies often bring high levels of variability that need to be balanced between different resources [1]. For this transition to succeed, it is crucial to use available renewable energy resources in the most efficient way and in combination to limit the need for storage [2], which is costly and often associated with losses. Moreover, matured technologies are already established in most countries, including Switzerland [3], and others are still being developed [4]. To ensure an efficient transition, resource availability needs to be quantified, including both its spatial and temporal aspects, to identify which resource is available where and when [5–7]. In Switzerland, solar and biomass resources have been estimated in detail throughout the country [8,9]. Indeed, biomass resources (material quantities) could be quantified at the municipality level for all biomass types available and solar resources (irradiation) at an even finer level. This information has since been converted into biogas yield and electricity generation potential, respectively.

Today, biomass is the biggest contributor (65%) to renewable energy sources in the EU and the second after hydropower in Switzerland [10]. Bioenergy can originate from various feedstock sources, including woody (e.g., forest wood and waste wood) and non-woody (e.g., manure, green wastes) biomass. In a previous study, we identified the largest remaining domestic biomass potential in Switzerland to be, by far, animal manure, with approximately 40 PJ of primary energy or an approximately 15 PJ biogas yield still to be mobilized [8]. One of the main benefits of biogas is that it can provide energy for an array of applications, including electricity generation, heat and transport. With the added inputs of other agricultural by-products, such as chaff, this untapped potential represents more than three-quarters of the biomass that could be mobilized in addition to what is used today. Farmers see their manure as an essential resource for fertilization [11], and its use for energy should therefore be embedded within the agricultural system. Although the number of agricultural biogas plants has increased slightly from about 100 to 110 in the last ten years [12], only about 5% of the manure potential is used [8]. Yet, a survey has shown that farmers are highly positive towards renewable energies and valued their contribution to the country's self-sufficiency [11].

Solar photovoltaic (PV) panels on existing rooftops have proven to be an efficient and viable sustainable energy resource for urban areas [13–16]. Indeed, they are well accepted, produce electricity and heat directly where needed, have a high potential and are now economically competitive with other technologies. In addition, solar panels can play an important role in integrating decentralized renewable energy resources in neighborhoods [17,18]. PV energy represented only 3% of the Swiss electricity supply in 2018, but is expected to cover up to 50% in 2050 [19]. The potential for electricity generation from PV energy in Switzerland has been estimated in previous studies [19]. Regarding the solar data, different levels of potential can be found. Potentials can consider general irradiation within a locality, the specific identification of suitable locations (roofs, facades, etc.) [20] and/or electricity production from different panel orientations which favor summer or winter electricity production [9]. The technical potential was found to be 65 TWh without economic considerations and between 22 and 54 TWh for a range of production costs [9].

The possible complementarity that could stem from using these two specific resources has only been partially studied, but several other complementarities have been looked into. Complementarity at the energy level can be defined as the capacity of two or more variable resources to work in a complementary way, thus improving the system's overall reliability and reducing periods of insufficient generation. For example, combining renewable energy with a different temporal availability at the grid level can limit the need for storage, e.g., the use of hydrological and geothermal energy as the base load, solar panels during the day and wind throughout the year. A number of these complementarities between different renewable energies have been studied, such as between PV and wind energy [21,22], wave and wind energy [23] or PV, wind and hydro energy [7], with these being reviewed partly in Ren et al. [24], both in terms of temporal and spatial complementarities.

The development of self-sufficiency thanks to decentralized energy generation based on available, local resources appears to be especially attractive as nations are transitioning to a new energy system while, at the same time, coping with the instability on the world market. A good setup can be found at the farm scale, where space, solar and biomass resources are available. The agricultural sector has already begun to generate energy in addition to producing food over the last few decades, and the value of autonomy, if not autarchy, is strong among farmers.

Due to a specific combination of resource availability, location characteristics and framework conditions, local complementarities could be favored, particularly in exclusively agricultural settings, for the solar resources available on farms and specific agricultural residues (animal manure and agricultural by-products). Indeed, farms are often further away from main settlements, and the value of autonomy is strong in this community [11,25].

Here, we investigate the solar and biomass resources at the local level in Switzerland, considering their spatial and temporal variability using geographic information systems (GISs). Indeed, to evaluate the spatial features and distribution of complementarity, GIS applications provide a wide range of analysis and visualization possibilities, enabling us to show the spatial repartition of the two resources to see where and to which extent a complementarity could be possible and where installations might be the most favorable. We then review and identify the technologies that could allow for complementarities to develop. Finally, we present the possible advantages of combining solar and biomass resources for energy by describing a case study. We conclude with the pertinence of our system boundaries and the relevance of the combination of solar and biomass to the energy transition.

2. Materials and Methods

Here, we describe the GIS investigation of the solar and biomass resources at the local level in Switzerland, considering their spatial and temporal variability (Section 2.1). We then review and identify the technologies that could allow complementarities to develop (Section 2.2). Finally, we present the possible advantages of combining solar and biomass resources for energy by describing a case study (Section 2.3).

2.1. Temporal and Spatial Resources Potentials

2.1.1. Agricultural Solar Potential

We applied a hierarchical GIS methodology to estimate the spatial and temporal rooftop solar PV potential of agricultural buildings in Switzerland. The methodology consists of three main steps: (i) The theoretical potential, which quantifies the total annual irradiation considering shading (average value for the years 2004–2014 based on the most exhaustive study to date for Switzerland); (ii) the technical potential, which reflects the technical constraints of the available roof area and to a lesser extent building facades and greenhouse roofs; and (iii) the agri-technical potential, which relates to the technical potential of agricultural buildings.

In Switzerland, the federal government conducted an extensive country-wide solar potential analysis to plan for the expansion of solar PV energy [26,27], indicating a technical electricity production potential from roofs and facades for the whole country of up to 67 TWh/a without considering economic constraints. The study distinguished between different areas in terms of their suitability for PV energy. The *Feature Analysis* extraction tool in ArcGIS was applied to remove from the technical potential the less suitable areas, e.g., roof areas smaller than 10 m^2 and those classified as having a "low" or "medium" suitability [20] were subtracted from the theoretical potential. Thus, a total irradiation of 78 TWh/a (solar irradiation is the quantity that measures the energy per unit area of incident solar radiation on a surface, i.e., the power received during a time period, measured in Wh/m^2) of the total estimated theoretical solar roof potential of 99 TWh/a could be technically used. The same approach was also applied to facades. For these surfaces, the technical potential is defined by areas larger than 20 m^2 and classified as having at least "medium" suitability. This data is provided yearly but also monthly, enabling us to provide a temporal variation of the resource. Based on the total irradiation, the electricity yield was calculated assuming an average module efficiency of 17% and a performance ratio (the relationship between actual and theoretical energy outputs for PV panels) of 80% [28]:

$$\text{Electricity yield [kWh/a]} = \text{Total irradiation [kWh/a]} \times 0.17 \times 0.8 \quad (1)$$

Farm coordinates [29] were used to locate buildings in an agricultural setting. However, these point coordinates indicate only the main building, whereas a farm comprises several buildings (e.g., stables and storage room) located in the vicinity. Considering the typical structure of Swiss farms, a 50-m buffer around the main farm point was used to detect the presence of these additional farm buildings (Figure 1). Hence, this buffer was used to assess the temporal estimation with a monthly resolution based on a 10-year average (2004–2014). Greenhouses often located a little further away from the farm building were also included in the overall PV potential assessment but could not be specifically assigned to one farm. In addition, we also used a 75-m buffer around the main farm point for sensitivity analysis and to assess how the local network could impact the solar potential (using agricultural buildings and neighbors' roofs).

Figure 1. Identification and assignation of roofs within an agricultural setting relative to the closest farm to estimate the local PV potential.

2.1.2. Agricultural Biomass Potential

The spatial potential of agricultural biomass was estimated based on data from the national agricultural inventory [29], which provide the numbers and types of animals as well as the surface of all the crops grown for the ~50,000 farms in Switzerland. Here, we used the available potential of farm animal manure and agricultural residues (the by-products of main crops and intermediate crops planted between main crops to preserve the soil) technically available according to current practice [8]. The animal manure potential is the total annually collected amount, which is the generated amount after removing losses occurring in the pastures. Only a small percentage of the theoretical potential of agricultural by-products was considered available, since most of them cannot be readily collected today. The potential biogas production in the present study was calculated using the specific biogas yield from fresh biomass (approximately 15 PJ for the year 2014) [8,30]. Neither the potential of co-substrates from industrial or municipal organic wastes nor energy crops were considered, but only biomass arising at the farm level.

Manure is by far the main agricultural input (>90%). Its monthly temporal resolution was performed considering the number of days the animals spend in the field according to official surveys [31] and splitting this number following the local regulation [32]. The approach was confirmed by local expert knowledge and the detailed calculations have been added to the Supplementary Material Information.

2.2. Possible Complementarities

Many complementarities are conceivable between biomass and solar potentials. Broad research of the available literature (e.g., [3,4], see Supplementary Material Information for a more detailed list) and several insightful meetings with technology developers and farmer associations [33] allowed us to identify the most promising ones within the Swiss agricultural system (Table 1, Figure 1). They mainly consist of seasonal and technical complementarities, described in more detail thereafter.

Table 1. Identified promising technologies for complementarities between biomass and solar resources for energy in the Swiss agricultural setting.

Technology	Description
Anaerobic digestion and combined heat and power (CHP) plant	Manure and agricultural by-products are fermented in a digester, and the produced biogas is then used to produce electricity and heat with a combined heat and power (CHP) plant. This represents the standard case today (if agricultural residues are used for energy).
Raw manure separation	Raw manure collected from stables is separated with a screw press into two fractions: solid and liquid.
Biomethane upgrading	Electricity generated from PV panels can be used to purify biogas into biomethane. Thus, a portion of the energy can be stored in the natural gas grid.
Power to X and electrolysis	The biogas provides CO_2 for the methanation process, while the electrolyzer is operated with PV electricity to produce the required hydrogen. The product is synthetic natural gas and can be stored in the natural gas grid.
Cooling	The heat produced during biogas combustion in a CHP can be converted to provide cooling with a heat pump powered by PV electricity.
Photovoltaic on biogas facilities	PV panels can be installed on extra infrastructure provided by the biogas facilities, mainly on additional biomass storage halls.

2.2.1. Seasonal Balance

Solar energy's low yield in winter can be offset by larger energy generation from agricultural biomass in winter. Indeed, animals spend more time inside stables in winter, and more biomass can be collected. The biogas plants are also not dependent on the day/night cycle. Moreover, biomass storage can also increase this effect; biomass collected in the summer could be kept for energy use later in winter. This can, however, lead to a loss of up to one-third of the biogas potential [30]. It is also important to note that the storage of manure for two to three months is standard practice (especially in wintertime when farmers are not allowed to spread manure on the fields to limit nitrogen run-off and water pollution), and there is thus flexibility on when to use it.

2.2.2. Technologies

The technologies with the most promising complementarities were chosen and are described in detail (Table 1, Figure 2). They include certain technologies that are already commercialized and others that are currently being developed. Their technical requirements, such as their size and energy consumption, are identified. This includes descriptions of the technologies and, when available, the necessary conditions for their use (e.g., a minimal amount of local resources). Here, we consider technologies for the conversion of energy into electricity and heat, heat for direct consumption as well as its further processing into storable energy carriers (e.g., biomethane and hydrogen).

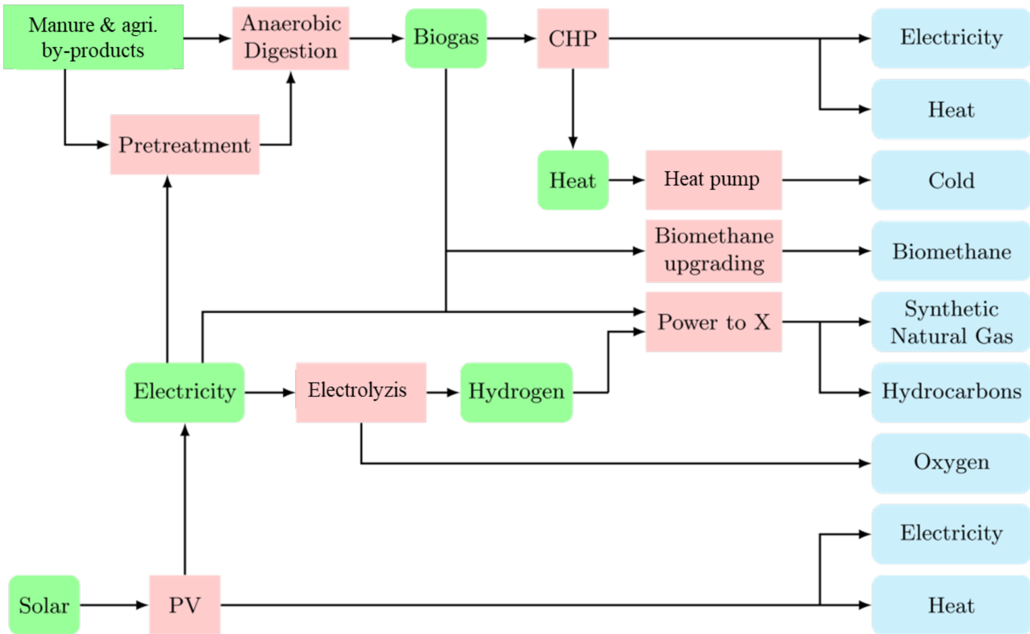

Figure 2. Overview of the various technologies identified as possible complementarities between solar and biomass resources and the possible links between the conversion paths. Conversion processes are shown in red, intermediate energy carriers in green and final energy carriers in blue.

2.3. Case Studies at Farm Level for Decentralized Energy Generation

Additionally, a case study regarding an individual farm was investigated. Valid data on load profiles are difficult to access due to data privacy. Switzerland is home to approximately 1.5 million cattle (primarily cows), representing the country's most important form of animal husbandry, with cattle being the animals that produce most of the manure (around three-quarters of the potential). Hence, we wanted to consider a farm holding cows. In recent studies [4], we assumed a minimal installed electric capacity of 10 kWh for the realization of a biogas plant (which corresponds to the manure of approximately 75 livestock units). However, Switzerland is characterized by small farms (holding, on average, around 25 livestock units only). Hence, for this approach, we wanted to consider a farm that was large enough to run its own biogas plant. Here, we focused on one farm where the farmer was willing to cooperate and provide us with the necessary data. This farm counted 67 cows, 9 fatted calves and 500 laying hens, leading to a production potential of 470 GJ in biogas yield [29]. The largest roof was 770 m^2, and the total roof area was 2063 m^2. Based on these numbers, we calculated the quantity of electricity the farm could produce with PV panels and a biogas plant ran only with its own manure resources. Then, we compared this electricity production potential with its actual consumption. The detailed load profile of the farm was measured over eight months (from January to August) [34] and the power demand during this period totaled 38,000 kWh. Hence, we estimated the extent to which this electricity potential could cover the farm's self-sufficiency and how much would still need to be provided by the electricity grid. The heat was not included in the analysis because no data on the heat demand was available. We assumed that the total available surface of all farm roofs might be used for photovoltaics. We calculated the self-sufficiency for the scenario of the agricultural residues of the farm (mainly manure) being fermented in an anaerobic digester according to their spatial distribution. The biogas would be fed directly into a CHP, producing electricity and heat as the base load. Self-sufficiency is reached when the electricity production covers the demand at any time.

3. Results

Here, we present the results of the GIS investigation on agricultural solar and biomass resources (Section 3.1). We then review the technologies identified for potential complementarities (Section 3.2). Then, we present a case study involving a combination of PV panels and a biogas CHP plant for a specific farm (Section 3.3).

3.1. Resources

For clarity, we present the spatial (Section 3.1.1) and temporal (Section 3.1.2) distribution of the two resources separately, as the temporal distribution was based on the total yearly value found from the spatial analysis.

3.1.1. Spatial Distribution

Here, we first describe the agricultural solar potential.

The agri-technical irradiation potential was found to sum up to 71.9 TWh/a (~259 PJ) for the roofs of agricultural buildings within a 50 m buffer. The spatial distribution shows that high irradiation potentials can be found across the whole country (SI). In addition, an agri-technical irradiation potential of 29.3 TWh/h was estimated for the facades of these buildings (thus +40%) and 4,8 TWh/a for greenhouses (+14.8%) that were not yet included in the 50 m buffer.

Regarding the electricity yield itself, a total of 9.6 TWh/a (~36 PJ) could be produced. This includes roofs on agricultural buildings (50 m buffer) (Figure 3). Additionally, 39.9 TWh/a could come from facades (+40%) as well as 0.7 TWh/a from greenhouses (+14.8%).

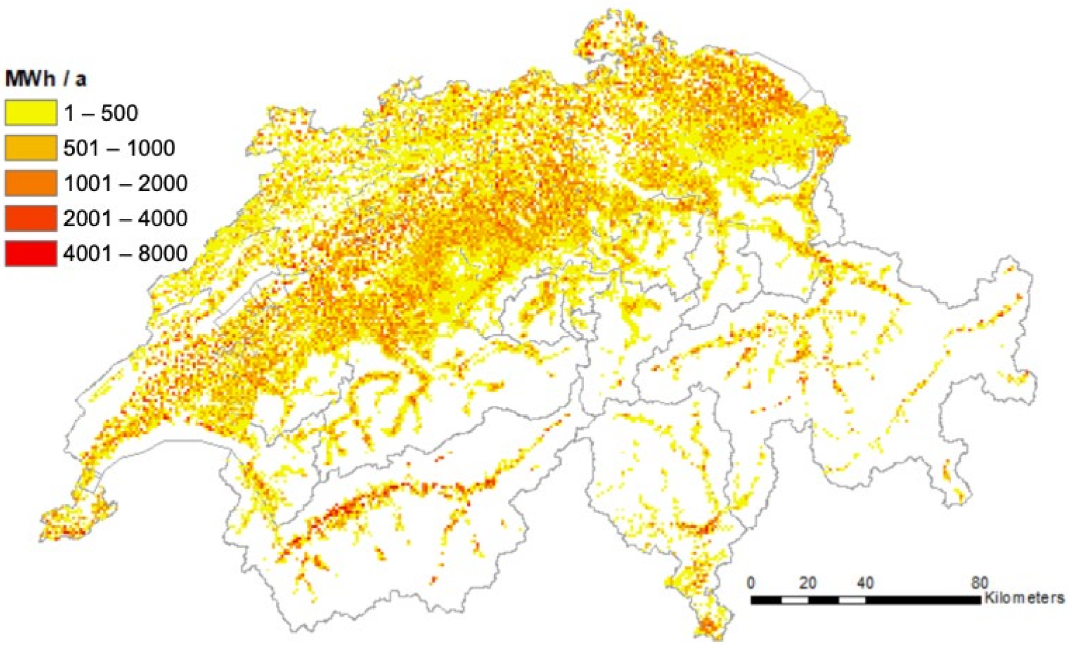

Figure 3. Agri-technical electricity production potential in MWh per year on agricultural roofs (50 m buffer around the main farm building).

This second part concerns the agricultural biomass potential.

As can be seen on Figure 4, agricultural biomass is widely distributed throughout the country, which complicates its exploitation for energy purposes. An increased occurrence is observed along Alpine valleys and in the central Plateau, where most animals are. After the subtraction of manure losses through grazing, the total technical potential for biogas yield is 15.15 PJ/annum.

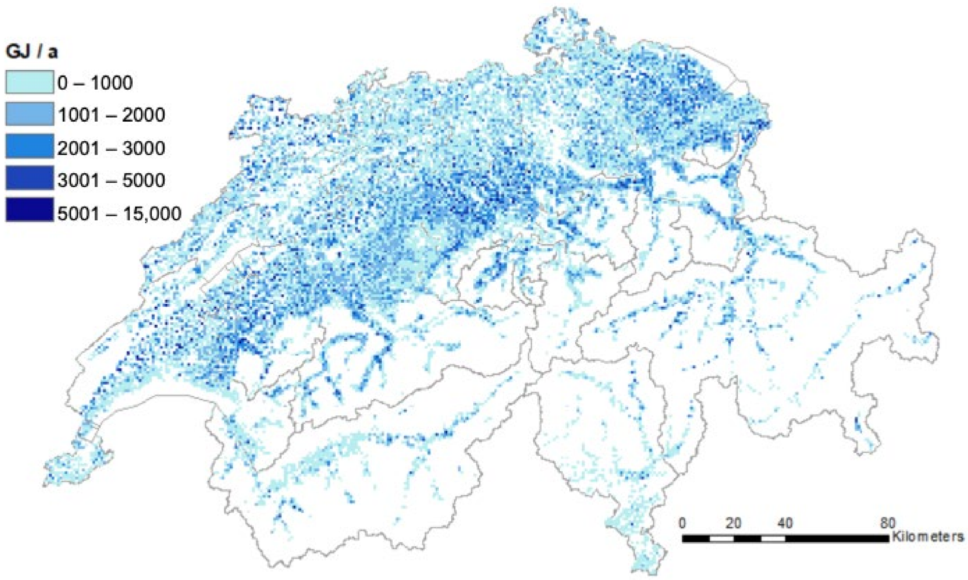

Figure 4. Technical potential of manure and agricultural residues in GJ per year of biogas yield.

3.1.2. Temporal Distributions

The temporal distribution of both resources shows a possible temporal complementarity, as they are very different throughout the year (Figure 5). As expected, the agri-technical solar irradiation potential reaches a peak in summer at almost 35 PJ for July (corresponding to 1.32 TWh of the electricity production potential), whereas it massively drops in winter, with below 6 PJ for December. Biomass presents a far less drastic change throughout the year, reaching 1.5 PJ/month in winter (December) and 1 PJ/month in summer (July).

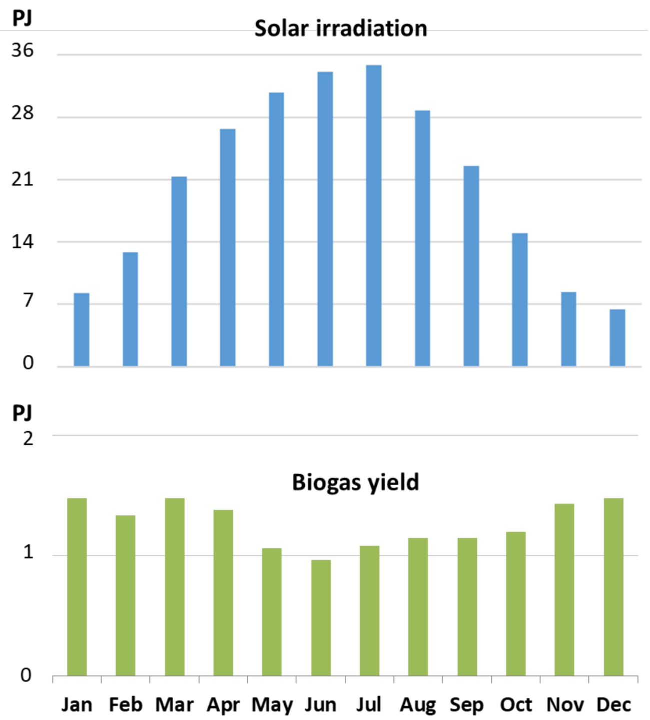

Figure 5. Monthly distribution of the agri-technical potentials: solar irradiation (above) and biogas yield (below) in petajoule (PJ) per month.

3.2. Identified Technologies Combining Solar and Biomass Resources

Here, we provide a description of the identified technology combinations, following our analysis and discussions with experts of the different technologies involved. The focus is set on the complementarity between solar and biomass energy resources, opportunities and challenges.

3.2.1. Separation

Raw manure consists of approximately 15% solids and 85% liquids in terms of volume [35]. This makes it difficult to store and transport. Moreover, during storage, part of the available primary energy is lost through easily degradable substances in the liquid fraction through fermentation. The separation of raw manure into a liquid (10–15% vol.-%) and a solid fraction (85–90% vol.-%) allows for the easier handling of the liquid slurry [36]. Both fractions contain about 50% of the primary energy. The liquid fraction is digested locally, and the solid manure is transported to a regional biogas plant. This manure pretreatment has several advantages: a reduction in costs and emissions regarding the transport of the solid fraction to a regional biogas plant when compared to raw manure and an increased overall biogas yield due to the earlier digestion of the easily degradable substances in the liquid fraction.

Press screws are usually used for separation. The separation leads to an increased concentration of primary energy in the solids. With a subsequent rapid fermentation of both the solids in a conventional regional biogas plant and the liquid manure in a high-performance membrane bioreactor (MBR) on site, a maximum energy yield can be achieved [35]. A pilot plant of an MBR under laboratory conditions with low-solids slurry was able to achieve twice the gas yield. In this process, the mass is led against a screen through which the liquid fraction can flow, and the solids are retained [37].

In principle, separation can occur on any farm collecting manure. Nevertheless, only farms with a minimum potential for which the use of a dedicated biogas plant is realistic should be considered, which is a minimum of 1.3 t/d manure equivalent to 474.5 t/a [38]. The power demand depends on the volume of the collected slurry and is calculated with Equation (2). The power demand corresponds to the largest power demand in the study from Meier et al. (2018) [36]. In this possible complementarity, PV energy provides the power for the separation process.

$$\text{Electricity demand [kWh]} = \text{Volume raw manure } [\text{m}^3] \times 1.5\ [\text{kWh/m}^3{}_{\text{separated liquid manure}}] \tag{2}$$

3.2.2. Power to X

Power to X describes the conversion of electricity into something else, such as hydrogen, synthetic natural gas, liquid fuels or chemicals. In the first step of our complementarity, electrolysis is used to split water into hydrogen and oxygen [4]. There are three different technologies for this: an alkaline electrolysis cell, a solid oxide electrolysis cell and a polymer membrane electrolysis cell (PEM). PEM electrolyzers have a 65% efficiency [39]. They bring the advantage of being quickly adjustable, with the possibly of them being operated in a variable capacity between 10–100% of a full load, thus following the fluctuating production profile of PV energy.

The following step consists of a methanation process. The produced hydrogen is mixed with biogas to convert the carbon dioxide it contains into methane and water. [4]. On the one hand, this makes it possible to improve the biogas quality to a high concentration of CH_4. On the other hand, part of the electricity from PV panels is also converted into chemical energy in the form of methane (power-to-methane). In addition, the excess heat from the exothermic methanation reaction and the downstream condenser can cover the heat demand of the anaerobic digestion. The produced synthetic natural gas (SNG) can be either fed to the grid or stored in a local fuel station. Methanation can be achieved using either a biological or a catalytic reactor (Figure 6). An economic study has shown that a system with a catalytic reactor is advantageous, since the large reactor volume in the biological variant results in much higher costs and requires more space [40]. Thus, we only considered the catalytic reactor further. Upstream, a desulfurization step is first needed to protect the catalyst, followed by a membrane unit to ensure a minimum methane content of 96%. The retentate is mixed back into the feed-in gas to minimize CO_2 and H_2 losses. The potential to store fluctuating PV electricity needs to be balanced with higher conversion losses due to the two conversion processes.

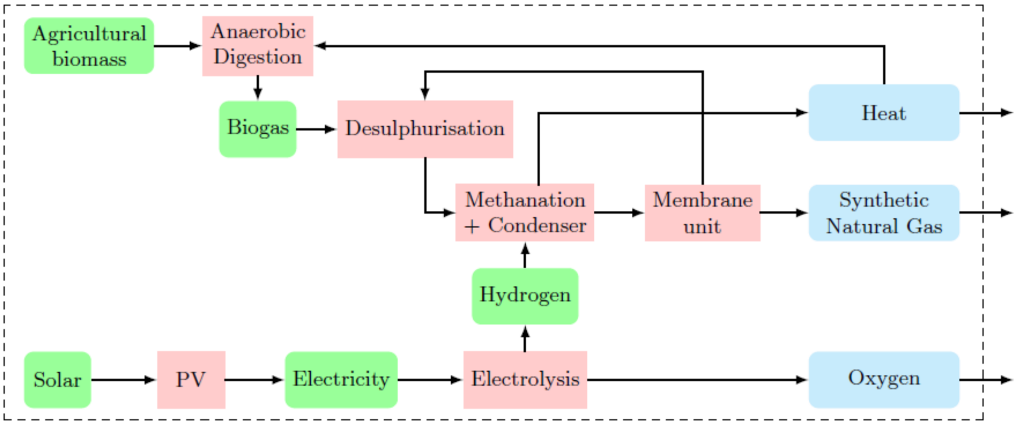

Figure 6. Power to X process flowchart using biogas as CO_2 source to produce synthetic natural gas. Resources and intermediate energy carriers are depicted as green, processes red and final products and energy carriers blue.

We estimated that the conversion of the produced hydrogen of a PEM electrolyzer with an installed capacity of 2 MW and 4360 operation hours per year would require at least 23.8 TJ biogas, with the installation needing to be close to the gas grid. The operating time was chosen to be approximately half a year to account for the lack of electricity potential from PV panels during the winter and overnight. The installed capacity is given in the context of the studied electrolyzers in Gantenbein et al. (2022) [40] to represent the scale of installations currently under research. According to data for 2018 [41], nowadays, biogas plants can vary in size between 5 and 740 kW in terms of installed capacity, so well under 1 MW.

3.2.3. Biomethane Upgrading

In this complementarity, the electricity provided by PV energy is used to upgrade the biogas (60% CH_4, 40% CO_2) to natural gas quality (minimum 96 Vol.-% CH_4). Thus, the energy from biomass can be stored in the gas grid for later consumption, e.g., in winter.

To feed into the gas grid, the CO_2 contained in the biogas and other undesirable pollutants for engines, especially hydrogen sulfide (H_2S), must be separated (Figure 7). There are different methods for biogas upgrading, such as physical and chemical absorption, membranes, pressure swing adsorption and pressurized water scrubbing. Pressurized water scrubbing appears to be a promising solution as it has a higher efficiency of about 95% with similar power requirements, compared to pressure swing adsorption, and does not require an upstream desulfurization step. In addition to purifying biogas, it is possible to collect the separated CO_2 in high concentrations with air stripping to use the carbon dioxide for other purposes [42]. The waste heat for heating the biogas plant fermenter is lacking and is required additionally.

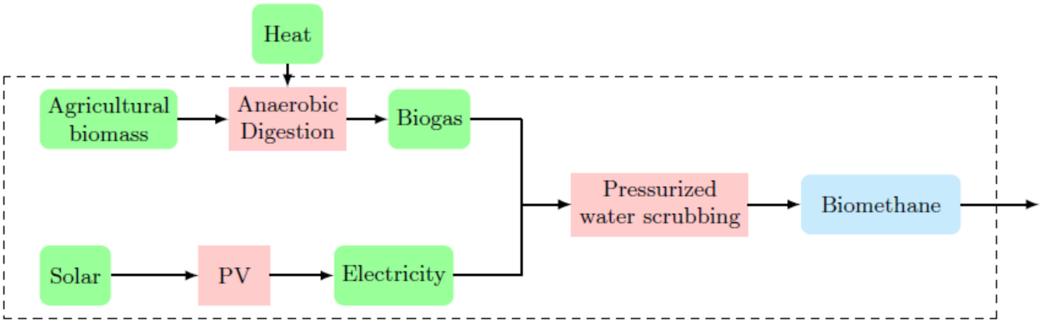

Figure 7. Process flowchart for biogas upgrading using pressurized water scrubbing. Resources and intermediate energy carriers are depicted as green, processes red and final products and energy carriers blue.

Unlike Power to X, a maximum capacity is defined in addition to a minimum capacity, and the installation needs to be close to the gas grid. The defined range is between a potential of 7890 GJ/y and 39,450 GJ/y, which correspond to biogas plants with installed CHP capacities of 100 kWh and 500 kWh, respectively, at 8000 operating hours per year. This range does cover approximately medium to large biogas plants in Switzerland [43].

3.2.4. PV Potential at New Biogas Plant Locations

The construction of biogas facilities offers new potential surfaces for PV panels. The additional infrastructure consists mainly of the biogas plant and the necessary substrate hall for storing biomass. Exhaust gases from the biogas plant, especially sulfur compounds, have a high material-aggressive effect on the PV modules and can lead to the corrosion of the glass. Consequently, PV panels should not be installed on the biogas plant itself. The exploitable area for PV modules can be calculated with simple geometry considering a tilted, rectangle mono-pitch roof for the substrate hall with Equation (3).

$$\text{Area } [\text{m}^2] = \text{total biomass from October to February } [\text{m}^3]/\text{storage building height } [\text{m}] \quad (3)$$

The size of the hall depends on the delivered volume of biomass. The minimum size of the storage building is specified by the national agricultural guideline [44], prescribing that the accumulating amount of manure can be stored for at least five months when farmers are not allowed to spread the manure in the fields in winter. The temporal distribution of manure indicates that the most biomass occurs between October and February. Considering a standard hall height of 6 m and a total biomass from October to February (45% of total yearly production) of 9.25 million m^3, these result in 1.5 km^2 in terms of the area available. Covering these roofs with solar panels assuming tilts of 11°, 20° and 30°, a total of 183 GWh, 191 GWh and 196 GWh electricity could be produced.

3.2.5. Cooling

Heat generated from the biogas plant can be used locally or fed into the district heating network. Alternatively, there is the possibility of providing cooling (5 to 20 °C) with an adsorption chiller powered by solar energy. Such an installation can be put in place even for small biogas plants. A permanent consumer of cooling is necessary throughout the year for a constant cooling system, such as an agro-industry factory or large office buildings. Otherwise, it is also possible to only provide cooling during the warm months and use the heat directly during winter for building heating at the farm level and, if possible, at the district heating level. For either system, the installation needs to be close to the district heating grid or the consumer of cooling.

3.3. Case Study

The chosen farm's electricity consumption or power demand was given by its load profile obtained from the electricity meter. The goal was to cover the demand in a direct mode (no storage) with power from PV panels and a local small biogas plant. Using both energy resources, a higher coverage degree of the own energy consumption can be achieved. In addition, waste heat from the biogas plant (CHP) can replace other resources for heating but was not quantified here due to a lack of data. We first compared the electricity demand provided by the profile load for eight months with the quantity of electricity that could be produced during the same period. For the purposes of self-sufficiency, we then identified when the local production could cover the local electricity demand in real-time.

For the specific farm described in the method, the potential electricity production for the total period of eight months from the PV panels and CHP plant would be higher in total than the electricity demand of the farm (Figure 8). However, when the constant operation of the CHP plant was assumed, self-consumption was only 79%, as the electricity would not always be produced when needed (e.g., needs are not covered when the blue line is higher than the sum of the red and green lines on Figure 8). The benefits of the CHP are particularly visible in winter when the energy demand is at its highest and the PV electricity production at its lowest. This autarchy level could increase if we consider that biomass can be stored to be used when the demand is highest and the operation of the CHP plant can also follow the demand. Assuming that the produced biogas can also be stored for a short time, the CHP plant would then be operated when the PV system cannot cover the demand.

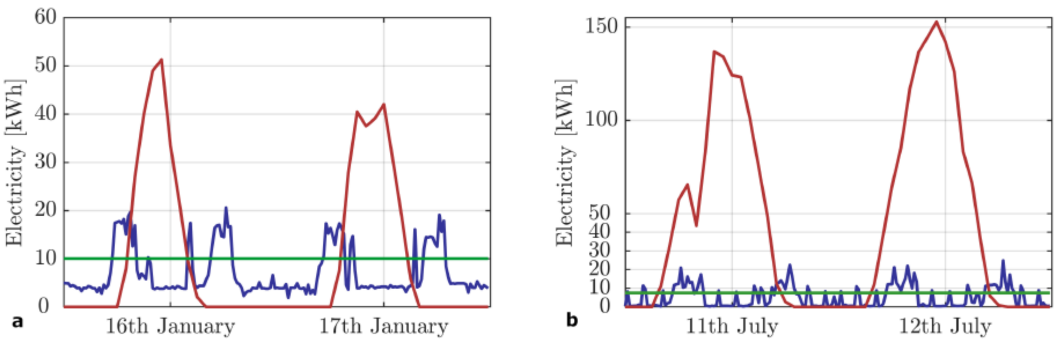

Figure 8. Farm's power demand (blue) compared to the potential solar roof electricity generation (red) and electrical yield of a manure-based CHP plant (green) for two selected days. (**a**) depicts the situation in mid-January, and (**b**) shows the situation in mid-July.

We have summarized all the results presented in Section 3 in the Table 2 below.

Table 2. Results summary.

Category	Description/Requirements
Potentials in agricultural settings	15 PJ/a of biogas from biomass. 10 TWh/a or 36 PJ/a of electricity from solar PV panels on roofs.
Raw manure separation	Minimum farm size of 1.3 t/d manure equivalent to 474.5 t/a. The power demand depends on the volume of the collected raw manure and is calculated with Equation (2). Electricity demand [kWh] = Volume raw manure [m^3] × 1.5 [kWh/m^3 $_{\text{separated liquid manure}}$] (2).
Power to X, Electrolysis	PEM electrolyzer with an installed capacity of 2 MW and 4360 operation hours per year. At least 23.8 TJ of biogas during the same period. Installation close to the gas grid for injection.
Biomethane upgrading	Biomethane upgrading installations with capacities between 8 TJ/y and 40 TJ/y (which corresponds to biogas plants with installed CHP capacities approximately between 100 kWh_e and 500 kWh_e).

Table 2. *Cont.*

Category	**Description/Requirements**
Cooling	Installation close to the district heating grid or the consumer of cooling.
PV on biogas facilities	Area [m^2] = total biomass from October to February [m^3]/storage building height [m] (3). Considering a standard hall height of 6 m and the complete storage of the biomass occurring from October to February, when it is not allowed to be spread on fields (45% of total yearly production or 9.25 million m^3), these lead to a potential surface for PV panels of 1.5 km^2. Covering these roofs with solar panels assuming tilts of 11°, 20° and 30°, a total of 183 GWh, 191 GWh and 196 GWh electricity could be produced.

4. Discussion

Here, we used GIS methods to assess the distribution of agricultural biomass and solar resources, focusing on their technical potential for energy use. Using today's current technologies, these potentials result in a yield of 15 PJ/a of biogas from biomass and 10 TWh/a or 36 PJ/a of electricity from solar panels on roofs. In comparison, in Switzerland in 2018, agricultural biogas plants provided 1.44 PJ of biogas (+1.24 PJ from industrial biogas plants), and solar panels produced 7.84 PJ of electricity (2.2 TWh) [45]. Compared with the country's 834 PJ/a final energy consumption [46], the agri-technical potentials of solar and biomass resources represent 4% and 2%, respectively. In a time of high uncertainty with regard to energy supplies, this is not negligible.

Other studies have also quantified and investigated possible complementarities between resources for energy at different scales. A global atlas of solar and wind resources' temporal complementarity was devised at the world level [5]. Depending on regions, the complementarities can be more or less substantial, and each resource should be used accordingly where its potential is highest or where the complementarities are the most beneficial. The different complementarities found in the literature at different spatial and temporal levels using different methods stress the necessity of using consistent methods for assessing various resources at one location to compare them adequately. Certain studies also considered a globalized energy system, where, for example, the diversity in local wind patterns can be used so that wind power production sites located on different continents may result in higher system resilience at the global scale [6]. It would also encourage the integration of different countries' energy grids, up to intercontinental electricity interconnections.

Our study only considered the potential of agricultural residues and solar on standing buildings. Therefore, implementing one does not prevent the implementation of the other. The only element of competition involved is economic, both in terms of the farmer's investment choices and the authorities' allocation of subsidies. However, in other settings, conflicts between renewable energies can also occur regarding land use [47]. Additionally, both bioenergy (energy crops in many countries) and freestanding solar panels can compete for marginal or even agricultural land. Depending on local regulation, this competition can be exacerbated and lead to a less than optimal use of resources. Within the Swiss context, energy crops are not common practice due to a lack of subsidies and hence not an issue [48]. The legal framework is not favorable for energy crops in Switzerland compared to other EU countries [49]. Regulations can also change (e.g., the recent discussion of a change in the law in Switzerland regarding freestanding PV panels in mountainous areas, where the licensing procedures are to be shortened and simplified [50]), and it is important that this is done following informed recommendations from holistic studies.

We did not find strict synergies between the assessed solar and biomass resources, which would lead to mutual benefits of at least distinct elements. Yet, several possible complementarities exist. Regarding spatial complementarity, the biogas installations can offer an amount of new surfaces but only to a limited extent, as it would be on storage buildings alone. Temporal complementarity at the farm level is rather limited and presents much more possibilities at a larger scale, as most farms are connected to the grid and could thus use or deliver electricity depending on the needs of the larger grid. Biogas production can be modulated daily or seasonally to partly compensate for the much lower solar irradiation at night or during winter. However, the case study we performed hinted that it is unlikely to achieve autarchy at very local scales without additional storage. Of course, this is only one example that would need to be replicated at different locations with different local characteristics (e.g., farm size, animal numbers, etc.). Anaerobic digestion is the most common technology in place for agricultural installations in Switzerland. However, this is not the only technology able to use biomass for energy purposes, and other avenues should be explored.

The energy transition is increasingly seen as a promising opportunity for the economic development of rural areas [51], which is primarily associated with the establishment and ownership of decentralized, small-scale installations. In fact, renewable energy-based rural development is often shown to be a beneficial by-product of the energy transition. However, its potential is still largely untapped and depends strongly on the energy resource considered, as solar panels are becoming common in these settings. We have shown here the possibilities of combining only two resources. Solar technology is steadily progressing, and its economics and logistics are favorable, with farmers increasingly installing PV panels on their farms. Regarding bioenergy, both hope and skepticism are there [52], and despite the clear interest, many factors stand in the way [11].

Anaerobic digestion is the most common technology in place for agricultural installations in Switzerland. However, this is not the only technology that is able to use biomass for energy purposes. Several other technologies could be implemented and would allow for complementarities: pre-treatments to increase biogas production, biogas upgrading, methanation and Power to X. However, not all technologies can be implemented everywhere. While, for instance, separation only needs small manure quantities to be processed, other technologies are much more demanding regarding the needed installation size: biogas upgrading, methanation and power to X all necessitate biogas quantities above the amounts that most of today's agricultural biogas plants produce. The installed capacity these technologies require to be technically and economically viable is also high compared to what is found today in agricultural biogas plants. Moreover, farms where new installations would need to be built do not always have a suitable location, e.g., one close to the gas grid, district heating or potential heating/cooling consumers [53]. To reach such a minimum size, the resources of several farms must be pooled together, but this is not a straightforward process [11]. All these technologies need electricity to function, which is where the complementarity with solar energy can play a role. This input could be provided by PV panels, particularly in summer, when there is an overproduction of electricity from PV sources, compared to consumers' demand, that is very difficult to store [4]. All in all, the economic aspects of these new technologies should not be neglected; whereas solar has become the cheapest renewable energy source, even state-of-the-art biogas technologies are still costly (anaerobic digestion), and new technologies considered here are even more expensive or not yet commercialized. These are major challenges that still need to be tackled.

Indeed, here, we only looked at agricultural residual biomass with a focus on energy generation. However, other biomass types, such as green wastes, would also be available for biogas production. Moreover, heat is also an essential form of energy that was not included here. The possibility of heating the fermenter of a biogas installation with a solar heat panel has shown an increase in the efficacy of the digestion process [54]. Additionally, drying wood to increase combustion efficiency is an interesting solution in the context of using the waste heat from the CHP [55]. The chosen system boundaries are also highly important. The possible complementarities will strongly vary depending on the size of the considered area (local vs. regional vs. international) and the storage put in place (batteries or intermediate carriers). In the end, however, it is to be expected that it is primarily the economic aspects (including subsidies), enforced by legal restrictions, that will determine which installations are built and maintained in the future energy system.

5. Conclusions

Using today's current technologies, 15 PJ/a of biogas from biomass and 10 TWh/a or 36 PJ/a of electricity from solar panels on roofs could be generated in Switzerland in an agricultural setting. This agri-technical potential of solar and biomass resources represents 6% of the country's final energy consumption. It is essential for the energy transition that these resources are used, while not necessarily at the same time and locations. We did not find strict synergies between the assessed solar and biomass resources, which would lead to mutual benefits of at least distinct elements. However, several possible complementarities exist, and their possible benefits should be better identified, particularly when looking at the economic viability of such systems. However, these complementarities are more likely to arise at a regional rather than a local scale and should be studied within the larger context of the whole energy system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16031486/s1, Table S1 Electricity yields, depending on the considered existing surfaces; Table S2 Yearly electricity yields, depending on the considered existing surfaces; Figure S1 Agri-technical solar irradiation potential in MWh per year on agricultural roofs (50 m buffer around the main farm building).

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