

ORIGINAL RESEARCH

How much land does bioenergy require? An assessment for land-scarce Switzerland

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Abstract

To reduce greenhouse gas emissions, countries need to transform their energy system by increasing the share of renewable energies. For years, the use of fossil fuels meant devoting little land area to energy provision. As renewables require much more space, the relationship between renewable energy and land area becomes highly relevant. In this context, land scarcity is an important challenge, especially for densely populated countries. The power density concept, describing the relationship between energy carrier and area used for its production in W/m^2 , can aid decision-making for resources allocation. Bioenergy plays a key role in the energy transition due to its diverse applications. Here, we assess how much area it takes to generate, transport and process various biomass types for energy purposes. We differentiate between 10 biomass types, determining area requirement (m^2) and energy input (kWh) for each process along the supply chain. Using the whole sustainable biomass available requires $>0.1\%$ of Switzerland's land area (31 km^2). Particularly for waste biomass, the area required for energy is negligible. Power densities vary widely within and between biomass types. Taking the average between minimum and maximum, they are highest for coniferous protection forest against natural hazards 114 W/m^2 ($22\text{--}267 \text{ W/m}^2$) and green waste 96 W/m^2 ($26\text{--}176 \text{ W/m}^2$). All of these are lower than literature values for fossil fuels ($>1000 \text{ W/m}^2$). However, sustainable power densities including compensatory land for greenhouse gas emissions are higher for biomass (average 2.4 W/m^2 , maximum 14.4 W/m^2) than for fossil fuels (natural gas 0.9 W/m^2 , coal 0.2 W/m^2). Estimating land requirement and power density facilitates weighing up whether and to what degree different biomass types should be used for energy.

KEYWORDS

biomass, energy efficiency, land-use, power density, sustainability, Switzerland

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1 | INTRODUCTION

Since the Paris agreement (United Nations Framework Convention on Climate Change, 2015), many countries have committed to strongly reduce their greenhouse gas emissions. To reach this goal, the way of providing and using energy has to be profoundly transformed. In Switzerland, as in other countries, the energy system is based on a variety of non-renewable and renewable resources. The Swiss government's Energy Strategy 2050 (SFOE, 2018) promotes a large increase in the share of renewables in the future energy mix. The restructuring of the energy system is highly complex (Energy Watch Group & LUT University, 2019; Theuerl et al., 2019) in terms of technology, economy and society.

An important factor while switching to renewables is land use, particularly for a small country like Switzerland. One-third of its area is covered by rocky mountains, one-third by forest, leaving one-third to settlements and agriculture. Due to domestic nuclear power production and large imports of fossil fuels from abroad, the land area used for energy production has long been negligible in Switzerland (BFS, 2015). The transition to renewables will require larger areas of land to meet the demand of renewable energy compared to fossil fuels. Renewable energy facilities and transportation will occupy different amounts of land (Cruz, 2018). These additional land requirements, under the assumption that the current levels of energy consumption will be maintained, could trigger land-use conflicts, as already shown for food production (Souza et al., 2017) or a solar energy scenario (Capellan-Perez et al., 2017), including examples in Switzerland (Huber et al., 2017; Kienast et al., 2017; Späth, 2018). Limited space was identified as an obstacle for energy autarky, which is possible in many European countries, but unlikely in Switzerland (Tröndle et al., 2019). The main renewable energy source is currently hydropower with 12.3% of the total gross energy consumption and biomass represents 6.7% (3.8% wood, 2.4% wastes, 0.5% biogas; BFE, 2019a, 2019b). Against this background, the concept of power density by Smil (2010) describing the relationship between energy carrier and area in W/m^2 will be used as a departure point in this study to address the question of where and to which extent it is feasible and acceptable to promote bioenergy use in densely populated countries like Switzerland.

The energetic use of biomass has many advantages compared to other renewables: Biomass is a raw material that can be locally produced, often even arising as waste or by-product. The necessity of finding sustainable, domestic, resource efficient biomass solutions is well established (Panoutsou & Singh, 2020). When following best practices, its utilization for energy contributes to climate change mitigation. Biomass can generate three energy types: heat, electricity, and fuel. Moreover, it is storable and can compensate fluctuating energy production from wind and sun. However, the Swiss national

biomass energy strategy gives first priority to food and feed production due to land limitations and population pressure to avoid displacement effects in Switzerland (Swiss Federal Office for Energy et al., 2009). For this reason and unlike in neighbouring countries, domestic production of dedicated energy crops and wood fuel plantations are not supported by the government and not economically viable in Switzerland. The emphasis of this study on sustainable bioenergy is therefore placed on biomass resources that are not cultivated for the sole purpose of energy production. In order to set the course for a smart energy transition, policy-makers and society need innovative, yet intelligible concepts that help to improve the general understanding of the system. Such concepts could make complex interrelationships tangible and thereby support the identification of possible bottlenecks and sustainable pathways for the energy transition. Smil's concept of power density (Smil, 2010, 2015) offers a promising approach. Power density is defined here as the power that can be produced per unit of horizontal land area in W/m^2 . As such, it describes the relationship between energy carrier and area. On the one hand, fossil fuels such as crude oil (up to 1000 W/m^2), gas (up to 2000 W/m^2) or nuclear (up to 1600 W/m^2) have very high power densities: Their extraction and conversion require little land area, while their energy content is high (MacKay, 2009; Smil, 2010, 2015). On the other hand, renewable energies such as solar ($4\text{--}10 \text{ W/m}^2$) and wind ($0.5\text{--}1.5 \text{ W/m}^2$) have much lower power densities and therefore require much larger areas on the production side. This can pose a challenge, as it will be difficult, for instance, to supply the steel industry with energy from photovoltaic panels, since it requires huge amounts of energy in the production process.

Not only can the power density of different sources vary greatly but also the power density for a particular energy source, depending on many factors. It is therefore important to define precisely which process chain, conversion path and system boundaries are considered for each resource. For example, Smil (2015) estimates the power densities of two coal fire plants varying by size, conversion efficiency and type and resource used origins (300 and 1600 W/m^2). Biomass has usually a low power density, but mostly the energy crops or wood plantation, which is not grown in Switzerland, have been studied. However, there are many other biomass resources such as agricultural or anthropogenic biowaste that have not been examined and are very promising regarding their area requirement. To our knowledge, power densities for different bioresources have not been estimated previously, especially with such details, although this concept could constructively contribute to the discussion on sustainable energy transition targets and pathways.

Therefore, the aim of this paper is to quantify how much land area the energy supply from today's domestic biomass resources (Burg et al., 2018; Thees et al., 2017) is required in Switzerland and to determine their related power densities. Based on these results, we can inform planning, allocation or

decision-making in bioenergy production in Switzerland. To do so, we first (i) determine each process of the supply chain of 10 biomass categories and consecutively, assess the space requirements (m^2) and energy input (kWh) for each category. In a second step, we (ii) calculate the power densities for each category (W/m^2 ; Smil, 2010, 2015). Then, we (iii) establish and visualize the spatial requirements for the corresponding biomass type in km^2 considering each biomass sustainable potential. Finally, we (iv) expand the concept by considering the notion of sustainable power density (Buceti, 2014).

2 | MATERIALS AND METHODS

2.1 | Power density calculations

Power density is the power that can be produced per unit of horizontal land area in W/m^2 (Equation 1). For each process of the supply chain, we estimate the area in m^2 and the energy use in kWh per tonne and per year based on own data sets and literature values. To be homogeneous, we focus on Swiss or European cases, as values (e.g. energy content of livestock manure) and systems vary across the world. Using the primary energy per tonne of fresh resource (Burg et al., 2018), we remove the energy required for its processing and provision. The power densities consider the secondary energy, which is the energy obtained after transformation. In this analysis, secondary energy occurs in the form of electricity and heat, while gas is considered as an intermediate energy carrier used before transformation into secondary energy. We use the conversion efficiency from the most common conversion technology to calculate the secondary energy produced (electricity and heat) per tonne resources (Bauer et al., 2017). As common technologies with different efficiencies are currently in use, we calculate a range of power densities between the highest and lowest possible. This range also includes the variation of area and energy input required for each process of the supply chain.

The general formula to establish a relation between power density (W/m^2) and energy (Joule) is:

$$\text{Power density (MJ/m}^2\text{)} = \left(\frac{\text{Energy produced (MJ)} - \text{Energy input (MJ)}}{\text{Area used (m}^2\text{)}} \right) \quad (1)$$

where 'Energy produced' is the secondary energy produced per tonne of fresh weight per year in MJ, 'Energy input' is the energy used for the whole processed chain per year in MJ, 'Area used' is the area needed for the whole processed chain in square metres m^2 .

We then convert MJ into W: as all the quantifications are made for one year, we have $1 \text{ W} = 1 \text{ J/s} = 3.6 \text{ kJ/h} = 31.5 \text{ MJ/year}$ (Smil, 2015) and this allows to calculate an equivalence between an energy (MJ) and a power (W).

2.2 | Sustainable power density

The concept of power density allows comparison between different energy production methods from manure to fossil fuels in relation to area. However, as environmental costs are not included, an important aspect to guide technology choices is still missing (Lovins, 2011; MacKay, 2009). Accordingly, we decided to include an additional approach to incorporate CO_2 emissions as sustainability aspect.

Buceti (2014) includes CO_2 emissions, obtaining the 'sustainable power density' which considers the CO_2 emissions linked to bioenergy use and adds the area of forest needed to compensate this amount of CO_2 . This is the net removal of CO_2 from the atmosphere by forest ecosystems occurring when plant photosynthesis exceeds all processes of consumption and respiration, resulting in above-ground plant growth and increased root and microbial biomass in the soil. This generally reduces the overall power density of most resources and strongly reduces the advantage of fossil fuels. The sustainable power density values for energy crops are then reduced to $0.22 \text{ W}/\text{m}^2$ (instead of $0.6 \text{ W}/\text{m}^2$), and to $0.025 \text{ W}/\text{m}^2$ for coal (instead of $1000 \text{ W}/\text{m}^2$). Buceti considered CO_2 emissions for the whole process and calculated the additional area for three different scenarios to compensate coal, oil and gas usage. For Switzerland, calculation from gas is the most appropriate due to its current energy mix, as gas is the largest fossil fuel resource for electricity, and nuclear power is being phased out (see Data S1). To calculate the surface to add for each biomass, we took the CO_2 sink values for the total Swiss forests (1.6 million tonnes CO_2 per year for a total area of $13\,100 \text{ km}^2$; BAFU and WSL, 2015), which results in $122 \text{ g CO}_2/\text{year}/\text{m}^2$ compensated. Natural gas has an emission factor of 56.7 t CO_2 per TJ of natural gas burnt (FOEN, 2016). This leads to $225 \text{ g CO}_2/\text{kWh}$. Accordingly, each kWh used during the process chain and produced with natural gas has to be compensated by a forest area of 1.84 m^2 .

$$\text{Sustainable power density (MJ/m}^2\text{)} = \frac{\text{Energy produced (MJ)} - \text{Energy input (MJ)}}{\text{Area used (m}^2\text{)} + \text{CO}_2 \text{ compensation area (m}^2\text{)}} \quad (2)$$

where 'Energy produced' is the secondary energy per tonne of fresh weight per year in kWh converted into MJ, 'Energy input' is the energy used for the whole processed chain per year in kWh converted into MJ, 'Area used' is the area needed for the whole processed chain in square metres m^2 , 'CO₂ compensation area' is the area of temperate forest needed to compensate the CO_2 emissions of the energy used to process one tonne of fresh biomass in square metres ($1.84 \text{ m}^2/\text{kWh}$ used).

We then convert MJ into W: as all the quantifications are made for one year, we have $1 \text{ W} = 1 \text{ J/s} = 3.6 \text{ kJ/h} = 31.5 \text{ MJ/year}$ (Smil, 2015) and this allows to calculate an equivalence between an energy (MJ) and a power (W).

2.3 | System boundaries

The power densities were calculated for each of the following 10 biomass types: manure, agricultural crop by-products, sewage sludge, organic fraction of household garbage, green waste from households and landscape, commercial and industrial organic waste, forest wood, wood from landscape maintenance, wood residues and waste wood. The sustainable energy potential of these biomass types was calculated in a previous study (Burg et al., 2018). It is defined as the maximum annual available domestic biomass regarding environmental, technical, economic and social restrictions. Energy crops and wood fuel plantations were not considered in this study.

Relevant process chains were identified for the 10 biomass categories. To calculate the power density for each biomass, we considered the area of land and energy use for the energy production necessary for all processes along the chain (Figure 1) on a yearly basis. This is the area and energy used in addition to the standard practice of treating these biomass types without

by-products from other processes, therefore do not necessitate additional area or energy for its supply.

2.4 | Biomass process chains for energy conversion: General path

In this chapter, we first describe the processes which are valid for all 10 biomass types. We then describe the specificity of calculation for the two biomass types manure and forest wood (Section 2.5), as they have the highest sustainable potential for energetic use in Switzerland and represent the two main conversion pathways important for biomass: anaerobic digestion and combustion. The other biomass types are described only briefly here and in much more detail in Data S1. The process chains are visualized in Figure 2.

For each process of the chains, we calculated the area necessary for energy production and energy input. The total was calculated as follows:

$$\begin{aligned} \text{Total area} = & \text{Generation area} + \text{Harvest area} + \text{Storage}_{\text{Harvest}} \text{ area} + \text{Pretreatment area} \\ & + \text{Transport}_{\text{Conversion}} \text{ area} + \text{Storage}_{\text{Conversion}} \text{ area} + \text{Conversion facility area} \\ & + \text{Storage}_{\text{Disposal}} \text{ area} + \text{Transport}_{\text{Disposal}} \text{ area} + \text{Final}_{\text{Disposal}} \text{ area} \end{aligned} \quad (3)$$

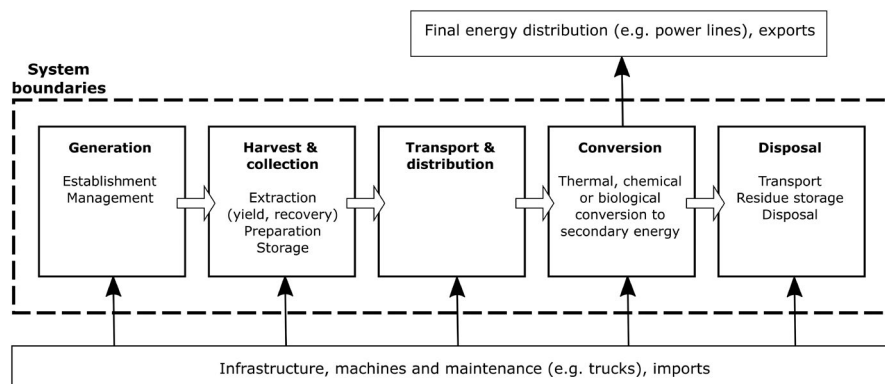
energetic use. Each process chain is separated in five main sections: biomass generation, harvest and collection, transport and distribution, energy conversion and residue disposal; each of which can be further divided. Most importantly, the boundaries are consistent between the 10 biomass types even though each biomass follows its own process chain. We only consider domestic resources. Underground space, for example, underground tanks, is not considered. Subsequent processes, that is, after the production of secondary energy (e.g. power lines), are outside our boundaries.

Each biomass process chain is described in detail in Section 2.5 and in Data S1. Some biomass categories were divided into subcategories. Only the additional land and energy use attributed to the energetic use of the resource is accounted for. Most of the biomass described here are waste or

All areas required are given in m².

‘Total area’ is the total area required for the whole biomass process chains for energy production, ‘Generation area’ is the area used to generate the biomass, ‘Harvest area’ is the area used to harvest the biomass, ‘Storage_{Harvest} area’ is the area used to store the biomass directly after harvest, ‘Pretreatment area’ is the area used to apply a pretreatment to the biomass, ‘Transport_{Conversion} area’ is the area of road used to transport the biomass from the generation area to the conversion facility, ‘Storage_{Conversion} area’ is the area used to store the biomass before conversion at the conversion facility site, ‘Conversion facility area’ is the area used for the conversion facility to process the biomass into energy, ‘Storage_{Disposal} area’ is the area used to store the biomass residues after conversion into energy, ‘Transport_{Disposal} area’ is the area of road used to

FIGURE 1 System boundary of the biomass process chain. The area and energy needed are only considered for the processes within the boundary. Externalities such as pollution are excluded



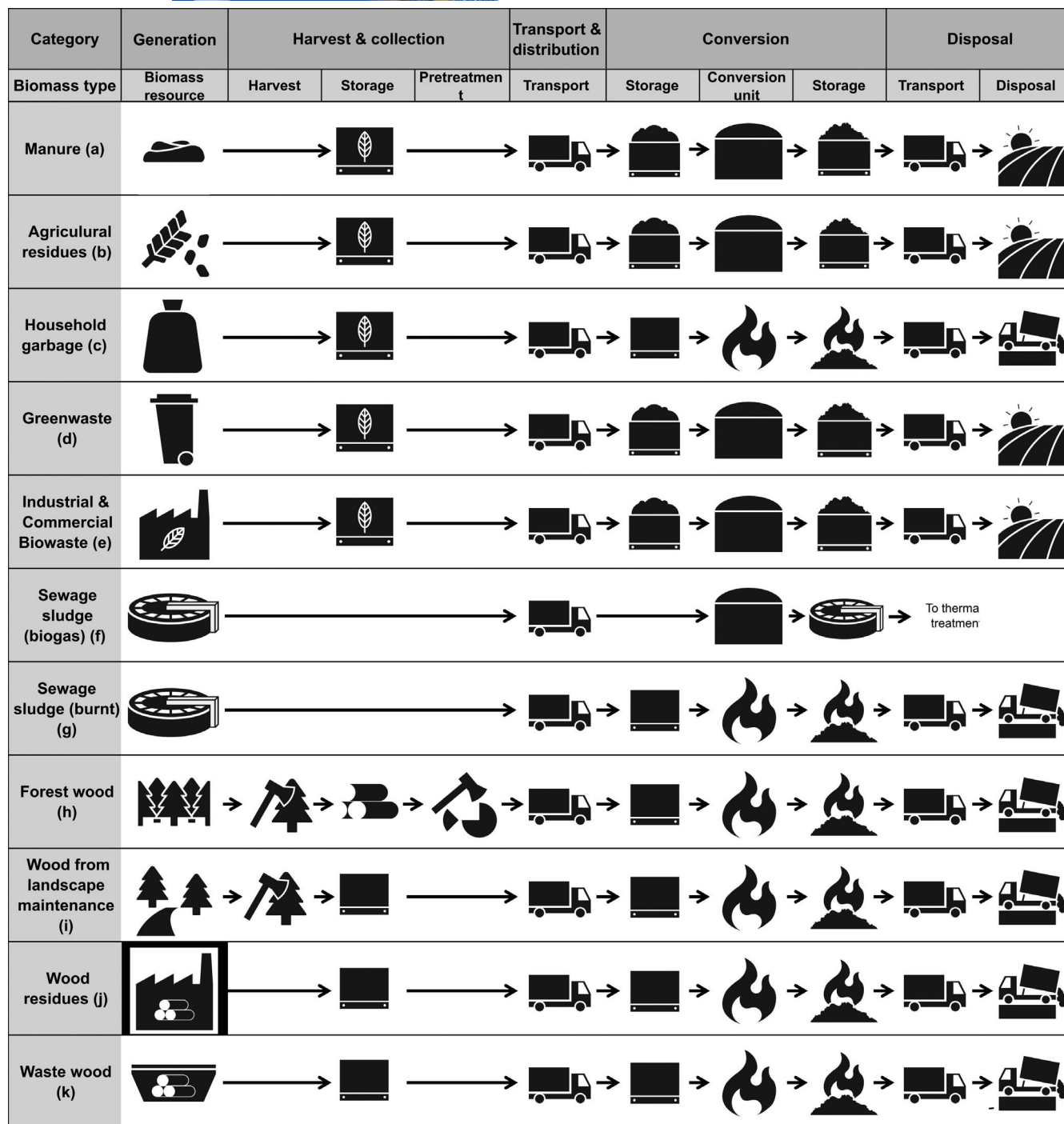


FIGURE 2 Process chains of biomass used for energy

transport the biomass residues from the conversion facility to the final disposal, 'Final_{Disposal}' area is the area used to store the biomass residues in the long term.

All energy required are given in kWh.

'Energy input' is the total energy input required for the whole biomass process chains for energy conversion, 'Energy

$$\text{Energy input} = \text{Energy generation} + \text{Energy harvest} + \text{Energy pretreatment}$$

$$+ \text{Energy storage}_{\text{Harvest}} + \text{Energy transport}_{\text{Conversion}}$$

$$+ \text{Energy storage}_{\text{Conversion}} + \text{Energy conversion facility}$$

$$+ \text{Energy storage}_{\text{Disposal}} + \text{Energy transport}_{\text{Disposal}} + \text{Energy final}_{\text{Disposal}}$$

(4)

generation' is the energy used to generate the biomass, 'Energy harvest' is the energy used to harvest the biomass, 'Energy storage_{Harvest}' is the energy used to store the biomass directly after harvest, 'Energy pretreatment' is the energy used to apply a pretreatment to the biomass, 'Energy transport_{Conversion}' is the energy used to transport the biomass from the generation area to the conversion facility, 'Energy storage_{Conversion}' is the energy used to store the biomass before conversion at the conversion facility site, 'Energy conversion facility' is the conversion facility to process the biomass into energy, 'Energy storage-Disposal' is the energy used to store the biomass residues after conversion into energy, 'Energy transport_{Disposal}' is the energy used to transport the biomass residues from the conversion facility to the final disposal, 'Energy final_{Disposal}' is the energy used to store the biomass residues in the long term.

These equations are then adapted to each biomass type in order to show the relevant processes only (see Data S1 for details).

2.4.1 | Transport

The estimation of the land area required to transport the bioenergy resources needs to consider the following factors: length of the overall road network, average width of streets, amount of transported biomass and vehicle type. The Swiss road network is about 71,520 km long and road freight reaches 28 billion tonne-kilometre (meaning that 28 billion tonnes of commodities have been moved over a distance of 1 km; OFROU, 2016). Most common in Switzerland are secondary road types which are 6 m wide on average (DAEC, 2013). We use half this width to calculate the road area used for each resource.

$$\text{Transport area} = \frac{(\text{Distance} * 0.003 \text{ km width}) * (71,520 \text{ km Total road length} / 28,000,000,000 \text{ Total t km})}{\text{Vehicle type}} \quad (5)$$

where 'Transport area' is the area needed to transport one tonne of fresh biomass in km²; 'Distance' is the average transport distance in metres, either from the generation point to the conversion facility ('Transport_{Conversion}') or from the conversion facility to the disposal ('Transport_{Disposal}') including the return trip; 'Width' is half width of the secondary road, 3 m; 'Total road length' is 71,520 km of Swiss road network; 'Total tonne-kilometres' is 28 billion tonne-kilometre road freight (service of moving one tonne of payload over a distance of one kilometre); 'Vehicle type' is 15–24 tonnes load depending on the biomass type.

2.4.2 | Conversion facilities

The conversion efficiencies vary according to the type of biomass, the technology used and the end product (electricity, heat, gas; Bauer et al., 2017; see Data S1).

Several biomass types such as manure are processed in agricultural or industrial biogas plants through anaerobic digestion. The resulting biogas is usually burnt to produce electricity and heat. Their efficiency range is 41%–56% (Bauer et al., 2017; Ökostrom Schweiz, 2018). Biogas can also be purified into bio-methane and injected into the natural gas grid (Scarlat et al., 2018). At the moment, this technology is not common in Switzerland (<1% of the existing facilities) and was not included here, but is expected to increase in the whole of Europe (Scarlat et al., 2018).

Biomass types such as the organic content of the household garbage or waste wood are treated in municipal incinerators. Other types of wood such as forest wood and wood residues are incinerated in small wood heaters, medium-sized combustion plants to large wood automated combustion facilities; they produce mainly heat. Their efficiency range is 12%–85% (Bauer et al., 2017; Stettler & Betbèze, 2016) and 26% was taken for wet biomass incineration (own calculation based on water content).

2.4.3 | Final step/disposal

In Switzerland, all non-recyclable combustible waste must be incinerated. These waste include household garbage, treated waste wood and sewage sludge. Incineration advantages are energy recovery, a significant volume reduction and reduced reactivity of waste before being landfilled. Ashes (BAFU, 2010) are stored before transport to specific landfills (BFS,

2016) that are subject to strict regulation (BAFU, 2019; see Data S1).

For the material that has been processed through anaerobic digestion, the land requirement and energy input for deposition of the digestate is irrelevant as, according to standard management, it is spread as fertilizer in agricultural fields and green spaces.

2.5 | Biomass process chains for energy conversion: Specific path for the different biomass types

Figure 2 illustrates the most important utilization paths of each biomass type, which are then explained below and in Data S1. All areas required are given in m² and all energy required are given in kWh.

2.5.1 | Manure

Animal manure refers to liquid and solid dejections from livestock farming. Farm animal excrements and urines form the basic components of this biomass category (Figure 2a). Depending on the stable system, liquid manure is produced without any additional material, except eventually water, while solid manure is mixed with bedding material. The sustainable primary energy potential for manure is 26.9 PJ/year and the biogas potential 9.9 PJ/year (Burg et al., 2018). We distinguish between solid and liquid manure based on their differing energy contents and management. Although manure is often digested with up to 20% co-substrate (BFE, 2015) in Switzerland, that is, together with material from green waste, energy and area requirements linked to co-substrates were not included in this category since they are already accounted for in the other categories.

Even though animals use pasture land and are kept in stables, we consider here only the additional land use needed for energy purpose related to transport and storage after the manure production in the stable. This includes the active collection from the stable, the transport to the conversion unit when it is not on the farm itself, the storage at the conversion unit built to receive the manure, the agricultural biogas facility itself and the extra storage for further maturation of the digestate. Later, the fermented digestate is then brought back to the initial farm. It is then spread on green spaces and agricultural fields. The adapted and simplified general formula (Section 2.4, Equations 3 and 4) can be found in Data S1.

2.5.2 | Forest wood fuel

In Switzerland, forest wood is first harvested for material use following sustainable management practice (Figure 2h). Parts not suitable for material use are used for energy. The allocation of resources to material or energy use is based on economic criteria. The share of forest wood used for energy is much higher for hardwood than for softwood (20%–30% vs. 50%–70%). Forest wood fuel consists of parts of stem and branch, brushwood and bark of merchantable wood. Needles and leaves are not included. It has a sustainable potential of 26.1 PJ/year primary energy (Burg et al., 2018). We differentiate between coniferous and broadleaf woods, as they have different energy contents. The management and logistic of coniferous and broadleaf have also different values (e.g. energy input for transport). The proportion of forest wood for energy varies depending on the region (BAFU, 2016). Similarly, we differentiate between two types of forest:

- Forests used for economical purpose, where we consider the percentage of its area (1.9 Mio m³ or 14 PJ/year) depending on the proportion of wood fuel collected (0.09%–98%;

BAFU, 2015a,b) and considering the other forest services (25%–40%), for example, recreation, ecosystem services... (Dai et al., 2017).

- Protection forests grown for protection against natural hazards, which growing area is therefore not considered as it is completely allocated to protection (1.5 Mio m³ or 12.1 PJ/year).

At the country level, they represent 51% (main purpose is economic) and 49% (main purpose is protection against natural hazards) of the total forest area with high regional variation (from 1% to 90% protection forest against natural hazard at the cantonal level; GEO Partner AG, 2016). For clarity, the power density of these two types of forest is calculated separately, although the biomass characteristics itself do not change.

After logging, trees dedicated to energetic use or parts of them are stored, left to dry in the forest, to be processed there later into logs or wood chips. These commodities are then transported by trucks to the facility for further conversion, with or without a first intermediary stop at a dispatching facility. The total length of forest roads in Switzerland of 30,000 km (Gautschi et al., 2017) is already included in the forest area. The adapted and simplified general formula (Section 2.4, Equations 3 and 4) can be found in Data S1.

2.5.3 | Other biomass types

Below is a short description of the other biomass types presented in this study. More details about energy contents, process chains and full calculations are provided in Data S1.

Agricultural residues: residues left on the fields after crop harvest, as well as intermediate crops sown for soil protection during winter to preserve nutrients.

Household garbage: green waste, paper-like material and organic natural products from municipal waste collected within the standard household garbage. The non-organic fraction is excluded.

Greenwaste from households and landscape maintenance: all non-ligneous waste of biomass collected separately by local authorities from households and during landscape maintenance in the settlement area.

Industrial and commercial biowaste: organic, non-woody waste from industries (e.g. food processing), retailers, catering services and paper manufacturing.

Sewage sludge: organic matter from central waste water treatment plants.

Wood from landscape maintenance: material from pruning trees and bushes, e.g. along roads. Following usual management, it is harvested. Depending on factors such as costs and safety, it is either left on site or removed to be further processed.

Wood residues: leftover wood (e.g. bark, splinters) from wood-product manufacturing and processing (e.g. in saw-mills, carpentries).

Waste wood: already used at least once for material use (e.g. wood from construction).

2.6 | Total area requirements

We calculated the area required per biomass types and sub-categories at the national and regional (see Data S1) level, if all the sustainable biomass potential was used, using the average values per tonne fresh weight for each biomass.

$$\text{Total area}_{\text{Biomass}} = \text{Total Sustainable}_{\text{Biomass}} * \text{Area Tonne}_{\text{Biomass}} \quad (6)$$

where 'Total area_{Biomass}' is the total area needed in Switzerland to exploit the sustainable potential of the biomass in m², 'Total Sustainable_{Biomass}' is the total sustainable potential in Switzerland of biomass quantity in tonnes, 'Area Tonne_{Biomass}' is the area required to process one tonne of biomass in m².

We took either the potential biogas yield (anaerobic digestion) or the primary energy (incineration) values from each biomass (Burg et al., 2018). The secondary energy was calculated assuming an average efficiency of 49% for biomethane (Bauer et al., 2017), 74% for wood incineration (Bauer et al., 2017) and 26% for wet biomass incineration (own calculation based on water content).

The additional potential (Burg et al., 2018) is the difference between the sustainable potential and the amount of biomass already used for energy. It was used to calculate the additional area required to use the whole available sustainable biomass for energy.

3 | RESULTS

3.1 | Process chain

The energy input required along the entire bioenergy process chain is mostly linked to harvesting and transport to the facility followed by residue disposal (Figure 3, top). Energy consumption of the incineration or biogas plant is included in the overall plant efficiency and therefore is not visible on these graphs (see tables in Data S2 for separate values). The energy used for disposal is mostly linked to the transport to the final destination. Forest energy wood (due to transport) and sewage sludge (due to water removal) require by far the largest energy input.

Land requirement for biomass generation becomes particularly relevant when the biomass is grown primarily for energy purposes as is sometime partly the case for forest grown primarily for economic purposes (69–522 m²/t). Other biomass types are by-products or waste; their land use is related to conversion and disposal (Figure 3, bottom; see Data S2 for details).

3.2 | Power density

The power densities are considerably scattered between and to a large extent also within the individual biomass types. They vary between −24 W/m² for incinerated sewage sludge for the worst case and 267 W/m² for coniferous forest for protection against natural hazard for the best case (Figure 4). Woody biomass has power densities one-third higher than the non-woody one on average (60 vs. 41 W/m²). Sewage sludge requires little extra space to produce biogas. However, it has to be incinerated afterwards for

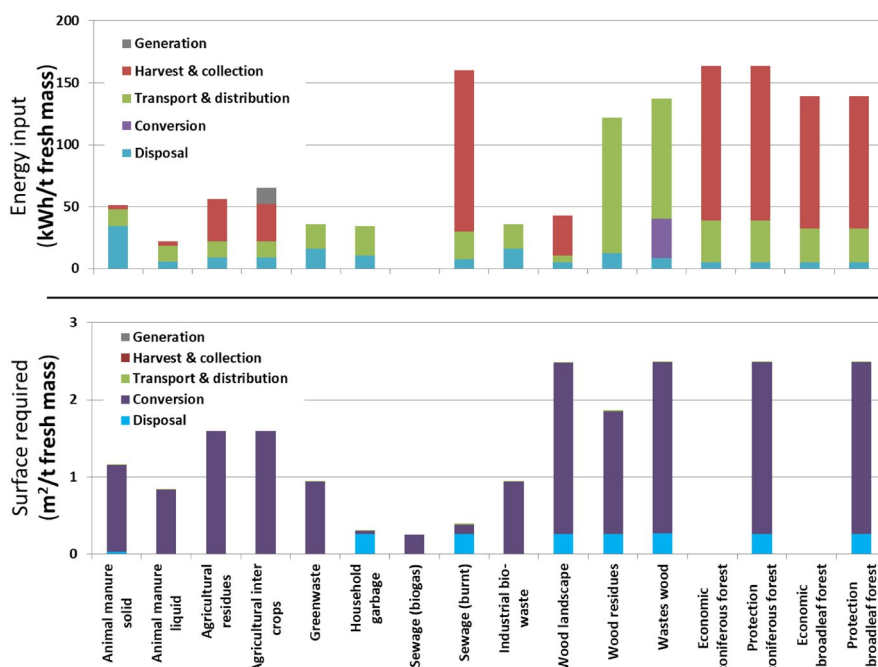


FIGURE 3 Average energy input (top) and average area (bottom) required for the generation of energy from different biomass along the process chain for one tonne fresh weight. For scaling reasons, the much larger area needed for coniferous and broadleaf economic forests (69–522 m²/t) are not shown here

legal reasons. Its energy production through combustion is often negative due to its high water content, which results in negative or very low power densities of -24 to $+1.5$ W/m². Similarly, the organic fraction of the household garbage contains a higher water content than other incinerated (woody) biomass and thus reaches lower power densities. Green waste has a particularly high power density as most of the space requirements for its transformation are already part of the existing waste management and its moisture content is lower than most other non-woody biomass. The low value for agricultural inter-crops is linked to the higher energy requirements to grow them.

When forests are considered primarily as energy production sites (forest grown for economic purposes), power density of wood fuel turns out low (0.2 – 0.4 W/m²), which represents the lowest value of all considered biomass types. In contrast, if forests are already present for protection against natural

hazards, wood fuel is very advantageous, with a maximum power density of 22 – 267 W/m². The differences in power densities of other biomass types are in large part explained by their primary energy content per tonne of fresh weight.

3.3 | Area for bioenergy

We calculated how much area would be needed per biomass to exploit the entire Swiss sustainable biomass potential. Animal manure and forest wood, the biomasses with the highest sustainable potentials, are those that require the most space to be exploited (Figure 5). Overall, the areas needed at the country level are fairly low (14 km² in the worst case for liquid manure for about 2 PJ/year secondary energy) and only partly related to the total amount of energy to be produced (the entire waste wood sustainable

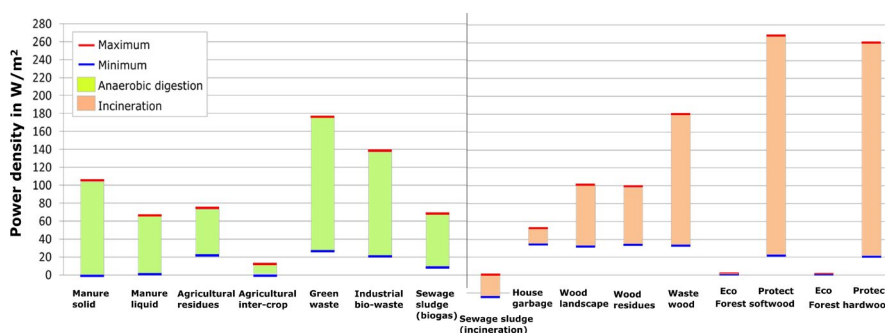


FIGURE 4 Power density of different biomass categories in total secondary energy (heat + electricity) considering either biogas production through anaerobic digestion which is then processed by a combined heat and power unit (left), or thermal treatment through incineration (right). Regarding wood fuel from forests, results are displayed separately for forest grown for economic purposes (Econom.) and the one grown for protection against natural hazard (Protect.)

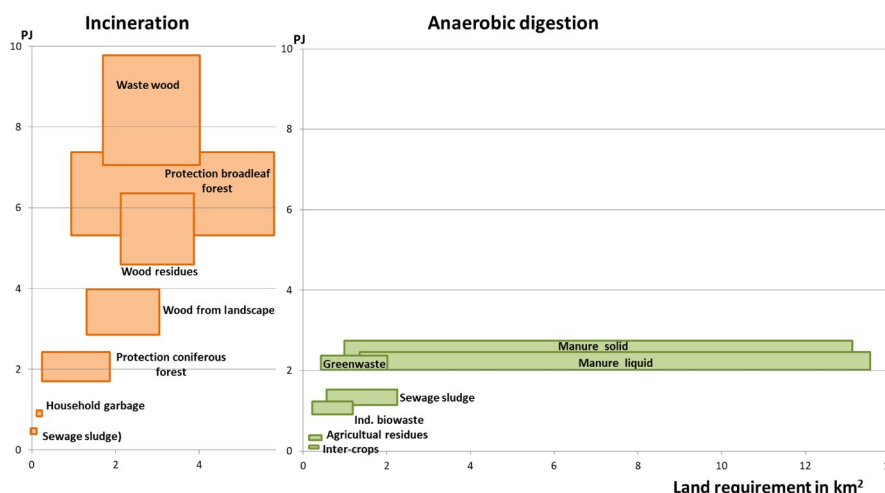


FIGURE 5 Average total area needed in km² per biomass in relation to secondary energy (sustainable potential) in PJ/year in Switzerland with maximum and minimum range (width: area in km²; height: secondary energy in PJ/year). The graphs on the left show the biomass primary energy (red). The graph on the right shows the biogas potential energy (green). Area needed for coniferous (73 km² for 2.4 PJ/year) and broadleaf (480 km² for 6.8 PJ/year) forests grown for economic purposes are not shown here for scaling reason

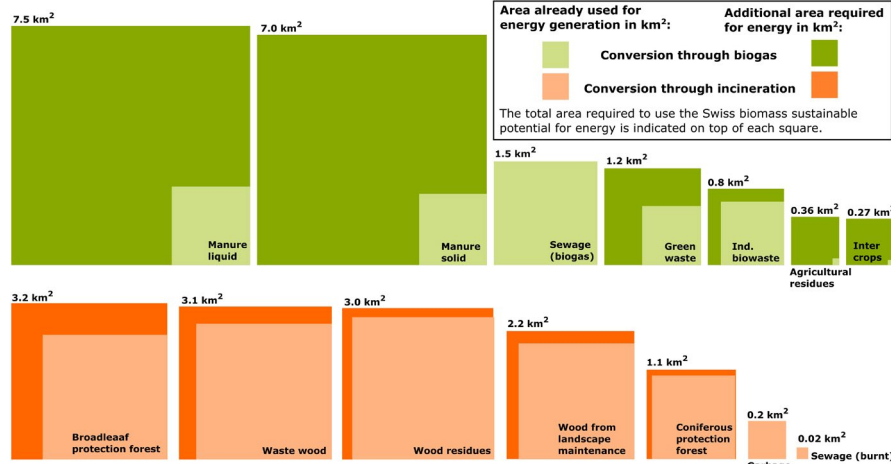


FIGURE 6 Area already used to exploit biomass (light colour) and the additional land required to exploit the whole sustainable potential (dark colour). The larger square and the number above indicate the total area needed to exploit the sustainable biomass potential of Switzerland. For scaling reason, the area of coniferous and broadleaf economic forest are not shown here. Wood fuels from forest requires 554 km² of forests (in Switzerland these forests already exist) and 4.4 km² for the other processes

potential can generate more than 8 PJ/year secondary energy using less than 5 km²). Excluding the economic forest, which requires a large area to grow, woody biomass requires on average less area to generate secondary energy compared to non-woody biomass.

However, the total area needed to use the biomass for energy can be divided between the area already occupied for the energetic use of the biomass and the area that will be required additionally for energy purposes (Figure 6). This area still required is overall smaller than what is already used. For manure and agricultural by-products, only a small quantity of biomass is already exploited so the additional area to be exploited is large in comparison to the area already used.

All in all, the energetic use of the entire sustainable biomass potential in Switzerland would require 16 km² of industrial land and 15 km² of agricultural land. Only an average of 17 km² would still need to be additionally occupied. This is the size of a small town. In comparison, according to the areal statistic (BFS, 2015), 14 km² are currently occupied in Switzerland by existing energy installations alone, without the distribution.

3.4 | Sustainable power density

The sustainable power densities (Table 1, left) of all biomass ranging from 0.03 to 28.9 W/m² with 2.4 W/m² on average were lower than the original power density calculated. This is higher than fossil fuel values, with an average of 0.42 W/m², particularly when looking at the waste biomass: indeed, the area needed to compensate the CO₂ emissions from fossil fuels is so large, that it drives the value of their sustainable power density below 1.

4 | DISCUSSION

This analysis started with the question if and how much biomass should be used for the Swiss energy transition, when considering power density, that is, the relation between energy output versus land requirement. The consideration of the land utilization associated with biomass use makes it possible to reflect on bioenergy production and its potential role in the energy transition, as little area (around 31 km²) is required in Switzerland to use the entire sustainable potential of these biomass types.

4.1 | Method

Here, we used power density (Smil, 2015) and sustainable power density (Buceti, 2014) for 10 types of biomass in the Swiss context. Based on data for Switzerland (Burg et al., 2018), we found that Smil's approach is useful to compare the different biomass types as well as to compare bioenergy with other renewable and non-renewable energies. Indeed, using an agricultural biogas plant as example, in Smil's calculation, the energy and space required for the manure was completely neglected as he considered only the amount produced by the corn silage, although half of the substrate came from animal excrements (Smil, 2015, p. 91).

However, the power density approach has some limitations, which make general comparisons difficult due to the importance of system boundary choices, process chain definitions and high variations in literature values for area and energy demand of each process. Choices were made to ignore certain parts (e.g. very small transport distances) while considering others (e.g. all installations which are only in part for the energetic use of the biomass). The

| Categories | Sustainable power density (W/m ²) with natural gas substitution | | | Power density (W/m ²) without environmental compensation | | |
|------------------------------------|---|------|------|--|-------|-------|
| | Min | Max | Mean | Min | Max | Mean |
| Animal manure solid | 0.0 | 28.9 | 14.4 | 0.4 | 104.0 | 50.7 |
| Animal manure liquid | 0.0 | 17.2 | 8.6 | 1.5 | 65.3 | 32.4 |
| Agricultural residues | 0.1 | 0.8 | 0.5 | 20.1 | 73.0 | 45.1 |
| Agricultural inter crops | 0.0 | 0.1 | 0.1 | 1.4 | 13.3 | 6.0 |
| Greenwaste | 0.2 | 0.6 | 0.4 | 26.0 | 175.5 | 95.9 |
| Household garbage | 0.1 | 0.1 | 0.1 | 33.5 | 51.9 | 74.6 |
| Sewage sludge (biogas) | 2.7 | 18.7 | 10.7 | 9.8 | 67.2 | 38.5 |
| Sewage (incineration) | 0.0 | 0.0 | 0.0 | −23.9 | 1.5 | −10.2 |
| Industrial biowaste | 0.1 | 0.5 | 0.3 | 20.0 | 136.7 | 38.8 |
| Wood from landscape maintenance | 0.5 | 0.0 | 0.3 | 31.9 | 101.5 | 57.1 |
| Wood residues | 1.0 | 1.3 | 1.1 | 33.6 | 97.7 | 58.8 |
| Waste wood | 0.3 | 1.1 | 0.7 | 32.3 | 181.6 | 78.4 |
| Coniferous economic forest | 0.0 | 0.0 | 0.0 | 0.4 | 2.4 | 0.1 |
| Coniferous protection forest | 0.1 | 0.4 | 0.3 | 21.8 | 267.4 | 114.4 |
| Broadleaf economic forest | 0.0 | 0.1 | 0.0 | 0.2 | 0.5 | 0.1 |
| Broadleaf protection forest | 0.2 | 1.9 | 1.0 | 21.5 | 259.4 | 109.1 |
| Natural gas | — | — | 0.09 | 200 | 2000 | 1100 |
| Coal | — | — | 0.02 | 100 | 1000 | 550 |
| Nuclear | — | — | 1.36 | 70 | 1600 | 835 |
| Wind | — | — | 0.49 | 0.5 | 1.5 | 1.0 |
| Solar | — | — | 0.40 | 10 | 20 | 15 |
| Energy crops | — | — | 0.22 | 0.5 | 0.6 | 0.55 |

TABLE 1 Sustainable power density for the biomass types investigated, as well as values for fossil fuels and other renewables for comparison from literature (Sustainable power density: Buceti, 2014; Power density without environmental compensation: Smil, 2010, 2015)

scattering of value for each power density matches the uncertainty found in the literature as well. This tells us that small differences in calculated values are probably irrelevant whereas the larger differences (order of magnitude) are more appropriate for decision-making. Similarly, this highlights the importance of conversion efficiencies: the higher the efficiency, the less relevant the variation in area use. Hence, values found for power density depend strongly on the method and assumptions chosen, as discussed by Lovins regarding nuclear, wind and photovoltaics using a similar metric (Lovins, 2011). The values, however, show similar scales and relations (Fthenakis & Kim, 2009; MacKay, 2009).

The method proposed here needs to be adapted to each region or country it is applied to following several steps: First, the relevant resources should be identified. Then, using local values, their process chain must be described and each process step should be assigned to the respective energy and area

it requires. Finally, the power density can then be calculated according to Smil (2015). Additionally, calculating the sustainable power density following Buceti (2014) will require the identification of the dominant energy to be replaced (e.g. coal, natural gas) and the amount of CO₂ compensated by local forests (e.g. temperate, boreal). In contrast to the methods for determining power densities that have been further developed here, the transferability of the results is limited. Power densities must be put in the local context.

This analysis, using both the standard power density (Smil, 2015) and the sustainable power density (Buceti, 2014) that includes compensatory land for GHG emissions, addressed only one aspect of sustainability. To obtain a truly sustainable power density value, however, other potential environmental damages (e.g. biodiversity loss, air and water pollution) should be taken into account. For example, looking at oil sands production, Jordaan et al. (2009) included fragmentation to consider edge effects of more distributed land

use. These additional environmental impacts need consideration but were beyond the scope of this paper.

4.2 | Energy transition

The power densities without environmental compensation range between -24 and 267 W/m^2 depending on the biomass (Figure 4). This is high in comparison to energy crops (0.5 W/m^2), wood fuel plantation (0.6 W/m^2 ; Smil, 2015) or bio-photovoltaic containing algae (0.5 W/m^2 ; Saar et al., 2018). We did not consider biofuel in the study as their power density is already low in warmer climate (Biodiesel: $0.1\text{--}0.2 \text{ W/m}^2$) and even lower in Switzerland temperate climate (de Castro et al., 2014). Similarly, Yeh et al. (2010) had calculated GHG emissions from biofuels and oil extraction, with GHG emissions per energy output more favourable for oil when considering land-use change only. Moreover, bio-energy from the biomass types presented here can be relatively low cost as all waste needs to be managed anyway and the additional space and costs required to exploit them as resources for bioenergy are limited. They present a similar or higher power density compared to other renewable energy, such as photovoltaic (20 W/m^2) and heat pumps (40 W/m^2) although a lower one than fossil fuels (e.g. 100 W/m^2 for forest wood compared to 1000 W/m^2 for natural gas). Their sustainable power density values are often higher than fossil fuels ($>0.09 \text{ W/m}^2$) and even nuclear ($>1.36 \text{ W/m}^2$). Thus, the relationship between required area and energy production shows that all the biomass types analysed here are worth exploiting as complement to the other renewables to replace fossil fuels.

Forest wood showed the highest maximal power density, up to 267 W/m^2 (and average 56 W/m^2) in strong contrast to the literature values for energy wood plantations, which has a huge area requirement and low power densities (up to 0.5 W/m^2 ; Buceti, 2014; MacKay, 2009; Smil, 2015). However, the assumptions could unfairly skew final results, because of the high number of other ecosystem services provided by the forest (Dai et al., 2017), in particular the high proportion (and high societal benefits) of protection forest in Switzerland (GEO Partner AG, 2016). Thus, as sustainable use of forest wood for energy should be strived for.

Anthropogenic waste is particularly interesting, as it is mostly produced in the same place where the highest energy demand occurs. Moreover, it has to be managed anyway for environmental and legal reasons. Also, treating organic wastes through anaerobic digestion and spreading the digestate in the field (vs. burning and putting the ashes in landfill) reduce the area needed for these wastes and close the nutrient loop. Distributing the energy where it is needed can be a challenge, but municipal waste combustion facilities, waste

treatment plants and even industrial biogas plants are fairly well accepted and often found in or close to cities. Photovoltaic on roofs (20 W/m^2) and geothermal heating systems ($10\text{--}400 \text{ W/m}^2$; Bayer et al., 2019) are usually welcome in or close to towns while other energy sources are less accepted.

Regarding the evolution on the mid- to long term, we can also expect that power density will increase with advance in technology development (Bauer et al., 2017; KTI, 2014), even if the bioresources quantities themselves are rather stable (Burg et al., 2019; Thees et al., 2020), with an increase of 6% expected for the amount of non-woody biomass available in 2050 (Burg et al., 2019). Also, combustion only plants could be replaced by more efficient technologies to produce, for example, both heat and electricity. The supply chain itself could be optimized regarding the area and the energy input needed. All in all, this should increase the use of domestic resources for energy potential for the country at a low area requirement. Biomass is likely to play a limited role quantity wise. Quality wise, however, it could be important for the Swiss energy transition thanks to its storage capacity and flexibility of use (heat, electricity, fuel). Thus, planning for the implementation of the energy transition in the field of biomass can include the consequences for land use and spatial planning. Small-scale facilities have different characteristics land-use wise compared to large scale, as shown for photovoltaic and wind installations (de Boer et al., 2015). Bioenergy installations can also span a large size range, according to local conditions: often, smaller installations display lower conversion efficiencies but shorter transport distances (Cleary & Caspersen, 2015) which have an impact on power density.

Planning the energy transition in general and biomass installations in particular should also consider a more global vision. Most of the area used for fossil energies production, and its pollutions and constraints, are located in other countries. Replacing imported foreign energy carriers with domestic alternatives makes the Swiss energy transition even more visible in terms of landscape impacts. An area used inland might be perceived as more problematic than a much larger area used abroad. Switzerland imports at the moment 85% of the overall energy needed for its gross energy consumption (BFE, 2019a) and a complete provision of renewable electricity at the country level is unlikely (Tröndle et al., 2019). Moreover, a fully renewable electricity supply could present very different physical appearances and have different impacts on landscapes and the population (Tröndle, 2020). The need to import energy can, however, lead to an energy sprawl in other countries, particularly those producing energy for export, leading to land occupation changes (Fthenakis & Kim, 2009) and even favour the ongoing global land grabbing, whereby investors buy or lease farmland to produce agricultural commodities for the global market and in detriment of the local population (Scheidel & Sorman, 2012). For

these reasons, it is important to implement the development of new energetic installations with the local population for a higher acceptance, while educating the population regarding the global impacts of their energy consumption.

Other possibilities to transform the energy system need to be explored and invented. The country energy demand could be reduced and efficient energy use can be optimized (SCCER CREST, 2020). Other important aspects need to be considered, for example, the food-energy-nexus for agricultural bioenergy (Burg et al., 2020; Christensen & Kjaer, 2009) which allows symbiosis between food production and energy generation. Moreover, one area can have multiple purposes (e.g. forests for site protection, material use and wood fuel production). One way of reducing the impact of bioenergy on used area could be to diversify usage per area as much as possible such as combining anaerobic digestion with wind on the same large North American farm (Ciliberti et al., 2016), agro-photovoltaic (Dias et al., 2019; Dupraz et al., 2011) or agroforestry (Gingrich et al., 2018).

5 | CONCLUSION

The relationship between energy and land area is highly relevant. For the first time, the power densities for various biomass types were determined and analysed in detail. The results enable a new sustainability-oriented evaluation of the energetic use of biomass. Bioenergy in Switzerland has a role to play in the energy transition, especially as the area needed to use and convert biomass is low. The biomass considered here is already available and should be more fully used to complement other renewable energies. Bioenergy cannot replace fossil energy on its own, but the quantity of land it requires is not an obstacle, especially when looking into multiple usage. Biomass is an underestimated resource that should gain more attention in both research and policy-making.

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DATA AVAILABILITY STATEMENT

Data are made available in the Supplementary Information files.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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