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Bioenergy in Switzerland: Assessing the domestic sustainable biomass potential

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ABSTRACT

This paper analyzes the sustainable domestic biomass potential for bioenergy in Switzerland. Relevant biomass resources were selected based on expert interviews and literature analyses. A definition of technical and sustainable biomass potentials was developed. The technical and sustainable biomass potentials were then assessed based on technical and sustainability constraints. The sustainable potentials were further subdivided into the already energetically-used potential and the remaining biomass potential. Data was collected from the literature and supplementary interviews with field experts. Finally, the primary energy potential from biomass was calculated and compared to the current Swiss energy demand.

We show that there is currently no sustainable potential for agricultural biomass, such as energy crops, crop residues and grass. On the other hand, there is a substantial potential from woody biomass, manure and waste biomass. The main constraints that limit the sustainable biomass potential are competing material utilizations, economic factors as well as the Swiss biofuels policy. Currently, 3.6% of Switzerland's energy demand is met by biomass resources, whereas the remaining potential could provide an additional 3.3%. Hence, with respect to a sustainable energy supply, bioenergy in Switzerland could cover a total share of 7%.

Contents

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1. Introduction

As fossil fuels are not only limited, but also contribute to global warming, a transition towards a sustainable energy supply is urgently needed. One important element of this transition is the increased use of biomass to generate renewable energy. Currently, biomass covers more than 10% of the world's primary energy demand (about 50 EJ yr^{-1}) [1] and biomass resources are by far not fully used [2]. Estimates for the long-term sustainable energy potential from biomass differ widely from, e.g. 100–400 EJ yr^{-1} [3]. The reason for this large uncertainty is the fact that a set of complex interacting factors has to be considered when assessing the future bioenergy potential.

The first one is land availability. Biofuels have been said to threaten the security of food supply by leading to increased food prices [4,5]. On the other hand, the demand for food and other biomaterials may limit the land available to produce energy crops [3,6,7]. A solution to the food-fuel dilemma could be the use of abandoned agricultural land. However, studies indicate that the global potential of such areas may be limited to 5–8% of the global energy consumption [8,9].

Second, future agricultural production yield levels will have major influence on the amount of biomass produced per surface and consequently on the amount of land available for biofuels production. Organic farming practices are being promoted by policy in some countries and associated lower yield levels could make large-scale biomass for energy production difficult [7,10]. This indicates an unresolved trade-off between two environmental policies—to increase renewable bioenergy production and to increase sustainable agriculture.

A third constraint to bioenergy is sustainability concerns. Results from life cycle studies demonstrate that greenhouse gas savings of conventional biofuels are usually small due to the carbon intensity of cultivation and fuel production [11]. An important share of biofuels even shows higher environmental impacts than their fossil references [12]. Moreover, the negative effects of biofuels are strongly dominating if carbon and biodiversity losses due to direct [13] and indirect [14,15] land transformation are considered in the full life cycle of biofuels.

In order to find a solution to what they call the "food, energy and environment trilemma", Tilman et al. [16] suggest alternative biomass sources – e.g. crop residues, wood and forest residues as well as municipal and industrial wastes – that could together meet a substantial share of the future energy demand.

With these considerations in mind, the aim of this paper is to assess Switzerland's sustainable biomass resource potential while distinguishing between the currently used potential and the remaining potential. To illustrate the role of bioenergy in Switzerland's energy supply, we compare the energy content of the sustainable biomass potential to the Swiss primary energy consumption. We close by discussing the main factors that could in the future constrain or drive the use of biomass resources.

2. Methodology

The approach used in this study consists of four steps: first, relevant biomass resources were selected. Second, the technical, sustainable, used and remaining biomass potentials were defined. Third, the biomass resource potentials were assessed and finally their primary energy content was calculated. These steps are described in the following.

2.1. Selection of biomass resources

In order to provide a comprehensive overview on the domestic potential of bioenergy in Switzerland, the study aimed at investigating all major biomass resources. The selection of biomass resources was based on two existing studies [17,18] and interviews with several experts of the field [19–24]. Table 1 provides an overview of the selected biomass resources that have been considered in our assessment.

2.2. Definition and assessment of biomass potentials

The availability of biomass often depends on a range of physical, technical, economic, environmental and other factors. These factors usually act as constraints to the use of the biomass, for example harvest losses, feedstock prices or environmental regulations. In this study, we distinguished between the technical and sustainable

Table 1
Overview of the selected domestic biomass resources that were assessed in this study.

Biomass resource type	Biomass resource
Energy crops	Energy crops Grass from meadowlands and mountain pastures
Agriculture and forestry residues	Crop residues Animal manure Forest energy wood
Waste biomass	Industrial wood residues Wood from landscape maintenance Waste wood Waste paper and cardboard Food industry waste Biowaste Sewage sludge

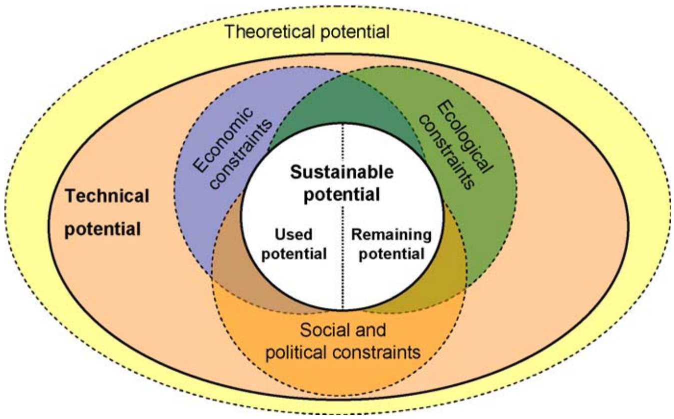

Fig. 1. Schematic illustration of the technical biomass potential and constraints to the sustainable biomass potentials as well as the currently used and remaining biomass potentials.

biomass potentials according to the different constraints they account for, and subdivided the sustainable potential into the already used and remaining fractions (Fig. 1). All potentials were assessed based on an analysis of existing literature and interviews with various field experts.

The first type of biomass potential is the technical biomass potential. It considers all biomass theoretically available within Switzerland during one year under the constraint that it can be technically supplied. An example for the technical biomass potential is the total annual quantity of a crop that can be grown and harvested with current technology constrained, e.g. by yield levels and harvest losses. In the case of a co-product it is simply the annual amount of the co-product generated.

The second type of biomass potential is the sustainable biomass potential. It has been designed to adopt a sustainability perspective by considering economic, environmental, as well as social and political constraints in addition to the constraints accounted for in the technical potential. Our assessment of the sustainable biomass potential was therefore guided by the following criteria: economic viability, environmental impacts (including indirect effects) as well as societal and political acceptance. In line with this, we adhered to general environmental principles such as the strategy of cascade utilization of biomass [25] (preferring material over energetic utilization) and the waste hierarchy (prevention, minimization, re-use, recycling, energy recovery, and disposal).

Finally, two types of potentials were introduced that subdivide the sustainable biomass potential into the fraction that is already energetically-utilized, which we call the used biomass potential, and the fraction that is not yet utilized, which we call the remaining biomass potential. The remaining biomass potential was calculated by subtracting the used biomass potential from the sustainable biomass potential. By doing this we obtain a clearer picture of the current and possible future contribution of biomass to the Swiss energy supply.

2.3. Energy calculation

The primary energy corresponding to the sustainable, used and remaining biomass potentials was then calculated under consideration of the lower heating values of the selected biomass resources.

3. Assessment of biomass potentials

3.1. Energy crops

Switzerland has roughly 1 million ha of arable land of which 60% or 640,000 ha are extensive meadowland and pastures [26]. 40% or 407,000 ha of farmland consist of cropland (278,000 ha) and intensive grassland (127,000 ha). In addition to that, there are almost 540,000 ha of mountain pasture land [27].

3.1.1. Energy crops on farmland

Cereals (e.g. wheat and corn), root crops (e.g. sugar beet, potatoes) or oilseeds (e.g. rapeseed) are energy crops that are grown in Switzerland.

3.1.1.1. Technical and sustainable biomass potentials. The technical potential of the agricultural production on Switzerland's cropland and intensively cultivated grassland is estimated at 3,516,000 t (dry weight, dw) [18].

Oettli et al. [18] assume that 10–15% of the 407,000 ha of farmland could be used for biofuels production in the long-term. Peter et al. [28], however, argue that the cultivation of energy crops will only become economically viable (a) if general energy prices increase significantly, (b) if biofuels will be exempt from the Swiss petroleum tax and (c) if Switzerland introduces import barriers to cheap biofuel imports.

These conditions are currently far from being fulfilled as the Swiss policy towards energy crops is rather conservative. Due to the fact that Switzerland is a net food importing country and due to environmental concerns, the Swiss Federal Office of Energy has declared that a large-scale production of biofuels on arable land is not desirable [29]. Switzerland is also the first country worldwide that has made a full environmental life cycle assessment a prerequisite for biofuels to be exempt from the petroleum tax [30]. Therefore, biofuels with aggregated environmental impacts significantly larger than the fossil reference do not fulfil Swiss regulations. Consequently, most agricultural biofuels are excluded from tax redemption [12]. For these reasons, the sustainable potential of energy crops in Switzerland is currently very small and has been neglected in this study.

3.1.2. Grass from extensive meadowland and mountain pasture land

Swiss extensive meadowland and pastures extends over 640,000 ha and there is an additional mountain pasture land of 540,000 ha. Both are either used for animal feed production or as pasture land for livestock.

3.1.2.1. Technical and sustainable biomass potentials. The annual technical biomass potential from extensive meadowland is estimated at 3,000,000 t (dw) [18]. Due to high harvesting costs and low yields of extensive agriculture, however, the sustainable potential is very small [18] or even negligible [21,22], especially if the competing use as animal feed production is considered.

The technical biomass potential from mountain pasture land is estimated at 2,016,000 t (dw) [18]. However, due to its remote location with limited road infrastructure and at high altitude it is even more costly to harvest [21,22]. Additionally, yield levels are lower than those of regular farmland [22]. Therefore, in agreement with [18], we assume that there is currently no sustainable biomass potential for grass from mountain pasture land.

3.2. Agriculture and forestry residues

3.2.1. Crop residues

Crop residues are organic materials which are produced as the co-product of either harvesting or the processing of agricultural crops [31]. In Switzerland, more than 70% of the cropland is used to grow cereals such as wheat, barley and corn, whereas the rest is used for oilseeds and root crops [26]. The crop residue with the highest potential is therefore straw, followed by a limited amount of other crop residues, e.g. residue potatoes or carrots.

3.2.1.1. Technical and sustainable biomass potentials. Oettli et al. [18] estimate that 20% of the harvest residues or 120,000 t (dw) can be used energetically. The Swiss Farmers Association [22] as well as the Swiss Federal Office for Agriculture [21], however, reject this estimation, pointing out that Switzerland already has to import straw to satisfy its current demand. Other crop residues are mostly used as animal fodder and small quantities are left on the fields for their nutrient content [21,22]. We therefore assume that the sustainable biomass potential is negligible.

3.2.2. Animal manure

Livestock breeding is an important source of revenue for farmers in Switzerland. Animal manure from cattle, pigs and other animals is often used as fertilizer. Anaerobic digestion of animal manure can be beneficial for the farmer for several reasons (see e.g. [32]): it provides an additional source of revenue through the production and sale of renewable biogas or electricity, it reduces unwanted odours and nuisance gas emissions from the application of raw animal manure on the fields and it generates a high quality fertilizer. The use of manure for energy generation does hence not compete with its material use as fertilizer.

3.2.2.1. Technical and sustainable biomass potentials. Oettli et al. [18] calculate that 1.3 million per year livestock units (mainly cattle) produce 2.8 million t (dw) of manure, which has been approximately confirmed by Baum and Baier [17]. The sustainable potential, however, may be substantially lower, mainly for economic reasons [19,22]: first, it may be assumed that only manure, which can be collected in the stable (as opposed to from the pasture) will be available for an energetic utilization. Second, it may not be cost effective for small farms to either run a biogas plant or to transport manure to a nearby biogas plant. For these reasons, Oettli et al. [18] argue that 50% or 1.4 million t (dw) of the theoretical potential are available for an energetic utilization. This is assumed to be the sustainable potential, despite the fact that a more detailed investigation in the future appears to be necessary [20–22].

3.2.2.2. Used and remaining biomass potentials. Currently, 76 biogas plants in Switzerland use manure as a feedstock [33]. In these plants, about 10,000 t (dw) of manure [17] and other biodegradable wastes from farms or the surrounding communities are converted to biogas. The biogas is mostly used in small co-generation plants to generate heat and electricity. The generated electricity is fed into the electricity network, while the heat is used on site or sometimes fed into a district heating network. Since only 10,000 t (dw) are used currently, the remaining potential of 1.4 million t (dw) is large. In order to mobilize the remaining potential, it might also be necessary to convince farmers of the benefits of an energetic utilization as opposed to a direct utilization as fertilizer [21,22].

3.2.3. Forest energy wood

The forest area in Switzerland amounts to 1.2 million ha which is equal to 31% of the overall land area in Switzerland. Forest energy wood is residual forest biomass originating either from thinning operations or from harvested timber fractions that are not used by the timber or the pulp and paper industry.

3.2.3.1. Technical and sustainable biomass potentials. An analysis of the Swiss National Forest Inventory [34] shows that Switzerland's forests produce around 5.4 million t (dw) of wood per year. When accounting for various factors, e.g. accessibility, harvesting costs, biodiversity, nutrient and soil quality requirements and natural parks, 3.9 million t (dw) of forest wood can be harvested.

As energy wood is a co-product of timber harvesting, its technical potential is therefore 3.9 million t (dw). An analysis of the same study showed that 38% of the harvested wood consists of assortments that are not used by the timber industry and are therefore suitable for an energetic use (e.g. bark, treetops, branches and twigs). In agreement with [35], the sustainable biomass potential is therefore 1.5 million t (dw).

3.2.3.2. Used and remaining biomass potentials. Currently about 1 million t (dw) of forest energy wood is used to generate energy in Switzerland [36]. The remaining potential therefore amounts to 0.5 million t (dw).

3.3. Waste biomass

3.3.1. Industrial wood residues

Industrial wood residues are co-products of the wood processing industry such as bark, sawdust and wood chips. Industrial wood residues can either be used in a material way by the pulp and paper industry or as a woodfuel, e.g. as wood chips or pellets.

3.3.1.1. Technical and sustainable biomass potentials. In 2007, 1.2 million t (dw) of stem wood were processed in Switzerland [37]. Approximately 40% of this amount is lost during processing and cannot be used by the timber industry [36–38]. The technical potential of these industrial wood residues is therefore quantified here at 470,000 t (dw) per year. According to the principle of cascade utilization a material use of this potential should be preferred. However, the use of industrial wood residues is strongly market driven and the demand by the Swiss pulp and paper industry is currently rather low (especially as Switzerland has just recently lost its biggest producer Borregaard [39]). The current quantity of industrial wood residues that is used in a material way by the pulp and paper industry is 124,000 t (dw) [23]. The rest is assumed to be available for an energetic utilization. Hence, we define the sustainable potential as the difference between the technical potential and the current material use, which is 263,000 t (dw) [36]. It should be kept in mind, however, that the potentials indicated here are to a large extent market-driven and may change in the future.

3.3.1.2. Used and remaining biomass potentials. As the wood processing industry depends on the economic valorisation of the produced industrial wood residues it can be assumed that the total volume is used. The used biomass potential is therefore 263,000 t (dw). To a large extent it is used to generate heat for the wood industry itself [38]. It is also assumed that there is this quantity cannot be increased without compromising the material use. The remaining potential is therefore zero.

3.3.2. Wood from landscape maintenance

Wood from landscape maintenance includes woody biomass from the maintenance of vegetation outside of forest areas, e.g. along streets, railroad lines, fields or rivers. About 10% of Switzerland's surface (400,000 ha) is covered by such vegetation, of which half is found in settlement areas and one third on agricultural land [40].

3.3.2.1. Technical and sustainable biomass potentials. A recent study [40] based on a geographical information system (GIS) and expert interviews estimated a technical potential of 527,000 t (dw) for wood from landscape maintenance in Switzerland. After considering economic and societal restrictions a sustainable potential of 420,000 t (dw) is calculated, which shall be adopted here, as the restrictions seem compatible with this study's sustainability constraints framework. The estimations are also in agreement with previous studies [36,41]. The main sources of wood from landscape maintenance are agricultural land (44%), settlement areas (21%) as well as hedges (21%), whereas wood from riverbanks, roads and railway lines only makes up 14%.

3.3.2.2. Used and remaining biomass potentials. Currently, 349,000 t (dw) of wood from landscape maintenance are effectively cut, of which 188,000 are energetically-utilized whereas the rest is mainly left at the cutting site. The remaining potential is therefore 232,000 t (dw), if all 420,000 t (dw) are used.

3.3.3. Waste wood

The Swiss Air Pollution Control Act [42] distinguishes two types of waste wood fuels depending on the degree of pollution and hence emissions generated during combustion: waste wood and problematic wood waste. Waste wood includes, e.g. residual wood from construction sites, wood from the destruction of buildings, disposed of furniture and packaging materials made of wood. Problematic wood waste includes, e.g. railroad ties, telephone poles or other specially treated wood and is therefore often highly contaminated with heavy metals, halocarbons such as PVC and other chemicals. We neglect problematic wood waste in the assessment due to its small volume and special requirements during thermal treatment.

3.3.3.1. Technical and sustainable biomass potentials. The technical potential of waste wood is 640,000 t (dw) [43,44]. About 392,000 t (dw) of waste wood are exported, mainly for the production of particle boards [45]. This practice has been criticized due to an exceeding contamination of the exported waste wood [43]. According to a random sample analysis of exported waste wood, only 40% of the exported quantity can be used without concerns for the production of particle boards [44]. The other 60% (235,000 t (dw)) could theoretically be used for energetic applications.

This will, however, depend on the political will to regulate the export of waste wood for the production of particle boards as well as on the future demand by the energy market [43]. In recent years, the exported quantity has already dropped in favour of a national energetic utilization due to higher prices offered by national energy companies. As this trend is expected to continue [43], we assume that the 235,000 t (dw) waste wood, which are too contaminated to be used in particle boards, will be available for an energy use in the future. The sustainable potential waste wood for energetic utilization is therefore 483,000 t (dw).

3.3.3.2. Used and remaining biomass potentials. In 2008, 142,000 t (dw) of waste wood were combusted in special incinerators [45]. The non-exported quantity of 108,000 t (dw) was either incinerated with municipal solid waste (MSW) or burned illegally [43]. The used potential is therefore 250,000 t (dw) and the remaining potential 234,000 t (dw).

3.3.4. Waste paper and cardboard

3.3.4.1. Technical and sustainable biomass potentials. According to the Information Platform for Paper and Cardboard Recycling [46], 1,507,000 t (dw) of paper and cardboard were consumed in 2008 in Switzerland, which is defined here as the technical potential. One approach to calculate the sustainable biomass potential would be to use the maximal recycling rates that are technically feasible during paper and cardboard production. According to a declaration by the European Recovered Paper Council, the European paper industry aims at recycling 66% of waste paper by 2010 [47]. In Switzerland, however, 82% of waste paper and cardboard are collected and recycled nationally or exported to the neighbouring countries paper industry [46]. In order to not compromise this material use, we therefore simply define the sustainable biomass potential as the amount that is not collected for recycling and incinerated with municipal solid waste. The sustainable potential is therefore 18% of the consumption or 276,000 t (dw) [18,46].

3.3.4.2. Used and remaining biomass potentials. The used potential amounts to 276,000 t (dw), which are incinerated with MSW. As it seems impossible to increase the energetic utilization without reducing the competing material use (recycling) [18], the remaining potential is zero.

3.3.5. Food industry wastes

Food industry wastes are a diverse mixture of organic substances produced during food processing.

3.3.5.1. Technical and sustainable biomass potentials. The technical potential of food industry wastes can be estimated at 813,000 t (dw) [17]. 640,000 t (dw) are currently used as animal feed (and a small part also in agriculture), 152,000 t (dw) are used for its energy content (e.g. fermentation, MSW incineration) and 21,000 t (dw) are composted. We consider the possibility of feeding animals as a constraint to a sustainable energetic utilization. The sustainable potential is therefore defined as the sum of the energetically-used and composted fractions, which is equal to 173,000 t (dw).

3.3.5.2. Used and remaining biomass potentials. The currently used potential is 152,000 t (dw) and the remaining potential is 21,000 t (dw). In addition to the use of the remaining potential, a considerable increase in the production of energy from food wastes could be possible, if the share of food industry wastes that is fermented was increased at the expense of incineration in municipal waste treatment plants. The key to achieve this will be to increase separate waste collection [18].

3.3.6. Biowaste

Biowaste is organic waste from households or the industry such as food or garden wastes. In Switzerland it is either collected separately for composting or fermentation or disposed of with municipal solid waste.

3.3.6.1. Technical and sustainable biomass potentials. A technical potential of 500,000 t (dw) of biowaste was produced in 2002, of which 40% were composted, 5% fermented and 41% disposed of in MSW [18]. Furthermore, 13% were food wastes from catering, which were used as animal feed and 1% was landfilled. Several possibilities were identified to increase the share of energetically-utilized biomass [18]: first, it was estimated that about half of the composted biowaste could be used energetically in fermentation. Second, as of 2011, Swiss legislation will prevent the use of food wastes from catering as animal feed (due to higher hygiene standards) and therefore an energetic utilization may be a meaningful alternative [20]. Third, separate collection of biowaste and MSW could be increased and consequently more biowaste fermented at the expense of incineration. With these improvements, the sustainable biomass potential is 80% of biowaste or 400,000 t (dw) [18].

3.3.6.2. Used and remaining biomass potentials. The currently used potential (in MSW incineration and fermentation) is 232,000 t (dw), whereas the remaining potential (from composting and food wastes from catering) is 169,000 t (dw).

3.3.7. Sewage sludge

Sewage sludge is the residual organic matter collected during waste water treatment. Directly after waste water treatment it is

Table 2
Summary of the biomass resource potentials.

Biomass resource	Technical potential	Sustainable potential	Used potential	Remaining potential
	t(dw)	t(dw)	t(dw)	t(dw)
Energy crops	3,516,309	0	0	0
Grass from meadowlands and mountain pastures	3,000,975	0	0	0
Crop residues	606,717	0	0	0
Animal manure	2,836,290	1,418,145	10,000	1,408,145
Forest energy wood	3,947,282	1,502,374	994,267	508,107
Industrial wood residues	387,418	263,444	263,444	0
Wood from landscape maintenance	420,000	420,000	188,000	232,000
Waste wood	640,000	484,093	250,233	233,860
Waste paper and cardboard	1,507,061	275,667	275,667	0
Food industry waste	812,627	172,695	152,050	20,645
Biowaste	500,322	400,667	231,622	169,045
Sewage sludge	346,947	346,947	346,947	0
Total	18,521,948	5,284,033	2,712,231	2,571,803

also called raw sludge, whereas once fermented in a digestion tower, it is called digested sludge. Since the heating value of digested sludge, which is usually incinerated, is very low [48], it has been neglected in this study.

3.3.7.1. Technical and sustainable biomass potentials. A technical potential of 346,000 t (dw) of raw sewage sludge was generated from households and the industry in 2006 in Switzerland [17]. This is also the sustainable potential, as energy recovery from sewage sludge seems to be the only meaningful utilization.

3.3.7.2. Used and remaining biomass potentials. Nearly all sewage sludge is currently used in an energetic way: approximately 85% of it is used for biogas production in digestion towers [17,18,24]. The rest is incinerated in MSW incineration plants or special incinerators [17,24]. The produced biogas is mainly used in co-generation plants to generate heat and power. A significant part of the heat is used on-site to provide heat to the digestion towers and the waste water treatment plant facilities. A small fraction of the biogas is upgraded to synthetic natural gas (SNG) and fed into the gas network. The remaining potential is therefore negligible and assumed as zero. Nevertheless, this may change in the future as a considerable energetic optimization potential seems to exist, especially with regards to the utilization of biogas and digested sludge [24,49].

3.4. Summary of potentials

Table 2 provides an overview of the technical, sustainable, used and remaining potentials. It can be observed that the sustainable biomass potential is substantially lower than the technical biomass potential. The two biomass resources with the highest sustainable potential are forest energy wood and animal manure. The currently used potential is about equal to the remaining potential.

4. Energy generation from biomass

Based on the assessment of the sustainable as well as the used and remaining biomass potentials, we now address the question of the energy content of these biomass potentials and how it compares to the Swiss primary energy demand. Table 3 shows the primary energy content for the biomass resources, based on the calculation of the lower heating value per ton of dry biomass according to [18], except for wood, where more precise data was available with regards to wood assortments and water contents [34,36,43,50].

The sustainable biomass potential in Switzerland adds up to 82 PJ, of which 43 PJ are currently used and 39 PJ are the remaining potential. Fig. 2 shows how the feedstocks discussed in this study contribute within the bioenergy mix. We can see that today woody biomass plays a major role and provides almost two thirds of the energy from biomass (64%). If the whole range of feedstocks of the sustainable potential were used, wood could provide about half of the total produced energy. Manure bears the greatest remaining potential and can ultimately provide one quarter of Switzerland's bioenergy. Wood and manure together supply about three quarters of the sustainable bioenergy potential.

Relative to the primary energy demand of 1186 PJ [51], the currently used biomass potential contributes 3.6% and the

Table 3
Calculation of the primary energy content of the biomass resources.

Biomass resource	Lower heating value	Sustainable potential	Used potential	Remaining potential
	GJ/t(dw)	PJ	PJ	PJ
Energy crops	17.3	0.0	0.0	0.0
Crop residues	17.2	0.0	0.0	0.0
Grass from meadowlands and mountain pastures	17.4	0.0	0.0	0.0
Animal manure	15.1	21.4	0.2	21.3
Forest energy wood	15.8	23.7	15.7	8.0
Industrial wood residues	17.6	4.6	4.6	0.0
Wood from landscape maintenance	15.7	6.6	3.0	3.6
Waste wood	15.3	7.4	3.8	3.6
Waste paper and cardboard	17.0	4.7	4.7	0.0
Food industry waste	15.1	2.6	2.3	0.3
Biowaste	14.0	5.6	3.2	2.4
Sewage sludge	15.0	5.2	5.2	0.0
Total		81.9	42.7	39.2

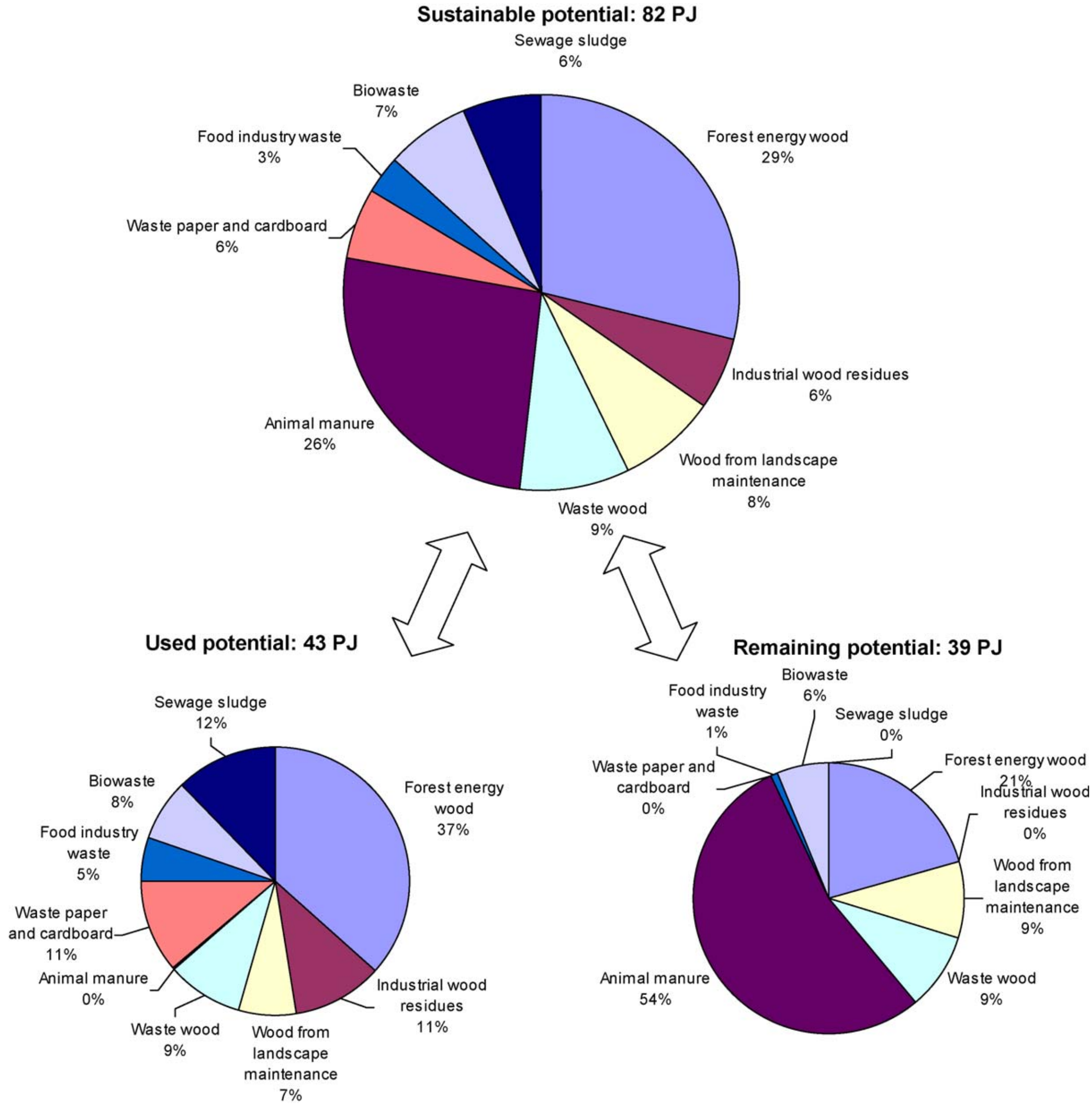

Fig. 2. Contribution of the biomass feedstocks to the sustainable, used and remaining biomass potentials.

remaining potential could contribute an additional 3.3% to the Swiss energy supply. Hence, if all of the sustainable biomass potential was used, a share of 7% of the primary energy demand could be supplied by biomass. As a comparison, a similar study conducted in the UK found that 4.9% of the primary energy could be supplied through its domestic biomass resources in a sustainable fashion [52].

5. Discussion

5.1. Constraints to the sustainable biomass potential

In this section we discuss some principal constraints with regards to Switzerland's sustainable biomass potential. Since the technical potential constitutes the upper limit to the sustainable potential, we include it in the discussion. Table 4 summarizes the constraints to the technical and the sustainable biomass potentials as discussed in Section 3.

5.1.1. Competing biomass utilizations

All of Switzerland's biomass resources are rather limited, e.g. by land availability, yield levels or because they are generated as a co-product. As biomass is scarce, competing material utilizations appear to be the dominant constraint to a larger sustainable biomass potential. The most prominent examples are the competition between food, feed, and energetic utilizations of biomass from agriculture and organic wastes as well as the competition between the material and energetic utilizations of woody biomass from the wood processing industry and waste wood.

5.1.2. Economic factors

Next to this, economic factors, such as biomass market prices and production costs seem to play an important role. It is obvious that the above mentioned competition for biomass is also reflected by market prices, which are in most cases higher for the material use. However, also biomass production costs may be a constraint as

Table 4
Overview of principal constraints to the technical and sustainable biomass potentials.

Biomass resource	Technical constraints	Sustainability constraints
Energy crops	Land availability; yield levels	Competition with food and animal feed; economic viability; environmental impacts and Swiss biofuel policy
Grass from meadowlands and mountain pastures	Land availability; yield levels	Competition with animal feed; high production costs; low yields
Crop residues	Co-product of agriculture	Competition with animal feed
Animal manure	Co-product of livestock breeding; collection losses	Cost of collection; organisation of collection; beliefs of farmers
Forest energy wood	Co-product of forestry; harvest losses	Soil nutrients
Industrial wood residues	Co-product of wood processing industry	Competition with pulp and paper
Wood from landscape maintenance	Annual growth; maintenance of landscape wood; harvest losses	
Waste wood	Co-product of construction industry	Competition with wood for particle boards; regulations on the export of contaminated waste wood
Waste paper and cardboard	Consumption of paper and cardboard; collection rate (the higher the smaller the potential)	Competition with paper recycling; (theoretical paper recycling rate)
Food industry waste	Co-product of food industry	Competition with animal feed, composting and agricultural use
Biowaste	Consumption of biodegradable materials	Competition with composting
Sewage sludge	Organic waste water content; sewage sludge generation	

is illustrated by the example of grass from meadowlands and mountain pastures. Even though these lands have recently not been used to their full potential and have been partially lost to scrub vegetation [27], biomass prices are currently not high enough to cover production costs.

5.1.3. Biomass policy

Another constraint to the sustainable biomass potential is the Swiss policy on biofuels, which excludes most biofuels from a tax exemption due to the environmental impacts that arise during the cultivation of energy crops.

5.1.4. Environmental aspects

Finally, environmental aspects may constrain the sustainable biomass potential. An example is the case of forest energy wood where the loss of nutrients could be problematic [53]. Even though this has been accounted for in the literature regarding the forest biomass assessment [34], fear of nutrient losses may keep forest owners from selling energy wood, as shown in a Swedish study [54]. A similar debate might arise with regards to the modified nutrient cycle when using animal manure as an energy source.

5.2. Possible bioenergy drivers

5.2.1. Biomass related markets and prices

Many of the feedstocks investigated in this study are co-products. Their generation depends therefore on the economic situation of the primary product market (e.g. the timber market for forest energy wood). On the other hand, the biomass that can be energetically-utilized depends on the competition for the feedstock itself (e.g. the pulp and paper market). Since Switzerland is a small country, changes in the industry landscape may have important consequences on the amount of biomass available, as illustrated for the case of industrial wood residues. Therefore, in the same way that future development of these markets may be a constraint to bioenergy, it may also be a driver. Furthermore, increased energy prices (e.g. oil price) may add to the attractiveness of biomass as an alternative energy source or help to overcome production cost, such as in the case of grass. Changes with respect to the biomass potentials, as assessed in this study, are therefore to be expected in the future and periodical revisions of the sustainable biomass potentials may be of interest.

5.2.2. Policy

Policy measures may be necessary to foster and facilitate the utilization of the sustainable biomass potential. One such measure is to give financial incentives for the investment in bioenergy plants. Even though electricity generation from biomass has been subsidized in Switzerland since 2007 [55], it has been criticized that the financial support is not enough for the development of the industry (e.g. in the case of biogas plants) [56]. Financial subsidies for the production of biogas could also drive future bioenergy development.

Another policy measure that could lead to an increased energetic utilization of waste wood would be a regulation that limits the export of contaminated waste wood [43].

5.2.3. Stakeholders

The future development of bioenergy in Switzerland will also depend on the initiative of stakeholders, such as farmers, forest landowners or the energy industry. This can be observed, e.g. in the case of manure, where economical, technical prerequisites as well as the resource potential would allow an increased resource utilization, but yet the level of biomass utilization is low. The establishment of stakeholder cooperatives to, e.g. supply larger scale biogas plants by the operation of a common collection system could potentially drive bioenergy from manure. In a similar fashion, forest landowner cooperatives could help to mobilize forest energy wood from small nonindustrial private forests, which has not been very successful in the past (see e.g. [57–59] for a discussion).

The energy industry on the other hand may need to provide more green energy in the future (driven by consumer demand) and is therefore also a stakeholder that could substantially drive an increased biomass use.

5.2.4. Stock reduction

As the sustainable growth of Swiss forests has not been fully used during the last decades [37], today's standing volume is rather too high and the age structure of trees not optimal to meet market demands. A systematic reduction of the stock could therefore be conceived, which would generate higher energy wood volumes during the upcoming decades. Thees et al. [35] estimate a 30% increase of energy wood quantities in this case.

5.2.5. Collection rates

A factor that seems important with regards to waste biomass is the collection rate. Even if an increased separation of waste biomass (e.g. biowaste) will not lead to higher biomass quantities, it may still lead to a higher energy output through the use in optimized conversion pathways (e.g. fermentation instead of incineration of wet biomass).

6. Conclusions

The biomass resources with the largest sustainable potential in Switzerland are woody biomass (forest energy wood, industrial wood residues, wood from landscape maintenance and waste wood) and animal manure. Other waste biomass also has a minor potential. The feedstocks with the greatest remaining potentials are manure and wood. Energy crops, crop residues and grass appear to have no sustainable biomass potential under current conditions.

The assessment of the sustainable biomass potential shows that biomass could provide 82 PJ or 7% of the present Swiss primary energy demand. While the currently used biomass potential covers 43 PJ (3.6%) of this demand, another 39 PJ (3.3%) could be mobilized from the remaining biomass potential in the future.

The major constraints to biomass based energy generation in Switzerland are competing material uses, economic limitations and the Swiss biofuels policy. These constraints have been accounted for in the assessment of the sustainable biomass potentials. Some of the identified constraints are potential drivers for bioenergy at the same time (e.g. market, policy and stakeholder related factors) and may change in the future. Therefore the sustainable biomass potentials are expected to change in the future and periodical reassessment may be of interest.

With a share of 7% in the present Swiss energy demand, biomass can only be a part of the solution for a sustainable energy supply. Hence, other renewable energy sources will have to be developed and the overall energy consumption reduced.

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References

[1] Heinimö J, Junginger M. Production and trading of biomass for energy—an overview of the global status. Biomass and Bioenergy 2009;33:1310–20.
[2] Parikka M. Global biomass fuel resources. Biomass and Bioenergy 2004;27:613–20.
[3] Berndes G, Hoogwijk M, Van Den Broek R. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 2003;25:1–28.
[4] Johansson DJA, Azar C. A scenario based analysis of land competition between food and bioenergy production in the US. Climatic Change 2007;82:267–91.
[5] Rathmann R, Szklo A, Schaeffer R. Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Renewable Energy 2010;35:14–22.
[6] Hoogwijk M, Faaij A, Van Den Broek R, Berndes G, Gielen D, Turkenburg W. Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 2003;25:119–33.
[7] Muller A. Sustainable agriculture and the production of biomass for energy use. Climatic Change 2009;94:319–31.
[8] Campbell JE, Lobell DB, Genova RC, Field CB. The global potential of bioenergy on abandoned agriculture lands. Environmental Science and Technology 2008;42:5791–4.
[9] Field CB, Campbell JE, Lobell DB. Biomass energy: the scale of the potential resource. Trends in Ecology and Evolution 2008;23:65–72.
[10] Reijnders L. Conditions for the sustainability of biomass based fuel use. Energy Policy 2006;34:863–76.
[11] Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM. Ethanol can contribute to energy and environmental goals. Science 2006;311:506–8.
[12] Zah R, Böni H, Gauch M, Hischier R, Lehmann M, Wäger P. Ökobilanz von Energieprodukten: ökologische Bewertung von Biotreibstoffen. Swiss Federal Laboratories for Materials Testing and Research (Empa); 2007.
[13] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319:1235–8.
[14] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. Science 2008;319:1238–40.
[15] Bringezu S, Schütz H, Arnold K, Merten F, Kabasci S, Borelbach P, et al. Global implications of biomass and biofuel use in Germany—recent trends and future scenarios for domestic and foreign agricultural land use and resulting GHG emissions. Journal of Cleaner Production 2009.
[16] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al. Beneficial biofuels—the food, energy, and environment trilemma. Science 2009;325:270–1.
[17] Baum S, Baier U. Biogene Güterflüsse der Schweiz 2006. Massen- und Energieflüsse. Umwelt-Wissen Bern: Zürcher Hochschule für Angewandte Wissenschaften, Fachgruppe Umweltbiotechnologie; 2008. p. 117.
[18] Oettli B, Blum M, Peter M, Schwank O, Bedniaguine D, Dauriat A, et al. Potentiale zur energetischen Nutzung von Biomasse in der Schweiz. Bundesamt für Energie (BFE); 2004.
[19] Baumann F, Köhli L. Personal communication. Brugg: Genossenschaft Oekostrom Schweiz; 2009.
[20] BiomassEnergie. Personal communication. Zurich: BiomassEnergie, Ernst Basler + Partner AG; 2009.
[21] BLW. Personal communication. Bern: Schweizerisches Bundesamt für Landwirtschaft (BLW), Reto Burkhard; 2009.
[22] SBV. Personal communication. Bern: Schweizerischer Bauernverband, Heinz Hänni; 2009.
[23] HES. Personal communication. Zürich: Holzenergie Schweiz, Christoph Rutschmann; 2009.
[24] Siegrist H. Personal communication. Dübendorf: Department of Process Engineering. Swiss Federal Institute for Environmental Science and Technology (Eawag); 2009.
[25] Haberl H, Geissler S. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecological Engineering 2000;16:111–21.
[26] BLW. Agrarbericht 2009. Bern: Bundesamt für Landwirtschaft (BLW); 2009.
[27] BFS. Arealstatistik Schweiz. Statistik der Schweiz. Bern: Bundesamt für Statistik (BFS); 2005.
[28] Peter S, Weber M, Lehmann B. Wirkungen der Produktion von Erdölsubstituten aus Biomasse auf den Agrarsektor in der Schweiz. Zurich: Institute for Environmental Decisions, Agri-food and Agri-environmental Economics Group, ETH Zurich; 2008. p. 88.
[29] BFE. Positionspapier biogene Treibstoffe. Bern: Bundesamt für Energie (BFE); 2008.
[30] UVEK. Verordnung des UVEK über den Nachweis der positiven ökologischen Gesamt-bilanz von Treibstoffen aus erneuerbaren Rohstoffen. Eidgenössische Departement für Umwelt, Verkehr, Energie und Kommunikation (UVEK); 2009
[31] Bhattacharya SC, Abdul Salam P, Runqing H, Somashekar HI, Racelis DA, Rathnasiri PG, et al. An assessment of the potential for non-plantation biomass resources in selected Asian countries for 2010. Biomass and Bioenergy 2005;29:153–66.
[32] Cantrell KB, Ducey T, Ro KS, Hunt PG. Livestock waste-to-bioenergy generation opportunities. Bioresource Technology 2008;99:7941–53.
[33] BFE. Statistik der erneuerbaren Energien. BFE; 2009.
[34] Hofer P, Altwegg J. Holz-Nutzungspotenziale im Schweizer Wald auf Basis LFI3. Geo Partner AG; 2008.
[35] Thees O, Frutig F, Breitenstein M, Lemm R, Kaufmann E, Keilen K. Schätzung des Potenzials an Energieholz im Schweizer Wald und Kalkulation der Bereitstellungspreise; 2003.
[36] Pauli B, Bürgi P, Brühlhart S. Holz als Rohstoff und Energieträger. Dynamisches Holzmarktmodell und Zukunftsszenarien. Zollikofen: Ressort forstliche Produktion, Schweizerische Hochschule für Landwirtschaft; 2010. p. 185.
[37] BAFU. Jahrbuch Wald und Holz. In: Pasi T, Gross D, Schmutz A, editors. Umwelt-Wissen. Bern: Abteilung Wald, Bundesamt für Umwelt (BAFU); 2009 .
[38] Primas A, Müller-Platz C, Kessler FM. Schweizerische Holzenergiestatistik. Erhebung für das Jahr 2008. Zürich: Basler und Hofmann AG; 2009. p. 78.
[39] Krähenbühl S. Waldwirtschaft Schweiz bedauert Schliessung der Borregaard Fabrik. Schweizer Bauer; 2008.
[40] Walther R, Bernath K, Walker D. Energieholzpotenziale ausserhalb des Waldes. Bern: Ernst Basler + Partner AG, Interface Politikstudien, Bundesamt für Energie (BAFU) und Bundesamt für Energie (BFE); 2009. p. 113.
[41] HES. In: Andreas Keel HS, editor. Holz - die natürliche Energiequelle. Zurich: Bürgergemeinden und Waldeigentümer Verband Kanton Solothurn (BWSo); 2008.
[42] LRV. Luftreinhalte-Verordnung (LRV) (Swiss Air Pollution Control Act). Schweizerischer Bundesrat; 2009.
[43] Riegger W. Personal communication. Zurich: Riegger GmbH; 2009.
[44] Riegger W. Künftige Verwertung von Altholz. Schweizer Holzzeitung; 2001. p. 113, 4–5.
[45] Vock W. Teilstatistik Spezielle energetische Holznutzungen: Feuerungen und Motoren für erneuerbare Abfälle. Maschwanden: Ingenieurbüro ABFALL und RECYCLING; 2009.
[46] RPK. Kennziffern Altpapier in der Schweiz. Informationsplattform Recycling Papier und Karton. RPK; 2009.
[47] ERPC. European Declaration on Paper Recycling 2006–2010. Brussels: European Recovered Paper Council; 2006.
[48] Houdková L, Borán J, Ucekaj V, Elsäßer T, Stehlík P. Thermal processing of sewage sludge. II. Applied Thermal Engineering 2008;28:2083–8.

[49] Kind E, Engeler I. Klärschlamm – ein erneuerbarer Energieträger. gwa - Gas, Wasser, Abfall; 2009. p. 461–7.
[50] LWF. Der Energiegehalt von Holz und seine Bewertung. LWF-Merkblatt Nr 12. Freising, Germany: Bayerische Landesanstalt für Wald und Forstwirtschaft; 2007.
[51] BFE. Schweizerische Gesamtenergiestatistik 2008. Bern: Bundesamt für Energie (BFE); 2009. p. 64.
[52] Thornley P, Upham P, Tomei J. Sustainability constraints on UK bioenergy development. Energy Policy.
[53] Stupak I, Asikainen A, Jonsell M, Karltun E, Lunnan A, Mizaraite D, et al. Sustainable utilisation of forest biomass for energy—possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. Biomass and Bioenergy 2007;31:666–84.
[54] Bohlin F, Roos A. Wood fuel supply as a function of forest owner preferences and management styles. Biomass and Bioenergy 2002;22:237–49.
[55] SFOE. Cost-covering remuneration for feed-in to the electricity grid (CRF). Swiss Federal Office of Energy (SFOE); 2009.
[56] BiomassEnergie. Kostendeckende Einspeisevergütungen. BiomassEnergie, Ernst Basler + Partner AG; 2009.
[57] Pudack T. Ansatzpunkte für den Strukturwandel in der Schweizer Forstwirtschaft. Schweizerischen Zeitschrift für Forstwesen; 2006 p. 157, 73–81.
[58] Amacher GS, Conway MC, Sullivan J. Econometric analyses of nonindustrial forest landowners: Is there anything left to study? Journal of Forest Economics 2003;9:137–64.
[59] Beach RH, Pattanayak SK, Yang JC, Murray BC, Abt RC. Econometric studies of non-industrial private forest management: a review and synthesis. Forest Policy and Economics 2005;7:261–81.