Joint Activity Scenarios and Modelling

biosweet
Biomass for Swiss Energy Future
Swiss Competence Center for Energy Research

# Biomass and waste potentials for energy use in Switzerland

## Report JASM - Biosweet

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# 1 Introduction

In a post-fossil world, biomass and waste are valuable resources both as chemical energy carrier and as carbon feedstock. They can be utilized in a variety of processes ranging from combustion for electricity and/or heat supply to a variety of transformation steps (fermentation, gasification, methanation) that lead to a chemical carrier of higher value such as synthetic or biological fuels and gases. In the latter form, biomass and waste can also be used in other energy sectors such as mobility.

In this paper we calculate the potentials for energy use until 2060 of both biomass and waste resources for three different scenarios of population and GDP (see Table 1). These scenarios correspond to the marker scenarios in the Joint Activity Scenarios and Modelling (JASM) (Marcucci et al., 2020).

Table 1: Macro-economic drivers in the JASM marker scenarios (Marcucci et al., 2020)

| | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** | **2010-2060** | **Reference** |
|---|---|---|---|---|---|---|---|---|
| Population (Million) | | | | | | | | |
| Reference | 7.86 | 8.71 | 9.49 | 9.99 | 10.23 | 10.36 | 0.55% p.a. | A-00-2015 (BFS, 2015) |
| High | 7.86 | 8.76 | 9.84 | 10.61 | 11.1 | 11.5 | 0.76% p.a. | B-00-2015 (BFS, 2015) |
| Low | 7.86 | 8.67 | 9.16 | 9.38 | 9.38 | 9.26 | 0.33% p.a. | C-00-2015 (BFS, 2015) |
| GDP ($BCHF_{2010}$) | | | | | | | | |
| Reference | 608.8 | 719.8 | 813 | 902.5 | 977.9 | 1048.7 | 1.09% p.a. | SECO (2018) |
| High | 608.8 | 723.2 | 853.4 | 974.7 | 1080.7 | 1181.2 | 1.33% p.a. | SECO (2018) |
| Low | 608.8 | 716.3 | 770.7 | 830.2 | 878.6 | 922.4 | 0.83% p.a. | SECO (2018) |

Data available at `https://data.sccer-jasm.ch/macroeconomic-drivers/`

In this paper we estimate the potentials for both biomass and waste resources. Biomass and waste are often mentioned together and the reason for this is that they are linked to each other: a sizeable portion of waste is actually biomass. It is therefore important to clearly distinguish these resources in order to avoid double-counting. We project sustainable potentials for energy use for wood, manure, green waste, sewage sludge and waste.

The following Sections describe the methodology used in the paper: In Section 2 we describe the available mass of each biomass and waste resource; in Section 3 we present the assumptions regarding energy content and in Section for the methodology used to calculate the $CO_2$ intensity of the resources. Finally, Section 5 presents the results and Section 6 the validation of the estimated potentials.

# 2 Available mass

The starting point of our analysis is the estimatation of already used and current sustainable potentials by WSL (Thees et al., 2017, Burg et al., 2018). Since the time horizon of our analysis extends to 2060, an extrapolation of these values is required. Here we need to identify which categories scale on other macro-indicators such as population growth or GDP and which are considered as an absolute limit that does not grow.

## 2.1 Wood

WSL distinguishes four categories of wood, namely forest wood, wood from landscape management, wood residues and waste wood.

### 2.1.1 Forest wood

The potentials of forest wood can vary depending on the exploiting policies, including stock management and utilization, and the wood prices. The WSL (Thees et al., 2018) analysed three stock management scenarios, including (1) Continued stock increase (CI); (2) Moderate stock reduction (MSR); and (3) Large stock reduction (LSR). As for the utilization, they evaluate two cases including *Energy friendly* and *Less energy friendly* scenarios, where the uses of wood are re-directed to energy in the first scenario. Moreover, they include potentials with alternative economic restrictions (higher than the 5.9 Rp/KWh in Thees et al. (2017)). The sustainable potential in Thees et al. (2017) includes a stock management scenario of Moderate Stock Reduction, a *Less energy friendly* utilization and a price limit for wood of 5.9 Rp/kWh. Table 2 presents different selected scenarios from Thees et al. (2018). According to the WSL, the combination MSR + *Energy friendly* + No cost limit, which results in 6.3 Mm3/a (46.4 PJ/a) does not meet the condition of increased cascade use of wood (BAFU, BFE and SECO, 2017), so we do not include it among the feasible potentials of forest wood.

Table 2: Scenarios for forest wood potential (Thees et al., 2018)

| Scenario | Description | Mton/a | PJ/a |
|---|---|---|---|
| (1) | MSR + *Less energy friendly* + Limit 5.9 Rp/KWh (Sustainable potential in Thees et al. (2017)) | 3.33 | 26.1 |
| (2) | MSR + *Energy friendly* + Limit 5.9 Rp/KWh | 4.1 | 31.9 |
| (3) | MSR + *Less energy friendly* + No cost limit | 5.0 | 37.9 |

For the future projections we assume that the potentials in Table 2 correspond to the long-term potential (from 2030) and that the currently usable amount corresponds to the already used potential found by WSL. For the years in between we make the simple assumption that the effective maximum usage of these resources will grow linear from today's values to the future (see Tables 3, 4 and 5).

#### 2.1.2 Wood from landscape management and wood residues

As in forest wood, we assume that the current potentials estimated by the WSL depend on geographical restrictions rather than economic developments. Therefore, we assume that the full sustainable potential calculated in Thees et al. (2017) corresponds to the available long-term potential (after 2030) and that the currently usable amount is the potential in 2015. For the intermediate periods we used a linear interpolation (see Tables 3, 4 and 5).

### 2.2 Waste wood

Waste wood comes from construction and from households, commerce and industry (*Altholz*). The approach to estimate the long-term potential of waste wood is slightly different than the previous categories: WSL states that 320 kton have been exported in 2014 (Thees et al., 2017, p. 146) while 644 kton are already used in Switzerland for energy purposes (Thees et al., 2017, p. 145). We assume that the total sum in 2015 increases from 964 kton (644 kton already used and 320 kton exported) in proportion to population, and that the exports decrease to zero from 2030 (0 kton of exports from 2030).

### 2.3 Animal Manure

Animal manure corresponds to all excretions from livestock farming (Burg et al., 2019). We assume that the currently usable potential (in 2015) corresponds to the already used potential found by Thees et al. (2017, p. 180). For the long term, we assume that after 2030 the amount of usable manure corresponds to the full sustainable potential found in (Thees et al., 2017, p. 180). Again, the potential for the years in between is linearly interpolated (see Tables 3, 4 and 5).

### 2.4 Sewage sludge

Sewage sludge refers to all the organic matter that is treated in waste water treatment plants (*Abwasserreinigungsanlagen, ARA*). It enters as fresh sewage sludge that normally undergoes a fermentation step during which biogas (CH4 and CO2) is produced. The residual sewage sludge is then incinerated in waste incineration, cement plants and the majority in *mono-Verbrennungsanlagen*. The use of sewage sludge as fertilizer is not allowed in Switzerland since 2006 (Swiss Federal Council, 2003). After 2026 only the use in sludge incinerators is allowed in order to allow for a subsequent extraction of phosphorus.

WSL estimated the current fresh sewage sludge to be 347 kton/a (dry substance) (Thees et al., 2017, p. 299). Two-third are organic substance, which is roughly halved by the fermentation step leaving 232 kton/a of residual sludge. Yearly statistics report quantities of residual sludge that are almost unchanged from 2002 (200 kton) to 2017 (210 kton). Assuming that residual sludge grows proportional to population one would expect a growth to 230 kton in 2017 which is close to the aforementioned value. We therefore take 347 kton/a of fresh sewage sludge for 2015 and assume that it grows proportional to population in the future (see Tables 3, 4 and 5).

## 2.5 Waste

Waste constitutes an important resource for the future energy system, it contains both fossil and biogenic fractions that given their carbon content can play an important role for combustion and fuel production.

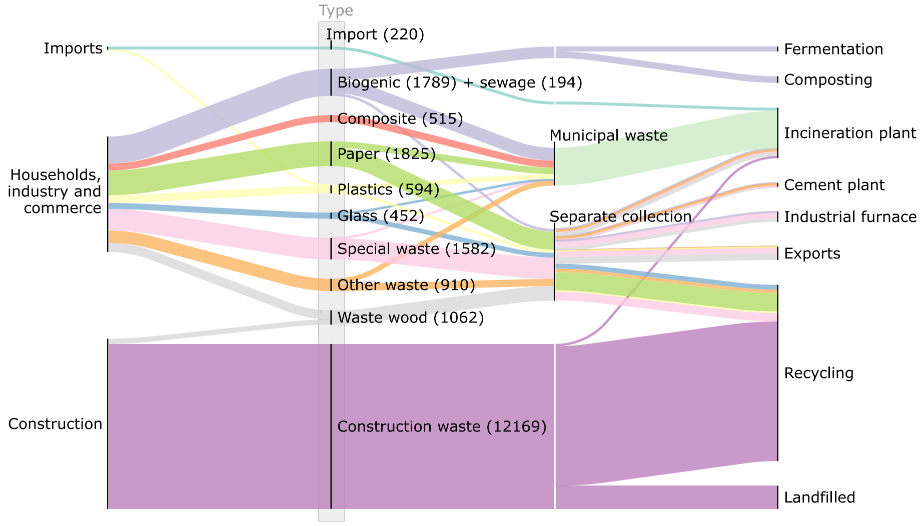


Figure 1: 2012 waste composition in Switzerland (kton). Based on Econcept (2014, p. 4)

The Sankey diagram in Figure 1 shows the origin and destination of the different types of waste in 2012. Waste is produced by (1) Households, industry and commerce and (2) Construction activities. The fraction produced by Households, industry and commerce is collected in two ways:

1. Municipal waste (*Siedlungsabfälle*) is the waste collected from household and commerce in the plastic bags.

2. Separate collection: Includes both waste collected by the municipality (*kommunale Sammlung*) and waste directly delivered to the waste incineration plants (*Direktanlieferung*).

The destinations of the waste in Switzerland are: (1) Incineration in waste incineration plants (*KVA*); (2) Incineration in cement plants and industrial furnaces; (3) Recycling; (4) Fermentation and composting; and (5) Landfills (just for construction waste). The Sankey diagram highlights especially the importance of other installations besides waste incineration plants.

In 2012, waste from biogenic origins corresponded to 24% of the waste produced by households, commerce and industry (34% of the municipal waste). In the next sections, we develop long-term projections of both waste and green waste, trying to disentangle these two categories. Our analysis splits the energy-relevant waste in two parts:

1. Municipal waste

2. Other waste: This includes the part of the collected waste that can be combusted: special waste (which is an important feedstock for industrial installations and is reported by BFS (BFS, 2018a)), other combustable fractions from construction activities, and various fractions that are collected separately such as plastics, old tires, waste oil, sewage sludge, and a number of smaller fractions.

### 2.5.1 Municipal waste

We start by considering municipal waste (*Siedlungsabfälle*) from households, commerce and industry (only under 250 employees) (BFS, 2018b). Municipal waste is treated along two routes, (i) recycling, or (ii) combustion in waste incineration plants. A third route of direct waste disposal is not allowed in Switzerland since 2005.

The composition of the recycled fraction (i) is known from yearly evaluations, the main fractions are paper and carton, biological waste and glass (BFS, 2018c). Biological waste is treated in either fermentation plants to produce biogas or in composting plants. The part that is burned (ii) can be split into the part that is collected by the municipality (*kommunale Sammlung*) and the part that is directly delivered to the waste incineration plants (*Direktanlieferung*). The composition of the collected fraction was analysed in the years 1993, 2001 and 2012 (BAFU, 2014, Table 3 on p. 24). The composition of the part that is directly delivered was estimated by Prognos (Prognos AG, 2018, Abbildung 6, page 16).

Combining this information allows us to split municipal waste into the fractions that are most relevant for the energy sector, namely green waste, paper, plastic and the residual waste (rest of the waste including glass, textiles, and others small fractions). These amounts need to be extrapolated to 2060. Prognos has studied a variety of scenarios for the overall amount of municipal waste. In 2015 the per-capita production was 724 kg/p. Estimates for 2050 range from 569-798 kg/p. We take a middle value of 700 kg/p and use it for 2060. We further assume that the overall split into the aforementioned main categories remains as of today. Following WSL, we also assume that eventually 80% of the green waste that ends up today in waste incineration plants will be recycled (see Tables 3, 4 and 5).

The information on organic waste from the various statistics needs to be compared to the WSL estimates. WSL considers various fractions: (i) the organic part of household garbage which is split into green waste and paper (Thees et al., 2017, p. 215), (ii) the green waste from households and landscape maintenance (Thees et al., 2017, p. 249), and (iii) the industrial organic waste (Thees et al., 2017, p. 278). Adding up green and organic waste (excluding paper) results in a total of 1.42 Mt.

According to our analysis the sum of collected organic waste and green waste which ends up in waste incinerators is 2.0 Mt (see Table 3). However, this includes the part of collected organic waste that goes into composting instead of fermenters. Assuming that 45% is composted (Thees et al., 2017, p. 233) our estimates match those of WSL.

### 2.5.2 Other waste

Municipal waste is not the only relevant waste fraction. Econcept (2014) studied the evolution of waste resources and management. We consider three additional fractions, namely (i) other construction waste (*brennbare Bauabfälle*); (ii) other mixed fraction that combines separately collected waste (*Getrenntsammlung*, plastics, old tires, animal fat and waste oil) and non specified residual waste (*übrige Abfälle*); and (iii) special waste (*Sonderabfälle*).

Econcept (2014) estimated an amount of 169 kton of construction waste in 2012. Combustable waste from construction activities was also evaluated by Wuest & Parter (Wuest & Partner, 2015, Figure 30 on p. 30). The number for 2015 is around 180 kton, close to the values found by Econcept. We assume the latter value for 2015 and scale it up with GDP. The second category of other mixed fractions amounted to 283 kton in 2012 (Econcept, 2014). We use this value for 2015 and scale it up with

GDP. Special waste is an important feedstock for combustion in industrial installations. BFS (2018a) reports that, in 2015, 679 and 214 kt/a were combusted in Switzerland and abroad, respectively. Analyzing the historical data we find that the growth of special waste is faster than the GDP. We make the conservative assumption that in the future it will grow further in proportion to the GDP. Additionally, we assume the reduction of exports down to zero from 2030. The three aforementioned waste fractions are very heterogeneous. Little reliable information is known on their properties such as lower heating value or $CO_2$ intensity. In the remainder of the analysis we therefore sum them up as other waste fractions.

Tables 3, 4 and 5 summarize the available mass of biomass and waste from 2015 to 2060 for the different population and GDP scenarios.

Table 3: Available potential for biomass and waste (kton): Reference

| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 2177 | 2552 | 2926 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 |
| | Scenario (2) | 2177 | 2818 | 3459 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 |
| | Scenario (3) | 2177 | 3118 | 4059 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 |
| | Wood from landscape | 299 | 403 | 507 | 611 | 611 | 611 | 611 | 611 | 611 | 611 |
| | Wood residues | 733 | 741 | 749 | 756 | 756 | 756 | 756 | 756 | 756 | 756 |
| | Waste wood | 644 | 795 | 948 | 1099 | 1135 | 1157 | 1172 | 1184 | 1193 | 1199 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1340 | 1474 | 1611 | 1742 | 1855 | 1960 | 2061 | 2159 | 2253 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 363 | 380 | 396 | 409 | 417 | 422 | 427 | 430 | 432 |
| | *Digested (dry)* | *232* | *242* | *253* | *264* | *273* | *278* | *281* | *284* | *287* | *288* |
| (E) Mixed fossil/ | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| organic waste | Export | 534 | 356 | 178 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1334 | 1503 | 1667 | 1764 | 1851 | 1931 | 2005 | 2076 | 2151 |
| | Municipal waste | 2850 | 2815 | 2873 | 2918 | 2938 | 2915 | 2874 | 2824 | 2765 | 2698 |
| | *including green waste* | *737* | *676* | *635* | *585* | *527* | *457* | *382* | *305* | *225* | *144* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

Table 4: Available potential for biomass and waste (kton): High

| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 2177 | 2552 | 2926 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 |
| | Scenario (2) | 2177 | 2818 | 3459 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 |
| | Scenario (3) | 2177 | 3118 | 4059 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 |
| | Wood from landscape | 299 | 403 | 507 | 611 | 611 | 611 | 611 | 611 | 611 | 611 |
| | Wood residues | 733 | 741 | 749 | 756 | 756 | 756 | 756 | 756 | 756 | 756 |
| | Waste wood | 644 | 801 | 971 | 1139 | 1193 | 1229 | 1258 | 1285 | 1309 | 1331 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1347 | 1505 | 1669 | 1830 | 1970 | 2104 | 2237 | 2369 | 2501 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 365 | 388 | 410 | 430 | 443 | 453 | 463 | 472 | 480 |
| | *Digested (dry)* | *232* | *244* | *259* | *274* | *286* | *295* | *302* | *309* | *314* | *320* |
| (E) Mixed fossil/ | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| organic waste | Export | 534 | 356 | 178 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1341 | 1547 | 1750 | 1883 | 1999 | 2110 | 2216 | 2318 | 2422 |
| | Municipal waste | 2850 | 2830 | 2933 | 3024 | 3086 | 3097 | 3085 | 3064 | 3034 | 2995 |
| | *including green waste* | *737* | *680* | *648* | *607* | *553* | *486* | *411* | *311* | *247* | *160* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

Table 5: Available potential for biomass and waste (kton): Low

| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 2177 | 2552 | 2926 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 | 3301 |
| | Scenario (2) | 2177 | 2818 | 3459 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 | 4100 |
| | Scenario (3) | 2177 | 3118 | 4059 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 | 5000 |
| | Wood from landscape | 299 | 403 | 507 | 611 | 611 | 611 | 611 | 611 | 611 | 611 |
| | Wood residues | 733 | 741 | 749 | 756 | 756 | 756 | 756 | 756 | 756 | 756 |
| | Waste wood | 644 | 790 | 927 | 1061 | 1079 | 1086 | 1088 | 1086 | 1080 | 1072 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1332 | 1444 | 1554 | 1656 | 1742 | 1819 | 1890 | 1955 | 2014 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 361 | 372 | 382 | 389 | 391 | 392 | 391 | 389 | 386 |
| | *Digested (dry)* | *232* | *241* | *248* | *255* | *259* | *261* | *261* | *261* | *259* | *258* |
| (E) Mixed fossil/ | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| organic waste | Export | 534 | 356 | 178 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1327 | 1457 | 1581 | 1642 | 1703 | 1756 | 1802 | 1843 | 1892 |
| | Municipal waste | 2850 | 2799 | 2815 | 2816 | 2793 | 2738 | 2667 | 2589 | 2503 | 2412 |
| | *including green waste* | *737* | *673* | *622* | *565* | *501* | *429* | *355* | *280* | *204* | *129* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

# 3 Energy content and carbon intensity

Biomass and waste are not well-defined fuels, therefore it is not easy to define the energy content corresponding to the quantities estimated in the previous section. It is a general practice to distinguish three types of substances: fresh substance (*FS*) is the original state in which the resource is used (e.g. combusted or fermented). Dry substance (*DS*) is a fraction of the fresh substance after removal of all moisture content, i.e. $m_{DS}/m_{FS} = 1 - x_W$, where $x_W$ is the moisture content. Finally, organic dry substance (*oDS*) is the fraction of the dry substance after subtracting the inert quantities (e.g. ash), i.e. $m_{oDS}/m_{DS} = 1 - x_{I,DS}$, where $x_{I,DS}$ is the inert fraction on the dry substance. The formula of Boie allows to estimate the lower heating value of dry substance from the elemental dry substance fraction of carbon ($x_{\mathrm{C},DS}$), hydrogen ($x_{\mathrm{H},DS}$), oxygen ($x_{\mathrm{O},DS}$), nitrogen (($x_{\mathrm{N},DS}$)) and sulfur ($x_{\mathrm{S},DS}$).

$$LHV_{DS} = 34.8 \cdot x_{\mathrm{C},DS} + 93.9 \cdot x_{\mathrm{H},DS} - 10.8 \cdot x_{\mathrm{O},DS} + 10.5 \cdot x_{\mathrm{S},DS} + 6.3 \cdot x_{\mathrm{N},DS} \tag{1}$$

The lower heating value of the organic dry substance scales simply with the fraction of inert substance, hence,

$$LHV_{oDS} = LHV_{DS}/(1 - x_{I,DS}). \tag{2}$$

The lower heating value of the fresh substance is reduced by two effects, (i) the dilution of the dry substance with water, and (ii) the fact that the water has to be evaporated during the combustion process (and is not recovered when considering a lower heating value), thus,

$$LHV_{FS}^{comb} = LHV_{DS} \cdot (1 - x_W) - 2.44 \cdot x_W. \tag{3}$$

For processes that do not have a combustion (e.g. fermentation), the the last term can be neglected in the calculation of the lower heating value of the fresh substance, thus,

$$LHV_{FS} = LHV_{DS} \cdot (1 - x_W). \tag{4}$$

## 3.1 Wood

The characteristics of solid fuels have been compiled by Spliethoff (Spliethoff, 2010). Table 2.10 on page 46 lists a typical elemental composition of wood ($x_{\mathrm{C},DS} = 0.5$, $x_{\mathrm{H},DS} = 0.058$, $x_{\mathrm{O},DS} = 0.434$, $x_{\mathrm{N},DS} = 0.002$, $x_{I,DS} = 0.005$). The formula of Boie (Eq. 1) results in a lower heating value of the dry substance of 18.2 MJ/kg$_{DS}$. Assuming $x_W = 0.5$, Equation 3 results in $LHV_{FS}^{comb} = 7.9$ MJ/kg, which compares well to the estimates of WSL on forest wood (Thees et al., 2017, p. 45) and wood from landscape management (Thees et al., 2017, p. 92). WSL assumes $x_W = 0.39$ for wood residues which gives $LHV_{FS}^{comb} = 10.1$ MJ/kg, again close to the WSL estimates (Thees et al., 2017, p. 113). Finally, we assume for waste wood $x_W = 0.2$, which results in a lower heating value of $LHV_{FS}^{comb} = 14.1$ MJ/kg, close to the WSL estimate (Thees et al., 2017, p. 139).

### 3.2 Manure

Animal manure is assumed to have a lower heating value of 21 MJ/kg$_{oDS}$ for the organic dry substance (Thees et al., 2017, p. 159). The fraction of inert substance is calculated from the ratio of organic dry substance to dry substance (Thees et al., 2017, p. 159) to $x_{I,DS} = 0.259$. This gives a dry substance lower heating value of $LHV_{DS} = 15.6$ MJ/kg.

### 3.3 Green waste

A typical elemental composition of collected organic waste is $x_{\text{C},DS} = 0.39$, $x_{\text{H},DS} = 0.056$, $x_{\text{O},DS} = 0.39$, $x_{\text{N},DS} = 0.0022$, $x_{I,DS} = 0.141$ (Thees et al., 2017, p. 209) . The formula of Boie (Eq. 1) gives a lower heating value of the dry substance of 14.8 MJ/kg$_{DS}$. Considering the high moisture content of $x_W = 0.64$, using Eq. 3, the lower heating value of the fresh substance is $LHV_{FS}^{comb} = 3.8$ MJ/kg if combustion takes place and, using Eq. 4, $LHV_{FS} = 5.3$ MJ/kg if the green waste is used without a combustion process, for instance in a fermentation process.

The characteristics of agricultural byproducts are again taken from WSL. The lower heating value corresponds to 21 MJ/kg$_{oDS}$ for the organic dry substance (Thees et al., 2017, p. 186), the water content and fraction of inerts are calculated from the sustainable potential (Thees et al., 2017, p. 202). This gives a lower heating value of the fresh substance of $LHV_{FS} = 10.8$ MJ/kg.

### 3.4 Sewage sludge

As for agricultural byproducts, we use the characteristics from WSL: MJ/kg$_{oDS}$=21 and calculate the water content and fraction of inerts (Thees et al., 2017, p. 286 and 299). This results in a lower heating value of the dry substance of $LHV_{DS} = 14$ MJ/kg. Fresh sewage sludge normally undergoes a fermentation step where biogas is produced. This increases the fraction of inert substance from approx. 33% to 50%. Assuming the same 21 MJ/kg$_{oDS}$, the lower heating value of the residual sewage sludge drops to $LHV_{DS} = 10.5$ MJ/kg. In order to be combusted, the water content has to decrease. This can be done by mechanical means leading to a fraction of 30% of dry mass (*Entwässerter Klärschlamm - EKS*). De-watering is sufficient to burn the residual sewage sludge in waste incinerators or sludge incinerators, although the lower heating value is apparently very low. In cement plants a pre-drying is necessary which reduces the water content to 10%. The resulting lower heating value is then 9.2 MJ/kg$_{WS}$. This compares well to the lower heating value of 10.4 MJ/kg$_{WS}$ that can be deduced from the yearly statistics of Cemsuisse (2018, pp. 16–17).

### 3.5 Waste

In absence of any other reliable data we assumed the lower heating value of municipal waste to 11 MJ/kg. The other mixed waste fractions contain for instance residual oil and solvents, so the it is assumed to be higher $LHV_{FS}^{comb} = 20$ MJ/kg.

### 3.6 Summary

Table 6 presents the moisture content ($x_W$), the inert fraction ($x_I$) and the lower heating value ($LHV$) for the different biomass resources.

Table 6: Characteristics of biomass and waste fractions

| **Category** | **Feedstock** | $x_W$ | $x_I$ | $LHV$ | $I^{Total}_{CO_2}$ | $I^{Fossil}_{CO_2}$ |
|---|---|---|---|---|---|---|
| (A) Wood | Forest wood | 50% | 0.5% | 7.9 | 116.5 | 0.0 |
| | Wood from landscape | 50% | 0.5% | 7.9 | 116.5 | 0.0 |
| | Wood residues | 39% | 0.5% | 10.1 | 110.3 | 0.0 |
| | Waste wood | 20% | 0.5% | 14.1 | 104.3 | 0.0 |
| (B) Manure | Animal manure (dry) | 0% | 25.9% | 15.6 | 96.9 | 0.0 |
| (C) Green waste | Collected organic waste | 64% | 14.1% | 5.3 | 96.9 | 0.0 |
| | Agricultural byproducts | 45% | 7% | 10.8 | 96.9 | 0.0 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 96% | 33% | 14.0 | 96.9 | 0.0 |
| | *Digested, dewatered* | *70%* | *50%* | *1.4* | *-* | *-* |
| | *Digested, dried* | *10%* | *50%* | *9.2* | *-* | *-* |
| (E) Mixed fossil/ organic waste | Imports | - | - | 11.0 | 92.0 | 46.0 |
| | Export | - | - | 11.0 | 92.0 | 46.0 |
| | Other waste fraction | - | - | 20.0 | 80.0 | 48.0 |
| | Municipal waste | - | - | 11.0 | 92.0 | 46.0 |

### 3.7 $CO_2$ intensity

Estimating the $CO_2$ intensity of biomass and waste is important to quantify the amounts of emitted $CO_2$. The combustion of biomass resources releases $CO_2$. However, this $CO_2$ is compensated during the growth of the biomass resource and, therefore, the carbon intensity of the different biomass categories when taking into account the complete carbon cycle is zero. In Table 6 we include two carbon intensities: the total ($I^{Total}_{CO_2}$) and the fossil ($I^{Fossil}_{CO_2}$). The first one corresponds to the $CO_2$ content of the resource (without considering the carbon cycle) and the second one to the carbon intensity when taking into account the $CO_2$ captured by the plant during growth (considering the carbon cycle).

$CO_2$ intensity is usually expressed in terms of $g_{CO_2}$/kWh. If the elemental composition of a fuel is known, the $CO_2$ intensity ($I_{CO_2}$) can be calculated considering that the carbon fraction turns into $CO_2$ with the molar ratio of $\frac{44}{12}$, thus,

$$I^{Total}_{CO_2} = \frac{44}{12}\frac{x_{C,FS}}{LHV_{FS}} \tag{5}$$

We use Equation 5 to calculate the carbon intensity of the various wood types and organic green waste. Due to lack of data, we assume that the other wet biomass categories have the same carbon intensity as organic green waste: 96.9 $g_{CO_2}$/kWh.

For the overall municipal waste and the other waste fractions we use 92 and 80 (from old oil) $g_{CO_2}$/kWh, respectively (BAFU, 2019, Table 2). Since a part of the waste is of biogenic origin, we also determined the total and fossil carbon intensity for the different types of waste.

# 4 Energy potentials

Tables 7, 8 and 9 present our projections from 2015 to 2060 in terms of energy content for the three population scenarios. Following WSL, we assume that the collected organic waste in Tables 3, 4 and 5 is not used solely in fermentation plants but is partly composted (Thees et al., 2017, p. 233). This fraction is assumed to grow from 50% today to 90% in 2060.

Table 7: Energy potential of biomass and waste categories (PJ): Reference

| | | **Potential (PJ)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 17.1 | 20.1 | 23.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| | Scenario (2) | 17.1 | 22.2 | 27.2 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 |
| | Scenario (3) | 17.1 | 24.5 | 31.9 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 |
| | Wood from landscape | 2.3 | 3.2 | 4.0 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 |
| | Wood residues | 7.4 | 7.5 | 7.6 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 |
| | Waste wood | 9.1 | 11.2 | 13.3 | 15.5 | 16.0 | 16.3 | 16.5 | 16.6 | 16.8 | 16.9 |
| (B) Manure | Animal manure (dry) | 2.5 | 10.5 | 18.4 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 |
| (C) Green waste | Collected organic waste | 3.3 | 3.9 | 4.6 | 5.4 | 6.3 | 7.1 | 8.0 | 8.9 | 9.8 | 10.8 |
| | Agricultural byproducts | 0.1 | 0.9 | 1.8 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 4.9 | 5.1 | 5.3 | 5.5 | 5.7 | 5.8 | 5.9 | 6.0 | 6.0 | 6.0 |
| (E) Mixed fossil/ | Imports | 4.2 | 2.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| organic waste | Exports | 5.9 | 3.9 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 26.7 | 30.1 | 33.3 | 35.3 | 37.0 | 38.6 | 40.1 | 41.5 | 43.0 |
| | Municipal waste | 31.4 | 31.0 | 31.6 | 32.1 | 32.3 | 32.1 | 31.6 | 31.1 | 30.4 | 29.7 |
| | *of which green waste* | *2.8* | *2.5* | *2.4* | *2.2* | *2.0* | *1.7* | *1.4* | *1.1* | *0.8* | *0.5* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

Table 8: Energy potential of biomass and waste categories (PJ): High

| Category | Feedstock | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 | 2055 | 2060 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 17.1 | 20.1 | 23.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| | Scenario (2) | 17.1 | 22.2 | 27.2 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 |
| | Scenario (3) | 17.1 | 24.5 | 31.9 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 |
| | Wood from landscape | 2.3 | 3.2 | 4.0 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 |
| | Wood residues | 7.4 | 7.5 | 7.6 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 |
| | Waste wood | 9.1 | 11.3 | 13.6 | 16.0 | 16.8 | 17.3 | 17.7 | 18.1 | 18.4 | 18.7 |
| (B) Manure | Animal manure (dry) | 2.5 | 10.5 | 18.4 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 |
| (C) Green waste | Collected organic waste | 3.3 | 3.9 | 4.7 | 5.6 | 6.6 | 7.6 | 8.6 | 9.6 | 10.8 | 12.0 |
| | Agricultural byproducts | 0.1 | 0.9 | 1.8 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 4.9 | 5.1 | 5.4 | 5.7 | 6.0 | 6.2 | 6.3 | 6.5 | 6.6 | 6.7 |
| (E) Mixed fossil/ | Imports | 4.2 | 2.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| organic waste | Exports | 5.9 | 3.9 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 26.8 | 30.9 | 35.0 | 37.7 | 40.0 | 42.2 | 44.3 | 46.4 | 48.4 |
| | Municipal waste | 31.4 | 31.1 | 32.3 | 33.3 | 33.9 | 34.1 | 33.9 | 33.7 | 33.4 | 32.9 |
| | *of which green waste* | *2.8* | *2.6* | *2.4* | *2.3* | *2.1* | *1.8* | *1.5* | *1.2* | *0.9* | *0.6* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

Table 9: Energy potential of biomass and waste categories (PJ): Low

| | | Potential (PJ) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| (A) Wood | Forest wood | | | | | | | | | | |
| | Scenario (1) | 17.1 | 20.1 | 23.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |
| | Scenario (2) | 17.1 | 22.2 | 27.2 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 | 32.3 |
| | Scenario (3) | 17.1 | 24.5 | 31.9 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 | 39.4 |
| | Wood from landscape | 2.3 | 3.2 | 4.0 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 |
| | Wood residues | 7.4 | 7.5 | 7.6 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 |
| | Waste wood | 9.1 | 11.1 | 13.0 | 14.9 | 15.2 | 15.3 | 15.3 | 15.3 | 15.2 | 15.1 |
| (B) Manure | Animal manure (dry) | 2.5 | 10.5 | 18.4 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 | 26.3 |
| (C) Green waste | Collected organic waste | 3.3 | 3.9 | 4.5 | 5.2 | 6.0 | 6.7 | 7.4 | 8.1 | 8.9 | 9.6 |
| | Agricultural byproducts | 0.1 | 0.9 | 1.8 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 4.9 | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.5 | 5.5 | 5.4 | 5.4 |
| (E) Mixed fossil/ | Imports | 4.2 | 2.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| organic waste | Export | 5.9 | 3.9 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 26.5 | 29.1 | 31.6 | 32.8 | 34.1 | 35.1 | 36.0 | 36.9 | 37.8 |
| | Municipal waste | 31.4 | 30.8 | 31.0 | 31.0 | 30.7 | 30.1 | 29.3 | 28.5 | 27.5 | 26.5 |
| | *of which green waste* | *2.8* | *2.5* | *2.3* | *2.1* | *1.9* | *1.6* | *1.3* | *1.0* | *0.8* | *0.5* |

Data available at `https://data.sccer-jasm.ch/biomass-potentials/`

# 5 Validation

The estimations in the previous sections include different assumptions based on the available material that is incomplete and some times inconsistent. Therefore, a few simple plausibility checks are necessary.

## 5.1 Waste: Lower heating values

Mass- and energy flows in waste incineration plants are known from yearly publications of the VBSA (Rytec, 2015, p. 17). In 2015 the amount was 3889 kton. Known subfractions are municipal waste with 2850 kton, imports of municipal waste of 384 kton, and residual sewage sludge with 134 kton. This leaves 521 kton of other fractions. We assume that 250 kton are actually waste wood whereas the remaining 271 kton belong to other waste fractions.

Combining this information with the lower heating values in Table 6 gives a total heat production in waste incineration plants of 44.5 PJ, consistent with the 43.3 PJ in the 2015 report of VBSA (Rytec, 2015, p. 16). The overall lower heating value of waste in incineration plants is 11.5 MJ/kg, which fits well to a range of 11-12 MJ/kg reported by the VBSA in 2016 (VBSA, 2016, p. 5) and to the 11.9 MJ/kg that BAFU reports (BAFU, 2019, p. 3).

## 5.2 2015 wood and waste potential

The total potential of wood and waste (excluding exports) for 2015 is 36 PJ and 58.4 PJ, respectively (see Tables 7, 8, 9). These values are consistent with the yearly energy statistics of BFE: 40.1 PJ for wood and 56.6 PJ for waste (BFE, 2015, Table 4).

## 5.3 $CO_2$ intensity of waste

Using our estimated $CO_2$ intensity, $CO_2$ emissions from waste incineration plants are 1900 kton in 2015. VBSA reports 2000 kton for the same year (VBSA, 2016, p. 22). Finally the emissions from all waste fractions with fossil content amount to 2750 kton (this includes fraction that are burned in cement plants and industrial installations). This number is very close to the 2738 kt$CO_2$ of fossil emissions from waste reported in the 2015 GHG inventory (BAFU, 2019, Table1.A(a)s1).

## 5.4 Comparison to WSL publications

We compare with two of the WSL publications: Thees et al. (2017), which calculated current potentials of biomass and Burg et al. (2019) that estimated potentials for 2035 and 2050.

The 2050 potentials for forest wood (in scenario (1)), wood from landscape and maintenance, wood residues, manure and agricultural byproducts are consistent with the 2017 WSL estimates (Thees et al., 2017) since we assume that these categories are not affected by the economic development nor the growth of the population. We assume that waste wood and sewage sludge grow with population so our potentials in 2050 are, of course, higher that those in Thees et al. (2017). As for collected organic waste, this feedstock corresponds to three of the categories in the WSL report: Organic fraction of household garbage (excluding Paper, cardboard, etc., which are included in Municipal Waste in our estimations), Green waste from households and landscape and Commercial and industrial organic waste. Adding up these three categories from Thees et al. (2017) results in 9.4 PJ. Our estimates in 2050 are higher because we assume a grow with population.

Table 10: Comparison of biomass potentials

| | | **Potential (PJ)** | | | |
|---|---|---|---|---|---|
| | | **This paper** | | **WSL (2017)**[a] | **WSL (2019)**[b] |
| **Category** | **Feedstock** | 2015 | 2050 | Current | 2050 |
| (A) Wood | Forest wood | | | | |
| | Scenario (1) | 17.1 | 26.0 | 26.1 | - |
| | Scenario (2) | 17.1 | 32.3 | - | - |
| | Scenario (3) | 17.1 | 39.4 | - | - |
| | Wood from landscape | 2.3 | 4.8 | 4.8 | - |
| | Wood residues | 7.4 | 7.7 | 7.6 | - |
| | Waste wood | 9.1 | 16.9 | 11.7 | - |
| (B) Manure | Animal manure (dry) | 2.5 | 26.3 | 26.9 | 25 |
| (C) Green waste | Collected organic waste | 3.3 | 10.8 | - | - |
| | Organic fraction of household garbage | - | - | 3.92 | 1.1 |
| | *of which Paper, cardboard, etc.* | *-* | *-* | *3.04* | *-* |
| | Green waste from households and landscape | - | - | 5.75 | 7.8 |
| | Commercial and industrial organic waste | - | - | 2.75 | 1.8 |
| | Agricultural byproducts | 0.1 | 2.6 | 2.6 | 2.7 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 4.9 | 6.0 | 4.6 | 6.0 |
| (E) Mixed fossil/ | Imports | 4.2 | 0.0 | - | - |
| organic waste | Export | 5.9 | 0.0 | - | - |
| | Other waste fraction | 22.8 | 43.0 | - | - |
| | Municipal waste | 31.4 | 29.7 | - | - |
| | *of which green waste* | *2.8* | *0.5* | *-* | *-* |

[a]Thees et al. (2017)
[b]Burg et al. (2019)

Burg et al. (2019) developed an analysis on the 2035 and 2050 potentials of wet biomass including a more detailed analysis on the different drivers for the development of the biomass than those considered in the JASM scenarios. The projections for manure, agricultural crop by-products and sewage sludge are consistent with our projections. The sum of the three green waste categories (Organic fraction of household garbage, Green waste from households and landscape and Commercial and industrial organic waste) is 10.7 PJ which is close to our green waste estimation of 11.3 PJ (adding up collected organic waste and the green waste part that is still in the category mixed fossil/organic waste burned in waste incineration plants).

# 6 Costs of the biomass resources

Thees et al. (2017) calculated supply costs per biomass subcategory. These costs are shown in Table 11.

Table 11: Costs of biomass resources by potential

| Category | Feedstock | Potential (PJ) | Cost (CHF/GJ) |
|---|---|---|---|
| (A) Wood | Forest wood – Hardwood | 0.45 | 3.75 |
| | | 5.64 | 8.89 |
| | | 6.63 | 11.81 |
| | | 1.58 | 14.72 |
| | | 0.95 | 17.50 |
| | | 0.90 | 20.42 |
| | Forest wood – Softwood | 0.27 | 5.28 |
| | | 2.91 | 12.64 |
| | | 3.50 | 16.67 |
| | | 1.52 | 20.69 |
| | | 0.94 | 24.72 |
| | | 0.93 | 28.75 |
| | Wood from landscape maintenance | 0.57 | 4.72 |
| | | 0.67 | 6.37 |
| | | 1.10 | 6.50 |
| | | 0.63 | 6.51 |
| | | 0.62 | 7.06 |
| | | 1.21 | 7.13 |
| | Wood residues | 3.16 | 0.00 |
| | | 4.73 | 2.00 |
| | Waste wood | 1.13 | -0.57 |
| | | 1.81 | -0.19 |
| | | 2.73 | 1.65 |
| | | 6.05 | 1.65 |
| (B) Manure | Animal manure (dry) | 8.50 | 0.00 |
| | | 18.40 | 1.66 |
| (C) Green waste | Organic fraction of household garbage | 3.90 | -1.81 |
| | *Of which Paper, cardboard, etc.* | *3.04* | |
| | Green waste from households and landscape | 5.80 | 4.22 |
| | Commercial and industrial organic waste | 2.70 | 5.38 |
| | Agricultural byproducts | 2.23 | 6.92 |
| | | 0.41 | 20.31 |
| (D) Sewage sludge | Fresh sewage sludge in water treatment plant | 3.52 | 0.00 |
| | Fresh sewage sludge to incineration | 0.80 | 23.37 |

## References


BAFU, 2014. Erhebung der kehrichtzusammensetzung 2012.

BAFU, 2019. Co2-emissionsfaktoren des treibhausgasinventars der schweiz. URL: https://www.bafu.admin.ch/bafu/de/home/themen/klima/daten-indikatoren-karten/daten/co2-statistik.html.

BAFU, 2019. GHG inventory 1990-2017. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/climate-reporting/latest-ghg-inventory.html.

BAFU, BFE and SECO, 2017. Ressourcenpolitik holz. strategie, ziele und aktionsplan holz.

BFE, 2015. Schweizerische Gesamtenergiestatistik 2015. Technical Report. Bundesamt für Energie. URL: https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/overall-energy-statistics.html.

BFS, 2015. Szenarien zur Bevölkerungsentwicklung der Schweiz ab 2015. Technical Report. Bundesamt für Statistik. URL: https://www.bfs.admin.ch/bfs/en/home/statistics/population/effectif-change/households.assetdetail.9787089.html, doi:https://www.bfs.admin.ch/asset/de/px-x-0104000000_102.

BFS, 2018a. Behandlung von sonderabfällen, je-d-02.03.02.14.xlsx. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/umweltindikatoren/alle-indikatoren/emissionen-und-abfaelle/sonderabfaelle.assetdetail.6967181.html.

BFS, 2018b. Siedlungsabfälle, je-d-02.03.02.10.xlsx. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/umweltindikatoren/alle-indikatoren/emissionen-und-abfaelle/siedlungsabfaelle.assetdetail.6967184.html.

BFS, 2018c. Siedlungsabfälle, je-d-02.03.02.11.xlsx. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/umweltindikatoren/alle-indikatoren/emissionen-und-abfaelle/siedlungsabfaelle.assetdetail.6967180.html.

Burg, V., Bowman, G., Erni, M., Lemm, R., Thees, O., 2018. Analyzing the potential of domestic biomass resources for the energy transition in Switzerland. Biomass and Bioenergy 111, 60 – 69. URL: http://www.sciencedirect.com/science/article/pii/S0961953418300382, doi:https://doi.org/10.1016/j.biombioe.2018.02.007.

Burg, V., Bowman, G., Hellweg, S., Thees, O., 2019. Long-term wet bioenergy resources in Switzerland: Drivers and projections until 2050. Energies , 3585URL: https://www.mdpi.com/1996-1073/12/18/3585.

Cemsuisse, 2018. Kennzahlen 2018. URL: https://www.cemsuisse.ch/kennzahlen/.

Econcept, 2014. Transformation der abfallverwertung in der schweiz für eine hohe und zeitlich optimierte energieausnutzung. URL: https://www.econcept.ch/media/projects/downloads/2018/01/1407_6062_01_Schlussbericht_def_neues_Titelblatt.pdf.

Marcucci, A., Panos, E., Guidati, G., Schlecht, I., Berger, M., Bollinger, A., Streicher, K., Zuberi, M.J.S., 2020. JASM drivers definition. Technical Report. ETH Zurich, Paul Scherrer Institute and U. Basel - JASM.

Prognos AG, 2018. Siedlungsabfallaufkommen schweiz 2050 - auswirkungen auf das kehrichtaufkommen für die thermische verwertung in den kva und die gesamtauslastung der kva.

Rytec, 2015. Einheitliche heizwert- und energiekennzahlenberechnung der schweizer kva nach europäischem standardverfahren, resultate 2015. URL: https://www.bafu.admin.ch/bafu/de/home/themen/klima/daten-indikatoren-karten/daten/co2-statistik.html.

SECO, 2018. Langfristszenarien BIP 2018–2065. Data provided by the BFE.

Spliethoff, H., 2010. Power generation from solid fuels. Springer-Verlag. doi:10.1007/978-3-642-02856-4.

Swiss Federal Council, 2003. Ban on the use of sludge as a fertiliser. URL: https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-1673.html.

Thees, O., Burg, V., Erni, M., Bowman, G., Lemm, R., 2017. Biomass for Swiss Energy Transition SCCER-BIOSWEET. Technical Report. Swiss Federal Institute for Forest, Snow and Landscape Research WSL / Swiss Competence Center for Energy Research. URL: https://www.envidat.ch/ui/#/metadata/swiss-biomass-potentials, doi:10.16904/18.

Thees, O., Erni, M., Lemm, R., Stadelmann, G., Zenner, E., 2018. Modeling the realistically sustainable potential of forest wood supplies for energetic use, in: 51th FORMEC Symposium.

VBSA, 2016. Monitoring-bericht zur co2-branchenvereinbarung für das jahr 2016. URL: https://www.bafu.admin.ch/bafu/de/home/themen/klima/daten-indikatoren-karten/daten/co2-statistik.html.

Wuest & Partner, 2015. Bauabfälle in der schweiz - hochbau, studie 2015.