Joint Activity Scenarios and Modelling

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

# BIOMASS AND WASTE POTENTIALS AND CONVERSION PATHWAYS FOR ENERGY USE IN SWITZERLAND

## REPORT JASM - BIOSWEET

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## Chapter 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 report we calculate the potentials for energy use until 2060 of both biomass and waste resources and describe potential pathways for their utilization in the future Swiss energy system. The potentials are calculated for three different variants of population and GDP (see Table 1.1). These variants correspond to the drivers in the Joint Activity Scenarios and Modelling (JASM) (Marcucci et al., 2020).

Table 1.1: Macro-economic drivers: Variants in JASM (Marcucci et al., 2020)

| | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** | **2010-2060** | **Reference** |
|---|---|---|---|---|---|---|---|---|
| Population (Million) | | | | | | | | |
| Reference | 7.86 | 8.68 | 9.42 | 10 | 10.43 | 10.79 | 0.63% p.a. | A-00-2020 (BFS, 2020) |
| High | 7.86 | 8.68 | 9.63 | 10.53 | 11.34 | 12.12 | 0.87% p.a. | B-00-2020 (BFS, 2020) |
| Low | 7.86 | 8.67 | 9.2 | 9.48 | 9.53 | 9.5 | 0.38% p.a. | C-00-2020 (BFS, 2020) |
| GDP ($\text{BCHF}_{2010}$) | | | | | | | | |
| Reference | 608.8 | 725.3 | 820.3 | 922.1 | 1022.9 | 1121.4 | 1.23% p.a. | SECO (2018) |
| High | 608.8 | 725.3 | 850.5 | 984.5 | 1123.3 | 1268.9 | 1.48% p.a. | SECO (2018) |
| Low | 608.8 | 725.3 | 794.9 | 867.7 | 931.4 | 984.6 | 0.97% p.a. | SECO (2018) |

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

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, i.e. the green waste not separated in the municipal waste. We estimate the sustainable potentials for energy use of wood, manure, sewage sludge and waste, including both the green part (of biogenic origin that can be separated by the households) and the mixed part (that includes both fossil and organic waste and is not separated). By clearly dividing these two categories of waste we avoid double-counting of certain potentials.

This report is organized as follows: in Chapter 2 we present the potentials for biomass and waste including the estimation of available mass of each biomass and waste resource; the assumptions regarding energy content; the methodology used to calculate the $CO_2$ intensity of the resources; and the resulting potentials as well as some validation of the estimated potentials and some estimates of the cost of the biomass categories. In Chapter 3 we present the possible conversion pathways and technology characteristics for Switzerland.

## Chapter 2

# Biomass and waste potentials

## 2.1 Available mass

The starting point of our analysis is the estimation of already used and current sustainable potentials[1] 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.

### 2.1.1 Biomass resources

**Wood**

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

- 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. The uses of wood are re-directed to energy in the first scenario and not redirected to energy uses in the other scenario (used, for instance, for furniture production). Moreover, they include two alternative economic restrictions: a maximum price of 5.9 Rp/kWh, which represents the maximum price at which wood will be extracted; or no cost limit that assume that the extraction price does not affect the available potential. Table 2.1 presents all the scenarios for wood potential. According to the WSL, scenario (4) MSR + *Energy friendly* + No cost limit does not comply with the condition of optimized cascade use of wood (BAFU, BFE and SECO, 2017), so we do not include it among the feasible potentials of forest wood.

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[1] WSL divides the potentials in 4 different categories: Theoretical, Sustainable, Already Used and Additional Sustainable. The theoretical potential represents the total amount available. The sustainable potential corresponds to the theoretical potential without the quantities that are not exploitable due to ecological and economic restrictions. The Already Used Potential is the part that has already been used. Finally, the Additional Sustainable potential corresponds to the sustainable potential without the already used potential (Thees et al., 2017, Burg et al., 2018).

Table 2.1: Scenarios for forest wood potential (Thees et al., 2020)

| Scenario | Description | Mm3/a | PJ/a |
|---|---|---|---|
| (1)[a] | MSR + *Less energy friendly* + Limit 5.9 Rp/KWh | 3.33 | 26.1 |
| | (Sustainable potential in Thees et al. (2017)) | | |
| (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 |

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[a] This scenario corresponds to the potential in Thees et al. (2017)

For the future projections we assume that the potentials in Table 2.1 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 assume that the effective maximum usage of these resources will grow linear from today's values to the future (see Table 2.3).

- 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 Table 2.3).

- 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 after 2030).

### Animal Manure

Animal manure corresponds to all excretions from livestock farming (Burg et al., 2019). We assume that the current sustainable potential (in 2015) corresponds to the already used potential found by Thees et al. (2017, p. 180), that is 163 kton. 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) (1693 kton). Again, the potential for the years in between is linearly interpolated (see Table 2.3).

### Sewage sludge

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

WSL estimated the current fresh sewage sludge to be 347 kton/a (dry substance) (Thees et al., 2017, p. 299). Two-thirds 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 232 kton estimated by WSL. We, therefore, take 347 kton/a of fresh sewage sludge for 2015 and assume that it grows proportional to population in the future reaching 396–506 kton by 2060 (see Table 2.3).

### 2.1.2 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.

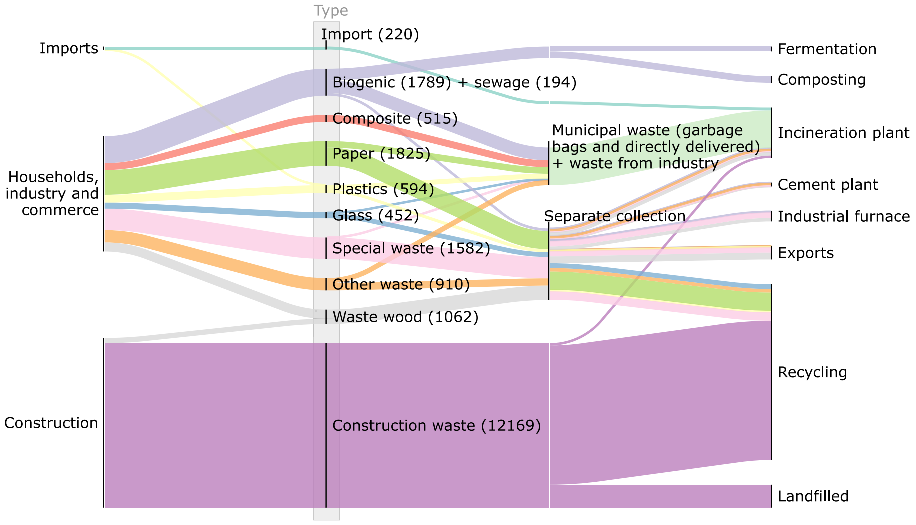

Figure 2.1: 2012 waste composition in Switzerland (kton). Based on Econcept (2014, p. 4)

The Sankey diagram in Figure 2.1 shows the origin and destination of the different types of waste in 2012. Waste is produced by Households, commerce and industry and Construction activities. The destinations of the waste in Switzerland are: Incineration in waste incineration plants (*KVA*); Incineration in cement plants and industrial furnaces; Recycling; Fermentation and composting; and Landfills (just for construction waste). We exclude from our analysis the construction waste because it is mostly recycled or landfilled so it does not contribute to the energy system.

The waste from households, industry and commerce is treated along two routes[2] (Table 2.2) :

1. Recycling: The composition of the recycled fraction is known from yearly evaluations done by the Swiss Federal Office of Statistics (BFS, 2018b). The main fractions are paper and carton, organic waste and glass, in 2017 they accounted for 40%, 41% and 11%, respectively (BFS, 2018b). Organic waste is treated in either fermentation plants to produce biogas or in composting plants.

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[2] A third route of direct waste disposal (landfills) is not allowed in Switzerland since 2005

2. Combustion in waste incineration plants, cements plants or industrial furnaces. This waste fraction is composed by municipal waste and waste from commerce and industry of more than 250 employees. Municipal waste (*Siedlungsabfälle*) is the waste collected by the municipality from households, commerce and industries with less than 250 employees, a part of which is collected by the municipality in the garbage bags (*kommunale Sammlung*) and another part that is directly delivered to the waste incineration plants (*Direktanlieferung*). The composition of the garbage bags 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 (both municipal and industrial waste) estimated by Prognos (Prognos AG, 2018, Abbildung 6, page 16).

Table 2.2: Waste from households, commerce and industry: origin, destination and composition

| **Origin** | **Destination** | **Main fractions** |
|---|---|---|
| Households, industry and commerce | Recycling | In 2017: 40% paper and carton, 41% organic waste and 11% glass (BFS, 2018b) |
| Municipal waste – garbage bags | Incineration | In 2012: 32.2% biogenic, 13,5% paper, 12.9% plastic, 12.8% composite (BAFU, 2014) |
| Municipal waste – directly delivered + waste from commerce and industry | Incineration | In 2012: From municipal waste: biogenic (12.5%), plastic (10%), waste wood (7.5%). From commerce and industry: sewage sludge (10.4%), construction waste (10%) (Prognos AG, 2018) |

In 2012, waste from biogenic origins (organic waste) accounted for an important fraction of the municipal waste. In the next sections, we develop long-term projections of both mixed and green waste, trying to disentangle these two categories and assuming that the recycling and waste separation behaviour will continue and improve in the future. Our analysis splits the energy-relevant waste in two parts:

1. Green waste: Includes the collected organic waste from households, commerce and industry and agricultural bioproducts.
2. Mixed 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.

### Green waste

Green waste includes both the collected organic waste, that is the biogenic waste from households, commerce and industry, and the agricultural bioproducts. To determine the future potential of the collected organic waste we need an extrapolation of municipal waste (both garbage bags and directly delivered). 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 assume that the split into the different fractions of municipal waste remains as of today (see Table 2.2). However, we assume a behavioral change that results in a higher portion of the green waste being recycled. Specifically, we assume that 80% of the green waste that ends up today in waste incineration plants will be recycled. Our projections grow from 1.2 Mtons in 2015 to 2.3 Mton in 2060 (see Table 2.3).

Regarding the agricultural byprodúts we assume that the current sustainable potential (in 2015) corresponds to the already used potential found by Thees et al. (2017, p. 180), that is 8 kton. 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) (244 kton). Again, the potential for the years in between is linearly interpolated (see Table 2.3).

#### 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: (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.

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.

These three 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.

### 2.1.3 Available potentials in kton

Table 2.3 summarizes the available mass of biomass and waste from 2015 to 2060 for the JASM population and GDP variants.

Table 2.3: Available potential for biomass and waste (kton)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Reference variant** | | | | | | | | | | | |

Table 2.3: Available potential for biomass and waste (kton) (continued)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **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 | 791 | 941 | 1090 | 1128 | 1158 | 1183 | 1207 | 1229 | 1249 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1335 | 1464 | 1599 | 1733 | 1858 | 1980 | 2103 | 2226 | 2348 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 362 | 377 | 393 | 406 | 417 | 426 | 435 | 443 | 450 |
| | *Digested (dry)* | *232* | *241* | *252* | *262* | *271* | *278* | *284* | *290* | *295* | *300* |
| (E) Mixed fossil/ | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| organic waste | Export | 534 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1233 | 1364 | 1491 | 1578 | 1656 | 1727 | 1794 | 1856 | 1924 |
| | Municipal waste | 2850 | 2805 | 2854 | 2897 | 2922 | 2920 | 2904 | 2881 | 2850 | 2812 |
| | *including green waste* | *737* | *674* | *630* | *581* | *524* | *458* | *386* | *311* | *232* | *150* |
| | | | | | | | | | | | |
| **High variant** | | | | | | | | | | | |
| (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 | 792 | 952 | 1115 | 1170 | 1219 | 1266 | 1313 | 1359 | 1404 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1336 | 1479 | 1636 | 1797 | 1956 | 2119 | 2287 | 2461 | 2639 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 362 | 381 | 402 | 421 | 439 | 456 | 473 | 489 | 506 |
| | *Digested (dry)* | *232* | *241* | *254* | *268* | *281* | *293* | *304* | *315* | *326* | *337* |
| (E) Mixed fossil/ | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| organic waste | Export | 534 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1239 | 1403 | 1565 | 1684 | 1788 | 1887 | 1982 | 2073 | 2167 |
| | Municipal waste | 2850 | 2807 | 2884 | 2963 | 3030 | 3074 | 3107 | 3133 | 3151 | 3160 |
| | *including green waste* | *737* | *674* | *637* | *595* | *543* | *482* | *413* | *338* | *257* | *168* |

Table 2.3: Available potential for biomass and waste (kton) (continued)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Low variant** | | | | | | | | | | | |
| (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 | 791 | 930 | 1065 | 1087 | 1097 | 1102 | 1103 | 1103 | 1100 |
| (B) Manure | Animal manure (dry) | 163 | 673 | 1183 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 | 1693 |
| (C) Green waste | Collected organic waste | 1256 | 1334 | 1449 | 1563 | 1668 | 1760 | 1843 | 1922 | 1997 | 2067 |
| | Agricultural byproducts | 8 | 87 | 166 | 244 | 244 | 244 | 244 | 244 | 244 | 244 |
| (D) Sewage sludge | Fresh sewage sludge (dry) | 347 | 362 | 373 | 384 | 391 | 395 | 397 | 397 | 397 | 396 |
| | *Digested (dry)* | *232* | *241* | *249* | *256* | *261* | *263* | *265* | *265* | *265* | *264* |
| (E) Mixed fossil/ organic waste | Imports | 384 | 256 | 128 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Export | 534 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1227 | 1323 | 1414 | 1468 | 1523 | 1571 | 1612 | 1649 | 1692 |
| | Municipal waste | 2850 | 2803 | 2823 | 2831 | 2813 | 2767 | 2704 | 2633 | 2556 | 2475 |
| | *including green waste* | *737* | *673* | *624* | *568* | *504* | *434* | *360* | *284* | *208* | *132* |

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

## 2.2 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 ($x_{\mathrm{S},DS}$).

$$LHV_{DS} = 34.8 \cdot x_{\mathrm{C},DS} + 93.9 \cdot x_{\mathrm{H},DS} - 10.8 \cdot x_{\mathrm{O},DS} + 10.5 \cdot x_{\mathrm{S},DS} + 6.3 \cdot x_{\mathrm{N},DS} \tag{2.1}$$

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

$$LHV_{oDS} = LHV_{DS}/(1 - x_{I,DS}). \tag{2.2}$$

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,

$$LHV_{FS}^{comb} = LHV_{DS} \cdot (1 - x_W) - 2.44 \cdot x_W. \tag{2.3}$$

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,

$$LHV_{FS} = LHV_{DS} \cdot (1 - x_W). \tag{2.4}$$

### 2.2.1 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. 2.1) results in a lower heating value of the dry substance of 18.2 MJ/kg$_{DS}$. Assuming $x_W = 0.5$, Equation 2.3 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).

### 2.2.2 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.

### 2.2.3 Green waste

A typical elemental composition of collected organic waste is $x_{\mathrm{C},DS} = 0.39$, $x_{\mathrm{H},DS} = 0.056$, $x_{\mathrm{O},DS} = 0.39$, $x_{\mathrm{N},DS} = 0.0022$, $x_{I,DS} = 0.141$ (Thees et al., 2017, p. 209) . The formula of Boie (Eq. 2.1) 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. 2.3, the lower heating value of the fresh substance is $LHV_{FS}^{comb}$ = 3.8 MJ/kg if combustion takes place and, using Eq. 2.4, $LHV_{FS}$ = 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.

### 2.2.4 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).

### 2.2.5 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.

### 2.2.6 Summary

Table 2.4 presents the moisture content ($x_W$), the inert fraction ($x_I$) and the lower heating value ($LHV$) for the different biomass resources.

### 2.2.7 $CO_2$ 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 2.4 we include two carbon intensities: the total ($I_{CO_2}^{Total}$) and the fossil ($I_{CO_2}^{Fossil}$). 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,

Table 2.4: Characteristics of biomass and waste fractions

| **Category** | **Feedstock** | $x_W$ | $x_I$ | $LHV$ | $I^{\mathbf{\mathit{Total}}}_{\mathbf{CO_2}}$ | $I^{\mathbf{\mathit{Fossil}}}_{\mathbf{CO_2}}$ |
|---|---|---|---|---|---|---|
| (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 |

$$I^{\mathit{Total}}_{\mathrm{CO_2}} = \frac{44}{12} \frac{x_{\mathrm{C},FS}}{LHV_{FS}} \tag{2.5}$$

We use Equation 2.5 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 $\mathrm{g_{CO_2}}$/kWh.

For the overall municipal waste and the other waste fractions we use 92 and 80 (from old oil) $\mathrm{g_{CO_2}}$/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.

## 2.3 Energy potentials

Table 2.5 presents our projections from 2015 to 2060 in terms of energy content for the three population variants. Following WSL, we assume that the collected organic waste in Table 2.3 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 2.5: Energy potential of biomass and waste categories (PJ)

| | | **Energy Potential (PJ)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Reference variant** | | | | | | | | | | | |

Table 2.5: Energy potential of biomass and waste categories (PJ) (continued)

| | | **Energy 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 | 13.2 | 15.3 | 15.9 | 16.3 | 16.6 | 17.0 | 17.3 | 17.6 |
| (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 | 6.2 | 7.1 | 8.1 | 9.1 | 10.1 | 11.2 |
| | 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 | 6.0 | 6.1 | 6.2 | 6.3 |
| (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 | 3.3 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 24.7 | 27.3 | 29.8 | 31.6 | 33.1 | 34.5 | 35.9 | 37.1 | 38.5 |
| | Municipal waste | 31.4 | 30.9 | 31.4 | 31.9 | 32.1 | 32.1 | 31.9 | 31.7 | 31.3 | 30.9 |
| | *including green waste* | *2.8* | *2.5* | *2.4* | *2.2* | *2* | *1.7* | *1.5* | *1.2* | *0.9* | *0.6* |
| **High variant** | | | | | | | | | | | |
| (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 | 13.4 | 15.7 | 16.4 | 17.1 | 17.8 | 18.5 | 19.1 | 19.7 |
| (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 | 4.6 | 5.5 | 6.5 | 7.5 | 8.6 | 9.9 | 11.2 | 12.6 |
| | 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 | 5.3 | 5.6 | 5.9 | 6.1 | 6.4 | 6.6 | 6.9 | 7.1 |
| (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 | 3.3 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 24.8 | 28.1 | 31.3 | 33.7 | 35.8 | 37.7 | 39.6 | 41.5 | 43.3 |
| | Municipal waste | 31.4 | 30.9 | 31.7 | 32.6 | 33.3 | 33.8 | 34.2 | 34.5 | 34.7 | 34.8 |
| | *including green waste* | *2.8* | *2.5* | *2.4* | *2.2* | *2* | *1.8* | *1.6* | *1.3* | *1* | *0.6* |
| **Low variant** | | | | | | | | | | | |

Table 2.5: Energy potential of biomass and waste categories (PJ) (continued)

| | | **Energy 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 | 13.1 | 15.0 | 15.3 | 15.4 | 15.5 | 15.5 | 15.5 | 15.5 |
| (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 | 5.3 | 6.0 | 6.8 | 7.5 | 8.3 | 9.1 | 9.9 |
| | 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 | 5.4 | 5.5 | 5.5 | 5.6 | 5.6 | 5.6 | 5.5 |
| (E) Mixed fossil/ organic waste | Imports | 4.2 | 2.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Export | 5.9 | 3.3 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Other waste fraction | 22.8 | 24.5 | 26.5 | 28.3 | 29.4 | 30.5 | 31.4 | 32.2 | 33.0 | 33.8 |
| | Municipal waste | 31.4 | 30.8 | 31.1 | 31.1 | 30.9 | 30.4 | 29.7 | 29.0 | 28.1 | 27.2 |
| | *including green waste* | *2.8* | *2.5* | *2.3* | *2.1* | *1.9* | *1.6* | *1.4* | *1.1* | *0.8* | *0.5* |

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

## 2.4 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.

### 2.4.1 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 2.4 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).

### 2.4.2 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 Table 2.5). 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).

### 2.4.3 2015 green waste

WSL considers various fractions of green waste: (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 in 2015.

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 2.3). 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.

### 2.4.4 $CO_2$ 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).

### 2.4.5 Comparison to long-term projections in 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.

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

Table 2.6: 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)

considered in the JASM projections. 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).

## 2.5 Costs of the biomass resources

Thees et al. (2017) calculated supply costs by potentials per biomass subcategory. These costs are shown in Table 2.7.

Table 2.7: Costs of biomass resources by category and 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 |

Table 2.7: Costs of biomass resources by category and potential (continued)

| **Category** | **Feedstock** | **Potential (PJ)** | **Cost (CHF/GJ)** |
|---|---|---|---|
| (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 |

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

## Chapter 3

# Biomass conversion pathways

Biomass and waste are key resources in Switzerland. The potential for biomass excluding mixed waste are in the range of 98.3–120.2 PJ in 2060 depending on the macro-economic assumption and the scenario for wood management. Waste potentials are projected to be 70 PJ by 2060 (Table 2.5). As biomass is both a source of energy and carbon it can be used to effectively manage the energy system towards a net-zero emissions world. This is realized by taking advantage of this twofold nature and simultaneously using the energy and carbon content. The carbon contained in the biomass can be recirculated in the energy system via appropriate capture technologies and as such, it can provide a viable building block for further synthesis of biofuels and biomaterials while reducing carbon emissions. When it comes to processing via conversion technologies, biomass can be divided into dry and wet biomass. Dry biomass consists of all types of wood while wet biomass includes biomass categories with higher moisture content such as green wastes, sewage sludge and manure. Figure 3.1 shows the main identified conversion routes for direct biomass conversion to fuels, heat and power (based on discussions with SCCER BIOSWEET, Balagurumurthy et al. (2015), Seif et al. (2016), Matsumura (2015), Waldner (2007)). It shows routes that are technically possible and potentially useful for a future energy system. However, it has to be noted that some are less likely to be realized than others and that this list is not exhaustive but includes the main technologies considered in the context of SCCER JASM.

Dry biomass (wood) can be used in direct combustion (7a) and gasification (5a). Combustion may occur in a boiler at near-atmospheric pressure that produces heat at any level from low temperature for domestic use (space heating and warm water) to high temperatures for industrial purposes (7a). The heat from combustion may be used further to drive a power cycle (water/steam for large size, organic Rankine for smaller size) or for combinations of heat and power production (7b). A fundamentally different route is the gasification of wood (5a). Here the basic constituents of wood (carbon, hydrogen and oxygen) are recombined in the presence of an oxidant (air or oxygen) to produce a syngas composed of carbon monoxide, hydrogen, $CO_2$ and other species. This syngas forms the basis for a variety of subsequent process steps that can lead to synthetic natural gas (via a methanation reaction, 5b and 5g), liquid fuels (via a Fischer/Tropsch synthesis, 5c) or hydrogen (via a water gas shift reaction, 5e). Alternatively, the syngas may be combusted in a gas motor or a gas turbine combined cycle to produce electricity and heat (5d).

Manure can be used in anaerobic digestion (6a) that produce raw biogas, a mixture that usually contains around 40-60% methane and the rest is mostly $CO_2$. Today, in Switzerland, the biogas produced from anerobic digestion is used mostly in small internal combustion engines to produce elec-

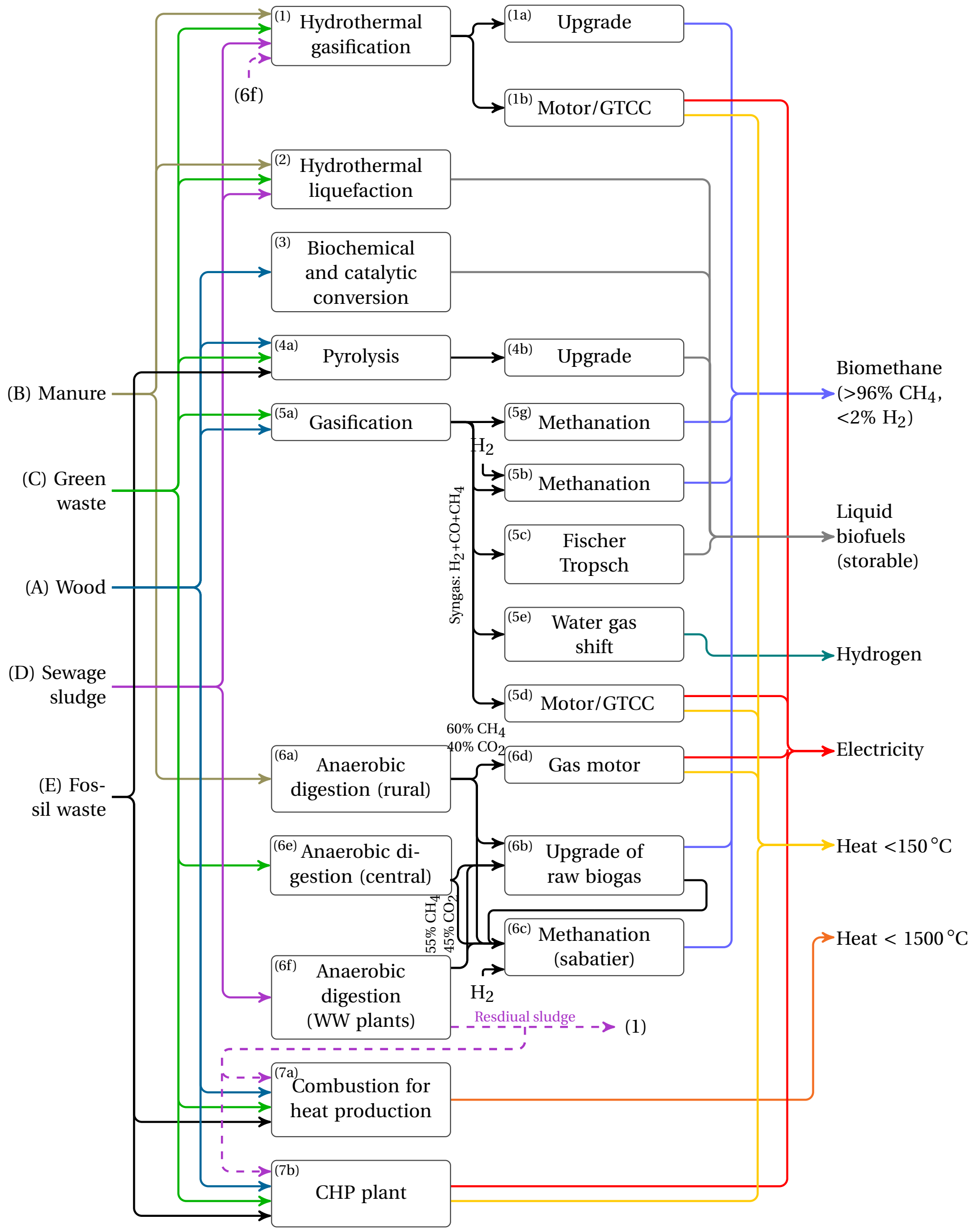

Figure 3.1: Mapping of Biomass Technologies and Resources

tricity and heat. The latter is used on-site as much as needed and the rest is discarded. A future energy system may profit from another route, namely an upgrading of the raw biogas (6b) to biomethane (by separating $CO_2$ and other species), which can then be injected into the natural gas grid. This gas may then be used for a variety of processes, including seasonal storage in neighboring countries such as Germany or France. The separated $CO_2$ may be further combined with hydrogen from electrolysis to produce additional methane via a Methanation (Sabatier) reaction (6c). Such an alternative route is hindered by the fact that the average farm size in Switzerland is very small. As shown in the report by WSL (Thees et al., 2017), even a reasonable amount of electricity production via the first route requires already a collection of manure within a 1 km range. All subsequent steps such as biogas cleaning, electrolysis or methanation would require an even larger size to be technically feasible and profitable.

Green waste can be used in central anerobic digestors (6e) and combustion plants (7b) and (7c).

Concerning sewage sludge, current Swiss regulations enforce the energetic use of sewage sludge from waste water treatment plants (WW, *Abwasser-Reinigungsanlagen*) with a cascade utilization (Thees et al., 2017, p. 279ff). The fresh sewage sludge undergoes goes first to an anaerobic digestor (6f) that produces biogas, which can be used on-site or injected into the gas grid after gas cleaning. The residual sludge is then combusted in waste incineration plants, specialized sludge incinerators and cement plants. An alternative route for the residual sludge is hydrothermal gasification (1).

The following sections describe in detail the conversion processes from biomass to the different energy carriers (Sections 3.1–3.5), including the different technology characteristics from an expert elicitation in Switzerland and the literature (Section 3.6). The different conversion processes generate a substantial amount of $CO_2$. This $CO_2$ can either be captured and stored or combined again with hydrogen from electrolysis to produce more synthetic natural gas or liquid fuels. We dedicate Section 3.7 to describe the different alternatives for the use of $CO_2$.

## 3.1 Hydrothermal Gasification (1)

Hydrothermal gasification (HTG) offers the possibility of converting wet organic streams into methane using high pressure to reach supercritical water conditions in a complex reactor scheme. Compared to traditional gasification, it offers the advantage that it utilizes the wet stream as it is, avoiding the preceding energy intensive drying step. Moreover, water in its supercritical condition has low density and dielectric constant. Consequently, it changes from polar to non-polar solvent and thus, the organic compounds dissolve easily in it. Furthermore, the supercritical conditions that prevail within the HTG reactor also ensure that the nitrous and phosphoric minerals contained in some forms of wet biomass such as sewage sludge and manure are released unharmed in the residual output stream. Apart from direct processing of wet biomass streams, HTG can be used to convert the lignin-rich digestates from anaerobic digestion. On the drawbacks of the process stand the energy needed to reach the operating conditions (around the critical point of water, i.e. 370 K and 220 bars) as well as the use of a catalyst, which in turn requires special attention with regard to maintenance (poisoning prevention, degradation handling etc.). According to Gassner et al. (2011), a mean efficiency (LHV methane vs. LHV feedstock) for various wet biomass types is around 0.60 with a simultaneous electrical efficiency of 0.04, especially if power recovery from the high pressure vapor phase is considered. This efficiecny value is consistent with current findings in the hydrothermal gasification plant being developed at PSI BIOSWEET (2009) that shows an efficiency (LHV methane vs. LHV feedstock, without including the electricity needs) of 60–70%.

## 3.2 Pyrolysis (4a)

Pyrolysis is a thermal cracking process for dry biomass processing that can deliver a number of products including gaseous, liquid and solid streams depending on the process design and the operating conditions. During pyrolysis, biomass is subjected to elevated temperatures in the absence of any oxidizing medium (i.e. inert atmosphere) resulting in a thermal breaking of the carbon matrix. The intensity of the carbon bond scission and thus, the physical state of the products is mostly dependent on the heating rate employed. Nowadays, the focus of pyrolysis is production of liquid bio-crude, produced when medium heating rates are used. Pyrolysis is often the first step in liquid biofuel production, as the output bio-crude requires an upgrading step (4b) prior to being used in fuel engines. Most pyrolysis processes employ fixed bed reactors and temperatures between 300 °C and 500 °C. According to Shemfe et al. (2015), the chemical efficiency (HHV output vs. HHV input+kW electricity) of pyrolysis is around 0.66, while at the same time if energy recovery is used; a simultaneous power production is possible. The produced power is equivalent to 2% of the fuel product energy content.

## 3.3 Gasification (5a)

Woody biomass can be converted through high-temperature gasification into a gaseous fuel stream comprised mainly of CO, $CO_2$ and $H_2$ (syngas). In the case of low-temperature gasification (below 900 °C), the syngas is accompanied by CH4, olefins, aromatics and tars. Gasification is a thermochemical process that employs biomass oxidation in sub-stoichiometric conditions to favour the production of CO instead of $CO_2$. Different oxidizing media such as steam, air or pure oxygen directly affect the product distribution in the outlet stream. Gasification is a mature technology that uses a number of different reactor configurations depending on the intended use of the produced syngas. Temperatures inside the gasifier can reach up to 700–1300 °C and usually the heat is partially provided by combustion of a fraction of the product gas.

The syngas obtained in the gasification process can be used to produce synthetic natural gas (via a methanation reaction, 5b and 5g), liquid fuels (via a Fischer/Tropsch synthesis, 5c) or hydrogen (via a water gas shift reaction, 5d). Alternatively, the syngas may be combusted in a gas motor or a gas turbine combined cycle to produce electricity and heat (5d).

### 3.3.1 Methanation (Sabatier) (5g, 5b)

The methanation is the upgrade of the syngas that enriches the produced gaseous fuel. It converts the CO and $CO_2$ in the Syngas to additional methane ($CH_4$) through the Methanation or Sabatier reactions with $H_2$:

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O \qquad \text{(Methanation)}$$

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \qquad \text{(Sabatier)}$$

The reaction can use the hydrogen already included in the syngas (5g) or add additional $H_2$ (5b) to increase the efficiency of the process. Literature reports an energy efficiency (LHV) of wood to biomethane (5a + 5b) of 62–74% (Schildhauer, 2018, E4Tech, 2010). If heat recovery and turbines are used, an additional production of around 10% heat and 4% power, with respect to the energy value of the product, can be achieved. The technology developed at PSI has an efficiency (LHV biomethane vs. LHV wood) of 62.5% and has a simultaneous heat production of 9% (Schildhauer, 2018).

### 3.3.2 Fischer-Tropsch synthesis (5c)

The Fischer-Tropsch (FT) reaction, first developed by Franz Fischer and Hans Tropsch in the 1920s, is a catalytic synthesis process realized as a polymerization of carbon atoms. It is mainly used to produce synthetic liquid fuels from gasification-derived syngas. Today more than 99% of the feedstock used for FT is fossil natural gas or coal but the process can also use feedstocks of biogenic origin, such as wood or green waste. i The chemical reaction is described by a simple representation of the form:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O,$$

where $n$ is the number of carbon atoms in the polymer chain. The conversion conditions (around 200–300 °C and pressure in the range of tens of bars) are used to inhibit the formation of small alkanes but rather push towards the production of long chain hydrocarbons with carbon chains of 10-20 atoms, according to the Anderson-Schulz-Flory (ASF) distribution. The FT process uses catalysts to promote the growth of the carbon chain, with nickel or cobalt being the most commonly used ones. However, their low poisoning resistance to sulphuric derivatives dictates stringent syngas cleaning steps prior to insertion in the FT reactor. The produced hydrocarbon blend must then undergo hydrotreatment in order to obtain the desired biofuel quality. The addition of hydrogen in a subsequent hydrocracking reactor leads to the chemical cleavage of the long-chain hydrocarbons and under controlled conditions, the acquisition of a paraffin blend (biodiesel) of desired quality. The energetic efficiency (LHV of liquid fuel vs. LHV feedstock) of the FT process is in the order of 0.45 (Peduzzi, 2015, Peduzzi et al., 2018) with a simultaneous heat recovery of 0.39 kW per kW equivalent biodiesel.

### 3.3.3 Waster gas shift

The water gas shift reaction is a commonly used reaction in the industry where hydrogen is produced from water or steam and carbon monoxide is converted into carbon dioxide, thus,

$$CO + H_2O \rightleftharpoons CO_2 + H_2.$$

The water gas shift reaction can be catalytic or non-catalytic. A variety of catalysts have been developed and the non-catalytic reaction occurs in certain environments such as supercritical water and plasma systems (Chen and Chen, 2020). Several upgrading steps are needed to obtain pure hydrogen.

## 3.4 Anaerobic Digestion (6a, 6e, 6f)

Anaerobic digestion is a biochemical process used to break the biogenic carbon of wet biomass and release it as biogas, consisting of methane and carbon dioxide in a molar ratio of approximately 60/40. Digestion of biomass under anaerobic conditions is realized with the aid of suitable microorganisms and proceeds through a complex series of (bio-)chemical reactions that can be grouped in three main stages: acidogenesis, acetogenesis and methanogenesis. A set of parameters including the temperature and pH are decisive for the efficient operation of anaerobic digestion. In particular, three types of microorganisms are used depending on the temperature of operation: thermophilic (45–55 °C), mesophilic (25–45 °C) and cryophilic (below 25 °C). The energy efficiency of anaerobic digestion depends on the nature of the digested biomass and the operating conditions. Together, they define the methane potential for each case (i.e. the produced volume of methane per mass unit of digestible matter). Overall efficiencies (LHV biogas vs. LHV biomass feedstock) range from 0.1 to 0.4 in the literature depending on the plant size and raw material (Pöschl et al., 2010).

Biogas produced from anaerobic digestion can be sent to an upgrading unit (6b) to separate $CO_2$ and thus, enrich the calorific value of the fuel by concentrating the biomethane content, it can be sent to a methanation process that uses additional H2 to increase the methane production (6c) or simply sent to combustion engines for electricity production with potential heat recovery (6d). Switzerland has a demonstration plant of Fluidised bed Methanation with membrane upgrading that converts the biogas with additional hydrogen to biomethane (6c) with an efficiency (LHV biomethane vs. LHV H2, the methane in the biogas is not considered) of 84% (Witte et al., 2018). Anaerobic digestion also results in a liquid by-product stream, the digestate, which contains all undigested biomass as well as the valuable nutrients originally in the feed stream (e.g. K, N, P etc.). Due to the latter, digestate streams are mostly used nowadays as soil fertilizers. However, the high carbon content of this residual stream leaves room for additional retrieval in the form of fuels by hydrothermal treatment.

## 3.5 Biomass to Alcohols

Primary alcohols such as methanol and ethanol are not only individually used fuels but also constitute chemicals used as the basis for synthesis of higher fuels, as for example aviation fuels. Alcohols can be produced from both woody or non-woody biomass using different conversion pathways. Methanol can be produced from wood gasification followed by a synthesis step to convert the produced syngas. Ethanol is primarily produced via the biochemical fermentation of biomass crops such as corn, wheat or sugarcane. Fermentation is usually preceded by pretreatment and handling steps like milling and hydrolysis that aims to isolate the sugars from the biomass matrix. Then the biological degradation step is able to transform the sugars in chemicals of fuels such as ethanol depending on the design of the process.

## 3.6 Technology characteristics

In collaboration with BIOSWEET we developed an expert elicitation on biomass technology characteristics for Switzerland, see Table 3.1. These are characteristics of technologies being developed in Switzerland. Moreover, Table 3.2 presents a summary of indicative values from the literature for different technologies.

## 3.7 $CO_2$ to X technologies

In the context of circular carbon systems, the recirculation of carbonaceous material within the system is needed to maintain high carbon utilization while reducing overall emissions. $CO_2$ capture could help to utilize an otherwise waste stream as a valuable resource for synthesis of chemicals and products. This could increase the substitution of fossil resources that would be otherwise used instead. Captured $CO_2$ can be used in a variety of processes, the most important of which are described

Table 3.1: Characteristics of biomass conversion technologies from expert elicitation in Switzerland

| | **Technology** | **Feedstock** | **Product** | **Inv. cost (CHF/kW chem LHV)** | **FOM (CHF/kW chem LHV)** | **Eff (LHV out/ LHV in, %)** | **Elec. use (MWhel/ MWh chem LHV)** | **Heat prod. (MWhth/ MWh chem LHV)** | **TRL** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) | Hyd. gasification | Wet (B, C, D) | Methane | 8268, 2035: 5788 | 517 | 60–70 | | | 6 | BIOSWEET (2009) |
| (5a) + (5b) | DFB Gasification+Fixed bed Meth (GoBiGas) | Wood (A) | Methane | 3500 | 40 | 62.5 | 0.094 | 0.09 at 80 °C | 8 | Schildhauer (2018) |
| (5a) + (5b) | DFB Gasification+Fluidised bed Meth (PSI technology) | Wood (A) | Methane | 2315 | 40 | 62.5 | 0.1 | 0.09 at 80 °C | 7 | Schildhauer (2018) |
| (6c) | Fluidised bed Methanation with membrane upgrading | Biogas (55% CH4, 45% CO2) + H2 | Biomethane | 781[a] | 102 | 83.95 (LHV methane/ LHV H2)[b] | 0.0205[a] | 0.072 at >280 °C, 0.087 at >150 °C[a] | 7 | (CEDA, 2021, Witte et al., 2018) |
| (6c) | Fixed bed Methanation with membrane upgrading | Biogas (55% CH4, 45% CO2) + H2 | Biomethane | 1015[a] | 129 | 83.95 (LHV methane/ LHV H2)[b] | 0.0135[a] | 0.073 at >280 °C, 0.079 at >150 °C[a] | 7 | (CEDA, 2021, Witte et al., 2018) |

[a] Does not consider the hydrogen production.

[b] This is only hydrogen to additional methane; the methane in the biogas is not considered.

Data available at https://data.sccer-jasm.ch/biomass-conversion-technologies/

below.

### 3.7.1 $CO_2$ to Synthetic Natural Gas

The catalytic reaction of $CO_2$ with $H_2$ under pressurized conditions and medium to high temperatures is simply known as methanation or Sabatier process (Section 3.3.1).

Power to gas (PtG) is the process of combining electrolysis to produce $H_2$ with the sabatier process to produce methane. The electrical power used to break the hydrogen-oxygen bonds in water can then be stored as chemical energy in the form of $H_2$ and subsequently synthetic natural gas. If renewable resources are used for the electrolysis, PtG can be used not only to harvest and exploit solar power and valorize captured $CO_2$ but also to regulate the fluctuations of the produced power from the PV due to the intermittency of the sun.

### 3.7.2 $CO_2$ to Methanol

As already noted, primary alcohols such as methanol and ethanol constitute not only important chemicals, but can also be used to synthesize fuels and other chemicals and they are considered

Table 3.2: Characteristics of biomass conversion technologies from literature review

| | **Technology** | **Feedstock** | **Product** | **Ref. Size (MW)** | **Inv. cost (CHF/kW chem LHV)** | **OM[a] (CHF/kW chem LHV)** | **Eff (LHV out/ LHV in, %)** | **TRL** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| (1) | Hydrothermal Gasification | Wet (B, C, D) | Biomethane | 1 | 1700 | 118 | Chem: 42.3,<br>Elec: 4 | 5 | Gassner et al. (2011) |
| (4) | Pyrolysis | Wood (A) | Liquid Biofuel | 1 | 2574 [2300–4000] | 128.7 | Chem: 66,<br>Elec: 1.6 | 8 | Brown et al. (2020), Shemfe et al. (2015) |
| (5a) + (5b) | Gasification + methanation | Wood (A) | Biomethane | 1 | 2930 [1000–3300] | 149 | Chem: 74,<br>Therm: 24 | 8 | E4Tech (2010) |
| (5a) + (5c) | Gasification + Fischer-Tropsch | Wood (A) | Diesel | 1 | 1955 [1900–4070] | 35.81 | Chem: 44,<br>Therm: 17.5 | 7 | Peduzzi (2015) |
| (6a, 6e, 6f) + (6b) | Anaerobic digestion + Upgrade | Wet (B, C, D) | Biogas | 0.4 | 1053 [900-2100] | 93.75 | Chem: 30 | 9 | Ro et al. (2007), Pöschl et al. (2010) |
| (6a) + (6d) | Anaerobic digestion + GTCC | Wet (B, C, D) | Heat/power | 5 | 1776 | 147 | Elec: 13,<br>Therm: 14.5 | 9 | Ro et al. (2007), Pöschl et al. (2010) |
| | Wood to Methanol | Wood | Methanol | 1 | 2500 [2200–3300] | 125 | Chem: 48 | 6 | Brown et al. (2020), Bandi and Specht (2004) |
| | Biomass to Ethanol | Crop residues | Ethanol | 115 | 2236 [2200–4000] | 156.7 | Chem: 56 | 8 | Tao et al. (2017), Han et al. (2017) |

Data available at https://data.sccer-jasm.ch/biomass-conversion-technologies/

industrial building blocks. Similar to the production of alcohols from raw biomass, the former can be catalytically synthesized using captured $CO_2$ as the carbon resource stream, together with $H_2$ which carries and transfers the chemical energy. Equivalent to the PtG technology, the synthesis of liquid fuels or chemicals using a carbon source and (renewable) $H_2$ results in the chemical storage of power in liquid form, a process known as Power to Liquids (PtL). Methanol can be produced via the following chemical reaction scheme:

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$
$$CO_2 + H_2 \rightleftharpoons CO + H_2O.$$

The process is highly exothermic, which on the one hand poses a challenge as the produced heat has to be continuously removed to enhance the rate of reaction, but on the other this exact characteristic constitutes a wasted heat resource. If harvested efficiently, the latter can be used to supply energy in the form of process heat to other (sub-)processes of an integrated system. Reports show an energy efficiency as high as 74% and associated equipment costs in the order of approximately

1800 CHF/kW for rather small scale systems, a value which is comparable to conventional biomass conversion technologies (Pérez-Fortes et al., 2016).

### 3.7.3 $CO_2$ to Liquid Fuels

Similar to the chemical synthesis of terrestrial mobility and aviation biofuels from biomass through catalytic processes, these fuels can be produced using captured $CO_2$ as the carbon resource. This concept exploits the same principles as the one for alcohols synthesis and requires additional $H_2$. Using the reverse Water Gas Shift (rWGS) reaction, the captured $CO_2$ is reduced to syngas ($CO + H_2$) which is then easy to convert into a blend of liquid hydrocarbons via the Fischer-Tropsch pathway. In this way, diesel, gasoline and/or kerosene type blends can be produced.

### 3.7.4 Technology characteristics

Table 3.3 presents a summary the most important characteristics of the $CO_2$ to X technologies from different literature sources.

Table 3.3: Characteristics of $CO_2$ to X technologies from the literature

| Technology | Ref. Size (MW) | Inv. cost (CHF/kW) | OM (CHF/kW) | Eff (LHV, %) | TRL | Reference |
|---|---|---|---|---|---|---|
| $CO_2$ to SNG | 1 | 280 [204–369] | 14 | 78 (LHV H2 to LHV CH4) | 8 | Gorre et al. (2019) |
| $CO_2$ to Methanol | 300 | 1794 | 149 | 74 (LHV H2 to LHV Methanol) | 6 | Pérez-Fortes et al. (2016) |
| $CO_2$ to Diesel | 10 | 680.75 | 68 | Diesel: 65, Gasoline: 25.2 (Only FT process, LHV H2 to LHV Diesel or gasoline) | 7 | Dimitriou et al. (2015) |
| $CO_2$ to Jet Fuels | 144 | 971.64 | 48.6 | 84 (Only FT process, LHV H2 to LHV Jet fuel) | 4 | Willauer et al. (2012) |

Data available at https://data.sccer-jasm.ch/biomass-conversion-technologies/

## 3.8 Synthesis of Chemicals and Plastics

As the industrial market for (bio-)chemicals is large and rather mature at a global scale, we also consider processes for producing important chemicals from “building block” compounds such as methane and methanol. These include acetic acid, olefins (ethylene and propylene), aromatics (benzene, xylene and toluene) as well as the production of polyethylene and polystyrene from their monomers. The technological options and pathways to produce these chemicals are indeed many and sometimes complex. We present some representative technologies in Table 3.4.

Table 3.4: Characteristics of technologies for the production of chemicals and plastics

| **Technology** | **Ref. Size (MW)** | **Inv. cost (CHF/kW)** | **OM$^a$ (CHF/kW)** | **Chemical eff (LHV, %)** | **TRL** | **Reference** |
|---|---|---|---|---|---|---|
| Methanol to Acetic Acid | 5 | 3034.4 | 151.7 | 48.4 | 9 | Smejkal et al. (2005) |
| Methane to Methanol | 1160 | 1023.7 | 51.18 | 65 | | Collodi et al. (2017) |
| Methanol to Olefins | 880 | 1570 | 78.5 | Propylene: 32.5, ethylene: 56.8 | 8 | Jasper and El-Halwagi (2015) |
| Methanol to Aromatics | 1 | 815 | 40.75 | Benzene.: 1.35, toluene: 8.5, xylene: 14 | 8 | Bazzanella and Ausfelder (2017) |
| Ethylene to Polyethylene | 16 | 769 | 38.45 | 97 | 9 | Lack et al. (2001) |
| Styrene to Polystyrene | 1 | 1174 | 58.7 | 95.2 | 9 | Towler and Sinnott (2013) |

Data available at https://data.sccer-jasm.ch/biomass-conversion-technologies/

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## Appendix A

# Potential with old population projections

The following potentials are calculated using the same methodology described in the report but using the previous BFS population projections (BFS, 2015).

## A.1 Macro-economic drivers

Table A.1: Macro-economic drivers: Variants in JASM (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/2020-06-11/

## A.2 Available mass

Table A.2: Available potential for biomass and waste (kton)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Reference variant** | | | | | | | | | | | |
| (A) Wood | Forest wood | | | | | | | | | | |

Table A.2: Available potential for biomass and waste (kton) (continued)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| | 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 | 1341 | 1475 | 1612 | 1743 | 1856 | 1961 | 2063 | 2161 | 2255 |
| | 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 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1233 | 1364 | 1491 | 1578 | 1656 | 1727 | 1794 | 1856 | 1924 |
| | Municipal waste | 2850 | 2817 | 2875 | 2920 | 2940 | 2917 | 2876 | 2826 | 2767 | 2700 |
| | *including green waste* | *737* | *677* | *635* | *586* | *527* | *457* | *383* | *305* | *225* | *144* |
| **High variant** | | | | | | | | | | | |
| (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 | 1348 | 1506 | 1671 | 1832 | 1972 | 2105 | 2238 | 2371 | 2503 |
| | 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 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1239 | 1403 | 1565 | 1684 | 1788 | 1887 | 1982 | 2073 | 2167 |
| | Municipal waste | 2850 | 2832 | 2935 | 3026 | 3088 | 3099 | 3087 | 3066 | 3036 | 2997 |
| | *including green waste* | *737* | *680* | *648* | *607* | *554* | *486* | *411* | *331* | *247* | *160* |

Table A.2: Available potential for biomass and waste (kton) (continued)

| | | **Available mass (kton)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Low variant** | | | | | | | | | | | |
| (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 | 1333 | 1445 | 1555 | 1658 | 1743 | 1820 | 1891 | 1957 | 2016 |
| | 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 | 301 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Other waste fraction | 1142 | 1227 | 1323 | 1414 | 1468 | 1523 | 1571 | 1612 | 1649 | 1692 |
| | Municipal waste | 2850 | 2801 | 2817 | 2818 | 2795 | 2740 | 2669 | 2591 | 2505 | 2414 |
| | *including green waste* | *737* | *673* | *622* | *565* | *501* | *430* | *355* | *280* | *204* | *129* |

Data available at https://data.sccer-jasm.ch/biomass-potentials/2020-07-08/

## A.3 Energy potentials

Table A.3: Energy potential of biomass and waste categories (PJ)

| | | **Energy Potential (PJ)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| **Reference variant** | | | | | | | | | | | |
| (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 |

Table A.3: Energy potential of biomass and waste categories (PJ) (continued)

| | | **Energy Potential (PJ)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| | 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* |
| | | | | | | | | | | | |
| **High variant** | | | | | | | | | | | |
| (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* |
| | | | | | | | | | | | |
| **Low variant** | | | | | | | | | | | |
| (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 |

Table A.3: Energy potential of biomass and waste categories (PJ) (continued)

| | | **Energy Potential (PJ)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Feedstock** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** | **2055** | **2060** |
| | 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/ organic waste | Imports | 4.2 | 2.8 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 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/2020-07-08/