

Appendix G: Illustrative Biogenic Process Attributes

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1. Introduction

The purpose of this appendix is to describe possible methods for developing values for biogenic process attributes, which are attributes that reflect feedstock carbon procured by a stationary source that exits assessment through pathways other than emissions from the stack. These biogenic process attributes can include feedstock carbon that is deviated from the process prior to conversion¹ to bioenergy (such as products produced from feedstock material or feedstock losses during transport, storing, and other processing) or feedstock carbon in products that exit the stationary source bioenergy conversion process (such as ethanol or ash).

For demonstrative purposes in this appendix, illustrative values are presented by general stationary source technology and/or process type for specific feedstocks. Values for products can depend on the specific process used at a stationary source, as well as the type of feedstock used.

¹ Conversion refers to technologies or processes that convert biomass into energy directly, in the form of heat or electricity, or may convert it to another form, such as liquid biofuel or combustible biogas. Examples of biomass conversion processes include biomass-fired or co-fired boilers, biomass gasification or pyrolysis systems, and anaerobic digesters.

Values for losses can depend on the type and duration of transport, storage, and processing. In cases where specific information is not available, or if the framework is being applied at a scale larger than stationary-source specific, estimated values for these terms may need to be generalized representative factors. The appendix also provides a detailed technical discussion of the data sources and analytical methods used to develop illustrative values.

2. Framework Representation of Feedstock Carbon Losses and Products for Forest- and Agriculture-derived Feedstocks

Feedstock carbon from forest- and agriculture-derived feedstocks can be transformed into products or exit the supply chain (pre- and post-conversion) through means other than the stack. The biogenic assessment factor (*BAF*) equation is designed to transform a measurable or estimated quantity (the carbon content of biomass feedstock used at the point of assessment, represented by potential gross emissions, *PGE*) into a quantity that cannot be directly measured (the net atmospheric contribution of biogenic carbon resulting from use of the quantity of biogenic feedstock that the entity is responsible for, represented by net biogenic emissions, *NBE*). The framework equation, as discussed in the main report as well as Appendix F, is:

$$BAF = \frac{NBE}{PGE} = (GROW + AVOIDEMIT + SITETNC + LEAK)(L)(P) \quad (EQ. G.1)$$

The terms below each play a specific role in this equation:

- *PGE* is carbon content of the biogenic feedstock used by a specific entity (or generally consumed). This is a quantity that could be measured or estimated at different points of assessment (e.g., at the boiler mouth, stationary source gate, feedstock production site, or at the stack: wherever the point of assessment needs to be. Thus, this term can have different values indicated by subscripts, representing different points along the supply chain).
- *L* is a unitless adjustment factor greater than or equal to 1 that represents biogenic feedstock carbon that leaves the supply chain (e.g., via transit or decomposition, deviated for use as a product) between the feedstock production site and input into the conversion process at a stationary source. *L* scales *PGE*, as it was measured at the point of assessment, up to account for any losses during transportation or storage between the feedstock production site and the point of assessment. *PGE* times *L* is thus the carbon content of the biomass that was grown at the feedstock production site in order to deliver the quantity of feedstock measured at the point of assessment.
- *P* is a unitless adjustment factor between zero and one, equal to the share of the carbon content of the feedstock at the point of assessment that is emitted to the atmosphere by a stationary source (versus that which is embedded in products). In effect, this term also reflects the share of carbon that remains in products, that is either not emitted to the atmosphere or is sold and eventually emitted to the atmosphere by a downstream user.

2.1. Equations Underlying *P* and *L*

2.1.1. *P*

P accounts for the carbon content of the feedstock material that is emitted to the atmosphere and therefore also accounts for biogenic carbon in products that is not emitted from the stack and leaves the producing entity (pre- and post-conversion) for downstream use or disposal. Examples of products that may exit the supply chain prior to conversion include:

- Wood material in products (lumber, wood pulp, panel products);
- Mill residues sold/transferred to a separate stationary source for use as raw material or fuel;
- Bark sold/transferred to a separate stationary source for fuel;
- Bark sold for mulch;
- Agricultural by-products (e.g., stover, stalks, straws, husks, hulls, etc.) sold/transferred to a separate stationary source for use as fuel; or
- Pulping by-products (tall oil, turpentine).

Examples of products that may exit the supply chain after conversion include:

- Dried distillers grains (from ethanol production);
- Ethanol; or
- Bottom ash, flyash, or biochar (e.g., materials containing unburned carbon).

Equation F.7 from Appendix F defines *P* as calculated in this example.

$$P = 1 + \frac{\sum_{i=1}^S PROD_i}{PGE_j} \quad (\text{EQ. G.2})$$

$PROD_i$ represents the sum of all pre- and post-conversion products and PGE_j is *PGE* evaluated at point of assessment (*j*). Note that for many stationary sources, biogenic feedstocks will be used to produce a number of final products, so the summation in Equation G.2 simply sums over all *i* products that are produced prior to the bioenergy conversion process with biogenic CO₂ stack emissions, indexed from 1 to *S*, where *S* is the last point on the carbon trail and represents the stack. For example, if $PROD_2$ is the only product, this summation would simply be equal to $PROD_2$. Since $PROD_i$ is always negative and the absolute value of the sum of all $PROD_i$ must be less than PGE_j , the sum of all $PROD_i$ divided by PGE_j will be a fraction that has a negative value, and *P* as calculated above will be a positive number between 0 and 1 (technically this expression is 1 plus a negative number). In effect, this calculation takes away the portion of carbon the products are responsible for, and attributing the remainder to the stationary source. Although this is a relatively simple example, the mathematical representation of this term and more complicated scenarios are illustrated in Appendix F.

The framework recognizes that some post-conversion materials—such as fly ash—can potentially be sold and used for a number of commercial purposes (i.e., cement manufacturing) or disposed of. Either way, such post-conversion materials are considered under the *P* term because they pass

through the stationary source, exiting through means other than emissions out the stack. There is limited data on some post-conversion materials: limited and/or emerging scientific data in some cases (such as biochar) and publically available production and market data (e.g., end uses, sales of such materials). Also, whether or not these materials are sold, the carbon contained in this material can in some circumstances remain sequestered for some duration of time.

2.1.2. *L*

The *L* term reflects biogenic feedstock losses in transportation to, storage, and processing at a stationary source and any products that exit the supply chain prior to the conversion process. This value facilitates the link between the quantity of feedstock received at the stationary source, the quantity of feedstock that enters the stationary source process, and the quantity of feedstock grown on or removed from (e.g., in the case of crop residues) the land. Some stationary sources may measure both feedstock delivered at the gate and at the point of entry into the conversion process (e.g., boiler mouth) and thus have the data to calculate its onsite *L* term. Depending on the data that stationary sources have, *PGE* could be estimated, measured (i.e., the mass of the biogenic feedstock as it enters a stationary source process and converting that mass into its CO₂ equivalents), or perhaps back calculated from the direct process emissions at the stationary source. An estimate of losses associated with storage at the stationary source and any pre-conversion products plays a role in the estimation of the amount of feedstock actually delivered to the site versus that entering the supply chain at the production landscape.

The purpose of *L* here is twofold. First, *L* represents the transformation of *PGE*₀ (*PGE* evaluated at the feedstock production/harvest site) to *PGE*_{*j*} (*PGE* evaluated at point of assessment *j*), implicitly capturing any losses (*LOSS*_{*i*}) and any pre-conversion products (*PROD*_{*i*}) that occur between these two *PGE*s. Note that this fraction will result in a positive number. Second, if considered in combination with the landscape effects term, it serves to bring the landscape effects in relation to *PGE*_{*j*}.

$$L = \left(\frac{PGE_0}{PGE_j} \right) \quad (\text{EQ. G.3})$$

Calculations presented in Section 4 of this document generate illustrative loss terms for when such site or supply chain-specific calculations are not possible or when representative factors are necessary within a specific program or policy application (e.g., regional application of the framework).

3. Evaluation of Post-Conversion Products

In addition to information on the carbon content of the input feedstock, the methodology applied in this appendix also requires knowledge of the relationship between input and output. This information is often necessary to properly express *P* as demonstrated in the equations below:

P Equation

$$P = 1 + \frac{\sum_i (\text{Mass of product}_i \times \text{Carbon content of product}_i)}{(\text{Mass feedstock input} \times \text{Carbon content of feedstock input})}$$

Thus:

$$P = 1 + \frac{\sum_i PROD_i}{PGE_j} \quad (\text{EQ. G.4})$$

Where:

$$PROD_i = (\text{Mass of product}_i \times \text{Carbon content of product}_i) \quad (\text{EQ. G.5})$$

$$PGE_j = (\text{Mass feedstock input} \times \text{Carbon content of feedstock input})$$

at the point of assessment j

As explained in Appendix F, P is 1 minus the share of PGE_j that remains in products or by-products and is either not emitted to the atmosphere or is sold and eventually emitted to the atmosphere by a different entity. (Note that because $PROD$ is negative, technically this expression is 1 plus a negative number.) Because of the variability of different conversion technologies (e.g., boiler types), this appendix relies on mass balance data to establish the relationship between input and output and then uses the equations above to calculate example values for P .

The following section explores methods that could be used to estimate $PROD_i$ parameters contributing to P . The example process and stationary source combinations below are addressed in this appendix for use in case study applications per different baselines:

- Co-firing in electric generating units (EGUs) (using forest-derived feedstocks); and
- Pyrolysis chambers in pyrolysis facilities (using corn stover).

Carbon content values for agricultural feedstocks are taken from Spokas (2010), while values for forest-derived feedstocks are from Skog (2008). Table G-1 shows values for each, expressed as percent carbon on a dry weight basis.

Table G-1. Carbon Content of Different Biogenic Feedstocks.

Input Feedstocks	Percent C by Dry Weight
Roundwood	50
Logging Residue	50
Corn Stover ²	44

3.1. Co-firing in Electric Generating Units (EGUs)

Some EGUs are designed for 100% biomass combustion (Johansson et al., 2003). However, most EGUs are optimized for coal, natural gas, or oil. Yet, some EGUs can co-fire a certain percentage of biogenic fuel to be used in addition to the fossil-based feedstock (Demirbas, 2005), depending on the biogenic fuel and boiler design (e.g., solid-fuel boilers may be able to co-fire solid biomass). Generally, any type of biogenic feedstock can be used, but most often in the U.S., feedstocks are

² Although presented more specifically in examples as 44% in this appendix, in Appendix L, the carbon content of corn stover is assumed to be 50% for consistency with other FABA feedstock case studies.

forest-derived (e.g., roundwood, logging, or mill residues), often converted to pellets or chips (Demirbas, 2005). Regardless of feedstock blend (i.e., percentage of biomass in fuel input), an EGU combusts the feedstock in a boiler to heat water into steam, which is used to drive turbines and generate electricity.

3.1.1. Estimated P Term Values

Application of the framework could first reflect the relevant stationary source technologies and processes used at EGUs, then the applicable biogenic feedstock inputs and residual outputs. The process of co-firing biomass at an EGU does not produce non-energy/heat commercial products other than post-combustion materials like ash. As noted above, an EGU combusts the feedstock in a boiler to heat water and produce steam, which is used to drive turbines and generate electricity.³

To calculate P in this illustrative scenario, the amount of carbon in the post-process materials produced can be expressed as a proportion of carbon in the input feedstock. This value differs depending on the boiler type and efficiency. Boilers vary from facility to facility, because there are a number of different boiler types to choose from, including fluidized bed boilers, stoker boilers, or cyclone boilers. Each functions at a different efficiency, and some can accept higher percentages of biogenic feedstock in the fuel blend. Differences among boilers in efficiency or temperature of combustion can result in different amounts of post-process materials, or different carbon content of the materials (Tarelho et al., 2011). Literature suggests boiler type is an important predictor of unburnt carbon remaining, but the feedstock blend could impact efficiency of combustion and thus result in more or less post-process materials (e.g., ash) or a higher or lower carbon content of the materials (Demirbas, 2005). Generally, agricultural biomass features higher ash content than woody biomass (Cassidy and Ashton, 2007).

Regardless of process, the amount of unburnt carbon remaining in the ash is typically expected to be low compared to the amount of feedstock carbon entering the conversion process (Kaufmann et al., 2000), but, as it depends on the conversion process efficiency, rates can vary substantially. Compared with modern, high-efficiency boilers, traditional grate boilers often result in less efficient combustion—and therefore feature higher levels of unburnt carbon. Tollin (2000) suggests carbon content of ash can approach 50% in low efficiency grate boilers. Biomass stoker boilers may have 30–40% carbon in the ash (Gustafson and Raffaelli, 2009). Pitman (2006) reports average carbon content in wood ash to range from 7 to 50% (average 26%) in commercial boilers in the eastern U.S.

Those values pertain to carbon content of the ash itself, not the proportion of incoming feedstock carbon remaining. The amount of ash generated in the combustion process is typically $\approx 10\%$ (by weight) of incoming feedstocks. Table G-2 shows an example calculation based on a feedstock with 50% carbon content, as well as other hypothetical assumption values based on Table G-1.

³Theoretically, if combustion in an EGU was 100% efficient in converting biogenic carbon to CO_2 , then P could be set to $P = 1$ to reflect that there is no carbon remaining in post-combustion material (ash) and that there are no products produced from the feedstock used in the EGU (i.e., $PROD = 0$).

Table G-2. Sample P for Ash Information for Low Efficiency Boiler.

Variable	Value
Incoming feedstock	1 ton
Carbon content of feedstock	50%
PGEj: Total incoming carbon	0.5 tons
Ash content of feedstock	10%
Ash remaining post-combustion	0.1 tons
Carbon content of ash	26%
Total remaining carbon post-combustion	0.026 tons
PROD: Proportion of initial carbon remaining post-combustion to PGEj	-0.052 ¹
P	0.948 ²

Notes:

1. Carbon in products is subtracted (i.e., has a negative value) because product carbon does not enter the atmosphere with the biogenic CO₂ from the conversion process. $PROD = -(0.026/0.5)$
2. $P = 1 + (-0.052) = 0.948$

PROD (ash) values would be lower for modern, high-efficiency boilers, leading to higher *P* terms. Nussbaumer and Hasler (1999) and Johansson et al. (2003) report fly ash carbon concentrations of 1–10% in modern boilers. Demirbas (2000) uses an average ash content of 0.5%. Kaufmann et al. (2000) analyzed ash samples and determined carbon content to be no more than 0.05%. Fluidized-bed boilers typically achieve nearly 100% combustion, meaning practically 0% carbon remains in ash (EPA, 2007; Gustafson and Raffaelli, 2009). As above, the mass of the ash itself is a small fraction of total incoming feedstock, meaning the remaining carbon is only a small percentage of the total incoming carbon. Tarelho et al. (2011) present the best data on this, showing total unburnt carbon left in post-combustion residuals to be only 0.7–2.8% of the original feedstock carbon (i.e., 0.007–0.028 tons per ton of feedstock carbon input).

The value varies depending on the efficiency of the boiler, but generally the majority of the incoming carbon will be released via combustion as CO₂. Table G-3 shows example illustrative values of the *P* term based on boiler efficiency. Actual values for *P* are expected to vary depending on boiler technology being used at a facility and feedstock type.

Table G-3. Example Estimated Range of P Values for Co-Firing Biomass in Electrical Generating Units.

Co-firing Boiler Type	P
High Efficiency	0.972 ¹ to 0.993 ²
Low Efficiency (as shown in Table G-2 above)	0.948

¹ $P = 1 + (-PROD/PGE) = 1 + (-0.028 \text{ tons C in ash/ton of C input in feedstock}) = 0.972$

² $P = 1 + (-PROD/PGE) = 1 + (-0.007 \text{ tons C in ash/ton of C input in feedstock}) = 0.993$

3.1.2. Discussion

Serious data gaps exist in developing representative *P* values for co-firing boilers at EGUs. Overall, little information exists about carbon content of post-combustion materials. Because of this, determining representative *P* values is difficult, and considerable uncertainty remains.

More detailed data from proximate and ultimate analysis of different biogenic feedstocks are required, as are engineering analyses related to combustion using different technologies. For example, ash content will impact boiler heat surface fouling, which will impact the completeness of combustion—and by extension the *P* value for different combustion technology—for different feedstock combinations. As noted above, the process of co-firing biomass at an EGU can be done with a number of different biogenic feedstocks and a number of different boilers. Furthermore, the fossil fuel/biomass blend can vary greatly depending on cost, supply, boiler specifics, and a number of other factors.

However, despite the lack of data, it is clear that in most scenarios much of the carbon is emitted as CO₂ during combustion. Therefore, although the carbon content of post-combustion materials may vary, the average is expected to be low.

3.2. Pyrolysis

The pyrolysis process involves the thermal destruction of organic materials in an environment void of oxygen (Demirbas, 2005). When the biomass is heated in a pyrolysis chamber, it produces a hydrocarbon rich gas mixture (syngas), an oil-like liquid (bio-oil), and a carbon rich solid material (biochar). The relative amounts of each product depend on whether the facility employs high heat fast pyrolysis or low heat slow pyrolysis. Typical mass yield ranges for fast pyrolysis are bio-oil 50–70%, syngas 10–30%, and biochar 10–25%. Typical mass yield ranges for slow pyrolysis are: bio-oil 20–50%, syngas 20–50%, biochar 25–35% (UK Biochar Research Center (UK BRC), 2009). In most pyrolysis processes, the syngas is used to fuel the system (Mullen et al., 2010). Figure G-1 shows the pyrolysis process in the context of the carbon cycle.

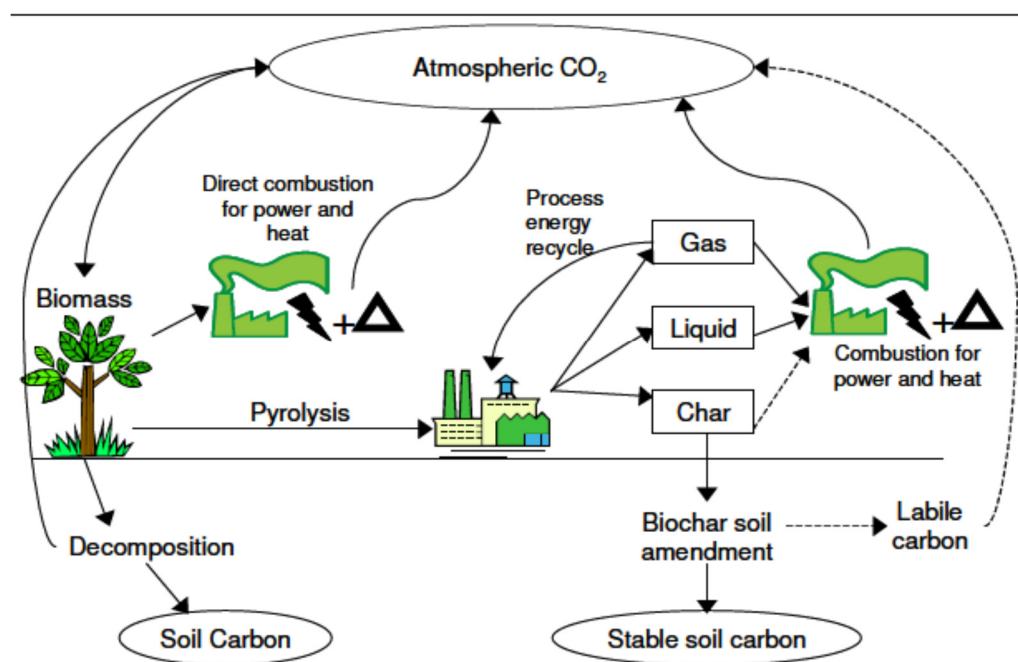


Figure G-1. Diagram of Pyrolysis Process.

3.2.1. Estimated *P* Term Values

For purposes of this framework, biochar, bio-oil, and syngas can be considered under the *P* term. Values are estimated for both fast and slow processes, based on the sample mass balance information in Table G-4. Table G-4 uses Mullen et al. (2010) numbers for fast pyrolysis and Ringer et al. (2006) numbers for slow pyrolysis. Carbon content of biochar is derived from Roberts et al. (2010) and Brown et al. (2010). Corn stover is used as an example feedstock, assuming a carbon content of 44%.

Note that carbon content of bio-oil and syngas is the same for both processes, the differences lie merely in the amount of each material produced (Mullen et al., 2010).

Table G-4. Sample *P* Information for Pyrolysis of Corn Stover.

Sample <i>P</i> Information	Fast Pyrolysis (high heat, 600°C)	Slow Pyrolysis (low heat, 300°C)
	%	
Input feedstock (Corn stover)	100	100
Bio-oil	61.6 (includes water content)	30 ^a
Syngas	21.9	35 ^a
Biochar	17.0	35 ¹
Carbon Content of Bio-oil	53.97	53.97 ²
Carbon Content of Syngas	16.7	16.7 ³
Carbon Content of Biochar	57.29	67.68 ^c

¹Ringer et al. (2006).

²Mullen et al. (2010).

³Roberts et al. (2010). p. 9.

This illustrative stover pyrolysis example assumes that the assessment boundary encapsulates the actual pyrolysis process chamber including the syngas boiler and represents a pyrolysis facility where all of the syngas is used onsite for process energy (instead of some of it being shipped offsite). In the syngas boiler stage, the syngas is fully combusted and therefore *P* (syngas) = 0. Thus, the *P* value in this example is only calculated for the bio-oil and biochar products. As explained in Appendix F, *P* is 1 minus the share of *PGE_j* that remains in products or by-products and is either not emitted to the atmosphere or is sold and eventually emitted to the atmosphere by a different entity. (Note that because *PROD* is negative, technically this expression is 1 plus a negative number.)

For fast pyrolysis, *P* values can be calculated as follows per ton of feedstock input:

P Equation for Fast Pyrolysis

$$\begin{aligned}
 P &= 1 + \frac{\sum_i (\text{Mass of product}_i \times \text{Carbon content of product}_i)}{(\text{Mass feedstock input} \times \text{Carbon content of feedstock input})} = \\
 &1 + \left(- \frac{0 + (\text{Mass bio-oil} \times C \text{ in bio-oil}) + (\text{Mass biochar} \times C \text{ in biochar})}{(\text{Mass of corn stover} \times \text{Carbon content of corn stover})} \right) \quad \text{(EQ. G.6)} \\
 P &= 1 + \{ - [0 + (0.616 \times 0.5397) + (0.17 \times 0.5729)] \div (1 \times 0.44) \}
 \end{aligned}$$

$$P = 1 + (-0.9769) = 0.0231$$

For slow pyrolysis P values can be calculated as follows per ton of feedstock input:

P Equation for Slow Pyrolysis

$$P = 1 + \frac{\sum_i (\text{Mass of product}_i \times \text{Carbon content of product}_i)}{(\text{Mass feedstock input} \times \text{Carbon content of feedstock input})} =$$

$$1 + \left(-\frac{0 + (\text{Mass bio-oil} \times C \text{ in bio-oil}) + (\text{Mass biochar} \times C \text{ in biochar})}{(\text{Mass of corn stover} \times \text{Carbon content of corn stover})} \right) \quad (\text{EQ. G.7})$$

$$P = 1 + \{-[0 + (0.30 \times 0.5397) + (0.35 \times 0.6768)] \div (1 \times 0.44)\}$$

$$P = 1 + (-0.9063) = 0.0937$$

3.2.2. Discussion

The values estimated in this appendix are meant to be illustrative examples only. Pyrolysis is not yet being undertaken on a commercial scale; as a result, it is difficult to derive robust values. Hammond (2011) notes that “pyrolysis has not yet been demonstrated at ... large scales,” and that “due to the immature state of [pyrolysis] technology ... there is a lack of good quality datasets and therefore greater uncertainty in the data than is desirable.” This is similarly true for stationary sources using dedicated energy crops (e.g., switchgrass) and short-rotation woody crops (e.g., poplar) as a feedstock for pyrolysis.

For example, Ringer et al. (2006), Enders et al. (2012), and Wright et al. (2008) show the production percentage of biochar can range from 0–77%. Much of this range is the result of differences in process, namely the decision to employ fast pyrolysis or slow pyrolysis. Slow pyrolysis produces more biochar (35%); fast pyrolysis produces less (17%). Table G-4 combines values from Enders et al. (2012), Wright et al. (2008), and Ringer et al. (2006).

Spokas (2010) notes that biochar “variability is based on the conditions of pyrolysis and the biomass parent material, with biochar spanning the range of various forms of black carbon. Thereby, this variability induces a broad spectrum in the observed rates of reactivity and, correspondingly, the overall chemical and microbial stability.” Furthermore, the literature is complicated by the lack of uniformity when it comes to the nomenclature for the products of biomass conversion. Char, charcoal, soot, graphitic carbon, ash, coal, and black carbon have all been used to describe the solid residual products.” As a result, the potential values of P for pyrolysis techniques could vary from facility to facility. Representative values could be calculated using ranges, averages or median values, as done in the example above.

3.3 Conversion of Forest-Derived Industrial Byproducts

Producers of industrial forest-derived products and by-products may use roundwood or wood chips as raw material to manufacture paper or wood products. Various wood product manufacturing processes can result in the production of mill residues including bark, saw dust, sander dust, and panel trim, which may be sold downstream to other users as products or used onsite as boiler fuel. The mass of wood converted to products is dependent on the specific products

being produced and production processes used. The amount of mill residues used as onsite boiler fuel instead of being sold for use as a raw material or fuel at a separate entity is highly site-specific.

This section provides an example of a hypothetical wood products facility that converts roundwood into veneer for onsite plywood manufacture, uses the cores remaining after peeling of veneer to produce lumber, and produces additional lumber from logs. This illustrative facility burns 60% of the mill residues it generates (bark, plywood trim, hog fuel, and sanderdust) in an onsite boiler and sells the remaining 40% of mill residues (sawdust and planar shavings) to other downstream users for fuel or use in other products (e.g., pellets, particleboard).

3.3.1 Estimated *P* Term Values

To calculate *P* for this example wood products facility, the amount of carbon in the products produced can be expressed as a proportion of carbon in the input feedstock. For each dry ton of carbon in the input feedstock, in this hypothetical example, a site-specific estimate of 0.2 dry tons of carbon in mill residues are generated, of which $0.6 \times 0.2 = 0.12$ dry tons of carbon are used onsite as boiler fuel and $0.4 \times 0.2 = 0.08$ dry tons of carbon are sold as products. Mill residues are collected from various points in the production process and are either routed to onsite boiler fuel storage (0.12 dry tons of carbon per dry ton of carbon in the input feedstock) or to loadout bins for transfer to other entities (0.08 dry tons of carbon per dry ton of carbon in the input feedstock). Mill residues collected for boiler fuel at this example mill are used within a few days so boiler fuel storage losses are negligible. In addition, this hypothetical example includes a site-specific estimate of 0.00012 tons of carbon remaining in the boiler ash following combustion of mill residues.

Because the boiler is supporting various different equipment for wood products manufacturing, it is separate from the plywood and lumber production lines. The mass of mill residues combusted in the boiler is not measured at every mill residue generation point in the facility, but instead is determined at the boiler. Similarly, the mass of mill residues (sawdust and planar shavings) sold as a product is determined at the loadout bins rather than being measured at every saw and planar within the facility. It may not be necessary to distinguish between pre- and post-conversion products because the facility can calculate the following dry mass amounts on a per-ton-of-carbon-input basis:

- Mass of carbon in the incoming logs ($PGE_i = 1$ ton of C input);
- Mass of carbon retained in the plywood and lumber products ($PROD_1 = 0.8$ tons of C in plywood and lumber);
- Mass of carbon in mill residues sold ($PROD_2 = 0.08$ tons of C in residuals sold);
- Mass of carbon in mill residues burned in the boiler (0.12 tons of C burned); and
- Mass of carbon remaining in the boiler ash ($PROD_3 = 0.00012$ tons of C remaining in ash).

All products may be considered within the *PROD* and *P* terms. *P* can be calculated as follows:

$$P = 1 + \frac{\sum_{i=1}^S PROD_i}{PGE_j} = 1 + \left[\frac{-(PROD_1 + PROD_2 + PROD_3)}{PGE_j} \right] \quad (\text{EQ. G.8})$$

$$P = 1 + \left[\frac{-(0.8 + 0.08 + 0.00012) \text{ tons C in products}}{1 \text{ ton C in the feedstock input}} \right] = 0.12$$

Carbon in products is subtracted (i.e., has a negative value) because product carbon does not enter the atmosphere with the biogenic CO₂ from the conversion process at this wood products facility.

3.3.2 Discussion

The hypothetical example above shows that, in the case of a wood products facility, the majority of the carbon entering the facility can remain in the wood products produced by the facility, including mill residues sold to other entities. The example also illustrates inclusion of all products (*PROD*) in the *P* term when it is not clear whether the products are pre- or post-conversion products because the material is collected from various points within the production process that are not necessarily upstream or downstream from the bioenergy conversion process (i.e., the boiler). In this case, use of the point of assessment (*PGE_j*) as the feedstock carbon input to the facility (roundwood) allowed for the *P* calculation to be done without distinguishing between pre- and post-conversion products in the facility.

As shown in Equation G.3 above, *L* in this example would be calculated as the ratio of *PGE_o* (at the feedstock production site) and *PGE_j* (roundwood entering the facility). Thus, for the calculation of *P* in this example, it is assumed that there are no physical feedstock losses (*LOSS*) prior to the residues entering the conversion process and therefore no need to distinguish products generated within the facility as pre- or post-conversion for purposes of calculating *L*.⁴

4. Evaluation of Pre-conversion Products and Losses During Transportation, Storage, and Processing

There are few established methods for tracking and/or calculating feedstock losses along the supply chain, especially for raw herbaceous feedstock (Miranowski et al., 2010). However, when conducting a mass balance-based calculation, having some means to estimate the flows of biogenic feedstock carbon from feedstock production to either emissions out of the stationary source stack or post-conversion products, some assessment of these supply chain flows can relate biogenic CO₂ emissions to feedstock production. This framework equation includes a term (*L*), which scales *PGE* as it is estimated or measured at the point of assessment up to account for any pre-conversion products exiting the supply chain or feedstock losses during transportation, storage, or processing between the feedstock production site (e.g., forest, farm) and the point of assessment.

As the feedstock moves through the supply chain, deviated or lost feedstock carbon may occur due to pre-conversion products or losses during transport, storage, and processing/handling between or within different stages of the supply chain. The *L* term actually refers to two separate loss components: one that reflects feedstock carbon taken from the supply chain for other purposes such as pre-conversion products (e.g., lumber, bark for mulch) and another that reflects physical losses between the feedstock production site and the point of assessment. The volume of physical losses can depend on feedstock type, technologies applied, storage length and type, and several other factors. Therefore, measuring direct stack CO₂ emissions at the stationary source would likely

⁴ Losses and only the pre-conversion products occurring between *PGE_o* and *PGE_j* are included in *L*.

be an underestimate of the total net biogenic CO₂ emissions associated with procurement and use of the biogenic feedstock. The adjustment of *PGE*, the carbon content of the biomass feedstock used by a specific entity at different points of the assessment, by the term *L* can vary for each supply chain, unless generalizations are made to create representative values.

Representative values for losses could depend on identification of different storage scenarios and transportation scenarios by feedstock type and could also take the region into consideration if appropriate (e.g., effects of regional climate on stored feedstock). Methods for calculating representative feedstock loss values related to transport, storage, and processing that could be developed for stationary sources to use, in lieu of case-specific, customized calculations, are shown below. This appendix does not develop values for possible products coming out of the supply chain between the feedstock production site and point of assessment because of the many different product possibilities and permutations that exist. More detailed discussion of the underlying mathematical computations related to how products can be accounted for in Appendix F. The remainder of this appendix focuses on the physical losses component of *L*.

4.1. Feedstock Losses during Transportation, Storage and Processing

Weighing the feedstock at the sale transaction point is considered common practice. In commercial operations, this is usually done at a stationary source's delivery point scale. The delivered moisture content can be used to calculate the dry weight in the load, and the payment is normally on a dry weight basis. The material is usually placed in storage prior to being introduced into the process. The conditions for storage, including feedstock type, moisture content, time of storage, climate conditions, and the amount of protection against added moisture offered by the stationary source, can affect feedstock storage losses. Feedstocks taken immediately from the scale to the process or into storage that is dry and cool are likely to have fewer losses than feedstocks stored in uncovered piles on the ground in a warm, moist climate for several months (see below for research findings relating to such losses).

As described above, a portion of the *L* term represents the CO₂ equivalent of feedstock losses (e.g., decomposition, too dirty or destroyed to use in boiler), or *LOSS*⁵, that occur between the weigh-in point of the feedstock at the stationary source and the entry point of the production process (boiler or other processor). If the feedstock is processed immediately by the stationary source, there may be minimal, or zero, losses in storage. In many situations, however, the feedstock must be stored prior to utilization, because harvest and delivery schedules are cyclical, whereas biogenic feedstock demand and utilization needs would be continuous. Those losses are due to the decomposition in a storage system, such as a chip pile and onsite storage, which is likely to last one year or less. Specific applications of the framework could include calculations of the emissions related to decay; however, the illustrative calculations in this appendix count those losses as immediate and do not include any long-term decay rates (see section below on onsite storage losses).

⁵ There can be various points of losses along the supply chain. These losses can be given individual loss terms (e.g., *LOSS*₁, *LOSS*₂, *LOSS*₃).

In contrast to stationary source onsite storage losses that can happen subsequent to the feedstock weighing, potential harvest and transport losses could also occur and thus could be considered for treatment in the framework, depending on available data. For some feedstocks, losses may occur during transportation between the feedstock production site and the stationary source. For example, some of the material harvested from a farm (e.g., switchgrass) may be lost from the truck while in transit, or decay might occur while the feedstock is in storage at the stationary source (Qin et al., 2006). Such losses are not typically calculated or included in the delivered weight; thus, few data are available on this aspect of losses. These losses are expected to be rather minor and likely depend on the biogenic feedstock material that is harvested or collected.

4.2. Possible Methods for Developing Illustrative *LOSS* Values for Onsite Storage and Processing

This section describes a methodology for calculating representative values for the relevant loss factors (*LOSS_i*) included in the *L* term. Biomass types considered below include herbaceous (switchgrass, hay, etc.), woody biomass (logging residues, etc.), and agricultural residues (corn stover, etc.).

In general, of all the biomass losses occurring across a given supply chain, the *storage* losses (e.g., decomposition, too dirty or destroyed to use in boiler) are potentially the most significant. Even for long-distance supply chains including international shipping, Hamelinck et al. (2005) estimated a total loss throughout the international supply chain of 15% of dry matter; 13% of these losses were associated with storage, 2% with processing, and <1% with handling.

One way to calculate onsite storage losses is to determine the feedstock delivered to the stationary source versus the amount that enters into the conversion process. The difference between the delivered weight and the pre-conversion input weight represents the onsite loss. This pre-conversion input weight can also be compared with the direct emissions (stack emissions) from the process to help determine accuracy of the calculation. However, such multi-point measurement onsite is currently not common practice. If the point of assessment, where *PGE* is calculated, is when the feedstock is entering the conversion process (e.g., after any storage losses have occurred), the *L* term (which includes losses represented by *LOSS_i*) is needed in the equation that converts *PGE* to *NBE*, to represent any losses (and pre-conversion products) that could have occurred prior to initial calculation of *PGE*.

Biogenic feedstocks contain a significant amount of water which can change as the material dries in storage and/or absorbs water through precipitation. Dry matter refers to the weight of material without water (i.e., the weight of material when it is completely dried). Dry matter loss in storage (e.g., due to decay, physical losses) is a function of several factors that will differ between stationary sources. The factors include (1) the type and packaging (loose, bundles, etc.) of feedstock; (2) the moisture content of the stored feedstock; (3) the type of storage facility at the stationary source; (4) the length of time the material is stored; and (5) the climatic conditions (e.g., temperature, humidity) during the storage period.

Several studies give estimates of dry matter loss for different types of feedstocks. For woody biomass, losses of 12% were found in green chips stored in a large pile for 7 months (Thornqvist and Jirjis, 1990). Although little to no dry matter losses can be expected when storing logs, bundles of logging residues exhibit higher dry matter losses (Jirjis, 1995). Afzal et al. (2010), for instance, observed higher dry matter losses in woodchip piles (8–27%) than in bundles ($\approx 3\%$) over one year. Jirjis and Nordén (in Eriksson and Gustavsson, 2010; 2002) observed only 5.8% dry matter loss of green logging residue bundles after 5½ months in Sweden.

Moisture is the most important factor in dry matter loss, because it directly affects the microbial activity that produces the loss (Ashton, 2008). Studies of switchgrass losses show results ranging from zero for a year's inside protected storage to 13% for unprotected bales stored outside for 6 months (Sanderson et al., 1997). Buckmaster (1992) showed dry matter losses in baled hay under indoor storage ranging from near zero dry matter loss at 12% moisture to around 7% dry matter loss at 25% moisture at baling. Studies of indoor hay storage indicate that, to reduce the risk of severe heat production and fire in the storage stationary source, moisture content of incoming bales should be 25% or less (Buckmaster, 1992).

The type of storage facility (indoor, outdoor unprotected, outdoor protected, etc.) and the underlying foundation (sod, concrete, gravel, etc.) affect storage losses, primarily through protection from increased moisture and differences in aeration (Sanderson et al., 1997). For instance, in a Swedish study on forest residue bales, the 10 month dry matter losses due to biological activity were highest in the outdoor-uncovered stack, which had an average total dry matter loss of 18.5%, while the indoor stacks had a dry matter loss of 14% (Eriksson and Gustavsson, 2010; Jirjis, 2003). For Atlantic Canada conditions, Afzal et al. (2010) estimate 6.6 to 15.6% dry matter losses during 6 months for uncovered birch chip piles of (naturally) dried and fresh forest residue, respectively.

Besides initial moisture content of feedstock, type of storage facility (indoor, outdoor unprotected, outdoor protected, etc.) and use of an appropriate foundation, storage losses also strongly depend on the “packaging” of the feedstock. For instance, losses are higher in chipped material than in loose residue piles, because chipping increases the amount of exposed surfaces on which microbial action can occur and releases soluble contents of plant cells that provide nutrition to microbes (Richardson et al., 2002). Small chips also reduce air flow in piles and prevent heat dissipation and moisture release.

The length of storage time affects losses in combination with moisture and facility type. The decay process starts as soon as 1 week, with the highest dry matter losses in the first weeks of storage (Wihersaari, 2005; for Finland). Indoor storage may result in moisture content going from 25% to around 12% after 2 months or more of storage (Buckmaster, 1992), at which point microbial activity will be minimized.

These studies indicate that, if necessary, it may be possible to develop a representative estimate that could be applied to a given stationary source on the basis of the five variables (type of biomass and particle size, initial moisture content, type of storage, average length of storage period, and regional climate conditions). Emissions will be composed almost entirely of CO₂ except in storage

facilities where aeration is limited. For example, one study of logging residues stored in laboratory vessels found maximum concentrations of CO₂, CO, and CH₄ to be 13.8%, 0.16%, and 0.15%, respectively, over a 35-day period (He et al., 2011).

A literature search identified studies that investigate dry matter loss over time for various types of biomass, including those with original research on dry matter loss. Based on 22 studies, a dataset containing 112 cases of reported dry matter loss over time was produced (see Addendum I in Section 6, with case categories including source, origin, region, biomass type, storage type, original moisture content, storage length, and dry matter loss). If data were presented from abroad, the study location was matched by climatic zones with one of the U.S. regions described in Smith and Heath (2002).

Addendum II (see Section 7) expands upon the literature review presented in this Section and in Addendum I, focusing on dry matter losses from storage of woody biogenic materials.

4.3. Representative Values for Storage Losses

Analysis of the dataset (see Addendum I in Section 6 below) revealed no clear trends in storage loss by biomass type. Even herbaceous crops that were assumed to produce comparable results across studies (usually baled and pre-dried) did not produce notable and distinguishable trend lines by region or storage type (see Figure G-2). Additional data and statistical analysis could provide more insights. Based on the available data, trend lines describing the storage losses for each of the three storage types (outdoor, uncovered; outdoor, covered; indoor) were produced for one feedstock (woodchips) (see Figure G-3). Because of the limited research on indoor storage losses for woodchips, all indoor storage data were aggregated irrespective of region and biomass type and a “worst-case” scenario was used, assuming rapid storage losses.

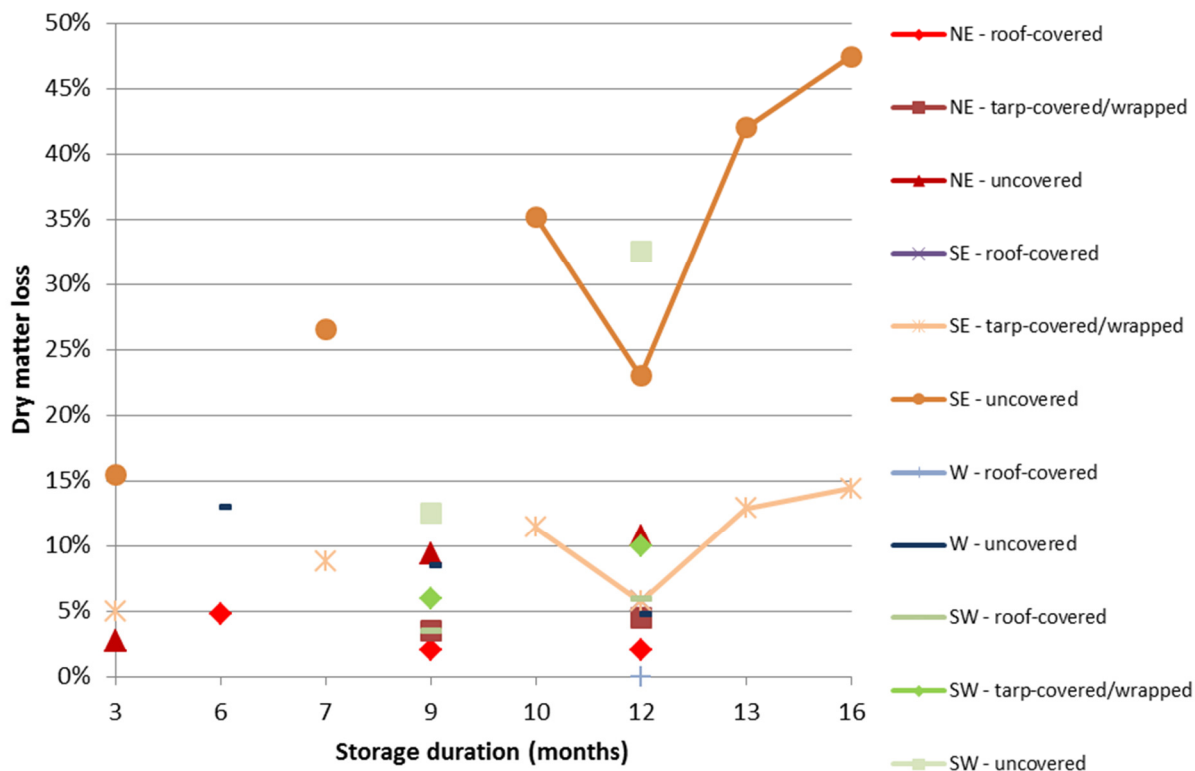


Figure G-2. Data Points for Herbaceous Crops Storage for Western (W), Southeastern (SE), Northeastern (NE) and Southwestern (SW) Regions. Storage losses are not clearly distinguishable by region or storage type (N = 69).

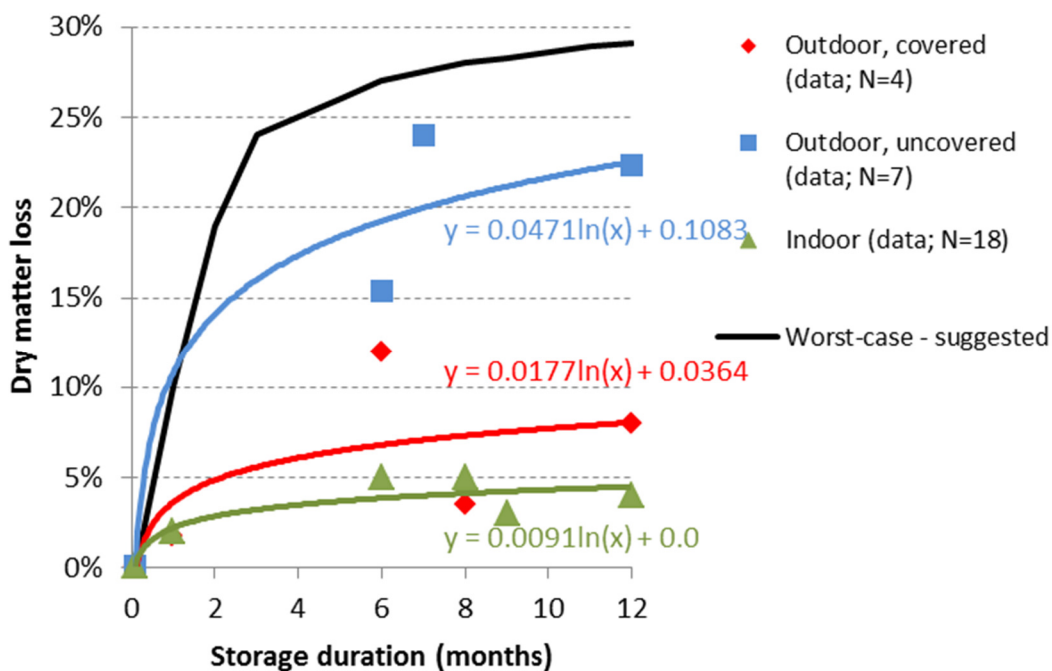


Figure G-3. Data Points and Trendlines for Storage Losses for Woodchips in the Northeast (N = 29).

Table G-5 describes the trend lines shown in Figure G-3 and is a first approximation for a storage loss term lookup table for woodchips in the Northeast provided for illustrative purposes only.

Table G-5. Example Representative Values for Storage Losses for Woodchips in the Northeast (based on Figure G-3).

Storage Duration (months)	Outdoor, Uncovered	Outdoor, Covered	Indoor
1	11%	4%	2%
2	14%	5%	3%
3	16%	6%	3%
4	17%	6%	4%
5	18%	6%	4%
6	19%	7%	4%
7	20%	7%	4%
8	21%	7%	4%
9	21%	8%	4%
10	22%	8%	4%
11	22%	8%	4%
12	23%	8%	5%

Based on the data identified in the figures and tables above, four options for developing representative *LOSS* values are explored (though other options could be used in applications of the framework):

1. Develop a “maximum” *L* term for each feedstock type by region. This could reflect a “highest possible case” system (see black line in Figure G-3) i.e., outside, uncovered, on-ground, long-term (>6 months) storage (assuming 50% initial moisture, which results in >20% loss ($LOSS_1 \Rightarrow 0.2$)).
2. Provide “loss deductions” that could be used to reduce the maximum losses in situations in which stationary sources use improved management (e.g., a system that stores material at a moisture content of 20% indoors on concrete for <1 month could lead to an estimate of a zero loss).
3. Provide for a stationary source-specific loss calculation method that could be used to estimate the *LOSS* term for a particular stationary source (Sale point dry weight (DW) – Process point DW) / Process point DW = *L*).
4. Provide one single representative *LOSS* value (at a broader scale than an individual stationary source, e.g., region) that presents average losses for herbaceous and woody biomass for an average storage time.

The following example discusses development of a regional representative *LOSS* value for illustrative purposes: 10% loss ($LOSS = 0.1$) for woody and herbaceous feedstocks, including stover, is discussed and calculated below using the Northeastern data.

It is assumed that stationary sources consuming woody biomass usually store a 3-month supply uncovered on their premises. Averaging covered and uncovered outdoor storage data for woodchips in the Northeast (Figure G-3), this would equal a loss of 11%.

There are limited data on storage-related data for stover and agricultural residues, but trends for these feedstocks were similar to herbaceous crops (Figure G-2), so both feedstock categories were combined. In terms of storage time for herbaceous feedstocks, this example assumes a 4-month harvest window. It is also assumed that during this harvest window, feedstocks are immediately converted to usable heat without storage losses. An average storage time of 2.7 months for feedstock was calculated based on an assumed 8 months of off-harvest season. This average storage time takes into account that some of the feedstock is burnt immediately after harvest (during the harvest months), while other sections of the feedstock are stored in decreasing quantities for up to 8 months until the next harvest window. The data points for a 3-month outdoor storage (Figure G-2) suggest a loss of 3 to 15% with an average of around 9 to 10% across all regions because no separate regional trends are discernible with current data.

The dataset contained no reports on storage losses for roundwood, and only one case was recorded for wood pellets. Because of this lack of data, this appendix does not provide illustrative examples of storage losses for these feedstock categories.

Potential feedstocks could also be oil seed crops and sugar-based feedstocks such as corn kernels or sweet sorghum. Sugar-based feedstocks can experience rapid storage losses in a matter of days (e.g., Bennett and Anex, 2009; Jasberg et al., 1984), which is usually not measured in dry matter losses and is therefore not compatible with the approach followed in the dataset described above.

4.4. Discussion of Other Losses: Transportation and Harvest

4.4.1. Transportation

Dry matter lost in transportation is almost wholly due to mechanical losses. Chemical losses, such as the degradation of dry-matter, generally occur during storage and at a much larger timescale than that which occurs during transport (weeks to months of sitting in storage vs. hours to days in transit). Although mechanical losses occur in the loading and unloading of dry matter, these losses are small and are considered more or less as inevitable with few mitigation options available.

Transport losses are often less than 1% (Sanderson et al., 1997) even in the case of long-distance supply chains for woody biomass (Hamelinck et al., 2005). One study found that bale weight changes and biomass loss of switchgrass during handling and transportation from the field resulted in a total dry matter loss of 0.4% (Sanderson et al., 1997). In the case of roundwood, transport losses are generally not expected to occur. As an example, developing a lookup table for transport losses could be done by using research specifying representative values by transport type (truck, vessel, train) and distance (e.g. <50 mi, 50–100 mi, >100 mi). If they are included, transport losses for one crop should be added together to provide an exhaustive view to systematically quantify total losses (Hamelinck, 2005). For instance, if biomass is transported by truck (e.g., 1% loss) followed by train (1% loss), total transport losses could equal 2%. However, due to lack of data, no such illustrative example is included in this appendix.

4.4.2. Harvest

Harvest losses are not included in the example calculations in this appendix, because such losses are not often measured or included in the delivered product weight and thus not typically calculated in yield computations. However, harvest losses could be significant in the case of specific feedstocks or for vertically integrated stationary source operations that oversee farm/forest operations. Harvesting efficiencies for crop residues using conventional multipass harvesting systems are relatively low, with only one-third to two-thirds of the available crop residues actually collected (Hess et al., 2009). For instance, Monti et al. (2009) note that “Unlike storage, major biomass losses⁶ occurred during harvest [of hay], either due to the biomass not picked-up by the baler machine (up to 17%), and uncut biomass by the mower machine (up to 29%). Overall, of the potentially harvestable biomass, only 64% was actually baled.” However, Hess et al. (2009) noted that for most farmers, it is general agricultural practice to intentionally leave a certain amount of crop residue on the landscape to ensure soil health. The amount of crop residue left behind is somewhere between 40% and 70%, with an average amount of biomass left on-site of 60% (Hess et al., 2009). Nevertheless, these harvesting values are for specific crop yields and are highly variant in nature; more data would be required to estimate such losses.

4.5. Representative Factor Discussion

There may be cases where information on supply chain losses is unavailable between the feedstock production site (e.g., farm, forest) and the feedstock conversion facility. For example, if an intermediate supplier or primary processing facility supplies feedstock (e.g., woody mill residues) to the stationary source, there may be little information about the transportation and storage losses incurred between the landscape where the feedstock is grown and the stationary source. Representative values for losses may be determined based on a review of literature as described in Section 4.3 above. Alternatively, a representative factor derived from the literature may be assigned for a particular feedstock type in the absence of refined information.

5. References

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⁶ The word “losses” in this quote refers to biomass left behind as opposed to the definition being used in the rest of this appendix.

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6. Addendum I. Literature Reviewed for Storage and Processing at Stationary Sources Facilities

Table G-6. Dataset Sources and Cases by Source for Storage and Processing at Stationary Sources.

Source	No of cases
Afzal, M., A. Bedane, S. Sokhansanj, and W. Mahmood. 2010. Storage of comminuted and uncomminuted forest biomass and its effect on fuel quality. <i>BioResources</i> , 5(1):55-69.	6
Buckmaster, D.R. 1992. <i>Indoor hay storage: Dry matter loss and quality changes</i> , Fact Sheet PSU/92. State College, PA: Agricultural and Biological Engineering Department, Pennsylvania State University.	2
Collins, M., D. Dirtsch, J.C. Henning, L.W. Turner, S. Isaacs, and G.D. Lacefield 1997. Round Bale Hay Storage in Kentucky. AGR-171, Kentucky Cooperative Extension Service.	8
Filbakk, T., Høibø, O.A., Dibdiakova, J., Nurmi, J. 2011. Modelling moisture content and dry matter loss during storage of logging residues for energy. <i>Scandinavian Journal of Forest Research</i> , 26 (3): 267-277	2
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7. Addendum II. Literature Review of Dry Matter Losses from Woody Biogenic Material Storage

7.1. Introduction

This addendum expands upon the literature review presented above in Section 4 on storage dry matter losses for woody biogenic material. Woody biomass contains roughly 50% (by weight) water when harvested. The water content of biomass can fluctuate between harvest and processing or use for bioenergy as a result of drying or reabsorption of water from precipitation. Dry matter loss (DML) is of interest because dry matter excludes the weight of water in the biomass and water does not contain biogenic carbon. The biogenic carbon is part of the dry weight fraction of the biomass (e.g., woody biomass dry matter contains approximately 50% carbon). For mechanical losses due to feedstock handling, there is no chemical change in the feedstock so it is reasonable to conclude that the proportion of carbon in material lost due to mechanical processes is the same as the proportion of carbon in the bulk feedstock. For chemical losses due to degradation of dry matter in storage, the DML can be assumed to be reasonably proportional to the weight percentage of carbon loss from the feedstock (e.g., a 1% loss in dry matter can be assumed to represent a 1% loss in feedstock carbon).^{7,8}

7.2. Storage Losses

Several factors, including storage method and time and related parameters such as material moisture content, temperature and particle size influence DML from woody biomass (He et al., 2012). According to Forest Products Laboratory (FPL) (FPL, 2010), most decay can progress rapidly at temperatures that favor growth of plant life in general. For the most part, decay is relatively slow at temperatures below 10°C (50°F) and above 35°C (95°F). Decay essentially ceases when the temperature drops as low as 2°C (35°F) or rises as high as 38°C (100°F).

Significant decay can occur only when the moisture content of wood is above the fiber saturation point (average 30% moisture). Only when previously dried wood is contacted by water in the form of rain or condensation or is in contact with wet ground will the fiber saturation point be reached. By itself, the water vapor in humid air will not wet wood sufficiently to support significant decay, but it will permit development of some mold fungi (FPL, 2010). Springer (1979) explained that

⁷ One Italian study (Barontini et al., 2014) of poplar chips from stem wood and crowns representative of logging residue found that the proportion of carbon in the feedstock before and after 6 months of storage was similar although the overall dry matter of wood decreased. For crowns, the fraction of carbon in the dry matter varied from 47.7 to 46.9% before and after storage, respectively. For stem wood, the fraction of carbon in the dry matter varied from 47.2 to 47.8% before and after storage, respectively.

⁸ In addition to observing a loss of dry matter over 1 year of storage, Nurmi (1999) found only a slight variation in the carbon fraction in the dry matter of comminuted Norway spruce logging residue feedstock (i.e., an increase of the carbon fraction in the dry matter from 50% to 51% before and after storage, respectively).

wood dried below its fiber saturation point (20% to 24% moisture) is not subject to bacterial and fungal attack.

Anheller (2009) noted that DML becomes higher when woody biomass is stored for longer periods and in larger piles. The shape of the piles influences the heat development during storage of biomass. To minimize biomass losses, Anheller (2009) recommended keeping the biomass as dry as possible before storage, keeping as large a particle size as possible, preferably under roof, uncommuted and uncompacted, as long as possible before combustion. Anheller (2009) suggested that the most advantageous way to store wood fuels is as uncommuted fuels, such as whole tree logs, reducing the size of fuel wood to chips as close as possible to the time of use, to shorten the time of storage as chips and decrease degradation losses associated with microbial activity. Similarly, Wilkerson et al. (2008) cited studies recommending that comminuted material be used as quickly as possible after grinding to minimize DML.

7.2.1. Forest Biomass Storage Methods

There are a variety of forest biomass storage methods depending on the source and intended use for the material. Forest biomass may be stored as whole logs, in wood chip piles, as logging residue prior to chipping (piled or in bales), as bark, or as wood pellets. Whole logs may be processed into forest products such as lumber or veneer or chipped for use in pulp, wood product, or bioenergy production. Bark is often stored separately from wood chips, especially at mills with different uses for bark (e.g., as fuel) and chips (e.g., forest product raw material).

Whole Logs

Wood can be too wet for decay as well as too dry. If the wood is water-soaked, the supply of air to the interior of the wood may not be adequate to support development of typical decay fungi. For this reason, logs stored in a pond or under a suitable system of water sprays are not subject to decay by typical wood-decay fungi. For logs, rapid conversion into lumber or storage in water or under a water spray is used to avoid fungal damage. (FPL, 2010)

FPL (2004) explained that, today, softwood logs decked in a log yard are typically protected by water sprinkling during warm weather. Sprinkling provides an effective method of reducing checking, sapwood stain, and decay. Sprinkling will not protect against insect attack, although it tends to be more effective than dry land storage. To be effective, the ends of logs and exposed wood must be kept wet continuously during the entire storage period. Sprinkling reduces available oxygen, thereby deterring sapwood staining and decay. Pond storage (e.g., in mill ponds, lakes, rivers, and saltwater estuaries), although once common practice, is seldom used in the continental U.S. today (FPL, 2004).

Sprinkling of logs has been practiced for decades. In 1959, Wright et al. of the USDA Forest Service Station (Portland, Oregon) discussed sprinkling to prevent decay in decked Western hemlock logs. Wright et al. (1959) noted that wood containing less than 20% moisture (dry-weight basis) does not decay, and for decay to progress fairly rapidly, a moisture content of 30% or more is required. However, oxygen is also necessary for the growth of wood-rotting fungi, and decay will not develop

when complete saturation with water eliminates air from the wood. Based on experimental research, Wright et al. (1959) concluded that:

- Both green and old western hemlock logs can be stored in un-sprinkled decks for 1 year without appreciable additional decay;
- Green logs can be decked for as long as 2 years without serious additional loss, but old logs containing decay when decked suffer considerable loss; and
- Constant sprinkling with water during the warmer months of the year, to keep ends and faces of logs wet at all times, effectively inhibits the development of additional decay in old logs.

Chip or Bark Piles

Outside chip storage at pulp mills has been practiced since the 1950's in order to maintain large inventories without the use of bins or silos. In Smook (2002), it is recognized that losses of 1% wood substance per month are typical of outside storage due to a combination of respiration, chemical reactions, and micro-organism activity. Smook (2002) reports that wood losses and degradation during outside chip storage can be minimized with effective chip pile management such as ground barriers (e.g., concrete, asphalt), fines screening, avoiding contamination of sound wood with decayed wood, and minimizing storage time. While bark may be a contaminant in the pulping process, bark is less problematic for chips destined for use as boiler fuel (Smook, 2002).

Mill residues may be stored in piles (indoors or outdoors) or silos. Mills and other wood-using facilities keep chip or sawdust piles on-site or at nearby facilities when supply is low. Woody biomass is reduced in size in the forest and then transported for storage, or it is transported, reduced in size at the mill, and then stored. The resulting material, usually chips, is stored outside in large piles and under cover in large silos or bins. Chips stored in bins are typically used within several hours or days while silos are used for longer-term storage needs. Silos and bins protect against contamination while at the same time allowing for uniform feeding and metering of the material. While storing, comminuted biomass makes handling and transport relatively easy. If not managed carefully, the biomass will succumb to DML and in some cases self-ignition. High temperatures and acetic acid odor are signs that a chip pile is in danger of DML and self-igniting. Additionally, chip piles with excessive mold and fungi growth can lead to health risks for humans (Hubbard et al., 2007).

Dry matter loss of forest biomass, which includes the degradation of lignin, cellulose, and hemicellulose, occurs when woody biomass, in any form, is not used immediately after harvesting and has to be stored within a facility. The degree to which DML occurs depends largely on the material's moisture content. Woody biomass having high moisture content is more susceptible to colonization by fungi and mold and at a faster rate. These microorganisms, via metabolic activity, generate heat, which in turn accelerates oxidation, moisture adsorption, hydrolysis, pyrolysis, and other chemical processes resulting in DML (Hubbard et al., 2007). Fungal activity is also responsible for the fermentation of the fractionated holocellulose. However, when this happens in the presence of aerobic bacteria and oxygen, they can change the ethanol produced by natural degradation processes into acetic acid or vinegar. The degradation of biomass through hydrolysis, fermentation,

and oxidation that results in the production of acetic acid lowers the average pH of the moisture in the wood chips. This decrease in pH can lead to rapid, premature decay of the piled material. For example, in a chip and bark pile during six months of storage, the initial pH dropped from near-neutral to neutral (5 to 7) to an average of 4 (Slaven et al., 2011).

As noted above, biomass moisture can lead to an increase in temperature in piled biomass, which in turn leads to DML. As shown in Figure G-4, Wihersaari (2005) used temperature to illustrate the pattern of DML for dried and fresh (green) feedstock. Wihersaari (2005) and others explain how pile temperature relates to DML as follows:

- Dry matter that is intentionally dried through a mechanical process and then stored undergoes an initial increase in temperature, which in turn increases microbial activity within the stored pile and acts as a catalyst to material degradation. However, this increase in temperature is short-lived since after approximately one week, microbial colonies begin to die out due to their residence in an inhospitable, low-moisture environment. The death of these microbes in turn reduces temperature within the pile and provides a decline in the rate of decay of the stored material (Wihersaari 2005).
- Stored piles of fresh forest matter generally do not reach internal temperatures as high as piled dry forest materials, but they maintain a higher temperature (above 40°C [104°F]) much longer than dried forest materials. As Figure G-4 shows, fresh forest matter tends to maintain a temperature above 40°C (104°F) for longer than 27 weeks. While fresh forest materials stored outdoors will lose less material due to mechanical losses such as wind, due to their weight, storing forest materials without drying them first creates problems. Storing fresh forest materials in large piles increases microbial activity by providing a hospitable environment for growth, which leads to rapid material decay. These fresh forest material piles, with extended periods of high internal temperatures, are also more susceptible to spontaneous combustion (Wihersaari, 2005; Slaven et al., 2011; Hubbard et al., 2007).

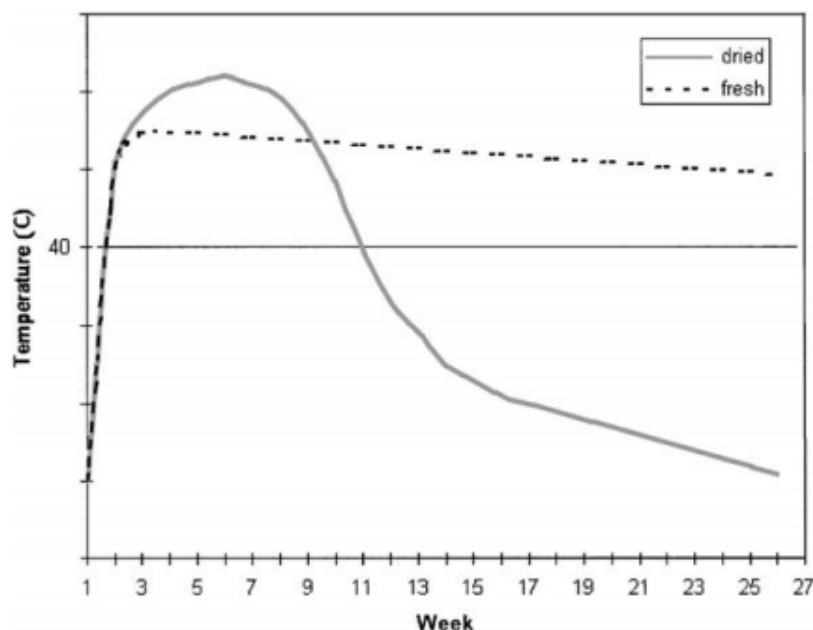


Figure G-4. Simplified Principle of Degradation Behavior (Wihersaari, 2005)

In his study, Wihersaari (2005) found that when the average chip size in a pile of dried forest matter was 30 millimeters (mm), the temperature rose to 40 to 50°C (104 to 122°F); but when the average chip size was 70 mm, the temperature did not rise above 30°C (86°F). Wihersaari (2005) explained that the biological activity producing heat takes place on the surface of the chips; the smaller the chip size, the larger the surface area per volume and consequentially the higher the biological activity leading to higher temperatures. Hubbard et al. (2007) explained that the small particle size gained by chipping restricts air flow and prevents heat dissipation, while chipping releases the soluble contents of plant cells providing microbes with nutrients.

Anheller (2009) also explained that heat development can occur in in chip piles if the moisture content is high enough for microbial growth, usually >20% for wood fuel. In fresh wood chips, respiration heat from the living cells contributes to initial heat development and the chipping process releases soluble sugar from the wood, which together with heat, moisture and oxygen can create a favorable environment for microbes. By chipping the material, the area where the microbes can attack increases. In a pile of chipped material, the air movement is also more limited because of the smaller material, which prevents heat dissipation and causes heat accumulation and thereby increases degradation losses. In large piles, the material can additionally become more compact because of weight, which further amplifies the abovementioned factors (Anheller 2009).

Similarly, Janze (2011) concluded that particle size within a biomass pile effects moisture absorption, heat build-up, heat dissipation and DML. Piles containing a large amount of fines absorb greater amounts of water, generally heat up faster due to greater microbial action, and restrict air movement through the pile, thereby limiting heat dissipation; all of this leading to increased DML and possibly spontaneous combustion. Conversely, piles consisting of large wood chunks heat up

more slowly, permit better air flow due to the large voids, dissipate the heat faster due to better air circulation, have lower rates of microbial action and lower DML.

Janze (2011) recommended that for long storage periods that fuel be stored in fairly large particles and only re-processed to the final size shortly before usage in the boiler. Janze (2011) further recommended that radically different types of material such as clean wood chips, short rotation coppice and forest debris should not be stored in the same pile, as they decompose at different rates, which can lead to spontaneous combustion. Such materials should be stored separately and blended just prior to transport to the boiler (Janze, 2011).

Logging Residue Prior to Chipping

Logging residues may be left in small piles at the feedstock production site, chipped after some time, or compacted into bundles. Chipping is the method most commonly used in North America (Afzal et al., 2010). Hubbard et al. (2007) explained that there are several advantages to storing unconsolidated woody biomass immediately after harvest. When stored unconsolidated in mounded piles of moderate size, leaves and needles can fall, reducing the material's ash content. Moreover, when woody biomass is stored in smaller piles, drying occurs (i.e., moisture escapes through leaves and other open wood surfaces). This process lowers the moisture content and increases the heating value. Drying occurs when biomass is stored in windrows as well, but it is not as efficient as small piles because foliage is not allowed to drop. Additionally, when stored on the harvesting site, vital nutrients are released back into the soil. The major disadvantages to storing woody biomass immediately after harvest on-site are (1) the need for detailed inventory tracking, (2) the cost of forgoing reforestation until the piles of biomass have been removed, and (3) the cost and time-sensitivity of having a contractor return to the site to collect, pre-process, and transport the material to the wood-using facility (Hubbard et al., 2007).

Woody biomass can be bundled and stored under cover to gain advantages (ease of handling and transport) that come along with storing chipped material. At the same time this approach protects the material from the disadvantages that come along with chipped material: DML, moisture retention, heat generation, and health hazards (Hubbard et al., 2007).

Logging Residue Chips

Wilkerson et al. (2008) noted that whole tree chips containing a large proportion of leaves and bark have a propensity to self-heat and can possibly cause chip pile fires. Wet chip pile heating can be mitigated by keeping pile heights under 9 meters (m) (30 ft) and/or limiting the amount of time the chips are piled to less than 10 days. Wilkerson et al. (2008) suggested that whole tree chips for energy that must be stored for more than 10 days may need some form of treatment to avoid degradation or spontaneous combustion. Drying to less than 20% moisture is the only viable option for safe long term storage of whole wood chips, but drying results in added expense, and dried fuel would need to be protected from rain with shelter or covering.

Earlier, Springer (1979) also explained that whole-tree chips deteriorate more rapidly than clean, debarked chips and present a greater hazard for spontaneous ignition when stored in outdoor piles. Springer (1979) noted that whole-tree chips can be stored for only a short period of time to prevent ignition, that frequently rotating storage piles increases handling costs, and drying prevents

deterioration and heating if the dried chips are stored under cover. According to Springer (1979), the costs of drying can be recovered if the chips are burned for fuel. Springer also referenced studies conducted in Norway in the last 1970's that concluded that bark and foliage increase the rate of chip deterioration, with chip weight loss during storage following the order: clean debarked chips < whole-tree chips < bark < foliage (Springer, 1979).

Wood Pellets

Wood used to form woody biomass pellets is dried prior to the pelletizing process. Drying temperatures from 100 to 400°C (212 to 750°F) are used to reduce moisture content to less than 10% (Yazdanpanah et al., 2014). The average moisture content of commercially produced pellets (in Sweden) is about 10% to 12% (Lehtikangas, 2001). The Pellet Fuels Institute (PFI) standards for pellets produced in the U.S. range from less than 8% to 10% moisture (PFI, 2011).

Wood pellets have flow characteristics and are well suited for storage in silos (Janze, 2011). Pellets must be kept dry during storage (Janze, 2011; NEBTWG, 2012).

7.2.1. Storage Time and Challenges in Tracking Biomass Inventory

Janze (2011) explained that the amount of woody biomass storage required depends upon:

- Minimum fuel storage; how much storage the plant's financiers, regulators, clients and/or insurers require as a minimum to ensure continuous operation;
- Known fuel delivery interruptions; the length of periods when fuel delivery can be anticipated to be interrupted, say for long weekends, or when supplier's mills are shutdown;
- Reliability of fuel delivery; there must be enough fuel on hand to cover likely transportation delays;
- Contingency supplies, to cover periods when forests are inaccessible for fire season, the wet season or during spring break-up;
- Fiber supply contractual requirements; the ability to continue to stockpile fuel when the power plant is shut down for annual maintenance; and
- Often the space available dictates the size and shape of the storage pile and the maximum amount of fuel that can be stored.

According to Janze (2011), typically, biomass-fired power plants [in the European Union] will stockpile a minimum of 20 to 30 days of fuel, but many will store for 60 days or more (i.e., 1 to 2 months storage). Wilkerson et al. (2008) noted that some areas of the U.S. can harvest woody biomass year around, and long term storage is not necessary. However, in other areas a 1 to 6 month supply of biomass may be required.

Hubbard et al. (2007) reported that chip-pile storage is most common type of storage in the southeastern U.S. and recommended that owners shorten the storage time of chipped material to minimize the risk of microbial decomposition which will in turn decrease DML. Hubbard et al. (2007) indicated that the ideal storage period typically varies from 2 to 6 weeks (0.5 to 1.5 months) as determined by each facilities wood supply situation.

Smook (2002) indicated that, because chip deterioration is largely a function of storage time, the most effective way to minimize losses is to minimize storage time (e.g., use first-in, first-out practices). Referring to pulp wood chips, Smook (2002) noted that optimum chip handling depends on use for the chip. For example, 2-month storage of chips used for sulfite pulping reduces extractives problematic in the sulfite pulping process. However, if maximum recovery of extractives-based pulping byproducts (e.g., tall oil, turpentine) is desired then fresh chips should bypass storage in order to maximize byproduct yield.

Janze (2011) explained some of the challenges with tracking biomass pile inventory, noting that problems stem from the variability in biomass physical properties, including different species, moisture contents, and bulk densities, and varying amounts of compaction and dry fiber loss. Additionally, using multiple inventory tracking measures, including “green” or “bone dry” mass, solid wood or bulk densities, and solid wood volumes or bulk volumes, lead to inventory errors when converting from one measure to another and back again (Janze 2011).

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