Appendix D: Feedstock Categorization and Definitions

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1. Introduction

The purpose of this appendix is to describe the categorization of biogenic feedstocks used in the assessment framework. A biogenic feedstock can be defined as any organic material originating from modern or contemporarily grown plants, animals, or microorganisms, excluding material embedded in geological formations or fossilized, that is used for combustion or product processes or otherwise decomposes at a stationary source. A multitude of feedstocks meet this definition, though some feedstocks are more commonly used for bioenergy than others. Feedstocks differ in physical properties; origin (including local climate and biogeochemical attributes); species; growth rates; management (from planting to harvesting); and whether they are deliberately raised as an energy feedstock or if they can be used for other purposes (e.g., human or animal consumption), are reclaimed wastes from other processes, or are salvaged following extreme events such as hurricanes or insect outbreaks. Duration of typical growth or decay periods also can differentiate feedstocks. Annual crops, for example, might be accounted for differently than perennial crops, and both might be accounted for differently than waste-derived feedstocks. Furthermore, a feedstock in continuous supply may need to be accounted for differently than a feedstock available only occasionally (e.g., short growing seasons, feedstocks that result from fire or insect infestation).

This appendix first lays out the broad feedstock categorization used in the framework. It then discusses the various feedstock attributes of commonly used biogenic feedstocks and why certain feedstocks are grouped together. This appendix also generally discusses other feedstock categories, including secondary use feedstocks, imports, and emerging markets. The list of feedstocks included in this categorization is not exhaustive and may need modification per specific policy applications and/or as new feedstocks come into the biogenic feedstock market. The broad feedstock categorizations in this appendix are not intended to represent specific regulatory definitions that currently exist or that may need to be developed as part of policy applications of the framework.

2. Summary of Biogenic Feedstock Categories Used

To account for differing feedstock characteristics, the framework separates biogenic feedstocks that might be used in a stationary source into three basic categories:

1. Forest-derived feedstocks: biomass derived from natural forests, tree plantations, and wood products production processes;
2. Agriculture-derived feedstocks: biomass derived from agricultural operations; and
3. Waste-derived feedstocks: biomass derived from any source of animal, industrial, or municipal waste.

The framework uses these categories because they are large enough to capture the important differences among feedstocks in terms of their biophysical attributes but small enough to be more manageable and understandable for application in a stationary sources context. Table D-1 includes examples of biogenic feedstocks under these common categories that have been used commercially, or could be used commercially in the near future, for bioenergy purposes.

Table D-1. Biogenic Feedstocks.

Forest-derived Feedstocks	Agriculture-derived Feedstocks	Waste-derived Feedstocks
Roundwood: Pulpwood, saw logs ***Logging Residue:*** Branches and limbs, debris ***Industrial Products and Processing By-products:*** • No current alternative market uses, such as pulping liquor • Has current alternative market uses, such as mill residues (bark, peeler shaving, sawdust); ethanol; pellets	***Conventional Agricultural Crops:*** Camelina, corn, canola, sorghum, soybeans, sugarcane, wheat ***Agricultural Crop Residues:*** Barley straw, corn stover, oat straw, rice straw, wheat straw ***Dedicated Energy Crops:*** Miscanthus, napier grass, switchgrass, short rotation woody crops (e.g., hybrid poplar, poplar, willow, eucalyptus) ***Industrial Products and Processing By-products:*** • No current alternative market uses, such as: shells, husks, and cobs • Has current alternative market uses, such as animal fats, oils, and greases; distillers grains; ethanol; biodiesel	***Municipal Solid Waste:*** Urban wood waste, yard trimmings, food waste from industrial processes, kitchen scraps ***Animal Wastes:*** Livestock manure, litter, manure wastewater ***Wastewater***

3. Biogenic Feedstock Characteristics

The feedstock categories are based on the key characteristics of feedstocks themselves as well as the feedstock source conditions that may lead to different net biogenic carbon-based emission profiles and thus merit different treatment under the framework. These characteristics generally include similarities and differences between feedstock growth and decay cycles, typical management and land use patterns associated with feedstock production, potential alternate market and carbon fate pathways, and other factors. More specifically, these characteristics include the following:

- *Time scale over which feedstock carbon sequestration and emissions occur.* For some feedstocks, carbon sequestration into the feedstock can occur over a short time (i.e., a year or less). For other feedstocks, sequestration occurs over a much longer time (i.e., decades to hundreds of years). Although emissions to the atmosphere occur instantaneously during combustion, some emissions-associated feedstock losses (e.g., decay) or alternative pathways may take place over days, weeks, months, or even years during storage and handling.
- *Alternate fate pathways (assumptions about "What would have happened otherwise?").* Baseline assumptions can involve consideration of the end-of-life emissions profile of each feedstock were it not used at the stationary source for energy. The baseline assumptions vary according to the feedstock type and could vary if there are other possible market uses. For example, some feedstocks may be left undisturbed to decompose if not used for energy, thereby emitting both CO_2 and CH_4, which is avoided when the feedstocks are combusted. If not used for energy, some feedstocks would otherwise have to be disposed of (landfilled or other means). Conversely, some feedstocks may have been used in other markets if they were not being used at a stationary source for bioenergy production.
- *Land use/land-use management changes.* The cultivation and use of certain biogenic feedstocks can create market competition that stimulates a shift in land use or land use management changes. Changes in land use and related management activities can generate emissions that contribute to the net atmospheric contribution from using the feedstock at a stationary source.
- *Leakage:* The use of some feedstocks for bioenergy may have GHG emissions effects outside of the biogenic feedstock production assessment boundary caused by the biogenic feedstock production activities (e.g., replacement of diverted crop, livestock, or forest products due to a change in land use from conventional products to biogenic feedstocks). The directionality and magnitude of these leakage effects may vary significantly according to feedstock type, location, and other factors. Further discussion can be found in Appendix E.
- *Storage and handling losses.* Various steps involved in converting a biogenic feedstock into a bioenergy product may involve losses of the biogenic carbon during transportation, storage, and handling. These feedstock losses vary according to the feedstock type.

The following subsections discuss how different feedstock categories could be considered within the framework according to their different characteristics.

3.1. Forest-derived Feedstocks

Forest-derived feedstocks currently constitute one of the largest sources of bioenergy in the United States (EIA, 2011). The majority of that energy production is currently derived from wood products processing. However, increased demand for bioenergy can result in higher prices being paid for bioenergy feedstock, and in doing so, increase competition with existing forest products markets, especially pulpwood (Becker et al., 2009; Galik et al., 2009; Lundmark, 2006). Increasing demand for pulpwood can have cascading effects on sawtimber markets, as few stems are left to grow into sawtimber size classes (Abt & Abt, 2013). The interaction between bioenergy harvests and broader timber market effects is somewhat dependent on the rate at which and the cost at which residues can be recovered. Abt & Abt (2013), for example, show that the assumed rate of logging residue recovery has a substantial influence on timber market response, and by extension, possible future changes to forest land management.

In this section, characteristics of roundwood, logging residue, and forest-derived industrial products and processing by-product feedstocks are presented.

3.1.1. Roundwood

Roundwood biomass includes trees of commercial size, species, and quality from a forest or plantation in an area with commercial markets. Roundwood is most often sent to sawmills or pulp and paper mills, though it is occasionally used for energy purposes (as clean chips, for example) at dedicated or cofiring electricity generating unit (EGU) facilities.

- *Time scale over which feedstock carbon sequestration and emissions occur.* Roundwood feedstocks typically have a longer harvest cycle than agriculture-derived feedstocks like traditional crops or dedicated energy crops. Example harvest cycles for roundwood pulp and sawtimber production are about 11 to 15 years for pulpwood and 25 years for sawtimber grown on plantations in the southern United States and 45+ years for sawtimber in the Pacific Northwest. Note that the overall average age of the U.S. forest inventory is older than these values because of the inclusion of less actively managed forest area.
- *Alternate fate pathways:* Roundwood, if used for industrial purposes other than energy, could lead to long-term carbon sequestration. For example, if the wood were used for furniture, buildings, or pulp and paper, its carbon would be sequestered for longer than if it is burned immediately for energy purposes (though pulp and paper products would generally have shorter sequestration time frames than more durable products) (Skog, 2008). Additionally, roundwood use at stationary sources for the sole purposes of bioenergy production could detract from roundwood use in other markets.
- *Land use/land use management changes:* Roundwood biomass can have several markets competing for the same raw material. For instance, pulp and biomass-to-energy markets can compete for the same tree sections. As such, changes in demand for roundwood biomass, whether for bioenergy or other uses, can lead to changes in production, potentially

causing direct land use or land use management changes. Such changes, including, for example, shortening rotation ages/increasing harvest frequency, can in turn cause the landscape to have different GHG emissions profiles and equilibrium states.

- *Leakage:* Increasing use of roundwood for energy production would likely also have ramifications throughout related commodity markets, causing leakage effects such as indirect land use change. For example, leakage could take the form of additional land outside of accounting boundaries converting from a previous use to accommodate displaced market demand (e.g., shifting cropland or pastureland to forestland, which could result in higher carbon sequestration on those newly forested lands, but potential carbon emissions due to conversion of other lands elsewhere to cropland).
- *Storage and handling losses:* Roundwood biomass is often harvested, preprocessed, transported, and used within a matter of days or weeks, which limits storage losses. However, depending on location, there may be longer storage needs at certain times during the year, and some degradation of woody biomass and associated dry matter loss could occur during storage and handling. The degree to which dry matter loss occurs depends largely on moisture content, where woody materials with high moisture levels are more likely to be colonized by fungi and mold, which can cause dry matter losses. In addition, the longer biomass is stored, the greater the dry matter loss, other things being equal. Accounting for forest-derived feedstocks like roundwood should cover losses in storage and material handling to provide a complete link between feedstock available at the source location and that used in the stationary source.

3.1.2. Logging Residue

Logging residues include biomass derived from harvest operations including treetops and non-merchantable sections of the stem, branches, and bark left on the ground after logging. If not left to decompose or open burned on site at the logging operation site, logging residues are often sent to sawmills or pulp and paper mills, though they are also used for energy purposes, either at EGUs or to fuel internal processes at sawmills and pulp and paper mills.[1]

- *Time scale over which feedstock carbon sequestration and emissions occur.* If left in the forest, logging residues may be either burned or left to decay over a period that can range from days to years, depending on the size and nature of the woody material and the surrounding environmental conditions (e.g., moisture, soil type, exposure to light) (Turner et al., 1993; Turner et al., 1995). Materials such as leaves of deciduous trees will decompose within a couple of years, while conifer needles will often take several years. In general, the wetter the biomass on the forest floor, the faster these residues will break down. If not burned, non-merchantable large woody material would decay slowly in the forest, and its carbon

[1] Traditional harvests (removing tree boles and leaving tops and limbs on site) in some instances may transition to more intensive practices such as whole-tree harvesting/chipping. In this presentation of the framework, whole-tree use is not attributed exclusively to the roundwood feedstock, because the practice also includes the harvest of what traditionally would have been left as residue. Thus, a whole-tree harvest can be viewed as removing two feedstocks: roundwood and logging residue. Thus, under the framework, whole trees could be divided into both roundwood and logging residue.

content in the forest can be estimated from sampling surveys. It can take several decades for pine logs with high resin content to fully decompose.

- *Alternate fate pathways:* If left in the forest, logging residues may be either burned or left on site to decay over a period that can range from days to years (as discussed above), which can have different net biogenic contributions to the atmosphere. Under current biomass market prices in most regions, logging residues are often not collected, and procurement of residue does not trigger the harvest operation (DOE, 2011).
- *Land use/land use management changes:* The type of harvest operation (e.g., whole tree versus non-whole tree harvest), stand and timber structure, and soil conditions play significant roles in the abundance and merchantability of logging residues. For instance, hardwoods in general yield higher percentages in non-timber biomass than softwoods. If soils are wet, logging residue material may be used to stabilize skid trails resulting in no surplus for feedstock supply. Extracting biomass for energy production often requires the simultaneous harvest of more valuable wood (timber, pulpwood) to justify the cost of collecting the residue material. Under current market conditions, increased demand for logging residues for bioenergy production is unlikely to expand the harvest area (i.e., land use change) though it could change the intensity of residue collection operations (i.e., a land use management change). If more logging residues are collected as biogenic feedstocks for energy production, this management change could impact the soil carbon contributions to the harvest landscape and, conversely, remove the volume of woody matter decaying on the forest floor or being burned on site.
- *Leakage:* Under current market conditions, there are no commercial alternative markets for logging residues and thus few pathways for increased logging residue removal inspire leakage effects such as indirect land use change. However, if the demand for logging residues increases substantially (e.g., as markets for bioenergy feedstocks develop), this could alter current practices to the extent that leakage could potentially occur.
- *Storage and handling losses*. As noted above, to the extent that forests are harvested and used on a fairly continuous year-round basis with only days, possibly weeks, between harvest and use, there will tend to be relatively little storage and handling loss. However, the longer storage is required, the greater dry matter loss will occur, other things being equal. Within forest-derived feedstock types, logging residues are more likely to experience feedstock losses during transport, storage, and handling than roundwood because of the smaller size of the feedstock pieces. Nonetheless, processing losses of forest-derived biomass are generally expected to be minimal.

3.1.3. Forest-derived Industrial Products and Processing By-products

Usual practices within the forest industry generate a wide variety of forest industrial products and processing by-products. These by-products include liquids such as black liquor from the pulping process and mill residues such as bark, shavings, sawdust, sanderdust, hog fuel, and unusable bole components (due to knots, holes, etc.).[2] Consideration of forest-derived industrial processing

[2] Forest products are characterized by a joint production function, as any products are produced from a single tree. Forest product industrial entities will try to optimize production to maximize the amount of high-value products

products and by-products should include assessment of whether these materials have current alternative market uses to bioenergy or not. Most residues from wood processing facilities are currently used for onsite energy production or sold for other forest products (e.g., particleboard). Deviating by-products that do have current market uses to additional energy production instead of their traditional use could have potential impacts on those traditional markets. For example, markets for sawdust, shavings, and chips from sawmills are well established. Sawdust and shavings may be used in composite wood products such as particleboard, medium density fiberboard (MDF), or pellets, shavings may be sold to farmers or pet owners for animal bedding, and bark may be sold for use as mulch or fuel. Very small amounts of mill residue go unused (USDA, 2007; U.S. Department of Energy, 2011). In addition, chips are often sold to pulp mills (USDA, 2007). Bark, slabs, edges, and other material may be burned on site at forest product mills for heat and energy production. Thus, when mill residues that were used in other markets are diverted into energy production, it may be an indication that leakage effects are possible (i.e., if sawdust goes to a biomass energy entity rather than a pulp mill, the pulp mill will need to make up the shortfall, possibly by increasing pulpwood harvests).

An example of a forest industrial processing by-product with no current alternative market use is spent pulping liquor. Spent pulping liquor (e.g., black liquor from the kraft pulping process) contains nearly half the original energy content of the wood and is not currently sold on the market, because it is typically combusted within the pulp mill chemical recovery process for purposes of reclaiming pulping chemicals and producing energy. If not combusted for chemical recovery and energy, black liquor-producing entities would need to dispose of the material (e.g., treatment in wastewater treatment systems, decay in lagoons, combustion without energy). When evaluating black liquor combustion on site for energy versus possible alternates fates (disposal and potential CH_4 and CO_2 emissions from decay), black liquor combusted for on-site energy is expected to have less net atmospheric biogenic CO_2 contributions. Also, because black liquor production is contingent on paper production and related paper market demand and prices, it is therefore unlikely that changes in demand for or prices of black liquor would lead to changes in paper production and related land use, harvest, or forest management decisions (e.g., no effect on landscape attributes). This may also be the case for other industrial processing by-products with no current alternative market uses. More information and analysis on black liquor can be found in Addendum A to this appendix.

- *Time scale over which feedstock carbon sequestration and emissions occur:* For this feedstock category, the analysis of the time scale for feedstock-related carbon fluxes will depend on the feedstock and landscape attributes and/or alternate paths associated with the feedstock (e.g., the feedstock production site and the alternate fate pathways [discussed below]).

(e.g., saw lumber) and minimize the amounts of low-value products (e.g., pulp, black liquor). Although there is some responsiveness to relative price movements (e.g., higher demand and prices for wood pellets may lead to an increased proportion of scrap going to this use and a decreased proportion going to particleboard), the elasticity of transformation between outputs may be very inelastic, and even with a negative price some low-value products would still necessarily be produced as a by-product of the production of high-value products (e.g., sawdust, black liquor).

- *Alternate fate pathways:* The alternate fate of forest-derived industrial products and processing by-products can vary widely per feedstock (those with and without alternative market uses) and per stationary source process. In the case of feedstocks with alternative market uses, these feedstocks typically would not be used for energy if there is a higher-value use (e.g., as raw material for pulping or composite wood products), and these feedstocks would pass through the stationary source through means other than the stack. For those feedstocks with no other current market uses, the alternate fate pathways could include use for energy (e.g., as boiler fuel) and disposal (e.g., through non-energy-related burning, landfilling, on-site storage), which might include decay causing CH_4 and CO_2 emissions.
- *Land use/land use management changes:* Under current market conditions, there is no evidence of land use or land use management changes related to producing forest-derived industrial products and by-products.
- *Leakage:* If demand for forest-derived industrial products and processing by-products increases for energy use, leakage could occur if these feedstocks currently have alternative market uses.
- *Storage and handling losses:* With some feedstocks in this category that require storage, the longer a feedstock is stored, the greater dry matter loss will occur, other things being equal. Within forest-derived feedstock types, industrial products and process by-products are more likely to experience feedstock losses during storage and handling than roundwood because of the smaller size of the feedstock pieces (Thornqvist and Jirjis, 1990; Jirjis, 1995; Afzal, 2010).

Furthermore, some products from the forestry sector are purposefully produced for energy production. These products include pellets or other fuels produced from woody biomass (these are covered in the secondary use feedstocks section below).

3.2. Agriculture-derived Feedstocks

Although the majority of biogenic feedstocks that have been used for energy generation in the United States to date are derived from forest materials, there is potential for large-scale use of agricultural feedstocks as well. Traditional agricultural crops that have historically been grown for food, feed, and fiber could be used as bioenergy feedstocks, as could crop residues, dedicated energy crops, or industrial products and processing by-products. This section describes characteristics of these agricultural feedstocks, separating them into three categories: (1) crops grown primarily for bioenergy use, whether conventional or dedicated energy crops; (2) crop residues; and (3) agricultural-derived industrial products and processing by-products.

3.2.1. Conventional Agricultural Crops

The conventional agricultural crops category includes feedstocks from crops traditionally grown for food, feed, textile, or other uses, such as corn and soybeans. These crops can be converted at stationary sources into conventional starch-based fuels, electricity, biodiesel, and cellulosic fuels. Use of these feedstocks in bioenergy production could result in changes in their production, price, and trade and potentially result in direct and/or indirect land use change. Crops for which only the processing by-products from a multiproduct processing activity (e.g., soybean oil, rice hulls) are used for bioenergy are covered under the agriculture industrial processing by-products subcategory below.

- *Time scale over which feedstock carbon sequestration and emissions occur:* Growth and harvest of, and related sequestration and emissions from, conventional crops generally occur at time scales of a few months to a year. Even though the net atmospheric biogenic contribution from the growth and harvest of the feedstock itself is in balance, other factors such as land use management and land use changes and related soil carbon effects can affect the overall assessment outcome.
- *Alternate fate pathways:* If conventional crops are not used for bioenergy, they would be used for other purposes, such as food, animal feed, or fiber or the production of liquid biofuels.
- *Land use/land use management changes:* There can be direct land use change effects if the demand for agricultural crops for bioenergy causes changes in land use and land use management. Changes in demand for agricultural biomass can lead to changes in cropping patterns, and production practices (e.g., intensification) can lead to changes in GHG emissions (e.g., impacts on soil carbon levels).
- *Leakage:* Leakage effects related to conventional crops for energy purposes can be substantial. The new or diverted production of feedstocks can affect commodity markets and thus lead to changes in production that alter land uses and land use management outside of the bioenergy feedstock supply chain (Murray et al., 2004; Searchinger et al., 2009; EPA, 2010a). For example, if forested land is converted to crop production for energy uses, the carbon storage occurring on the landscape changes in both standing biomass and soil carbon pools. Also, other forested lands outside of the bioenergy supply chain could become managed or be managed differently to meet the market product demand displaced when the original forestland was converted to crops for energy use.
- *Storage and handling losses*. Agricultural feedstocks generally need to be processed before they can be used for energy, which can lead to low levels of decomposition or physical feedstock losses. Additionally, because of their seasonal nature, conventional agricultural biomass needs to be stored to provide a year-round supply of energy. Thus, agricultural biomass may experience more feedstock losses than forest biomass, on average, simply because it typically needs to be stored longer. Dry matter losses during storage inside buildings are expected to be less than 5% (Collins et al., 1997; Huhnke, 2006; Shinners et al., 2007). Outside storage could lead to substantially greater losses because of the exposure to weather and increased losses to pests.

3.2.2. Agricultural Crop Residues

Agricultural crop residues, such as corn stover, wheat straw, and rice straw, can be collected for conversion or combustion at stationary sources to generate electricity and cellulosic fuels. These residues are traditionally tilled into the soil, providing nutrients for the next planted crop. However, crop residue management changes, such as the removal of residues that would otherwise remain on the field or be open burned, result in impacts on soil conditions (e.g., increased erosion) as well as soil carbon levels (e.g., lower carbon inputs to the soil). In addition, in some instances (e.g., the removal of corn stover) there may also be a loss of nitrogen in the soil. In such cases, to address this loss of soil nitrogen following the removal of corn stover, additional fertilizer may be added to ensure continuing yields of the main corn crop. Thus, additional N_2O emissions may be incurred as a result of residue removal.

- *Time scale over which feedstock carbon sequestration and emissions occur:* Crop residues are generated on an annual basis when crops are harvested, with subsequent decomposition taking place over a period of months or years depending on production practices and environmental conditions.
- *Alternate fate pathways:* Agricultural residues, like forest residues, would decay, emitting CO_2 and CH_4, and make small contributions to soil carbon if they are not removed for bioenergy or other uses. Removing residues may increase the return of carbon to the atmosphere from the residues in the short term and reduce the amount of carbon stored in the soils over a longer term.
- *Land use/land use management changes:* In the case of changes only to land use management, there may potentially be effects from removing agricultural residues from the landscape and using agricultural processing by-products, because land use management changes can affect soil GHG fluxes.
- *Leakage:* In addition, to the extent that a market develops for crop residues, this additional coproduct of crop production may increase returns to production of agricultural crops with marketable residues and induce land movements from other uses to crop production with residues.
- *Storage and handling losses*. Accounting for agricultural feedstocks such as residues and by-products should cover any losses in storage and material handling. Although these losses may be small compared with feedstock use (less than 10%), these losses in the supply chain are required to link what is being used in the stationary source process to what is grown at the feedstock source location.

3.2.3. Agriculture Industrial Products and Processing By-products

Similar to those produced in the forestry sector, agriculture industrial products and processing by-products are considered in two subcategories: those with current alternative market uses and those without. Again, if these industrial product and processing by-product feedstocks are used to produce bioenergy instead of traditional market uses, this alternative use for energy can potentially disrupt the traditional markets and have related land use and/or land use management changes.

Examples of agriculture industrial processing by-products with a current alternative market use include animal fats, oils, and greases that come from livestock production and distillers grains that are produced during the grain ethanol production process. Animal fats, oils, and greases are used in a variety of markets, including the manufacture of beauty products, pet foods, and many other goods. Distillers grains are used as animal feed, often serving as a substitute for corn and soybean meal in feedlots.

Examples of agriculture industrial processing by-products with no current alternative market use (outside of renewable fuel production) include shells, husks, and cobs.

However, some agriculture-derived products are produced for energy purposes but not necessarily for use at stationary sources. These include ethanol and biodiesel produced from a variety of agriculture sources: grains, oilseeds, cellulosic material, sugar-based crops, and more. These products tend to be produced for use in the mobile source sector, but their use in a stationary source remains a possibility.

- *Time scale over which feedstock carbon sequestration and emissions occur:* For this feedstock category, the time scale over which sequestration occurs for the primary crop is typically less than a year because the biogenic feedstock is derived from the production of annual crops. For emissions from the industrial products and by-products, the time period over which emissions would take place will depend on the specific feedstock being considered and the alternate fate pathways.
- *Alternate fate pathways:* The alternate fate of agriculture industrial products and processing by-products varies across feedstocks and by stationary source process. Some feedstocks have active alternative markets, whereas others do not currently have alternative market uses. In the case of feedstocks currently being used in alternative uses (e.g., distillers grains, oils), they would typically not be used in energy production as long as there are higher-valued uses. For feedstocks without current alternative market uses, the alternate fate pathways could include use for energy. Materials such as corn shells, husks, and cobs may be spread back on the field as the combine harvests the grain, which helps maintain soil quality. Thus, using these materials in alternate ways may necessitate the addition of more fertilizer or other soil amendments to maintain soil quality. A given alternate fate pathway for these feedstocks may potentially result in CO_2 and CH_4 emissions from decay.
- *Land use/land use management changes:* Under current market conditions, using agricultural industrial products and processing by-products that are currently being used in making animal feed, cosmetics, or alternative fuels not used at stationary sources is likely to lead to market impacts. Land use may change as demand for agricultural commodities that generate industrial products and by-products that can be used for energy production increases. Diverting the use of by-products that are not currently used in other markets is less likely to have effects on land use, though there may be effects on land productivity and input use due to nutrient removal, as discussed above. It is also possible that creating a new demand for corn by-products (e.g., shells, husks, and cobs), for instance, would lead to more land moving into corn if the additional revenue available from corn by-products becomes sufficiently high.
- *Leakage:* If there is sufficient demand for agricultural industrial products and processing by-products for use in energy production, there could be leakage because these products are diverted from their current market uses.
- *Storage and handling losses:* It is possible that there would be some physical losses or decomposition of some feedstocks, with losses tending to increase with length of storage, other things being equal.

3.2.4. Dedicated Energy Crops

Dedicated energy crops, including switchgrass, miscanthus, energy sorghum, and short-rotation woody crops (e.g., poplar, willow), can be converted at stationary sources into heat and power, cellulosic fuels, and biodiesel. Direct and indirect land use change can occur as a result of dedicated feedstock production because existing forestlands, croplands, or grasslands would likely need to be converted to grow these feedstocks since they are not currently produced commercially at large scales in the United States.

- *Time scale over which feedstock carbon sequestration and emissions occur:* Growth and harvest of dedicated energy crops generally occur at time scales of a year or a few years, with short-rotation woody crops having the longest growth cycle in this subcategory (3 to 20 years, depending on site and management conditions). For some energy crops like sweet sorghum, sequestration and emissions related to a single rotation typically occur over the course of a few months to a year. For these energy crops on rotations similar to traditional agricultural crops, the net atmospheric biogenic contribution from the growth and harvest of the feedstock itself is considered in balance, though other factors such as land use management and land use changes and related soil carbon impacts can affect the overall net contribution outcome. For energy crops with rotations longer than a year, the rotation ages and harvest regimes (and thus resulting sequestration and emissions related to growth and harvest) depend largely on specific species and site and management conditions.[3] Many energy crops also have extensive root systems that are left during bole/limb harvests to regenerate for multiple cycles. These root systems and minimal/no tillage practices can lead to high levels of soil carbon sequestration over time. In some circumstances, dedicated feedstocks may have substantial direct land use and/or leakage impacts related to cultivation if its production has displaced other land use types (especially in the case of displaced forest), which may have implications for landscape carbon equilibrium over time.
- *Alternate fate pathways:* If not used for bioenergy, there would be no dedicated planting of energy crops aside from those cultivated currently for biofuel production, which is not yet conducted on large scales commercially.
- *Land use/land use management changes:* There can be direct land use change effects if the demand for dedicated energy crops causes changes in land use and land use management. Numerous alternative energy crops could be grown on land currently being used for production of other forestry or agricultural commodities. Changes in demand for energy crops could displace traditional crops and forest products, and these changes in cropping patterns and production practices can cause substantial GHG emissions changes. For example, land may be converted from traditional crops such as corn or soybeans to energy crops, which would lead to increases in soil carbon sequestration as well as other carbon

[3] Site requirements, regeneration potential, growth and yield estimates, pests, and fertilization regime all affect species growth and influence management decisions (in addition to cost for the latter). Management regimes for energy crops can vary widely, from active management to low-intensive/unmanaged regimes, which causes widely different growth and harvest-related emissions.

pools. Land converted from forests to energy crops can increase GHG emissions from the landscape initially.

- *Leakage:* Leakage effects related to dedicated energy crop production can be substantial. The new or diverted production of feedstocks can affect commodity markets and thus lead to changes in production that alter land uses and land use management outside of the energy feedstock supply chain (Murray et al., 2004; Searchinger et al., 2009; EPA, 2010a). For example, if corn-producing cropland is converted to a short-rotation woody crop for energy production, this change displaces corn from the marketplace and the corn could be replaced by production elsewhere. Even though there may be more carbon sequestration occurring on the production landscape (due to more carbon stored in root systems and soil carbon pools), there is potential significant leakage and related emissions effects elsewhere, particularly if forested or grassed lands are brought into crops.
- *Storage and handling losses*. Dedicated energy feedstocks generally need to be processed before they can be used for energy, which can lead to low levels of decomposition or physical feedstock losses. Additionally, because some energy crops have shorter rotations and thus a seasonal nature, these feedstocks may need to be stored to provide a year-round supply of energy. Therefore, energy crop biomass may experience more feedstock losses than forest biomass, on average. Dry matter losses during storage inside buildings are expected to be less than 5% (Collins et al., 1997; Huhnke, 2006; Shinners et al., 2007). Outside storage could lead to substantially greater losses because of the exposure to weather and increased losses to pests.

3.3. Waste-derived Feedstocks

A critical difference between waste and other biologically based material is related to the connection to the land providing the material. The biologically based material in waste is removed from land for other certain end uses (e.g., for manufacture of consumer and industrial products such as newspaper, food, and construction), after which it is disposed of. Given that the treatment of waste itself does not drive the management of the growth and harvesting of biomass, it is more difficult to quantify a connection between the consumption of waste-derived feedstocks at stationary sources and the landscape from which the biogenic component of the feedstock was originally produced.

The treatment of waste-derived feedstocks at a waste management system emits carbon as CO_2 (and CH_4) that would have otherwise been returned to the atmosphere as predominantly CO_2 from natural decay of waste, regardless of the management or status of the land providing the biological material. The human management of the waste materials affects only the timing or location of these GHG emissions.

In addition to biogenic CO_2 emissions, waste management systems can emit large quantities of CH_4 if they manage wastes under anaerobic conditions. Methodologies for estimating and accounting for CH_4 from waste management are available and widely used in many GHG accounting programs. Many waste systems already account for CH_4 using methodologies from the EPA Greenhouse Gas Reporting Program (GHGRP). The decision to consider avoided CH_4 emissions in an analysis should be made in the context of the type of baseline that is most appropriate given the policy context.

This framework considers the comparison of CO_2 emissions from waste management sources to the biogenic CO_2e emissions implications associated with decomposition of the same waste in other types of managed systems. For example, an assessment of waste materials diverted from a landfill to an incinerator for energy production could consider the biogenic CO_2 emissions that occur at one point in time (at the incinerator) against the avoided CO_2 and CH_4 generated over decades through decomposition in the landfill and also avoided carbon storage in the landfill (EPA, 2010b, 2013; IPCC, 2006), or it could consider the biogenic CO_2 emissions against the CO_2 that would be emitted through the natural decay of the original biomass.

Feedstocks listed here are those that would have been produced in the waste sector regardless of any potential use for bioenergy production. In this way, they are not comparable to various residue feedstocks listed elsewhere in this document.

3.3.1. Municipal Solid Waste (MSW)

MSW includes waste generated by residential, commercial, and institutional entities. It contains a variety of biogenic materials, the composition of which varies by region, season, and long-term trends in waste generation. The average national composition of MSW in 2011 was estimated by EPA (2013) in Municipal Solid Waste Generation, Recycling, and Disposal in the United States Detailed Tables and Figures for 2011. The biogenic fractions of MSW include paper, food waste, yard waste, wood, diapers, natural fiber textiles, and natural rubber. MSW is defined slightly differently by different states. Both the overall carbon content and the ratio of fossil carbon to biogenic carbon of MSW vary widely. About one-third of MSW generated is recycled (including composting). Of the MSW that is not recycled, about 80% of MSW is disposed of through landfilling, and 20% of MSW is treated using combustion (EPA, 2013). Disposal of MSW in landfills causes some of the biogenic materials to be converted to methane; well over half of the methane (CH_4) generated in U.S. MSW landfills is captured for combustion (EPA, 2013).

- *Time scale over which feedstock carbon sequestration and emissions occur:* MSW waste disposed of in a landfill will degrade slowly over one to several decades. Food waste typically degrades more quickly than other MSW components like wood and paper wastes. The time scale of MSW degradation is also affected by the climate, with faster degradation occurring in moist, warm climates. It is generally estimated that half of the biogenic carbon disposed of in an MSW landfill will not degrade and will remain sequestered in the landfill. The time scale for composting MSW is on the order of 1 month. The time scale for MSW combustion is very short, on the order of minutes.
- *Alternate fate pathways:* Landfill gas generated as a result of the degradation of MSW in a landfill will generally contain about 50% methane and 50% CO_2 (by volume, dry basis). For landfills with no gas collection system, this landfill gas will be emitted to the atmosphere. For landfills with gas collection and combustion systems, a significant portion of the methane in the landfill gas can be converted to CO_2 prior to release into the atmosphere. Composting can be used as an alternative to MSW landfilling, particularly for food and yard wastes. Degradation of MSW in composts is primarily aerobic, but methane emissions occur as a result of anaerobic pockets that develop within the compost pile. Direct combustion of

MSW is another alternate pathway; essentially all of the carbon in MSW is converted and released as CO_2,

- *Land use/land use management changes*: Not applicable.
- *Leakage:* Not applicable.
- *Storage and handling losses*. Loss of MSW due to storage or transport of the MSW prior to receipt at the centralized treatment location is not considered. For example, only that portion of MSW as received at the landfill is considered in the methodology. All emissions from "storage" of the waste at an MSW landfill are considered part of the emissions source, whether the emissions are captured for combustion or uncaptured and released to the atmosphere. Storage of the waste at an MSW combustor facility is assumed to have negligible emissions because of the relatively short on-site storage times and is not specifically considered in the methodology.

3.3.2. Animal Agriculture Wastes

Livestock manure, litter, and manure wastewater are typically treated in a manure management system that stabilizes and/or stores wastes in one or more of the following system components: uncovered anaerobic lagoons, liquid/slurry systems with and without covers (including but not limited to ponds and tanks), storage pits, digesters, solid manure storage, dry lots (including feedlots), high-rise houses for poultry production (poultry without litter), poultry production with litter, deep bedding systems for cattle and swine, manure composting, and aerobic treatment units. International convention considers all carbon in animal agriculture waste to be biogenic (IPCC, 2006). Decomposition of the manure can occur through anaerobic or aerobic decomposition. Some manure management systems combust CH_4 from anaerobic treatment.

- *Time scale over which feedstock carbon sequestration and emissions occur:* Animal agriculture waste degradation typically occurs over several weeks to several months.
- *Alternate fate pathways:* Animal agriculture waste degradation typically generates predominately CO_2 (for aerobic systems) or a mixture of CO_2 and CH_4 (for anaerobic, facultative, or anoxic systems), depending on the type of manure management system used. When anaerobic treatment systems are used, the CH_4 in the biogas can be collected and combusted to CO_2. For dry animal agriculture wastes, direct combustion of the manure is an alternative treatment option, which will convert and release the biogenic carbon as CO_2 emissions.
- *Land use/land use management changes*: Not applicable.
- *Leakage:* Not applicable.
- *Storage and handling losses:* Most manure treatment occurs on site, and the methodology considers all emissions from the storage or treatment of the manure, whether the emissions are captured for combustion or uncaptured and released to the atmosphere. When centralized treatment is used, loss or degradation of animal agriculture wastes due to storage or transport prior to receipt at the centralized treatment location is not specifically considered; the methodology primarily considers only the quantity of waste as received at the centralized treatment location. Storage of the manure prior to direct manure

combustion is assumed to have negligible emissions due to the relatively short on-site storage times and is not specifically considered in the methodology.

3.3.3. Wastewater

Wastewater is typically treated through processes that treat or remove pollutants and contaminants, such as soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants, from wastewater prior to its reuse or discharge from the facility. Sources include municipal and industrial wastewater treatment facilities. International convention considers all CO_2 generated as a result of aerobic wastewater treatment to be biogenic (IPCC, 2006). Some wastewater treatment facilities use anaerobic processes, which results in CH_4 emissions; some facilities capture and combust CH_4 derived from anaerobic digestion.

- *Time scale over which feedstock carbon sequestration and emissions occur:* Wastewater treatment processes degrade organic matter over a time scale of a few hours to a few days, although some large surface impoundments can have residence times as long as several months.
- *Alternate fate pathways:* Aerobic wastewater treatment processes convert the degradable organic matter almost entirely to CO_2; anaerobic, wastewater treatment processes convert approximately 50% or more of the organic carbon to CH_4; and facultative or anoxic wastewater treatment processes produce CO_2 predominately, but also produce appreciable amounts of CH_4. Gas generated in anaerobic wastewater treatment systems can be collected and combusted to convert the CH_4 in the biogas to CO_2 prior to release into the atmosphere.
- *Land use/land use management changes*: Not applicable.
- *Leakage:* Not applicable.
- *Storage and handling losses:* Most wastewater treatment operations occur on site, and the methodology considers all emissions from the storage or treatment of the wastewater, whether the emissions are captured for combustion or uncaptured and released to the atmosphere. When centralized treatment is used, loss or degradation of degradable carbon in the wastewater due to storage or transport prior to receipt at the centralized treatment location is not specifically considered; the methodology primarily considers only the quantity of wastewater as received at the centralized treatment location.

4. Other Possible Feedstock Categories

4.1. Secondary Use Feedstocks

Secondary use feedstocks are feedstocks that leave the stationary source where the original biogenic feedstock material is transformed into a product or by-product (i.e., primary stationary source) that is used for energy production at a different stationary source (i.e., secondary stationary source). For example, if a secondary stationary source chooses to use for energy an agriculture- or forest-derived industrial processing product such as distillers grains or woody residuals from a primary stationary source, the net biogenic emissions value (landscape and process attributes from the original feedstock at the primary source) for the biogenic feedstock carbon of that material could be used at the secondary entity. Hypothetically, the same treatment could be used in the case of energy products such as pellets or ethanol used for energy at a secondary stationary source.

Secondary use feedstocks could be addressed in many different ways, and different policy applications of the framework may necessitate certain treatments. One consideration when applying the framework in specific policy contexts is how to avoid possible instances of double-counting landscape and process attribute values as they relate to biogenic materials used or processed at the primary stationary source and transferred for use at a secondary stationary source. For example, counting total biogenic feedstock attributes values at both the primary and secondary stationary sources could result in double-counting these values. For a more detailed example, see Appendix F. Evaluation of all the different possible policy treatments for secondary feedstocks is outside the scope of this report.

4.2. Feedstock Imports and Exports

International feedstock production and the importation of those feedstocks can significantly affect overall biogenic feedstock resource availability in the United States and demand pressures on those resources. The pricing and flow of feedstocks and related commodities have the potential to significantly affect domestic supply chains, and, conversely, U.S. biogenic feedstock production can affect international commodity markets and land use activities. The framework could either include or exclude international biogenic feedstocks, depending on policy requirements and international agreements related to GHG emissions accounting. However, decisions as to the inclusion/exclusion of international feedstocks and the treatment of such feedstocks if included would depend on the specific application of the framework. The general framework description and illustrative examples given in this report do not address the export of U.S. feedstocks or the import of feedstocks produced abroad.

4.3. New, Unconventional, or Otherwise Unanticipated Feedstocks

The framework is designed to be flexible so it can be modified as needed to be applicable to nearly all domestic biogenic feedstocks currently in use or under consideration for bioenergy production. However, new and unconventional or otherwise unanticipated feedstocks may emerge over time. Feedstock categorization in the framework should be broad enough that any feedstocks not already included can fit into the predefined categories if possible and if not, new categories could be made. The current feedstock categories are structured with this in mind, though some emerging feedstocks (e.g., algae) will require additional parameters that could be added on an as-needed basis.

For purposes of this report, biogenic feedstocks have been classified broadly into the feedstock categories identified above based on the physical attributes those feedstocks possess. This categorization does not represent a formal or legal definition, nor does it intend to replace any existing legal definitions. For example, under existing regulations, certain feedstocks are already regulated using specific definitions. Thus, although tire-derived fuel might fall under the waste-derived feedstock categorization in the framework presented here because of its attributes relative to biogenic CO_2 accounting, it is classified as a fuel under other policy applications. The same might be true for other feedstocks.

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6. Addendum: Spent Pulping Liquor—Overview of Processes and Possible Alternate Fates

6.1. Joint Production of Industrial Products and By-products

Some industries may produce by-products useful for bioenergy generation in the process of making their primary market products. For example, manufacturers may generate agricultural by-products such as shells, husks, and cobs that have little or no market value and may be disposed of if not used for energy. A second example is kraft pulp mills, which generate black liquor that is burned on site to recover chemicals for reuse in the pulping process as well as to produce energy. Other than for on-site use within the pulp mill (i.e., captive use within the mill), black liquor has no commercially feasible alternative use. Unlike by-products in other industries, black liquor is not only limited in commercially viable alternative uses, but it also has limited disposal options (Gaudreault et al., 2012).

Forest products, in general, are characterized by a joint production function, because many products can be produced from a single tree. Firms strive to optimize production to maximize the amount of high-value products (e.g., saw lumber, paper) and minimize the amounts of low-value products (e.g., black liquor). Although there is some responsiveness to relative price movements (e.g., higher demand and prices for wood pellets may lead to an increased proportion of scrap going to this use and a decreased proportion going to particleboard), the elasticity of transformation between outputs may be very inelastic, and even with a negative price, some low-value products would still necessarily be produced as a by-product of the production of high-value products (e.g., sawdust, black liquor).

When estimating the landscape biogenic emissions outcome from biomass production and usage, the SAB Panel advocated the use of a future anticipated baseline approach that would capture additionality—"i.e., the extent to which forest carbon stocks would have been growing or declining over time in the absence of harvest for bioenergy." Capturing additionality requires that the framework model "a 'business as usual' scenario along some time scale and compare that carbon trajectory with a scenario of increased demand for biomass" (Swackhamer and Khanna, 2011). Because of the joint-production nature of the forest products industry, care needs to be taken in how a "scenario of increased demand for biomass" is created.

In a partial equilibrium framework, there are different options for simulating an increase in demand for a biogenic feedstock relative to a "business as usual" case. One option is to introduce into, or shock, a model with *X* additional tons of production of a specific biogenic feedstock, which will likely result in increased production of all the other products that are jointly produced with that bioenergy feedstock. The landscape effects associated with increased production of the specific biogenic feedstock would be conflated with the effects of the increased production of other jointly produced products. Another option is to shock a model with an increased price for the specific biogenic feedstock of interest (mechanically, this could be achieved in the model with a subsidy for the specific feedstock). If the feedstock of interest is jointly produced as a by-product from the production of other products, the increase in price for the specific feedstock is not likely to increase production of or increase procurement of raw materials to generate that by-products-based biogenic feedstock. For black liquor, it would be expected that a model run that increased the demand for and price of black liquor explicitly would result in very little change in forest harvest and land use decisions, because even a large increase in the price for black liquor would have a small impact on the value of the overall product mix.

For residues and materials diverted from the waste stream, the SAB Panel endorsed considering their alternate fates (e.g., some forest residues may be burned if not used for bioenergy, waste-derived materials might be otherwise landfilled) and information about decay (e.g., using decay functions to evaluate ecosystem carbon storage in forest residues not burned for energy or disposal). Furthermore, in the case of waste-derived materials, the SAB stated that "after calculating decay rates and considering alternate fates, including avoided methane emissions, the agency may wish to declare certain categories of feedstocks with relatively low impacts as having a very low [biogenic accounting factor], or setting [biogenic accounting factors] equal to 0 or possibly negative values in the case where methane emissions are avoided" (Swackhamer and Khanna, 2011). In terms of net atmospheric contributions of biogenic CO_2e[4] emissions, as shown in the following sections of this addendum, it is more beneficial that black liquor is burned for on-site energy use and chemical recovery because black liquor has no other commercially viable alternative uses and no practical disposal options. It is also unlikely that changes in demand for or prices of black liquor would lead to changes in land use, harvest, or forest management decisions because black liquor is not produced for its value alone but is only produced as a by-products of manufacturing high-value pulp for use in papermaking.

The purpose of this addendum is to provide background information on the chemical pulping process leading to generation of black liquor and to explore hypothetical alternate fates of black liquor in the context of biogenic CO_2e accounting and avoided emissions. The information in this appendix, including example calculations of alternate fate-related biogenic emissions, supports that a 0 or negative assessment factor for black liquor may be reasonable. This finding is based on the joint function production rationale presented above; the related expectation that there would not be any perverse outcomes with respect to land use, harvest, or forest management decisions; and an analysis of hypothetical potential alternate fates and related avoided emissions.

6.2. Overview of Pulping Processes

The pulp and paper industry consists of facilities that manufacture pulp and/or paper. Pulp is the fibrous raw material for papermaking (Smook, 2002). Pulp is manufactured using either chemical or non-chemical pulping processes. Paper can be manufactured at mills that also produce virgin pulp or at mills that do not produce pulp but instead purchase pulp or use recycled fiber to manufacture paper. Some mills produce only market pulp to sell to other mills and do not manufacture paper.

[4] This addendum generally uses CO_2e in the context of biogenic emissions because both CO_2 and CH_4 are specifically discussed.

Different processes are used for pulp production. Kraft pulping is by far the most common pulping process used by plants in the U.S. for virgin fiber. The kraft pulping process produced approximately 86% of all U.S. pulp tonnage in 2010. Non-chemical pulping processes are also used in the U.S., including mechanical pulping and secondary (recycled) fiber pulping. Non-chemical processes do not produce spent pulping liquor. Approximate percentages of U.S. pulp production for other processes in 2010 were sulfite pulping (1%), semi-chemical pulping (6%), and mechanical pulping (8%) (RISI, 2011). Thus, the remainder of this addendum focuses on the kraft pulping process.

Chemical (i.e., kraft, soda, and sulfite) pulping involves "cooking" of raw materials (e.g., wood chips) using aqueous chemical solutions and elevated temperature and pressure to extract pulp fibers. The kraft pulping process uses an alkaline cooking liquor (known as "white liquor") of sodium hydroxide (NaOH) and sodium sulfide (Na_2S) to digest wood, while the similar soda process uses only NaOH to digest the wood. The cooking liquor in the sulfite pulping process is an acidic mixture of sulfurous acid (HSO_3) and bisulfite ion (HSO_3^-). The bases used in cooking liquor preparation are typically calcium, magnesium, and sodium. Semi-chemical pulping uses a combination of chemical and mechanical (i.e., grinding) energy to extract pulp fibers. The chemical portion (e.g., cooking liquors, process equipment) of the pulping process and pulp washing steps are very similar to kraft and sulfite processes.

For economic and environmental reasons, chemical and semi-chemical pulp mills employ chemical recovery processes to reclaim spent cooking chemicals. Typically, a combustion unit (e.g., recovery furnace) is used to recover the cooking chemicals from spent cooking solutions (or liquors). Kraft and soda mills have an additional chemical recovery process in which a lime kiln is used to regenerate a portion of the chemical cooking solution. In addition to spent pulping liquor, other by-products such as turpentine, soap, and tall oil may be produced during the kraft pulping process and are typically sold commercially.

6.3. Generation of Pulp and Black Liquor

Wood is the predominant raw material used for pulp and papermaking in the U.S. Following wood input procurement and handling operations, digestion of wood chips is the first step in kraft pulping. As shown in Figure D-1, the kraft digester has two primary products: pulp and black liquor. About half of the wood input to the kraft pulping process (digester) is dissolved into the solution of spent pulping chemicals to form weak black liquor. The weak black liquor is separated from the pulp by washing and is concentrated in evaporators and sent to the kraft recovery furnace where inorganic pulping chemicals are recovered for reuse and dissolved organics (e.g., lignin) are burned for fuel to make steam and electricity.

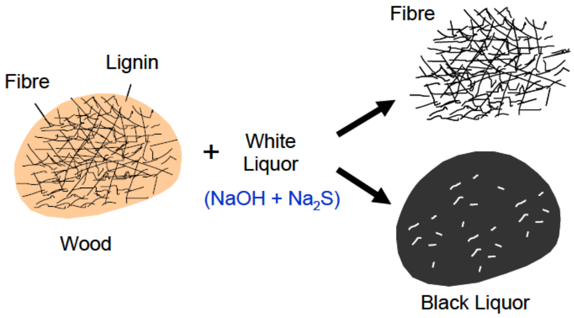

Figure D-1. Products of the Kraft Mill Digester (Tran and Vakkilainnen, 2008).

The amount of wood input to the pulping process that becomes wood fiber in the digester is referred to as pulp yield. The remainder of the wood can generally be assumed to partition to the black liquor.

The yield of pulp (expressed as a percentage by weight on a moisture-free basis) obtained from a given species of wood is influenced by the severity of the pulping process used. A yield figure of 50% means that 1 ton of dry wood yields 0.5 tons of dry pulp.[5] Mechanical pulping processes have yields of 90 to 95%, while chemical processes have yields of 40 to 55%, and semi-chemical processes have yields of 50 to 80%. Typical pulp yields for the kraft process are 40 to 50% (Smook, 2002). The lowest yield is obtained from drastic chemical digestion that gives pulp consisting of nearly pure cellulose fibers. The yield of pulp obtained by digesting wood also depends on the chemical composition of the wood. Because the principal chemical components of the normal roundwood of most species do not vary much in amount, the percentage yield of pulp obtained by a given process does not vary greatly from one species to another. The chemical composition of wood, and consequently the yield of chemical pulp, generally varies more between softwoods (coniferous woods) and hardwoods (broadleaf woods) as classes than between the individual woods within these classes (USDA, 1980).

Black liquor solids (BLS) refers to the dry weight of the solids in the black liquor that enters the chemical recovery furnace. BLS contain the spent cooking chemicals (inorganics) and dissolved organics. The BLS exiting the washer in the weak black liquor are sent for further processing in the kraft recovery system, which regenerates the inorganic pulping chemicals, burns the dissolved organics for energy production, and sometimes results in the recovery of other organic by-products. Weak black liquor exiting the washing process typically contains 13 to 17% BLS (Smook, 2002). Weak black liquor is evaporated and concentrated to 65 to 80% solids prior to burning in the recovery furnace.

A nominal value of 1.6 tons of BLS per air-dried short ton of pulp (ADTP) is often used to represent BLS production, though this value ranges from approximately 1.3 to 1.9 ton BLS/ton pulp (1,300 to

[5] Note that commercial pulp production rates are usually referred to in "air dried" units, which are generally considered to have a moisture content of 10%. "Moisture-free" or "bone-dried" mass refers to pulp or wood at 0% moisture.

1,900 kg solids/metric ton of pulp) (NCASI, 2011). The heating value of black liquor ranges from 5,400 to 6,600 btu/lb BLS (NCASI, 2011).

The chemical composition of black liquor varies based on its solids content. The solids alone comprise a complex mixture of both inorganic and organic constituents. The inorganic constituents in black liquor are derived from the cooking liquor and comprise various sodium and sulfur compounds, including NaOH, sodium sulfate (Na_2SO_4, also known as "salt cake"), Na_2S, sodium thiosulfate ($Na_2S_2O_3$), sodium carbonate (Na_2CO_3), and sodium chloride (NaCl). Collectively, inorganic salts constitute between 18 and 25% of the solids in black liquor.

The organic compounds found in black liquor are derived from wood. They are either (1) natural wood extractives (or their reaction products) that are released as a result of the pulping process or (2) materials formed through the reactions of the pulping chemicals with the lignin or cellulose components of wood. Therefore, the compounds can be classified as lignin derived, cellulose derived, or extractives derived. Typical content ranges in kraft liquor are:

- Lignin derived (39 to 54%); primarily consisting of polyaromatic macromolecules with lesser amounts of molecular weight alcohols, aldehydes, and simple phenolic compounds such as phenol, p-methyl phenol, catechol, and guaiacol;
- Cellulose derived (25 to 35%); primarily a mixture of carboxylic acids such as formic, acetic, glycolic, lactic, and glucoisosaccharinic; and
- Extractive derived (3 to 5%); primarily resin acids and fatty acids that are converted to salts at the high pH of the mixture.

In sum, spent pulping liquor can have hundreds of constituents (AF&PA, 2001). The exact composition depends on wood type, the concentration of the components in the white liquor used to digest the wood chips, and the actual process parameters. Information on different estimates of the elemental composition of black liquor is shown in Table D-2.

Table D-2. Elemental Composition of Black Liquor (Weight % of BLS).

Element	TAPPI (Clay, 2008)	GA Tech (IPST, Undated)	EPA (EPA, 1997)
Carbon, C	35	34–39	35.2
Hydrogen, H	3.3	3–5	3.6
Oxygen, O	35.7	33–38	35.2
Sodium, Na	19.7	17–25	19.2
Sulfur, S	4	3–7	4.8
Potassium, K	1.6	0.1–2	1.0
Chloride, Cl	Unspecified	0.2–2	0.1
Nitrogen, N	Unspecified	0.04–2	Unspecified
Others, including non-process elements (Ca, Al, Si, Fe)	<1	0.1–0.3	0.2
Carbonate, CO_3	8	Included in C and O above	
Sulfate, SO_4	3	Included in S and O above	

6.4. Biogenic CO_2 Emissions from Kraft Black Liquor Chemical Recovery

To assess biogenic CO_2 emissions associated with the kraft pulping process, it is helpful to understand how biogenic CO_2 emissions are currently estimated for kraft pulp mills. Carbon originating in the wood input into the pulping process primarily apportions to the pulp product and black liquor, as shown in Figure D-1 above.

The kraft chemical recovery process can be depicted by two interconnected loops, the sodium loop and calcium loop, as shown in Figure D-2. In the kraft pulping and chemical recovery process, biomass carbon from the wood is dissolved and either emitted as biomass CO_2 from the recovery furnace or captured in sodium carbonate (Na_2CO_3) in the smelt discharged from the bottom of the recovery furnace. In the process of converting the Na_2CO_3 into new pulping chemicals, this biogenic carbon (i.e., the carbonate ion) is transferred to calcium carbonate ($CaCO_3$). In the lime kiln, the $CaCO_3$ is converted to calcium oxide (i.e., CaO or lime, a material used in the chemical recovery process) and biogenic CO_2, which is released to the atmosphere (EPA, 2009).

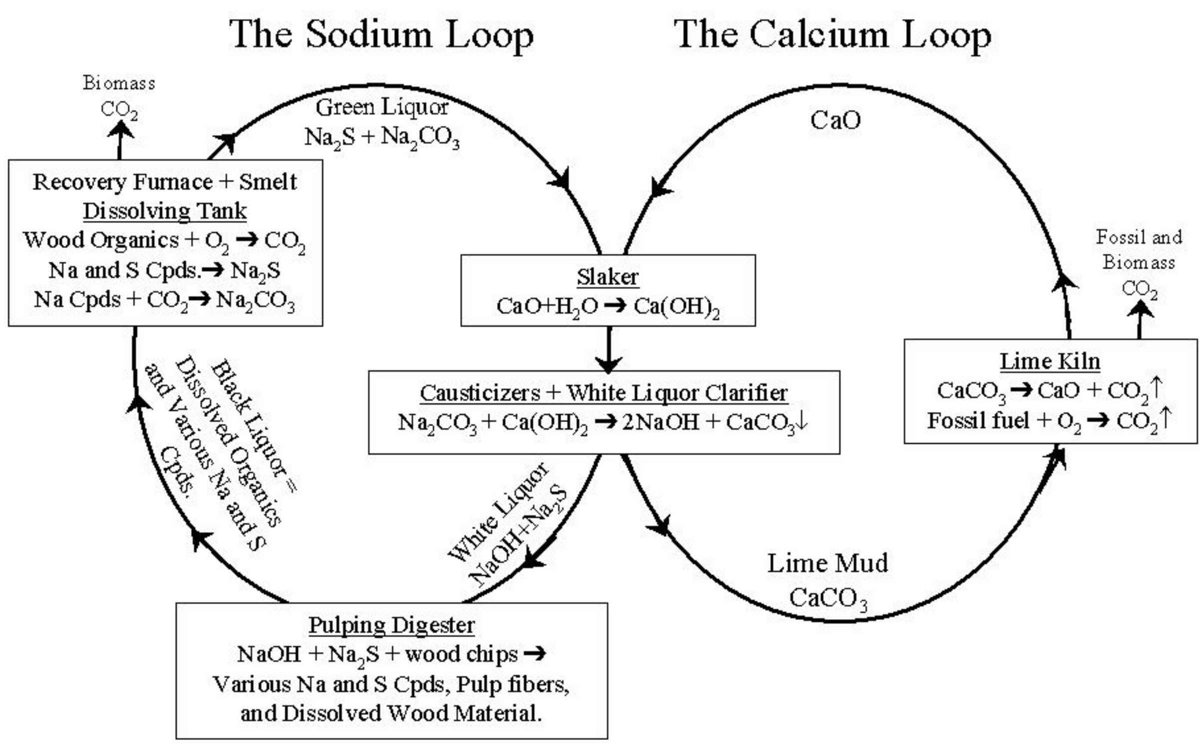

Figure D-2. Simplified Representation of the Kraft Pulping and Chemical Recovery System (EPA, 2009).

The majority of the wood-derived carbon within the black liquor either:

- Exits the pulping process as biogenic CO_2 emissions from the recovery furnace stack; or
- Reacts with sodium compounds to form Na_2CO_3 in the smelt that exits the bottom of the recovery furnace as smelt.

The carbonate in the smelt makes its way through the chemical recovery loop to the lime kiln (becoming $CaCO_3$ along the way). In the lime kiln, the $CaCO_3$ is converted to CaO, emitting the biogenic CO_2 originating from the wood in the black liquor. The red text in the simplified diagram below shows what happens to the wood-derived carbon (fossil CO_2 emissions from the recovery furnace and lime kiln are not shown).

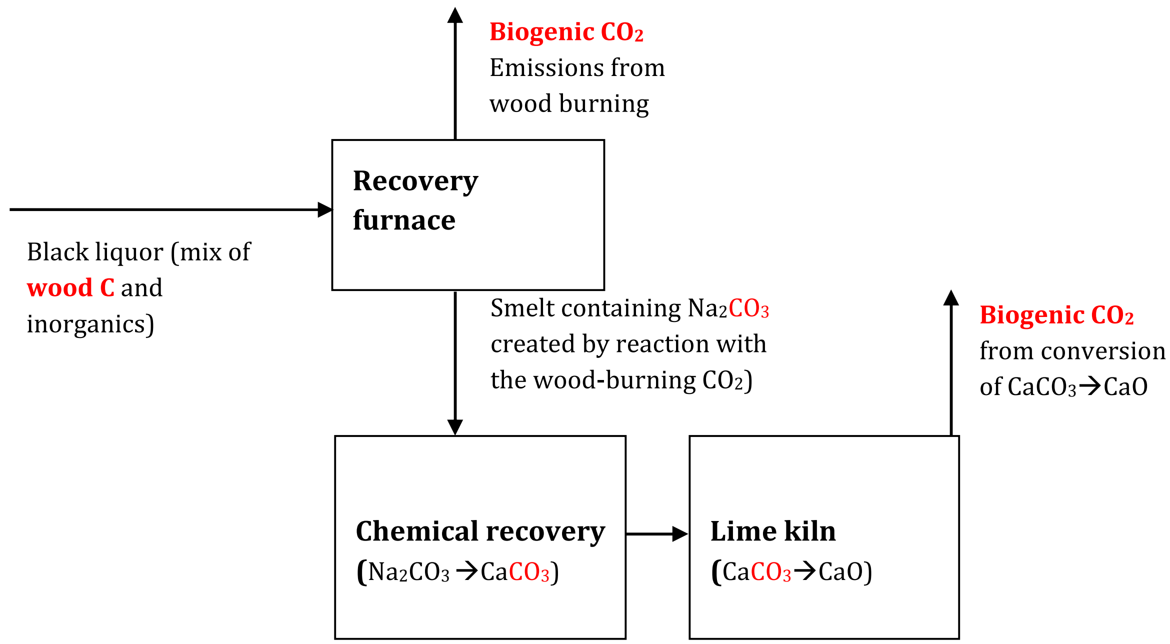

Figure D-3. Simplified Diagram Showing How Biogenic CO_2 Emissions Are Emitted from Both Kraft Recovery Furnace and Lime Kiln.

The emission factors used to estimate biogenic CO_2 emissions from the black liquor chemical recovery process are based on the carbon content of black liquor and therefore account for biogenic CO_2 emissions from both the recovery furnace and lime kiln. Thus, rather than depicting the biogenic CO_2 accounting boundary around the recovery furnace as the sole biogenic CO_2 emissions unit, it would be more consistent with the current biogenic CO_2 emissions estimation practice (including that required under the U.S. EPA's Greenhouse Gas Reporting Program) to consider the biogenic CO_2 emissions unit as the entire pulping process.

Fossil-fuel-related CO_2 emissions are estimated separately for the recovery furnace and lime kiln. The only other non-biogenic carbon introduced into the process is from carbonated makeup chemicals, for which CO_2 emissions are estimated using a mass balance approach. Fossil-fuel and makeup chemical CO_2 emissions estimates are independent of the biogenic CO_2 accounting method presented in this report and need not be discussed further in this document.

6.5. Alternate Pathways for Black Liquor

Consideration of alternate fate pathways for black liquor (as opposed to reuse within the kraft process) is purely hypothetical for U.S. mills because U.S. mills have taken steps to maximize recovery of black liquor. If black liquor is not reused within the pulping process and instead is disposed of, disposal methods might involve incineration without the benefit of energy recovery or discharge of the black liquor in liquid form (e.g., weak black liquor) into a wastewater treatment system or lagoon. The benefits of recovering black liquor include:

- Energy value;
- Avoided cost of replacement chemicals, primarily equivalent saltcake;
- Reduction in biological oxygen demand load on the effluent treatment system; and
- Reduction in color and chemical oxygen demand (COD) discharge in the treated effluent (EPA, 1997).

For many reasons U.S. mills have opted to use chemical recovery furnaces as opposed to disposing of black liquor. Depending on its volume and concentration, if released into the environment, black liquor can be odorous, toxic to aquatic life, and cause a dark caramel color in water (EPA, 1997). Black liquor contains sulfur from the kraft pulping process, which results in malodorous total reduced sulfur emissions detectable via olfactory senses in very low concentrations. Although the cellulosic constituents in black liquor may be biodegradable, lignin is very difficult to biodegrade, leaving a portion of the COD and much of the dark brown color to be discharged to receiving waters following wastewater treatment. EPA has established Best Management Practice regulations to protect the environment from the negative consequences of spent pulping liquor spills (40 CFR 430.03, 430.28, and 430.58). These rules were promulgated in 1998 as part of the effluent guidelines and standards for the pulp, paper, and paperboard source category (40 CFR Part 430) developed under the Clean Water Act.

In the hypothetical alternate fate pathway examples below, equations from Appendix N of this document were used to estimate emissions from treatment of black liquor sent for incineration without energy recovery or wastewater treatment. The black liquor is the biogenic feedstock in this example (as opposed to the wood input to the pulping process) because the black liquor (which is a complex mixture of organic and inorganic chemicals) differs from the wood input to the pulping process both chemically and physically and is generated within the pulping process. As explained in Appendix N, the following terms can be dropped from the biogenic assessment factor (*BAF*) equation when conducting an alternate fate analysis: Net feedstock growth on the production landscape (*GROW*); total net change in production site non-feedstock carbon pools (*SITETNC*); leakage associated with feedstock production (*LEAK*); the feedstock carbon losses during storage, transport and processing (*L*); and the feedstock carbon embodied in products (*P*). As a result, the assessment framework equation as applied to estimating biogenic CO_2 emissions from the alternate fate of black liquor feedstocks can be simplified to:

BAF = AVOIDEMIT

AVOIDEMIT represents the avoided biogenic emissions that could have occurred per an alternative management strategy instead of the feedstock's use in bioenergy production, relative to the feedstock's use for bioenergy production. The *AVOIDEMIT* term, as applied to the black liquor biogenic feedstock, is expressed as:

$$\boldsymbol{AVOIDEMIT = 1 - \frac{\text{CO}_2\text{e emissions from treatment alternative to combustion}}{\text{CO}_2\text{e emissions from combustion treatment}}}$$

The *AVOIDEMIT* term must be calculated for the specific feedstock being managed relative to a specific, alternative practice. A positive *AVOIDEMIT* value implies that use of the feedstock for bioenergy production contributes more emissions to the atmosphere than would have occurred under the alternative management strategy. A 0 value implies that both practices are equivalent in terms of how much emissions they contribute to the atmosphere. A negative value implies that using the feedstock for bioenergy production contributes less emissions to the atmosphere than the alternative management practice.

The CO_2e emissions in the *AVOIDEMIT* equation above include both CO_2 and methane (CH_4) resulting from each feedstock management alternative. The following subsections present calculations of CO_2e emissions for the two hypothetical alternative management approaches.

6.5.1. Alternate Fate Scenario 1: Black Liquor Incineration without Energy Recovery

Table D-3 presents emission factors and calculated emissions for incineration of black liquor normalized per ADMT of pulp produced. The emissions from incinerating black liquor without energy recovery would be the same as the emissions from burning the material in a recovery furnace. The inorganic chemicals in the smelt produced from burning the black liquor would remain and could be recovered in either case. No emissions would be avoided by treating the black liquor through incineration, and the stack emissions would be about the same as combustion without energy recovery. Therefore, the resulting hypothetical example BAF is 0.

Table D-3. *AVOIDEMIT* for Scenario I Where Black Liquor Is Incinerated Without Energy Recovery.

Emissions Factors:		
CO_2	94.4	kg/MMBtu HHV (40 CFR 98, subpart AA)
CH_4	0.0019	kg/MMBtu HHV (40 CFR 98, subpart AA)
Process Parameters:		
	1.6	Ton BLS/ADTP (NCASI, 2011)
	0.9072	ADMT pulp/ADTP (conversion factor for metric tons: short tons)
	1.8	Ton BLS/ADMT pulp (calculated)
	6600	Btu/lb BLS based on NCASI, 2011 range of 5,400 to 6,600 Btu/lb for BLS
	13.2	MMBtu/ton BLS (calculated)
CO_2	2.20	Metric tons CO_2/ADMT pulp (calculated)
CH_4	4.42E-05	Metric tons CH_4/ADMT pulp (calculated)
CH_4 GWP	25	(40 CFR 98, subpart AA)
CO_2e	2.199	Metric tons CO_2e/ADMT pulp if the black liquor is burned
***AVOIDEMIT* numerator**	2.199	Emissions from treatment alternative (incineration without energy recovery)
***AVOIDEMIT* denominator**	2.199	Emissions from burning black liquor for chemical and energy recovery, metric tons/ADMT pulp
BAF = AVOIDEMIT	0	= 1− (emissions from treatment alternative) / (emissions from burning black liquor for chemical and energy recovery)

6.5.2. Alternate Fate Scenario 2: Black Liquor Decomposition in a Wastewater Treatment System

The equations related to CO_2 and CH_4 emissions from wastewater treatment in Section 6.1 of Appendix N were used to evaluate two hypothetical wastewater treatment scenarios for the disposal of black liquor: (1) treatment in a deep anaerobic lagoon; and (2) treatment under aerobic conditions. Under both alternate pathway conditions (anaerobic and aerobic), emissions from treatment of black liquor as wastewater exceeded those from the current practice of burning black liquor for chemical and energy recovery. The resulting hypothetical example BAF varied from slightly negative (−0.09) to −1.2 depending on the wastewater management method, indicating that using the black liquor feedstock for bioenergy production contributes less biogenic emissions to the atmosphere than the alternative wastewater management practice. Table D-4 presents the equation terms and calculated values for avoided emissions from wastewater treatment.

Table D-4. *AVOIDEMIT* for Scenario 2 Where Black Liquor Is Disposed Through Wastewater Treatment.

Equation Term	Description	Anaerobic Deep Lagoon Treatment	Aerated Treatment Process with Anoxic Areas
Input Values			
Q_{ww}	Wastewater influent flow rate	9.7 m^3/ADMT pulp[1]	9.7 m^3/ADMT pulp[1]
OD	Oxygen demand of influent	92,700 mg/l[2]	92,700 mg/l[2]
EffOD	Oxygen demand removal efficiency of the biological treatment unit	0.75[3]	0.75[3]
MCF_{ww}	CH_4 correction factor (from Appendix N, Table N-13)	0.8	0.3
BG_{CH4}	Fraction of C as CH4 in generated biogas (default is 0.65)	0.65	0.65
λ	Sludge biomass yield (from Appendix N, Table N-13)	0	0.45
GWP_{CH4}	Methane global warming potential	25	25
Calculated Values			
CO_{2WW}	CO_2 emission rate (metric tons CO_2/ADMT pulp)	0.45	0.41
CH_{4WW}	CH_4 emission rate (metric tons CH_4/ADMT pulp	0.18	0.036
CO_{2S}	CO_2 emission rate (metric tons CO_2/ADMT pulp)	Not applicable (λ = 0)	0.34
CH_{4S}	CH_4 emission rate (metric tons CH_4/ADMT pulp	Not applicable (λ = 0)	0.03
***AVOIDEMIT* numerator**	$= CO_{2WW}+CO_{2S} + (CH_{4WW}+CH_{4S})*GWP_{CH4}$	4.8	2.4
***AVOIDEMIT* denominator**	Emissions from burning black liquor for chemical and energy recovery, metric tons/ADMT pulp	2.2	2.2

Equation Term	Description	Anaerobic Deep Lagoon Treatment	Aerated Treatment Process with Anoxic Areas
BAF = AVOIDEMIT	= 1− (emissions from treatment alternative) / (emissions from burning black liquor for chemical and energy recovery)	−1.2	−0.09

[1] Based on typical industry parameters of 1.6 tons BLS/ADTP and assuming that weak black liquor is 15% solids (i.e. 0.15 ton BLS/ton liquor) with a density of 1.1 g/cm^3. Thus: 9.7 m^3/ADMT pulp = (1.6 tons BLS/ADTP) x (ADTP/0.9072 ADMT) x (ton liquor/0.15 ton BLS) x (907185 g/ton liquor) x (cm^3/1.1 g) x (m^3/100^{3}cm^3)

[2] Chemical oxygen demand for weak black liquor derived from pine (Yang, 2003).

[3] A relatively low oxygen demand removal efficiency of 75% was used considering the low biodegradability of the lignin component in the wastewater stream.

6.5.3. Discussion

The two scenarios presented above illustrate that current black liquor management practices (burning for energy and chemical recovery in a recovery furnace) result in the same or less emissions than the hypothetical alternate fate for black liquor (disposal via incineration or wastewater treatment). Black liquor is produced as a by-product from the pulping process and, under current market conditions, has no commercially viable alternatives other than use for chemical and energy recovery within the pulping process. Because black liquor is jointly produced with other forest industry products (pulp production), black liquor management practices and increased demand and/or price for black liquor are likely to result in no to little change in land use, harvest, and forest management decisions. The avoided emissions associated with disposal of black liquor as compared to the current management practice (burning for energy and chemical recovery in a recovery furnace) resulted in hypothetical example BAFs ranging from different negative values to 0, depending on the treatment method. Because of the joint production function rationale as well as the hypothetical alternate fate example calculations conducted above, an estimated BAF of 0 can be considered for black liquor and is consistent with the approach suggested by the SAB Panel for materials diverted from the waste stream (Swackhamer and Khanna, 2011).

6.6. References for Addendum

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