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Agricultural Residue Availability in the United States

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Abstract

The National Energy Modeling System (NEMS) is used by the Energy Information Administration (EIA) to forecast US energy production, consumption, and price trends for a 25-yr-time horizon. Biomass is one of the technologies within NEMS, which plays a key role in several scenarios. An endogenously determined biomass supply schedule is used to derive the price–quantity relationship of biomass. There are four components to the NEMS biomass supply schedule including: agricultural residues, energy crops, forestry residues, and urban wood waste/mill residues. The EIA's *Annual Energy Outlook 2005* includes updated estimates of the agricultural residue portion of the biomass supply schedule. The changes from previous agricultural residue supply estimates include: revised assumptions concerning corn stover and wheat straw residue availabilities, inclusion of non-corn and non-wheat agricultural residues (such as barley, rice straw, and sugarcane bagasse), and the implementation of assumptions concerning increases in no-till farming. This article will discuss the impact of these changes on the supply schedule.

Index Entries: Agricultural residues; corn stover; wheat straw; feedstock cost; biomass supply.

Introduction

The Energy Information Administration (EIA) estimates that there is 491 million dry tons (t) (445 million dry metric tons [mt]) of biomass available in the United States on an annual basis. EIA has compiled available biomass resource estimates from Oak Ridge National Laboratory (ORNL) *(1)*, Antares Group, Inc. *(2)*, and the US Department of Agriculture (USDA) *(3)*. This article discusses how these data are used for forecasting purposes by the National Energy Modeling System (NEMS). One of the key determinants for the growth of biomass is the price–quantity relationship of biomass feedstocks. The raw data for the supply curves are available at the state or county level and these are aggregated to form regional supply schedules. Supply data are available for four fuel types: agricultural residues, energy crops, forestry residues, and urban wood waste/mill residues.

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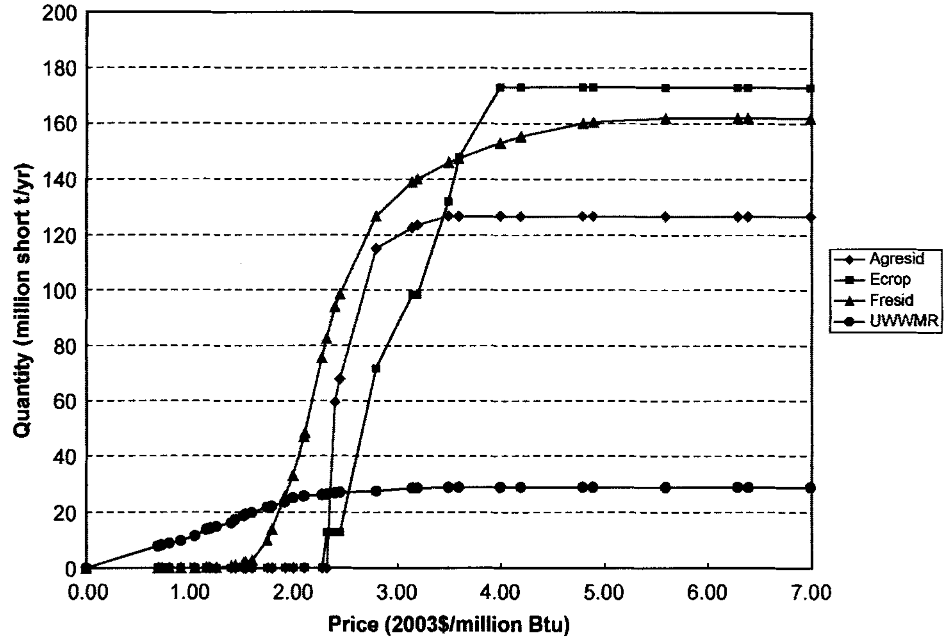

Fig. 1. Biomass resource availability, 2025.

Figure 1 shows the variation in biomass resource as a function of price. A relatively small portion of biomass supply is available at $1.50/million Btu ($1.42/GJ) or less. As a point of comparison, EIA's *Annual Energy Outlook 2005 (AEO2005) (4)* projects coal prices to remain relatively stable (compared with natural gas prices) at $1.28/million Btu ($1.21/GJ) in 2003 to $1.31/million Btu ($1.24/GJ) (in real 2003$) by 2025. Feedstock cost is a major factor that limits biomass growth under AEO2005 reference case assumptions. The available low-cost feedstock (at less than $1.50/million Btu [$1.42/GJ]) is almost exclusively urban wood waste/mill residue. This category of biomass continues to be the only significant resource available at prices up to approx $2/million Btu ($1.90/GJ). At $2/million Btu ($1.90/GJ) and higher, agricultural residues become viable as a second source of biomass. Energy crops and forestry residues begin to make significant contributions at prices around $2.30/million Btu ($2.18/GJ) or higher.

Agricultural Residues

The underlying assumption behind the agricultural residue supply curve is that after each harvesting cycle of agricultural crops, a portion of the stalks can be collected and used for energy production. Agricultural residues cannot be completely extracted, because some of them have to remain on the soil to maintain soil quality (i.e., for erosion control, carbon content, and long-term productivity). The Department of Energy (DOE)

Biomass Program is currently focusing on agricultural residues as the primary (and most likely) source of biomass feedstock supplies for the growing bioenergy industry over the next 10–15 yr. Given the importance of agricultural residues with respect to bioenergy commercialization, EIA decided to update the agricultural residue component of their biomass supply curve in modeling projected energy supplies for AEO2005 and other service requests. Specifically, three aspects of the agricultural residue supply were revised: updated corn stover availability, inclusion of residues other than corn stover and wheat straw, and incorporation of assumptions regarding no-till farming practices in the United States.

Over the last few years a substantial amount of effort has been devoted to developing new county-level estimates of potential corn stover residues, taking into account environmental considerations regarding the amount of corn stover that can be harvested when soil erosion constraints are considered. New estimates have also been made regarding the potential increase in corn stover resources that could be available if no-till cultivation practices were to be more widely adopted (currently 20% of US corn grain is produced using no-till cultivation *[5]*). No-till farming generally allows for a greater portion of the corn stover to be removed because erosion problems and constraints are substantially reduced. Since 1990, the number of acres of farmland using no-till cultivation has increased by about 1%/yr on average. The Conservation Technology Information Center (CTIC) notes that "50% of cropland acres are suitable for some form of conservation tillage to mitigate soil loss" *(6)*.

Corn Stover Revisions

ORNL recently completed new county-level estimates of available and sustainably removable corn stover for the United States. *(7)*. These estimates include projected costs for the stover at the "farm gate."* These costs include nutrient replacement costs (estimated at \$6.50/dry t [\$7.17/dry mt] of stover removed), as well as fixed and variable collection costs for producing and delivering round bales of corn stover (stems/leaves/cobs) wrapped with twine and left at the edge of the field. Payments for a farmer premium/profit, as well as transportation costs from the farm-gate to a conversion facility, were treated as separate additional costs. Supply has been constrained by equipment harvest efficiency (75% of gross) and the need to leave residues to limit rain and wind erosion to tolerable losses and to maintain soil moisture in rain-limited regions.

Two sets of new corn stover availability estimates were obtained from ORNL: (1) A base-case assuming corn is produced with the current mix of agricultural tillage and crop rotation practices and; (2) upper-bound case assuming all corn grain would be produced using no-till practices. There

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*These costs do not include transportation and handling costs for delivering the stover from the farms to a conversion facility.

are various farm-specific soil and crop rotation constraints that limit the maximum percent of overall no-till acres that can be adopted in the United States. The all no-till scenario provides a useful upper-level benchmark in estimating potential future stover supplies. As noted earlier *(6)*, approx 50% of US farms could use conservation tillage practices such as no-till, thus we viewed 50% no-till as the practical upper limit for this cultivation approach. In our analysis we assumed that no-till corn production would reach a level of 30% by the year 2025; this would be a 10% increase in no-till cultivation practices as compared with current practices in which about 20% of corn production is via no-till. A continuation in the trend toward increased no-till farming practices is considered likely owing to soil conservation requirements under US Farm Bill programs, and growth of markets for the production of biofuels and bioproducts from cellulosic feedstocks such as corn stover.

Base-case estimates for corn stover are shown in Table 1. The total amount of corn stover available with current tillage practices is about 64 million dry t/yr (58 million dry mt/yr) (30% of the gross amount, after taking into account the need to leave some of the residue for erosion protection and other soil quality concerns). For the all no-till scenario, Table 1 shows an estimated 111 million dry t/yr (101 million dry mt/yr) of sustainably removable corn stover (51.5% of the gross amount, taking into account the fact that less corn stover would need to be left in the field with no-till practices) this amount of sustainably removable corn stover is shown in the column labeled "total available supply" in Table 1 (note that most, but not all of this amount is estimated to be available at less than $40/dry t [$44/dry mt]; a small fraction of the total is estimated to cost more than $40/dry t [$44/dry mt]).

The base-case numbers from the prior ORNL year 2000 estimate of corn stover availability *(1)* indicated that a maximum of 119 million dry t/yr (108 million dry mt/yr) of corn stover was available. The new ORNL base-case numbers reflect a significant reduction in anticipated corn stover availability, now that in-depth county-level considerations regarding erosion constraints have been addressed. For the new EIA biomass supply curve, the old maximum of 119 million dry t (108 million dry mt) of stover has been replaced with the new estimate of 62.7 million dry t (56.9 million dry mt) of stover available at less than $40/dry t ($44/dry mt) (farm-gate costs) for the year 2005. Anticipating that no-till practices for corn production will increase over time, the new EIA biomass supply curve assumes that no-till practices will increase from the current level of 20% no-till in year 2005 to 30% no-till in 2025. As a result, the new biomass supply curve has corn stover supplies increasing to 68.4 million dry t/yr (62.0 million dry mt/yr) by 2025 at stover costs of less than $40/dry t ($44/dry mt).* The corn stover supply and cost

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*An increase of (30%–20%)/(100%–20%) = 1/8th of the potential increase from current practices relative to 100% no-till practices.

values used in the new EIA biomass supply curve for year 2025 are provided in Table 2, based on the assumption of 30% no-till practices.

At \$2/million Btu (\$1.90/GJ) (equivalent to \$31/dry t [\$34/dry mt], assuming an energy content of 15.5 million Btu/dry t [18.0 GJ/dry mt]), approx 60 million dry t (54 million dry mt) of corn stover would be available under current tillage practices. This amount of corn stover would be equivalent to 0.93 Quads (0.98 EJ) of energy. For comparison purposes, coal use in 2004 amounted to 22.92 Quads (24.18 EJ) of energy. Therefore, at \$2/million Btu (\$1.90/GJ), corn stover using current tillage practices could displace 4% of the energy provided by coal in the United States if all corn stover were to be used for electricity generation.

Over the last 30 yr, corn productivity has been increasing by about 1%/yr on average (in terms of the bushels of corn grain produced per acre each year). If this trend continues into the future, it is possible that corn stover quantities will also increase over time, along with corn grain productivity. This potential increase in stover availability has not been included in the newly revised biomass supply curve, pending further input and analysis regarding the likelihood that the trend will continue into the future, and the need for further clarification regarding the anticipated relationship between the amount of stover available per pound of grain produced in the future. More evaluation is needed concerning whether the current ratio of about 1 pound of stover produced per pound of corn grain produced is likely to stay the same or change if corn productivity continues to increase in the future.

There has been a substantial amount of debate regarding the appropriate farmer premium that should be included in determining the total delivered price for corn stover as well as the optimum approach and technology for harvesting and storing stover *(8)*. The bulk of the corn stover supply is anticipated to be available at a cost of \$30/dry t (\$33/dry mt) at the farm gate. Assuming an average transportation distance of 40 miles (64 km) to deliver round bales from the field edge to a biomass conversion site via flat bed truck, ORNL staff has estimated the transportation cost to be about \$7.75/dry t (\$8.54/dry mt) of stover *(9)*.

Considering a range of factors, the new EIA biomass supply curve assumes an additional fixed cost of \$12/dry t (\$13/dry mt) on top of the farm-gate costs in calculating the total delivered price for supplying corn stover to conversion facilities. The \$12/dry t (\$13/dry mt) fixed cost reflects an adjustment to cover transportation and handling costs, plus farmer premium payments. It is recognized that these costs could be higher than \$12/dry t (\$13/dry mt). However, this estimation is based on the assumption that cost savings and cost containment will be achieved as integrated harvest and supply operations benefit from experience and operational enhancements (in which custom harvesters are likely to play an important role), in combination with anticipated harvesting technology improvements. With a typical \$30/dry t (\$33/dry mt) farm-gate cost, plus an additional

Table 1
ORNL Estimates Regarding Corn Stover Availability and Costs *(7)* (in dry t)

	With current tillage practices (i.e., approx 20% no-till)							If 100% no-till corn production					
State	Corn acres (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	Total available supply t (000)	Gross stover produced t (000)	$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	Total available supply t (000)	Gross stover produced t (000)
Alabama	205	0	0	0	0	2	394	0	0	0	0	6	394
Arkansas	142	23	30	30	31	37	404	137	194	194	197	201	404
Arizona	31	0	0	0	0	0	132	0	0	0	0	0	132
California	220	0	0	0	0	0	855	0	0	0	0	0	855
Colorado	1012	1	93	99	100	101	3256	11	797	981	982	983	3256
Connecticut	0	0	0	0	0	0	0	0	0	0	0	0	0
Delaware	154	228	268	268	268	268	428	280	288	288	288	288	428
Florida	55	1	2	3	3	4	105	1	24	31	32	36	105
Georgia	358	8	48	55	55	65	832	58	208	254	259	270	832
Iowa	11,983	10,474	14,465	14,745	14,928	15,116	39,619	16,580	21,618	21,924	22,059	22,311	39,619
Idaho	47	0	0	0	0	0	167	1	1	1	1	1	167
Illinois	10,667	6391	10,916	11,178	11,293	11,563	34,137	16,132	20,049	20,172	20,399	20,542	34,137
Indiana	5535	3005	5717	5941	6038	6207	16,916	7977	9499	9677	9791	9888	16,916
Kansas	2658	7	370	444	579	658	8786	101	2003	2275	2348	2432	8786
Kentucky	1176	0	33	49	62	70	3187	0	73	100	120	133	3187
Louisiana	387	1	56	63	67	69	1009	17	256	256	264	269	1009
Massachusets	0	0	0	0	0	0	0	0	0	0	0	0	0
Maryland	403	141	285	300	303	311	1107	219	414	421	424	430	1107
Maine	0	0	0	0	0	0	0	0	0	0	0	0	0
Michigan	2074	1702	2946	3062	3096	3139	5639	2463	4067	4067	4067	4067	5639
Minnesota	6582	10,637	12,829	12,917	12,964	13,036	21,419	13,885	15,305	15,305	15,305	15,334	21,419
Missouri	2402	384	549	577	588	633	6767	600	1083	1131	1150	1265	6767
Mississippi	400	0	10	11	11	16	960	2	73	85	85	112	960

Montana	16	0	0	0	0	0	46	0	9	10	12	13	46
North Caroli	754	25	528	632	651	684	1649	58	976	986	990	995	1649
North Dakota	685	0	2	3	14	25	1664	0	10	14	200	403	1664
Nebraska	8241	1969	5298	5759	5961	6134	25,937	7576	13,653	13,912	14,001	14,080	25,937
New Hampshire	0	0	0	0	0	0	0	0	0	0	0	0	0
New Jersey	82	0	0	0	0	1	197	0	0	0	0	6	197
New Mexico	80	0	9	9	10	10	322	0	65	67	76	83	322
Nevada	0	0	0	0	0	0	0	0	0	0	0	0	0
New York	579	0	64	102	102	138	1444	5	591	707	719	738	1444
Ohio	3214	2061	2737	2812	2828	2885	9938	3414	4935	5046	5077	5126	9938
Oklahoma	207	0	20	20	20	20	684	2	201	205	207	210	684
Oregon	30	6	12	12	12	12	124	25	25	25	25	25	124
Pennsylvania	1005	0	18	39	54	89	2491	0	180	251	300	430	2491
Rhode Island	0	0	0	0	0	0	0	0	0	0	0	0	0
South Caroli	299	0	146	172	177	195	525	0	282	296	300	310	525
South Dakota	3354	38	478	478	478	659	8323	320	3281	3283	3283	4562	8323
Tennessee	594	11	25	25	36	42	1519	27	50	50	62	72	1519
Texas	1810	0	43	46	91	106	5118	0	645	699	765	868	5118
Utah	21	0	0	0	0	0	67	0	0	0	0	0	67
Virginia	269	58	104	114	115	118	681	60	135	148	150	153	681
Vermont	0	0	0	0	0	0	0	0	0	0	0	0	0
Washington	90	22	26	27	27	27	393	126	179	179	179	179	393
Wisconsin	2940	322	1525	1634	1709	1799	8905	2657	4518	4541	4622	4660	8905
West Virgini	29	0	0	0	0	0	69	0	0	0	0	0	69
Wyoming	51	0	0	1	1	1	151	0	4	40	40	44	151
United States	70,840	37,517	59,652	61,630	62,673	64,242	216,366	72,732	105,692	107,621	108,777	111,526	216,366
Quads equiv.		0.58	0.92	0.96	0.97	1.00							

Table 2
Estimated Corn Stover Availability for Year 2025

	Current stover supplies (20% no-till)				Year 2025 stover supplies (30% no-till)			
State	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)
AL	0	0	0	0	0	0	0	0
AR	23	30	30	31	37	51	51	51
AZ	0	0	0	0	0	0	0	0
CA	0	0	0	0	0	0	0	0
CO	1	93	99	100	2	181	209	210
CT	0	0	0	0	0	0	0	0
DE	228	268	268	268	235	271	271	271
FL	1	2	3	3	1	5	6	6
GA	8	48	55	55	15	68	80	81
HI	0	0	0	0	0	0	0	0
IA	10,474	14,465	14,745	14,928	11,237	15,359	15,642	15,820
ID	0	0	0	0	0	0	0	0
IL	6391	10,916	11,178	11,293	7609	12,058	12,303	12,431
IN	3005	5717	5941	6038	3627	6190	6408	6507
KS	7	370	444	579	19	574	673	800
KY	0	33	49	62	0	38	55	70
LA	1	56	63	67	3	81	87	92
MA	0	0	0	0	0	0	0	0
MD	141	285	300	303	151	301	315	318
ME	0	0	0	0	0	0	0	0
MI	1702	2946	3062	3096	1798	3086	3188	3217
MN	10,637	12,829	12,917	12,964	11,043	13,139	13,215	13,256
MO	384	549	577	588	411	616	647	658
MS	0	10	11	11	1	18	20	20
MT	0	0	0	0	0	1	1	2
NC	25	528	632	651	30	584	677	694
ND	0	2	3	14	0	3	4	38
NE	1969	5298	5759	5961	2670	6343	6778	6966
NH	0	0	0	0	0	0	0	0
NJ	0	0	0	0	0	0	0	0
NM	0	9	9	10	0	16	16	18
NV	0	0	0	0	0	0	0	0
NY	0	64	102	102	1	130	177	179
OH	2061	2737	2812	2828	2230	3012	3091	3109
OK	0	20	20	20	0	42	43	43
OR	6	12	12	12	9	13	13	13
PA	0	18	39	54	0	38	65	85
RI	0	0	0	0	0	0	0	0
SC	0	146	172	177	0	163	188	192
SD	38	478	478	478	74	829	829	829
TN	11	25	25	36	13	29	29	39
TX	0	43	46	91	0	118	127	176

(Continued)

Table 2 *(Continued)*

	Current stover supplies (20% no-till)				Year 2025 stover supplies (30% no-till)			
State	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)	<$25/t (000)	<$30/t (000)	<$35/t (000)	<$40/t (000)
UT	0	0	0	0	0	0	0	0
VA	58	104	114	115	58	108	118	119
VT	0	0	0	0	0	0	0	0
WA	22	26	27	27	35	45	46	46
WI	322	1525	1634	1709	614	1899	1998	2073
WV	0	0	0	0	0	0	0	0
WY	0	0	1	1	0	1	6	6
US	37,517	59,652	61,630	62,673	41,919	65,407	67,379	68,436
Quads	0.58	0.92	0.96	0.97	0.65	1.01	1.04	1.06

$12/dry t ($13/dry mt) in transport and miscellaneous costs, the total delivered price used in EIA's new biomass supply curve is about $42/dry t ($46/dry mt) for the bulk of the stover supplies. In comparison, experience with corn stover harvesting and delivery during 1997–1999 illustrated a range in delivered corn stover prices of between $31.60 and $35.70/dry t ($34.84–$39.36/dry mt) *(10)*.

Non-Corn and Non-Wheat-Based Agricultural Residue Supply Estimates

Although corn stover and wheat straw are anticipated to be the largest potential sources of agricultural residues, there are many other types of crops that could potentially supply biomass residues. Although these other crop residues may tend to represent niche opportunities, on a national aggregate level they offer an expansion in the geographic range and supply for future bioenergy facilities beyond the Corn Belt and Great Plains states. Figure 2 illustrates the limited geographic concentration of corn stover supplies in the United States.

Crop residue supply estimates have been developed for nine crops: sorghum, barley, oats, rye, cotton field trash, cotton gin trash, rice straw, bagasse (the residue from sugar cane processing), and orchard prunings *(3,11)*. Although a large amount of soybeans are produced in the United States, the field residues from this crop are comparatively modest and readily decompose in the field, making collection of soybean plant residues unattractive (at least with the variety of soybean plants currently used by farmers).

In order to reduce the effects of varying yearly crop yields, for each of the "other" crop categories average annual crop production in all US states was calculated over a 3-yr span (1998–2000). The rules-of-thumb used for estimating the dry crop residues produced per pound of crop harvested

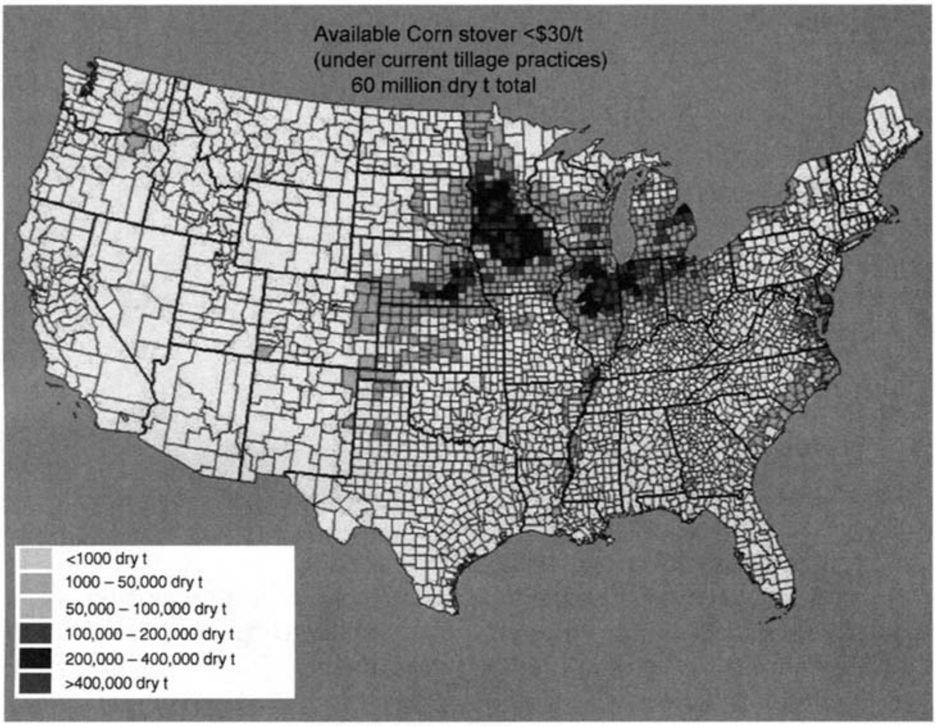

Fig. 2. Geographic distribution of corn stover supplies in the United States (Graham, 2004).

and the estimated percent of sustainably harvestable residues for each crop type were obtained from a variety of sources.*

- Barley: 48 pounds of barley/bushel (0.62 kg/L); 1.67 dry pounds of barley straw/pound of barley; 50% of barley straw harvested (net after erosion requirements and livestock use).
- Rye: 56 pounds of rye/bushel (0.72 kg/L); 1.67 dry pounds of rye straw/pound of rye; 40% of rye straw harvested (net after erosion requirements and livestock use).
- Oats: 32 pounds of oat/bushel (0.41 kg/L); 1.67 dry pounds oat straw/pound of oat; 40% of oat straw harvested (net after erosion requirements and livestock use).
- Sorghum: 56 pounds of sorghum/bushel (0.72 kg/L); 0.74 dry pounds of sorghum stover/pound of sorghum; 30% of sorghum stover harvested (net after erosion requirements and livestock use).

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*For barley, rye, oats, sorghum, rice straw, and bagasse, the rules-of-thumb are from the USDA agricultural residue report *(11)*. Percent harvestable factors were derived by averaging state values in the Gallagher report, taking into account limits related to erosion and competing livestock demand for the residues. The factor for orchard prunings is an average for orchard prunings from a California Energy Commission report on biomass residues *(12)*. Cotton gin trash and cotton field residue factors are based in input from staff at the USDA Cotton Ginning Research Laboratory *(13)*.

- Rice: 0.845 dry pounds of rice straw per pound of rice available, with 100% harvested.
- Bagasse: 0.25 dry pounds of bagasse per pound of sugarcane yield.
- Cotton Gin Trash: 0.9 dry pounds of cotton gin trash per pound of cotton harvested using "stripper" type harvesters.*
- Cotton Field Trash: 0.6 dry pounds of cotton field trash remain per pound of cotton harvested for acreage harvested using spindle-type harvesters.†
- Orchard Prunings/Thinnings: 0.7 dry pounds/acre (0.78 dry kg/he) (average for all types of fruit and nut trees).

The USDA report on crop residues *(11)* used detailed county level data to determine erosion constraints, and detailed livestock data to estimate competing demands for residues. In compiling the new EIA biomass supply curve, the USDA data was used in those states in which the report provided crop residue estimates. For states where the USDA report did not provide crop residue data, estimates were made using USDA-NASS data on average crop production by state, in combination with the rules-of-thumb summarized earlier. The specific states where crop residue estimates from the USDA agricultural residue report were used in the new EIA agricultural residue supply curve are as follows:

- Sorghum–CA, CO, KS, MT, ND, NE, OK, and SD;
- Barley–CA, CO, KS, MT, ND, OK, OR, SD, and WA;
- Oats–CA, CO, KS, MT, ND, NE, OK, OR, SD, and WA;
- Rice Straw–AR, LA, MO, and MS.

For pricing delineation, the "other" (non-corn and non-wheat) agricultural residues were separated into two categories:

1. Lower cost residues including bagasse, cotton gin trash, rice straw, and orchard prunings. These are categorized as "under \$25/dry t" (\$28/dry mt) at the farm gate, as there are either negligible added costs to harvest these residues or the costs for harvesting them are covered through normal crop management practices. The \$12/dry t (\$13/dry mt) adder for transportation, handling, and profit was used for these lower cost residues in order to simplify modeling functions. However, adding this cost may overstate the actual price of these residues since they could potentially be converted to energy at the locations where they are produced (especially regarding bagasse residues).

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[*] This as a "blended" number considering that a portion of the cotton harvest is field cleaned with stripper harvesting. About 85% of the cotton in Texas and Oklahoma is harvested with stripper-type harvesters and 0.3 dry pounds of cotton gin trash is produced per pound of cotton harvested using "spindle" type harvesters. Spindle harvesters are used for essentially all of the cotton produced, except for Texas and Oklahoma. The 0.3 dry pounds number is based on the assumption that the difference between the trash produced by the stripper versus the spindle type harvesters (0.9 – 0.6 = 0.3 extra pounds of trash left in the field by spindle-type harvesters) is left in the field in cotton producing states other than Texas and Oklahoma.

[†] Cotton stalks must currently be ground down to avoid bole weevil pest problems in the following year.

2. Higher cost agricultural residues including sorghum, barley, oats, rye, and cotton field trash in which farmers would have to make an extra effort to collect residues, similar to wheat straw collection. For this category of residues similar cost factors were used as for wheat straw in the existing EIA biomass supply curve. Seventy-five percent of the higher cost residues were assumed to be available at a cost of \$30/dry t (\$33/dry mt) or less at the farm gate; 88% is assumed to be available at less than \$35/dry t (\$39/dry mt), and 100% is assumed to be available at \$40/dry t (\$44/dry mt) at the farm gate. Similar to corn stover residues, an additional \$12/dry t (\$13/dry mt) were added to the "farm gate" costs to reflect delivered costs, taking into account various factors such as transportation, handling, and farmer profit.

Wheat Straw Estimates and Adjustments

The wheat straw estimates were generally kept unchanged as they had been in the EIA supply curve, pending revised county-level estimates. However, for the state of Oklahoma the amount of available wheat straw available was reduced substantially in the new EIA biomass supply curve. The old EIA supply curve showed only one state, Oklahoma, with wheat straw available at the lower cost category of less than \$20/dry t (\$22/dry mt) at the farm gate. It showed a substantial (3.2 million dry t/yr [2.9 million dry mt/yr]) of wheat straw available in Oklahoma in this low-price range. The USDA agricultural residue report *(11)* shows only 565,000 dry t (512,000 dry mt) of wheat straw available in Oklahoma, taking into account wind erosion as well as rain erosion constraints, whereas the source document for the existing EIA wheat straw estimates *(1)* only accounted for rain erosion limits, not wind erosion, which is a major consideration in Oklahoma. Based on this observation, the new EIA biomass supply curve includes a revised estimate for wheat straw availability in Oklahoma, now set at 565,000 dry t available/yr (512,000 dry mt/yr) at less than \$30/dry t (\$33/dry mt) at the farm gate (with none available at less than \$20/dry t [\$22/dry mt] at the farm gate). Another change regarding wheat straw is that transportation costs (plus some handling and profit costs) have been changed to \$12/dry t (\$13/dry mt) whereas the old EIA biomass curve had assumed an additional \$10/dry t (\$11/dry mt) cost adder for transportation in determining delivered costs for wheat straw.

Biomass Bulk Density and Transportation Issues and Costs

Transportation costs represent a significant fraction of the delivered cost of biomass feedstocks. Transportation costs are impacted by the bulk density of biomass and the transportation mode (truck or rail). A substantial amount of analysis is underway by various organizations (such as ORNL) to determine optimized and improved approaches and technologies for harvesting, handling, storing, and transporting biomass such as agricultural residues. As noted earlier, the agricultural residue supply estimates for the new EIA biomass supply curve assumes that round bales are produced and that these bales will be stored at the farm field edge for later transport directly to conversion facilities, with no intermediate storage. The density of round corn stover bales is around 9 dry pounds/ft^3 (144 kg/m^3) *(14)*.

Rather than storing bales at the "farm gate," an alternative is to store them at one or more central storage sites. Round bales can be stored in the open or in covered storage (round bales shed rainfall and can tolerate exposure to the weather), or square bales can be produced that are easier to stack, but are more susceptible to weather damage and thus need to be in covered storage. One alternative approach being investigated is the transport of loose bulk residues to an intermediate wet storage site for later transport to a conversion facility, probably via rail *(15)*. The bulk density of corn stover ejected by a standard corn combine is approx 3 dry pounds/ft^3 (48 dry kg/m^3), which could be increased to about 6 dry pounds/ft^3 (96 dry kg/m^3) with a forage chop approach. The higher density could help to reduce costs for transporting bulk residues to an intermediate storage site *(16)*. The anticipated density of stover removed from a wet storage site is around 12 dry pounds/ft^3 (192 dry kg/m^3). The higher bulk density of the feedstock, as well as other logistics benefits with the dispatch and transport of residues to conversion sites may offset the added costs associated with operating an intermediate storage site.

Densification of agricultural residues to pellets or cubes could increase the bulk density of biomass to as high as 28–40 pounds/ft^3 (448–640 dry kg/m^3) *(17)*. A primary drawback to densification is that it increases the cost for biomass in comparison with conventional approaches such as baling. One recent analysis estimated that densification costs might be in the range of $10 or $11/dry t ($11 or $12/dry mt) *(17)*; however, there are many alternatives for densification (such as the use of various binder additives) that will significantly impact costs. The added benefits of densification in terms of handling, storage, transport, and use may make this an approach attractive in certain applications particularly, whereas competing conventional energy options are expensive.

The approach and equipment used for harvesting, handling, storing, and transporting biomass will also have an impact on the amount of dry matter losses that can occur. For example, one evaluation of bunker storage options for agricultural materials found that storage losses could range from 10 to 16% *(18)*.

Although it is beyond the scope of this article to present and evaluate all of the many options and parameters that could impact biomass supply systems, the observations above help provide a sense of the range of factors that could impact biomass feedstock costs in the future.

Integrated Agricultural Residue Supply Curve

Table 3 provides a state-by-state summary of the agricultural residue supplies that have been included in the new EIA biomass supply curve.

Table 3

Maximum Agricultural Residue Supplies Available in the United States on a Sustainable[a] Basis (1000 dry t/yr)

State	Wheat straw	Corn stover (current till)	Sorghum	Barley	Oats	Rye	Rice straw	Bagasse	Cotton gin trash	Cotton field trash	Orchard prunings/residues	Total
AL	19	2	2	0	6	0	0	0	41	83	20	174
AR	857	37	74	0	6	0	3017	0	97	195	10	4293
AZ	169	0	6	116	0	0	0	0	52	104	44	491
CA	887	0	0	1	0	0	1572	0	150	299	2010	4919
CO	252	101	14	4	0	1	0	0	0	0	4	376
CT	0	0	0	0	0	0	0	0	0	0	2	2
DE	301	268	1	42	0	0	0	0	0	0	1	613
FL	15	4	0	0	0	0	0	2080	7	14	626	2746
GA	343	65	11	0	19	31	0	0	114	229	102	914
HI	239	0	0	0	0	0	0	339	0	0	25	603
IA	1123	15,116	0	0	122	0	0	0	0	0	2	16,363
ID	1456		0	1126	19	0	0	0	0	0	5	2606
IL	713	11,563	71	0	43	5	0	0	0	0	6	12,401
IN	0	6207	0	0	18	1	0	0	0	0	4	6230
KS	4456	658	853	0	0	6	0	0	2	3	5	5983
KY	1163	70	6	11	0	0	0	0	0	0	3	1253
LA	80	69	125	0	0	0	775	1696	59	118	11	2933
MA	0	0	0	0	0	0	0	0	0	0	4	4
MD	273	311	6	69	2	3	0	0	0	0	3	667
ME	0	0	0	23	20	0	0	0	0	0	3	46
MI	682	3139	0	17	52	11	0	0	0	0	83	3984
MN	1432	13,036	0	488	74	15	0	0	0	0	3	15,048
MO	1224	633	206	0	11	0	226	0	33	65	15	2414
MS	38	16	39	0	0	0	525	0	117	234	11	980

MT	370	0	0	492	2	0	0	0	0	0	1	865
NC	475	684	5	27	18	10	0	0	78	157	9	1463
ND	3715	25	0	3670	423	45	0	0	0	0		7878
NE	327	6134	122	5	2	6	0	0	0	0	1	6597
NH	0	0	0	0	0	0	0	0	0	0	2	2
NJ	33	1	0	6	0	3	0	0	0	0	8	51
NM	214	10	34	0	0	0	0	0	8	15	30	311
NV	15	0	0	7	0	0	0	0	0	0	0	22
NY	130	138	0	12	54	10	0	0	0	0	69	413
OH	1374	2885	0	9	73	3	0	0	0	0	9	4353
OK	566	20	21	1	0	38	0	0	28	3	62	739
OR	94	12	0	115	7	0	0	0	0	0	67	295
PA	1031	89	3	102	88	10	0	0	0	0	35	1358
RI	0	0	0	0	0	0	0	0	0	0	0	0
SC	240	195	2	3	18	8	0	0	24	48	17	555
SD	827	660	2	62	115	28	0	0	0	0	0	1694
TN	302	42	11	0	0	0	0	0	44	89	2	490
TX	1529	106	1218	0	57	8	81	160	824	92	157	4232
UT	154	0	0	129	5	0	0	0	0	0	6	294
VA	463	118	4	100	0	4	0	0	11	22	18	740
VT	0	0	0	0	0	0	0	0	0	0	2	2
WA	955	27	0	262	9	0	0	0	0	0	218	1471
WI	155	1799	0	67	199	7	0	0	0	0	7	2234
WV	12	0	0	0	1	0	0	0	0	0	6	19
WY	84	1	0	149	16	0	0	0	0	0	0	250
Total	28,787	64,242	2836	7112	1480	253	6195	4276	1691	1771	3731	122,374

[a] Taking into account erosion and soil maintenance requirements.

Table 4

2025 Supply and Cost Estimates for All Agricultural Residues Assuming 30% No-Till Corn Tillage Practices (1000 dry t/yr)

State	Corn stover				Other crop residues				All agricultural residues			
	<$25/t	<$30/t	<$35/t	<$40/t	<$25/t	<$30/t	<$35/t	<$40/t	<$25/t	<$30/t	<$35/t	<$40/t
AL	0	0	0	0	61	61	116	171	61	61	116	171
AR	37	50	51	51	3124	4260	4260	4260	3161	4310	4310	4310
AZ	0	0	0	0	96	491	491	491	96	491	491	491
CA	0	0	0	0	3731	4919	4919	4919	3731	4919	4919	4919
CO	2	181	209	210	4	275	275	275	6	456	484	485
CT	0	0	0	0	2	2	2	2	2	2	2	2
DE	235	271	271	271	0	101	223	344	235	373	494	615
FL	1	5	6	6	2714	2743	2743	2743	2714	2748	2749	2749
GA	15	68	80	81	216	851	851	851	231	919	931	931
HI	0	0	0	0	364	603	603	603	364	603	603	603
IA	11,237	15,359	15,642	15,820	2	1248	1248	1248	11,239	16,607	16,890	17,068
ID	0	0	0	0	5	2606	2606	2606	5	2606	2606	2606
IL	7608	12,058	12,303	12,431	6	838	838	838	7614	12,895	13,140	13,269
IN	3626	6190	6408	6507	4	23	23	23	3630	6213	6431	6530
KS	19	574	673	800	6	5325	5325	5325	25	5899	5998	6125
KY	0	38	55	70	3	482	832	1183	3	519	888	1253
LA	3	81	87	92	2541	2864	2864	2864	2543	2945	2951	2956
MA	0	0	0	0	4	4	4	4	4	4	4	4
MD	151	301	315	318	3	356	356	356	154	657	671	674
ME	0	0	0	0	3	46	46	46	3	46	46	46
MI	1797	3086	3188	3217	83	843	843	845	1880	3929	4031	4062
MN	11,043	13,138	13,215	13,256	3	2011	2011	2011	11,046	15,150	15,227	15,268
MO	411	616	646	658	274	1756	1768	1781	685	2372	2415	2439

MS	1	18	20	20	653	653	809	964	654	671	829	985
MT	0	1	1	2	1	865	865	865	1	866	866	866
NC	30	584	677	694	88	777	777	780	117	1361	1454	1473
ND	0	3	4	38	0	30	3941	7853	0	33	3945	7891
NE	3	6	7	7	1	463	463	463	2671	6805	7241	7429
NH	0	0	0	0	2	2	2	2	2	2	2	2
NJ	0	0	0	0	8	50	50	50	8	50	50	50
NM	0	16	16	18	38	301	301	301	38	317	317	319
NV	0	0	0	0	0	22	22	22	0	22	22	22
NY	1	130	177	179	69	275	275	275	70	405	452	454
OH	2230	3012	3091	3109	9	1468	1468	1468	2240	4480	4559	4577
OK	0	42	43	43	90	718	718	718	90	761	762	762
OR	8	13	13	13	67	283	283	283	76	297	297	297
PA	0	38	65	85	35	272	771	1270	35	310	836	1355
RI	0	0	0	0	0	0	0	0	0	0	0	0
SC	0	162	188	192	41	360	360	360	41	523	548	553
SD	74	829	829	829	0	1035	1035	1035	74	1863	1863	1863
TN	13	28	28	39	47	448	448	448	60	476	476	488
TX	0	118	127	175	1223	4126	4126	4126	1223	4244	4254	4302
UT	0	0	0	0	6	294	294	294	6	294	294	294
VA	58	108	118	119	29	411	517	622	87	519	635	742
VT	0	0	0	0	2	2	2	2	2	2	2	2
WA	35	45	46	46	218	1443	1443	1443	253	1488	1490	1490
WI	614	1899	1998	2073	7	435	435	435	620	2334	2433	2508
WV	0	0	0	0	7	20	20	20	7	20	20	20
WY	0	0	6	6	0	249	249	249	0	249	255	255
US	41,919	65,407	67,379	68,436	15,893	47,710	52,921	58,133	57,812	113,117	120,300	126,568

The corn stover quantities are based on current tillage and crop rotation practices. As discussed earlier, the wheat straw quantities are essentially the same values that were in the old EIA biomass supply curve, with updated Oklahoma values.

The "other" non-wheat/non-corn residues account for about 24% of total potential agricultural residue supplies. Although the other crop residues are dispersed in relatively small amounts, there are a few states in which these resources are concentrated, with the potential to supply larger biomass conversion facilities at these locations. For the most part, however, the "other" agricultural residue supplies will require small modular biomass conversion systems in order to be utilized.* Table 4 provides the new agricultural price–quantity pairs for the EIA biomass supply curve data for year 2025.

Conclusion

Although a significant amount of effort has gone into estimating the available quantities of agricultural residues, the amount of residues that can be sustainably removed is an issue that continues to be evaluated. Further analysis and field experience in the farming community is needed to solidify consensus views regarding the amount of residues that need to remain in the field, and the associated costs for harvesting and supplying these residues for use as energy feedstocks. Given these uncertainties, the current supply curves represent our best understanding of the availability of biomass at this point in time.

Summary

The National Energy Modeling System (NEMS) is used by the Energy Information Administration (EIA) to forecast US energy production, consumption, and price trends. Biomass is one of the technologies within NEMS, which plays a key role in several scenarios. An endogenously determined biomass supply schedule is used to derive the price–quantity relationship of biomass. The EIA's *Annual Energy Outlook 2005* includes updated estimates of the agricultural residue portion of the biomass supply schedule. This article had discussed the impact of these changes on the supply schedule.

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*For example, a smaller-scale gasifier coupled to an engine-generator (e.g., 100–300 kWe) currently has a typical heat rate of around 20,000 Btu/kW h (21.1 mJ/kW h) *(19)*, and would need roughly 1000 dry t/yr (907 dry mt/yr) of biomass feedstock to fuel a 100 kW system.

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