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**ABSTRACT**

The University of Kentucky Center for Applied Energy Research has conducted a survey of Kentucky’s utility coal-fired power plants every 5 years since 1992. The survey includes a collection of the feed coal and the coal combustion products (CCPs). The latest collection was in 2012, with the accompanying information survey covering trends in 2011. Overall coal-fired energy production decreased, and the nature of the CCPs changed for a number of reasons, including but not limited to, increased gas production in the Appalachians, a series of warm winters, energy conservation, depletion of Appalachian coal reserves, and utility responses to regulations. From 2011 to 2012, Kentucky’s coal-fired generation decreased from 91.656 to 82.762 GWh, while gas-fired generation rose from 1.163 to 2.401 GWh. About 10% of the CCPs produced in 2011 were sold compared with 30% in 2006. Some of this can be attributed to an increase in the amount of CCPs in certain categories, primarily flue-gas desulfurization (FGD) gypsum. The latter increase was due to regulations requiring the installation of FGD, while stagnation and decreases in sales were due to multiple factors, including the slowdown in housing construction and to the saturation of the Ohio River Valley market. Overall, comparing 2011 with 2006, all categories of CCPs experienced a decline in sales. The change from low-S to high-S coal with the installation of wet-FGD units has resulted in a shift from low-Fe to high-Fe fly ashes.

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### Table 1

| Disposal | Disposal | Sold | Used | Used | Stored | Total | % sold | % sold +
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>landfill (Mt)</td>
<td>ponds (Mt)</td>
<td>(Mt)</td>
<td>(Mt)</td>
<td>(Mt)</td>
<td>(Mt)</td>
<td>(Mt)</td>
<td>used</td>
</tr>
<tr>
<td>Fly ash</td>
<td>1.910</td>
<td>1.437</td>
<td>0.253</td>
<td>0.000</td>
<td>0.073</td>
<td>0.000</td>
<td>3.672</td>
<td>6.89</td>
</tr>
<tr>
<td>Bottom ash/ slag</td>
<td>0.621</td>
<td>0.558</td>
<td>0.269</td>
<td>0.097</td>
<td>0.027</td>
<td>0.000</td>
<td>1.571</td>
<td>17.10</td>
</tr>
<tr>
<td>FGD gypsum</td>
<td>0.757</td>
<td>1.601</td>
<td>0.635</td>
<td>0.059</td>
<td>0.248</td>
<td>0.627</td>
<td>3.927</td>
<td>16.16</td>
</tr>
<tr>
<td>FGD sulfite</td>
<td>2.421</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>2.421</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>5.709</td>
<td>3.593</td>
<td>1.156</td>
<td>0.156</td>
<td>0.348</td>
<td>0.627</td>
<td>11.591</td>
<td>9.98</td>
</tr>
</tbody>
</table>

Note: FGD = flue-gas desulfurization.

### 3. Results and Discussion

#### 3.1. Trends in CCP utilization

As noted in the “Introduction,” the physical sample collection is supplemented by an information survey. The return of questionnaires was not as complete as in the past, so we had to rely on information reported to the U.S. Energy Information Administration (EIA, 2014). In reality, the basic CCP production and utilization information provided to us directly by the utility is the same as is on the EIA forms, with the exception of the nuances of the tonnages going to different end uses and the insight into anticipated changes.

In 2011, the information year accompanying the 2012 sample collection, 42.47 Mt of coal with an average 9.99% ash yield and 2.60% S (both as received) were combusted to produce 91.656 GWh at Kentucky power plants rated at 15.432 GW capacity. As an indication of the state of the coal-fired power industry in Kentucky, to be discussed in more detail herein, in 2012, the coal-fired generation fell to 82.762 GWh, while natural gas generation rose from 1.163 GWh in 2011 to 2.401 GWh in 2012 (EIA, 2014). Kentucky does not yet have a large natural gas-generating capacity, so the latter numbers are lower than many other states, but they do reflect the national trend. The reasons for the 2011 to 2012 fall in coal-fired power generation are varied and include wider availability of natural gas coincident with the expansion of production in Appalachian gas shales; a warm winter (2011–2012); energy conservation, including the use of increasingly energy efficient appliances; depletion of the thickest, highest, quality, and most accessible Central Appalachian coal reserves following over 100 years of mining; and utility responses to U.S. Environmental Protection Agency (EPA) regulations.

In 2011, Kentucky sold 9.98% of all of the CCPs produced (Table 1), a marked decline from the 30.1% sold in 2006. Comparing 2011 with 2006 (Table 2), every category of CCP, including flue-gas desulfurization (FGD) sulfite, which is almost never sold, saw a decline in sales. Some of the decline in the percentage is a function of the increased production of CCPs, but that does not account for the entire decline. For example, FGD gypsum sales to the wallboard manufacturing industry were impacted by the slowdown in housing construction, as well as by the saturation of the regional market with the construction of new scrubbers in the Ohio River Valley area. The total FGD gypsum sold, used on-site and off-site, and stockpiled in anticipation of future sales in 2011 (1.57 Mt) is less than the 1.753 Mt sold in 2006.

Fly ash sales, generally not as high as FGD gypsum or bottom ash/slag sales, were also hindered by the uncertainty in the EPA’s prolonged discussion of a Resource Conservation and Recovery Act (RCRA) subtitle D (nonhazardous) versus subtitle C (hazardous) classification. In February 2014, following a January 2014 consent decree in the United States District Court for the District of Columbia in the case of Appalachian Voices et al. v. Gina McCarthy ordering EPA action (Walton, 2014), the EPA’s Office of Solid Waste & Emergency Response ruled that fly ash and FGD gypsum, as encapsulated in concrete and wallboard, were not hazardous (EPA, 2014a). Some aspects of the background for the latter ruling were based on studies by Yost et al. (2010), Garrabrants et al. (2014), and Kosson et al. (2014). According to the EPA, it is unlikely that there will be a review of unencapsulated uses in the near future because each use constitutes a unique case (Hegstead, 2014). Now that the ruling has been issued, it remains to be seen if the market for fly ash returns to levels experienced prior to the December 2008 ash spill at the Tennessee Valley Authority’s Kingston power plant in Tennessee (EPA, 2014b).

---

**Table 2**

<table>
<thead>
<tr>
<th>Year</th>
<th>MW rating</th>
<th>Fly ash production (Mt)</th>
<th>% sold</th>
<th>Slag/bottom ash production (Mt)</th>
<th>% sold</th>
<th>FGD gypsum (Mt)</th>
<th>% sold</th>
<th>FGD sulfite (Mt)</th>
<th>% sold</th>
<th>Total production (Mt)</th>
<th>% sold</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>15955</td>
<td>3.672</td>
<td>6.90</td>
<td>1.571</td>
<td>17.10</td>
<td>3.923</td>
<td>16.20</td>
<td>2.421</td>
<td>0.00</td>
<td>11.591</td>
<td>9.98</td>
</tr>
<tr>
<td>2006</td>
<td>15000</td>
<td>3.098</td>
<td>11.40</td>
<td>1.283</td>
<td>47.50</td>
<td>2.245</td>
<td>78.10</td>
<td>1.466</td>
<td>0.30</td>
<td>8.092</td>
<td>30.10</td>
</tr>
<tr>
<td>2001</td>
<td>15000</td>
<td>3.414</td>
<td>3.60</td>
<td>1.213</td>
<td>36.30</td>
<td>1.979</td>
<td>61.50</td>
<td>2.070</td>
<td>0.00</td>
<td>8.676</td>
<td>20.50</td>
</tr>
<tr>
<td>1996</td>
<td>15240</td>
<td>3.237</td>
<td>4.00</td>
<td>1.081</td>
<td>42.60</td>
<td>1.498</td>
<td>11.20</td>
<td>1.707</td>
<td>0.00</td>
<td>7.523</td>
<td>10.10</td>
</tr>
<tr>
<td>1991</td>
<td>16000</td>
<td>2.519</td>
<td>4.80</td>
<td>1.386</td>
<td>52.70</td>
<td>0.617</td>
<td>0.00</td>
<td>1.997</td>
<td>0.00</td>
<td>6.519</td>
<td>1.30</td>
</tr>
<tr>
<td>1978</td>
<td>11500</td>
<td>2.807</td>
<td>4.00</td>
<td>1.424</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>4.231</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: FGD = flue-gas desulfurization; na = not applicable.

Several of the power plants sampled in 2012 have announced plans to close by the end of 2015. These decisions are driven by EPA regulations governing emissions of SO₂, NOₓ, and Hg. It is generally anticipated that controls on CO₂ emissions for existing plants will be added to the latter list. For new plants, limits of 1100 lb (498.95 kg) CO₂/MWh gross over a 12-month operating period or 1000–1050 lb (453.59–476.27 kg) CO₂/MWh gross over an 84-month operating period were proposed (EPA, 2013c). As has been the case with previous EPA regulations, EPA authority is being challenged in U.S. courts, in this case, the U.S. Supreme Court (Liptak, 2014).

Changes seen from the time of the 2007 collection up to the end of 2012 were a consequence of responses to EPA’s Cross-State Air Pollution Rule (CSAPR) (EPA, 2013a) and EPA’s Mercury and Air Toxics Standards (MATS) (EPA, 2012). Under CSAPR, Kentucky power plants are required to reduce emissions of NOₓ during the May through September ozone season, reduce annual emissions of SO₂ and NOₓ by the guidelines of the 1997 Annual PM₂.₅ National Ambient Air Quality Standards (NAAQS) and the 2006 24-hour PM₂.₅ NAAQS (EPA, 2013b), and make significant additional reductions in SO₂ emissions by 2014 in order to eliminate their contribution to air-quality problems in downwind areas. The construction of wet FGD units to control SO₂ emissions resulted in a shift of coal supply from low-S Central Appalachian coals to high-S Illinois Basin coals. Further changes include the outright closing of certain plants, usually small, old plants, and the conversion to gas turbine power generation at additional plants. Overall, we estimate that the 2012 coal-fired capacity of 15.9 GW in Kentucky will be reduced to 13 GW in 2016.

3.3. Coal, pulverizer rejects, and fly ash quality

3.3.1. Coal

Compared with the feed coals collected in 2007 (Hower et al., 2009), there are fewer coals in the <1% S and 1–2% S categories in Kentucky coal utilities in 2012 (Table 3). The data in Table 3 were collected at 20 different Kentucky utilities, and in many cases, multiple coals at each plant were collected. The data in Table 3 are representative of the energy content and S content of the coals burned at Kentucky power plants in 2012. The data in Table 3 also provide a snapshot of the current quality of coal burned at Kentucky power plants, which is important for understanding the challenges faced by coal power plants in meeting EPA regulations for SO₂, NOₓ, and Hg.

Note: Mois = moisture; VM = volatile matter; FC = fixed carbon.

### Table 3
Coal quality parameters for coal burned at Kentucky utilities in 2012: proximate and ultimate analysis, heating value (HV), and Cl on as-received basis; major oxides by percent in 750°C ash; mercury on whole coal basis; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal.

| S code | Ash | Mois | VM | FC | C | H | N | S | O | S py | S sulfur | Sorg | HV | Cl (MJ/kg) | S code | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | Na₂O | K₂O | P₂O₅ | TiO₂ | SO₃ | Hg |
|-------|-----|------|----|----|---|---|---|---|---|------|---------|------|-----|-------------|-------|------|-------|-------|-----|-----|------|------|-----|------|-----|
| <1%   | Avg. | 8.43 | 8.10| 31.56| 46.42| 66.55| 5.62| 1.25| 0.70| 17.46| 0.15   | 0.03 | 0.53 | 27.26 | 36 |
|       | St. Dev. | 1.98 | 8.03| 5.68 | 67.37| 9.89 | 0.76| 0.30| 0.17| 11.88| 0.23   | 0.01 | 2.39 | 89.50 |
|       | Count | 2    | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2    | 2      | 2    | 2    | 2    |
| 1–2%  | Avg. | 10.92| 3.31| 36.64| 49.13| 66.49| 4.89| 1.48| 1.84| 14.39| 0.90   | 0.11 | 0.84 | 28.86 | 519 |
|       | St. Dev. | 0.93 | 0.47| 0.93 | 0.76| 5.98 | 0.17| 0.04| 0.13| 6.99 | 0.16   | 0.02 | 0.05 | 52.73 |
|       | Count | 2    | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2    | 2      | 2    | 2    | 2    |
| 2–3%  | Avg. | 10.93| 3.95| 37.22| 47.90| 67.68| 5.11| 1.42| 2.82| 12.04| 1.27   | 0.13 | 1.42 | 28.37 | 222 |
|       | St. Dev. | 2.17 | 1.35| 1.75 | 1.76| 2.19 | 0.19| 0.19| 0.11| 1.89 | 0.44   | 0.08 | 0.43 | 87.38 |
|       | Count | 15   | 15  | 15   | 15  | 15   | 15  | 15  | 15  | 15   | 15     | 15   | 15   | 15   |
| >3%   | Avg. | 13.42| 4.24| 35.99| 46.76| 66.49| 5.05| 1.22| 3.38| 10.44| 1.85   | 0.13 | 1.40 | 27.64 | 170 |
|       | St. Dev. | 3.14 | 1.80| 2.39 | 4.24| 3.53 | 0.15| 0.29| 0.29| 2.50 | 0.48   | 0.08 | 0.48 | 1.38 | 213 |
|       | Count | 9    | 9   | 9    | 9   | 9    | 9   | 9   | 9   | 9    | 9      | 9    | 9    | 9    |

Note: Mois = moisture; VM = volatile matter; FC = fixed carbon.
the 2012 collection (Table 3). As noted already, this is a function of the switch from low-S to high-S coals coincident with the switch to wet-FGD removal of flue-gas SO$_2$. A two-unit plant currently burning low-S (1%) coal will convert at least one unit to natural gas before our next collection (planned for 2017). A 1–2% unit will be connected to an existing dry FGD unit at another plant with no planned change in the coal supply (Melnykovych, 2014).

The relatively high CaO content of the 1% S feed coal reflects the use of a western U.S. bituminous/Powder River Basin subbituminous blend in one power plant. The blending of a high-CaO, low-S coal with high-S Illinois Basin coal in one of the 2–3% S feed coal units is barely evident in the 3.12% CaO in the average of the feed coals.

3.3.2. Pulverizer rejects

The pulverizer rejects, often called ‘pyrites’ in the power plants, live up to the latter name in having an average of up to 34.5% total S in the >3% S feed coal category (note that the rejects and the fly ash summaries follow the S categories of the feed coals; Table 4). The Fe$_2$O$_3$ content, largely from the pyrite, mirrors the high-S content of the rejects. Toxic trace elements, notably As and Hg, are significantly higher in the rejects than in the feed coal. Even though the pulverizer rejects represent a small portion of the raw feed coal, the amount of As and Hg in the rejects can mean a reduction of perhaps 10–15% of the As and Hg in the pulverized feed coal (Mardon and Hower, 2004; Hower et al., 2005, 2006).

3.3.3. Fly ash

While up to five rows of ESP and FF were collected at some power plants, not all plants have that many rows, and even where present, the back rows did not always have fly ash at the time of sampling. The first two rows account for about 96% of the fly ash (based on the rule of thumb stating that each row collects about 80% of the fly ash entering that row), and our comparison is limited to the first two rows (Tables 5 and 6). Aside from the relationship between the chemistry of the feed coal and the resulting fly ash, there is a relationship between the collection point (ESP or FF row) and the concentration of trace elements (Meij, 1994; Bool and Helble, 1995; Robl et al., 1995; Hower et al., 1997, 1999c,d,e, 2005, 2006, 2009, 2010; Sakulpitakphon et al.,

Table 4

<table>
<thead>
<tr>
<th>S code</th>
<th>Ash</th>
<th>Mois</th>
<th>VM</th>
<th>FC</th>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>O</th>
<th>S$_{pp}$</th>
<th>S$_{sulf}$</th>
<th>S$_{org}$</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1%</td>
<td>Avg.</td>
<td>33.19</td>
<td>4.45</td>
<td>31.20</td>
<td>31.17</td>
<td>47.38</td>
<td>4.08</td>
<td>0.89</td>
<td>3.42</td>
<td>11.05</td>
<td>2.72</td>
<td>0.11</td>
<td>0.60</td>
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<tr>
<td>St. Dev.</td>
<td>4.31</td>
<td>3.87</td>
<td>1.17</td>
<td>0.63</td>
<td>2.09</td>
<td>0.37</td>
<td>0.08</td>
<td>1.65</td>
<td>7.87</td>
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<td>0.25</td>
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<td>2</td>
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<td>2</td>
<td></td>
</tr>
<tr>
<td>1–2%</td>
<td>Avg.</td>
<td>46.24</td>
<td>1.20</td>
<td>28.15</td>
<td>24.41</td>
<td>30.25</td>
<td>2.40</td>
<td>0.70</td>
<td>24.50</td>
<td>&lt;0.1</td>
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<td>0.28</td>
<td>2.92</td>
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<td>nd</td>
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<td>nd</td>
<td>nd</td>
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<tr>
<td>2–3%</td>
<td>Avg.</td>
<td>39.94</td>
<td>2.36</td>
<td>30.83</td>
<td>26.87</td>
<td>36.11</td>
<td>2.90</td>
<td>0.73</td>
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<td>17.92</td>
<td>0.60</td>
<td>5.52</td>
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<td>St. Dev.</td>
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<td>16.76</td>
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<tr>
<td>&gt;3%</td>
<td>Avg.</td>
<td>58.70</td>
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<td>15.56</td>
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<td>4</td>
<td>4</td>
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<td></td>
</tr>
<tr>
<td>S code</td>
<td>SiO$_2$</td>
<td>Al$_2$O$_3$</td>
<td>Fe$_2$O$_3$</td>
<td>CaO</td>
<td>MgO</td>
<td>Na$_2$O</td>
<td>K$_2$O</td>
<td>P$_2$O$_5$</td>
<td>TiO$_2$</td>
<td>SO$_3$</td>
<td>Hg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1%</td>
<td>Avg.</td>
<td>47.87</td>
<td>14.04</td>
<td>21.76</td>
<td>6.93</td>
<td>1.61</td>
<td>0.24</td>
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Note: Mois = moisture; VM = volatile matter; FC = fixed carbon; nd = not determined.
Table 5
First-row electrostatic precipitator or fabric filter fly ash at Kentucky utilities in 2012: ash, moisture (Mois), carbon, and sulfur on as-received basis; major oxides on percent in 750°C ash; and minor elements in parts per million in 750°C ash; groupings are based on the amount of S in the feed coal

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2000, 2004; Mardon and Hower, 2004; Mastalerz et al., 2004; Depoi et al., 2008; Levandowski and Kalkreuth, 2009; Meij and te Winkel, 2009). In general, for most volatile trace elements, with exception of Hg (discussed in Hower et al., 2010) and Se (discussed in Hower et al., 2009), the concentration of the element will increase from the first row of the ash collection system through to the last row due to the decrease in flue-gas temperature and the increase in particle surface area (and decrease in particle size) in the same direction. Mercury capture, not addressed in this study due to technical difficulties in the determination of Hg in the CAER laboratories, is a function of the flue-gas temperature (increasing as temperature drops), the amount of carbon in the fly ash (increasing as the C content increases), the surface area of the carbon (increasing with an increase in surface area), and the type of carbon (Hower et al., 2010). Anisotropic carbon has the best Hg capture in fly ashes derived from bituminous coals (Maroto-Valer et al., 2001), but lignite- or subbituminous-derived char has better Hg-capture potential (Kostova et al., 2011).

Among the major oxides, CaO is relatively enriched in the low-S feed coal owing to the use of western U.S. coals, which are typically higher in CaO than eastern U.S. coals, in the feed coal at one plant. Iron oxide is enriched in the fly ashes from >1% S coals; this is not a surprise since a large percentage of the S is associated with pyrite. Volatile trace elements, such as Zn and As, increase from the first to second ESP rows, but the trends are not as evident in the group averages. Among the more significant trends is the increase from 150 to 347 ppm As in a three-row ESP. Zinc increases from 1070 to 1593 ppm in the first two of three ESP rows at a plant burning a small amount of tire-derived fuel (tdf) with the high-S feed coal. Concentrations of >2000 ppm V and up to 648 ppm Ni were observed in two plants burning several 10s percent of petroleum coke with high-S coal. One of the latter plants was scheduled to be idled in February 2014 (Reuters, 2014), but the plans were delayed when a short-term contract to purchase electricity was announced (Associated Press, 2014).

4. Outlook

Over the next few years, there will be a further narrowing of the fly ash quality available in Kentucky. Although one currently unscrubbed unit will be converted to dry-FGD controls with no anticipated change in its current medium-S Central Appalachian...
### Table 6
Second-row electrostatic precipitator or fabric filter fly ash at Kentucky utilities in 2012: ash, moisture (Mois), carbon, and sulfur on as-received basis; major oxides by percent in 750 °C ash; and minor elements in parts per million in 750 °C ash; groupings are based on the amount of S in the feed coal

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<th>C</th>
<th>S</th>
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### References


