The U.S. Fly Ash Market: Production & Utilization Forecast

American Coal Ash Association 2020 Edition

About the American Coal Ash Association

The American Coal Ash Association's (ACAA's) mission is to advance the management and use of coal combustion products in ways that are environmentally responsible, technically sound, commercially competitive, and supportive of a sustainable global community.

We achieve this by hosting workshops, symposia, and many other industry gatherings to promote understanding and facilitate connections. We publish a biannual magazine, *ASH at Work*; an exclusive weekly member e-newsletter, *The Phoenix*; and provide news briefs and updates to keep members and stakeholders engaged in ongoing developments. We archive research reports and industry documents going back 40 years, and we offer expertise in recycling coal ash, boiler slag, and FGD materials.

Every two years, the ACAA co-hosts the industry's most prominent event, "The World of Coal Ash," with more than 1,000 participants from about 30 countries.

About ARTBA and ARTBA-TDF

The American Road & Transportation Builders Association (ARTBA) is a federation whose primary goal is to aggressively grow and protect transportation infrastructure investment to meet the public and business demand for safe and efficient travel. In support of this mission, ARTBA also provides programs and services designed to give its more than 8,000 public- and private-sector members a global competitive edge.

Established in 1985, the ARTBA Transportation Development Foundation (ARTBA-TDF®) is a 501(c)3 tax-exempt entity designed to support research, education, and public awareness. The Foundation supports a variety of initiatives, including educational scholarships, awards programs, professional development courses, safety training, a national exhibition on transportation, and a facility dedicated to improving safety in roadway construction zones. Corporate and personal contributions to support the activities of the Foundation may be tax-deductible.

About the Author

This research was conducted by Dr. Alison Premo Black, Senior Vice President and Chief Economist for the American Road & Transportation Builders Association in Washington, D.C. Ms. Lital Nada also contributed to the report.

Dr. Black, who earned her Ph.D. in Economics at The George Washington University in the nation's capital, also holds an M.A. in International Economics and Latin American Studies from the Johns Hopkins School of Advanced International Studies. She graduated magna cum laude from Syracuse University, where she was a member of Phi Beta Kappa and the Golden Key Honors Society, with majors in International Relations, Latin American Studies, and Spanish. Since joining ARTBA in 2000, Dr. Black has led teams and authored over 100 studies examining state transportation funding and investment patterns, including the 2011 report "The Economic Impacts of Prohibiting Coal Fly Ash Use in Transportation Infrastructure Construction." She is also the author of the "The U.S. Coal Combustion Products Market Forecast" and "The U.S. Coal Combustion Products Market: A Historical Market Analysis," published in 2015.

Executive Summary

Fly ash production is forecasted to average 32 million short tons per year between 2018 and 2039. Production will decline in the next three years before stabilizing as the amount of coal-generated electricity in the United States reaches a new equilibrium.

The beneficial use of fly ash is expected to grow during this time, relying on harvested material, technology and logistics improvements, and imports to provide additional supply.

Fly ash is one of several coal combustion products (CCPs) produced when coal is burned to generate electricity. Fly ash is the material that exits a combustion chamber in the flue gas and is captured by emissions control equipment, such as electrostatic precipitators and baghouses.

Beneficial uses of fly ash include serving as a key input for concrete and related products, blended cement, structural fills, waste stabilization, agriculture, soil modification, and applications in the mining industry.

Under alternative assumptions, the total average annual change in fly ash production could range between +1 and -2 percent. This depends largely on the amount of coal-generated electricity in the United States, although technological improvements could increase the amount of fly ash suitable for beneficial use.

Utilization is forecasted to increase 38 percent over the forecast period, from 20.1 million short tons in 2018 to 27.8 million short tons in 2038.

Fly Ash Production

Total fly ash production is forecasted to average 33.2 million short tons per year between 2018 and 2039.

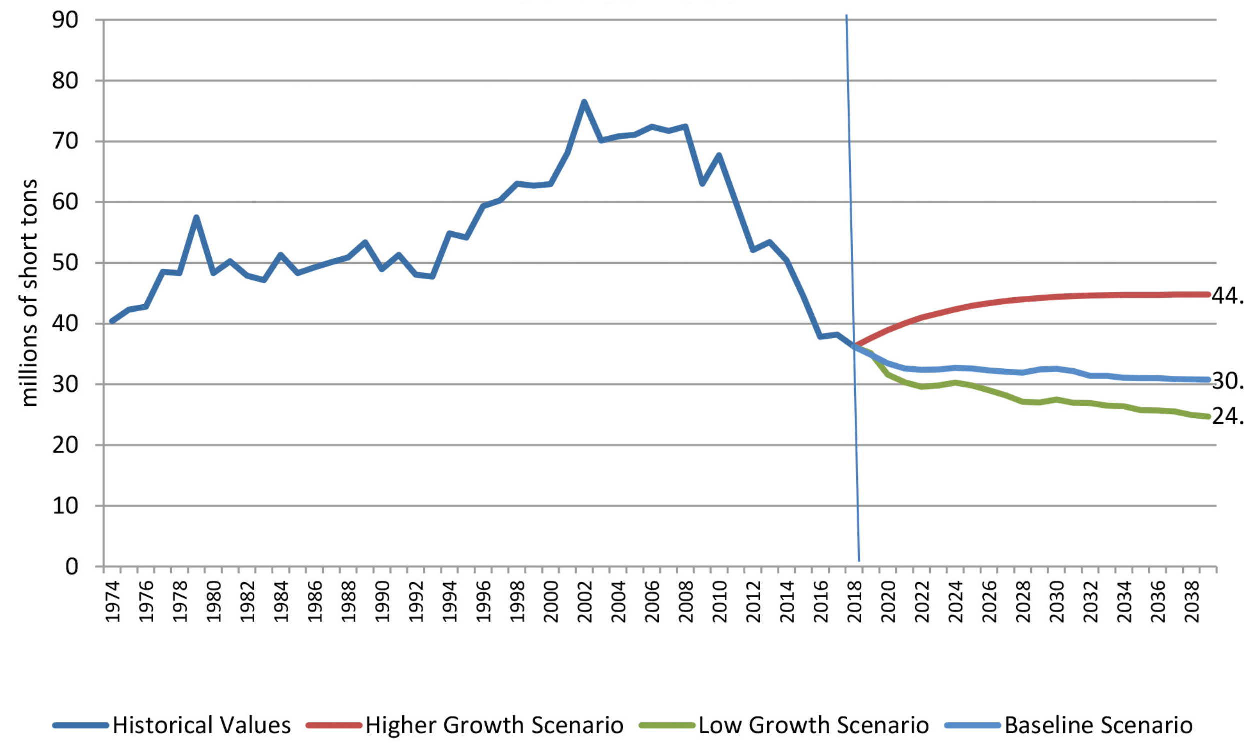

Figure 1. Various Scenarios for Fly Ash Production, 1974 to 2039

Table 1. Fly Ash Forecast Scenarios (in millions short tons)

	Volume 2018	Projected Volume 2039	Projected Total Change	Projected Avg. Annual Growth Rate
Fly Ash Production				
Baseline Forecast	36.2	30.8	-14.9%	-0.8%
High Growth Scenario	36.2	44.8	23.8%	1.0%
Low Growth Scenario	36.2	24.9	-31.2%	-1.8%
Fly Ash Utilization	20.1	27.8	38.3%	1.6%

Production is dependent on the total volume of coal-fueled electricity generation by utilities, which is expected to average 1 trillion megawatt hours between 2019 and 2039, according to EIA's *Annual Energy Outlook 2019*.

Total fly ash production has been declining since 2002 as the total volume of coal-fueled electricity generation has decreased. Greater competition from natural gas and renewable energy sources, the retirement of coal-fueled power plants, and decreases in plant capacity have contributed to this shift in coal-fueled electricity generation.

Despite these changes, the baseline forecast for fly ash production is stable. The average annual growth rate of fly ash production over the next 20 years could range from +1 percent to -2 percent, according to the forecast models.

This means that fly ash harvesting and imports, in addition to advances in transportation and technology, will be of growing importance to meet the forecasted increased demand for fly ash from the industries that rely on coal combustion products.

Baseline Forecast

Fly ash production will decline from 36.2 million short tons in 2018 to 30.8 million short tons in 2039, according to the baseline forecast model, decreasing at an average annual rate of just under 1 percent.

In this scenario, the total volume of coal-generated electricity will decline at an average annual rate of 1 percent, from 1.165 trillion megawatt hours in 2018 to 0.941 trillion megawatt hours in 2039.

The expected decline in coal-generated electricity is in part a result of the recent retirement of coal-fueled electricity generation capacity, which increased from 6 gigawatts in 2017 to 14 gigawatts in 2018.[1] Electric utilities are expected to retire a total of 4 giga-

[1] U.S. EIA. 2018. "U.S. Coal Consumption in 2018 Expected to Be the Lowest in 39 Years." Today in Energy, available at https://www.eia.gov/todayinenergy/detail.php?id=37692.

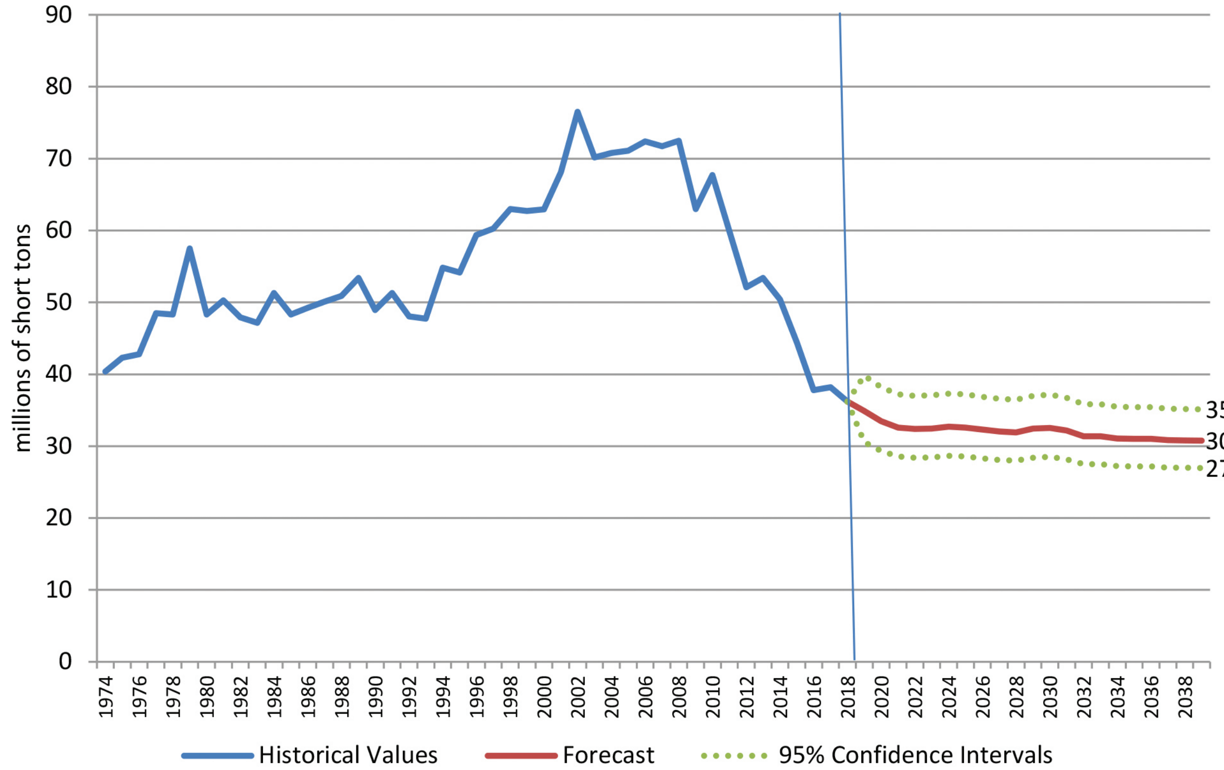

Figure 2. Fly Ash Production 1974 to 2039

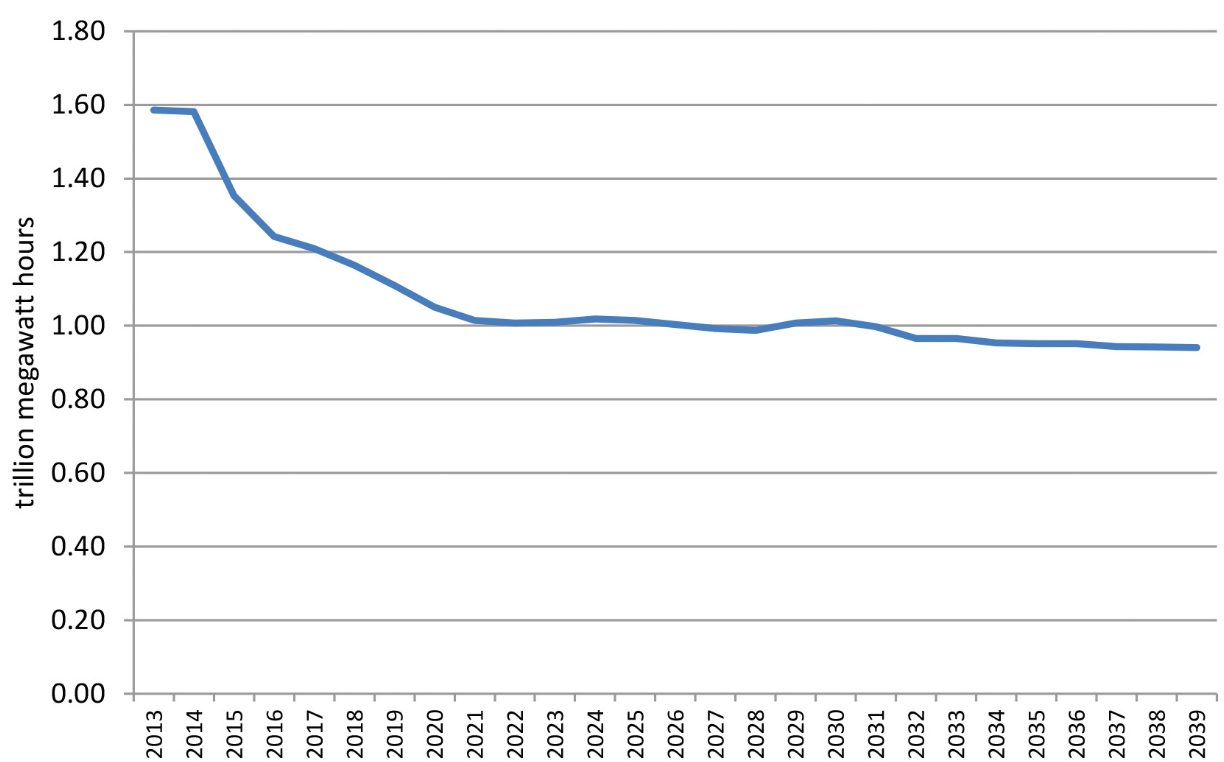

Figure 3. Coal Generated Electricity 2013 to 2039

watts of capacity in 2019 and less than 2 gigawatts in 2020. The slowing pace of retirements will help stabilize fly ash production.

Alternative Forecasts

Fly ash production could be higher or lower than the baseline case, depending on the changes in coal-fueled electricity generation. The assumptions in these scenarios are based on EIA's alternative outlooks in the *Annual Energy Outlook 2019*. Although the terms "high-growth" and "low-growth" are used here, the differences between these and the base case are small..

Under a high-growth scenario, fly ash production would increase from 36.2 million short tons in 2018 to 44.8 million short tons in 2039, an average annual growth rate of 1 percent. The total volume of coal-generated electricity would decline from 1.168 trillion megawatt hours in 2018 to 1.14 trillion megawatt hours in 2039, a slower decline averaging just -0.1 percent a year.

In this case, the per-unit cost of crude oil and natural gas development in the U.S. is higher than the baseline, making investment in these energy sources more expensive. As a result, the total volume of coal-fueled electricity generation remains stable.

Under a low-growth scenario, the per-unit cost of crude oil and natural gas development is below the baseline, making these fuel sources more competitive. The total volume of coal-fueled electricity generation would decline at an average annual rate of 2.4 percent, declining from 1.167 trillion megawatt hours in 2018 to 0.706 trillion megawatt hours in 2039. As a result, fly ash production would be predicted to decline from 36.2 million short tons in 2018 to 24.7 million short tons in 2039.

Additional Supplies of Fly Ash

As U.S. fly ash production has begun to decline, the ash marketing industry has begun developing additional sources and strategies that will likely have an impact on the overall supply of materials for beneficial use. Some of these potential sources and strategies are discussed below.

Harvesting of Fly Ash from Ponds or Landfills

A variety of existing technologies can be used to facilitate the beneficial use of harvested fly ash that was previously disposed in either wet or dry disposal units. These could have significant impact on the supply and utilization of fly ash.

In 2017, there were 179 utility plants that disposed of 20.2 million short tons of fly ash in ponds and landfills.[2] Analysis of utility-reported data on more than 700 disposal units indicates that well over 1 billion tons of ash materials were previously disposed in facilities now subject to closure under federal regulations.[3]

Harvesting of previously disposed ash for use in concrete markets is already taking place on a commercial scale. An industry consensus specification, ASTM Specification E-3183-19 "Standard Guide for Harvesting Coal Combustion Products Stored in Active and Inactive Storage Areas for Beneficial Use," has been finalized and is guiding industry activities in this area. Large-scale harvesting operations are now supplying high-quality fly ash for use as a supplementary cementitious material (SCM) to concrete producer markets in South Carolina and Pennsylvania.[4]

In addition to producing ash for SCM use in concrete, harvested ash may be utilized in other product applications. One study examined the use of ponded ash as a fine aggregate substitute in cement concrete.[5] Ponded ash has also been used in the production of clay-fired bricks and fertilizer, and work has been done to explore its use in ceramics.[6, 7]

A pilot plant in Sowlany, Poland uses landfilled coal ash to produce 40,000 metric tons of lightweight aggregate per year.[8]

The number of ponds to be excavated in the coming years is expected to increase as the wet disposal of coal combustion products is phased out. This change in ash disposal management was part of the December 19, 2014, Final Rule for Disposal of Coal Combustion Residuals from Electric Utilities.[9] Harvesting fly ash and other coal combustion products will allow utility owners to recoup some of the expenses associated with the pond closures, as well as reduce the volume of material that must be placed in new disposal units. Additionally, as some utilities convert from wet to dry handling of coal ash at power plants that continue to operate, materials that were previously disposed can become directly available for beneficial use.

Technologies to Increase Fly Ash Quality

Technologies to improve fly ash quality are helping to increase the portion of material suitable for beneficial use as well as increase the supply during seasonal fluctuations. Known as commercial fly ash beneficiation, these techniques include chemical treatment, electrostatic separation, carbon burn-out, and other proprietary methods.[10] The result is a higher-quality ash that meets ASTM standards and is suitable for use in concrete production and other materials.

Technologies that have been used for harvesting of fly ash in ponds and landfills include:

- **Carbon Burn-Out**—In this process, residual carbon in fly ash is combusted, which produces a low-carbon, low-loss-on-ignition, high-quality pozzolan.
- **MP618™ Multi-Process Fly Ash Beneficiation**—This is a thermal process that reduces loss-on-ignition, ammonia, and moisture in dry and wet fly ash.

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[2] ARTBA analysis of EIA 923 data.

[3] Cox, David. 2019. "Using Business Intelligence to Gauge the U.S. Coal Ash." *Ash at Work,* Volume 2.

[4] Knowles, Jimmy C. and Fedorka, Bill. 2015. "A New Solution for a Long-Standing Dilemma." *Ash at Work,* Volume 2. Minkara, Rafic, Ph.D. 2019. "Digging Through the Past: Harvesting Legacy Ash Deposits to Meet Future Demand." *Ash at Work,* Volume 1.

[5] Arumugam, K. and Manohar, D. James. 2011. "A Study on Characterization and Use of Pond Ash as Fine Aggregate in Concrete." *International Journal of Civil & Structural Engineering* 2.2. pp. 466-474. http://www.ipublishing.co.in/jcandsevol1no12010/voltwo/EIJCSE3038.pdf

[6] Sonawane, Prashant and Dwivedi, Dr. Arun Kumar. 2013. "Technical Properties of Pond Ash – Clay Fired Bricks – An Experimental Study." *American Journal of Engineering Research,* Volume 2, Issue 9. http://www.ajer.org/papers/v2%289%29/P029110117.pdf

[7] Katait, Sanjay Keshaorao, Dr. 2017. "Potential Application of Waste Fly Ash in Agriculture & Construction: Preventive Measures to Protect Health & Environment." *International Journal of Management, IT & Engineering,* Vol. 7 Issue 6. http://www.ijmra.us/project%20doc/2017/IJMIE_JUNE2017/IJMRA-11712.pdf.

[8] Minkara, Rafic, Ph.D. 2019. "Digging Through the Past: Harvesting Legacy Ash Deposits to Meet Future Demand." *Ash at Work,* Volume 1.

[9] http://www.gpo.gov/fdsys/pkg/FR-2015-04-17/pdf/2015-00257.pdf.

[10] American Coal Ash Association. 2015. "Beneficiation & Reclamation." *Ash at Work,* Issue 2.

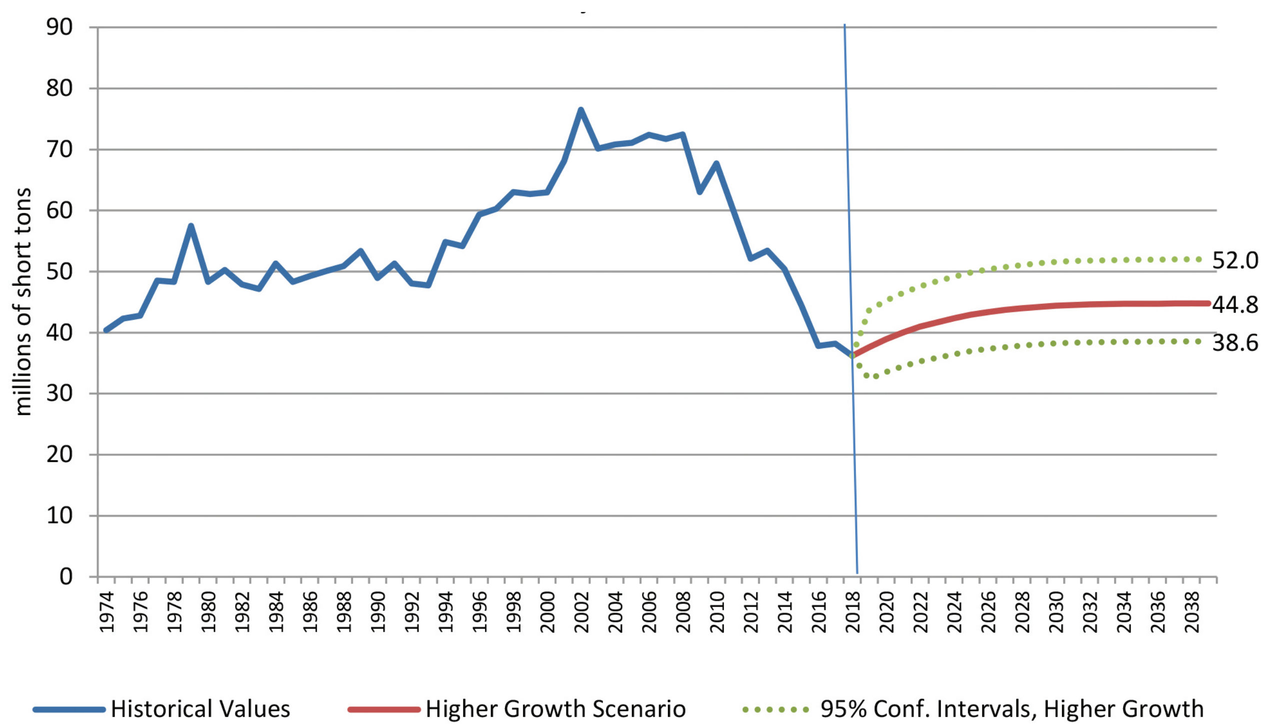


Figure 4. High-Growth Score of Fly Ash Production, 1974 to 2039

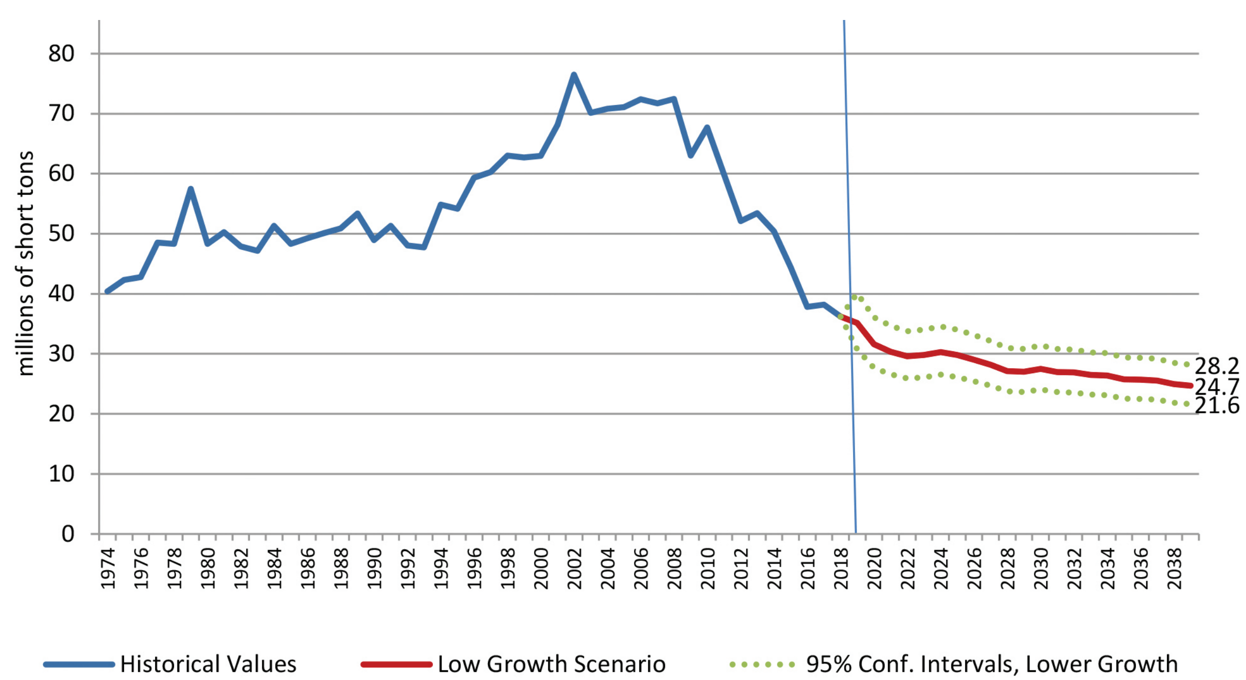


Figure 5. Low-Growth Scenarios for Fly Ash Production, 1974 to 2039

- **STAR® Technology**—This thermal beneficiation process was the first technology in the world to be used on ponds on a commercial scale.

Investing in these technologies may also provide benefits for fly ash suppliers. An economic case study found that the thermal beneficiation management of ash compared to the installation and operation of a landfill to manage disposal would yield a net saving of $15 million over a 20-year period.[11]

Role of Logistics in Fly Ash Availability

Fly ash supply for beneficial use also increases as the ash marketing industry invests in a variety of strategies related to logistics.[12] Chief among these strategies is the construction of ash storage and distribution infrastructure to address seasonal and geographical disconnects between ash production and use. Other strategies growing in popularity include blending of materials and the potential of grinding bottom ash to produce a concrete-quality SCM.

International Fly Ash Markets

The international market for fly ash includes potential supply sources from China, India, Mexico, Turkey, and Western Europe, among others.

The U.S. imported $71 million in slag and ash in 2018, according to the U.S. Census Bureau's import and export merchandise trade statistics.[13] This was up from $57 million in 2017 and $41 million in 2016. States importing the largest volumes included Florida, Washington, Louisiana, Nevada, Ohio, and Texas.

Global fly ash production is robust, and it continues to grow in countries with expanding coal fleets, such as China and India, which account for 60 percent of global production.[14] International supplies of fly ash that meet U.S. standards could be used as an input as domestic production is unable to meet the high demand for beneficial use. Fly ash imports can make up for domestic shortages and act as a "safety valve" to meet high demand in areas with insufficient supply.[15]

The production and utilization of fly ash around the world are well documented:

- In Australia, fly ash production was estimated at 10.96 million tons in 2016, an 11 percent decrease from 2010 levels; at the same time, utilization increased by 2 percent, to 44 percent, and the quantity sold increased by 8 percent.[16]
- According to the European Coal Combustion Products Association, 26.8 million tons of fly ash was produced in 2016, with a utilization rate of 42 percent, primarily in the building and construction industry.[17] China is estimated to produce about 600 million tons of fly ash each year, with a utilization rate of 70 percent in 2015, up from 20 percent in 1999. This means that approximately 200 million tons of fly ash require storage annually.[18] Chinese fly ash production is expected to continue to grow slowly in the coming years, at 600-620 million tons per year. However, there are several challenges to continuing to increase the utilization rate, including the deceleration of the Chinese real-estate industry; long distances between areas where fly ash is produced and demanded; and recent regulatory changes enacted by the Chinese government.[19]
- Growth has continued in the Indian fly ash market, with 80 percent of the country's electricity coming from coal-fueled plants using coal with high ash content (ranging from 30 to 45 percent). Fly ash utilization has also increased in India, reaching 132 million tons in 2017-18 at a utilization rate of 67 percent, compared to 7 million tons in 1996-97 at a utilization rate of 10 percent. At the same time, however, since utilization is below production levels, surplus ash stock has accumulated, which has grown in recent years.[20]

Fly Ash Utilization

Total fly ash utilization is forecasted to increase 38 percent over the next twenty years, from 20.1 million short tons in 2018 to 27.8 million short tons in 2039. The overall utilization is expected to grow from 55 percent of production in 2018 to 90 percent by 2039.

The forecasted utilization in the latter years of the forecast would be equal to expected production. To meet the growing demand for fly ash, additional supply from harvested material, technology and logistics additions, and imports will be necessary.

Concrete, blended cement, and related products account for over 77 percent of fly ash beneficial use. Future demand for fly ash will depend on the market for ready-mixed concrete and growth in the U.S. infrastructure and construction markets.

It is estimated that fly ash is utilized in more than 75 percent of the concrete used in highway and bridge construction. Based on an evaluation conducted in 2011, states such as as California, Florida, Louisiana, New Mexico, Nevada, Utah, and Texas use fly ash for virtually all their concrete highway and bridge projects.[21]

Outlook for Ready-Mixed Concrete and the U.S. Economy

As the largest market for U.S. fly ash, concrete demand is closely linked with fly ash utilization. Historically, the production of ready-mixed concrete in the United States has grown at an average annual rate of 2 percent.

Because it cannot travel for long distances before hardening, local demand for ready-mixed concrete is highly dependent on

[11]Gardner, Devin and Greenwood, Scott. 2017. "Beneficial Reuse of Coal Ash from Dominion Energy Coal Ash Sites Feasibility Assessment." Available at https://www.southernenvironment.org/uploads/words_docs/Coal_Ash_Recycling_Feasiblity_Assessment.pdf.

[12]Ward, John. 2018. "Future Coal Ash: What Lies Ahead for Beneficial Use of Coal Combustion Products?" *Ash at Work,* Volume 2.

[13]Import statistics are for the harmonized system code 2621.90, which includes "other slag and ash, including seaweed ash; ash and residues from incineration of municipal waste."

[14]Sheikh, Vassiem. 2018. "Limited Availability of Cementitious Materials Could Impact the Value Chain." *Ash at Work,* Issue 1.

[15]Stanley, William and Haverland, Rick. 2018. "Global Trends in Coal-Fueled Power Generation and the Need for CCP Imports to the Americas." *Ash at Work,* Issue 1.

[16]Ash Development Association of Australia. 2016. *Annual Membership Survey Report.* http://www.adaa.asn.au/resource-utilisation/ccp-utilisation.

[17]European Coal Combustion Products Association. "Production and Utilisation of CCPs in 2016 in Europe." http://www.ecoba.com/ecobaccpprod.html.

[18]National Development and Reform Commission of China. 2014. *Annual Report on China's Resource Comprehensive Utilization.*

[19]Ma, Shu-Hua, et al. 2017. "Challenges and Developments in the Utilization of Fly Ash in China." *International Journal of Environmental Science and Development,* Vol. 8, No. 11. http://www.ijesd.org/vol8/1057-C3001.pdf.

[20]Government of India, Ministry of Power, Central Electricity Authority. 2018. *Report on Fly Ash Generation at Coal/Lignite Based Thermal Power Stations and its Utilization in the Country for the Year 2017-18.* http://www.cea.nic.in/tcd.html.

[21]Black, Alison. 2011. *The Economic Impacts of Prohibiting Coal Fly Ash Use in Transportation Infrastructure Construction.* Available at https://www.artba.org/wp-content/uploads/2017/06/study2011flyash.pdf.

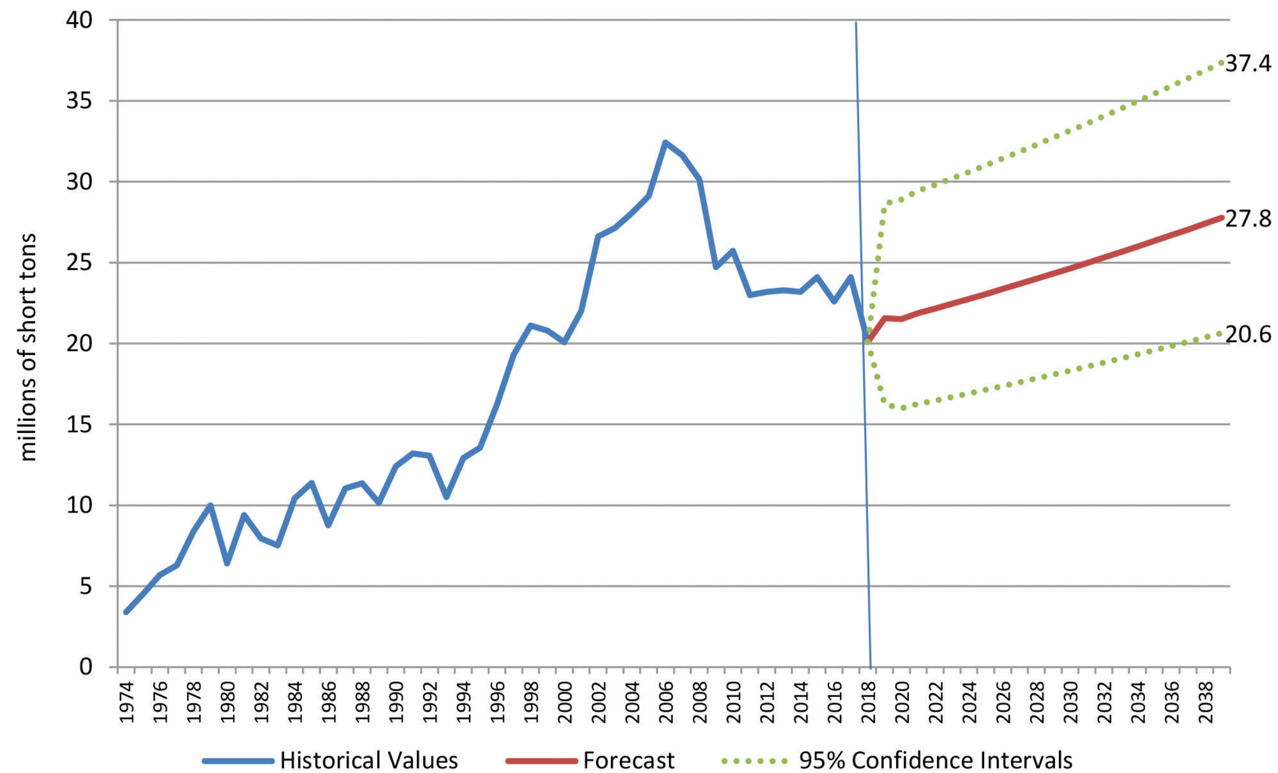


Figure 6. Fly Ash Utilization, 1974 to 2039

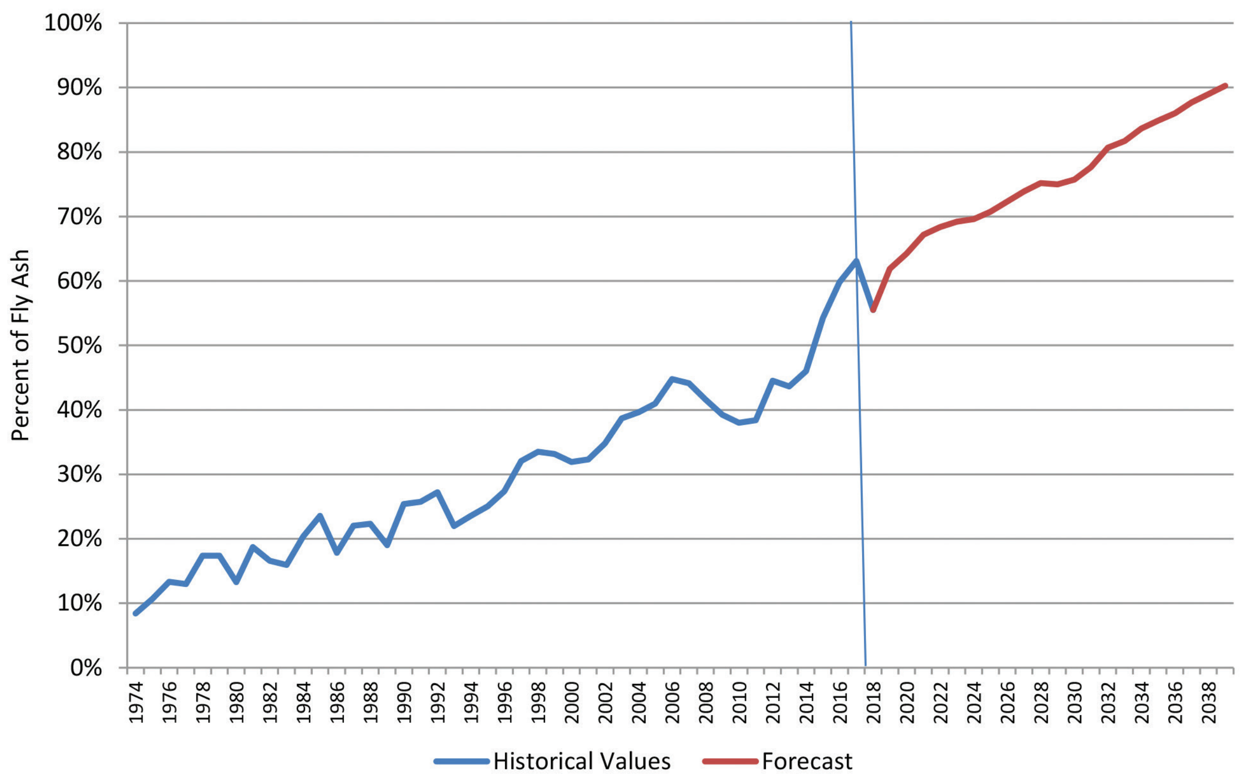
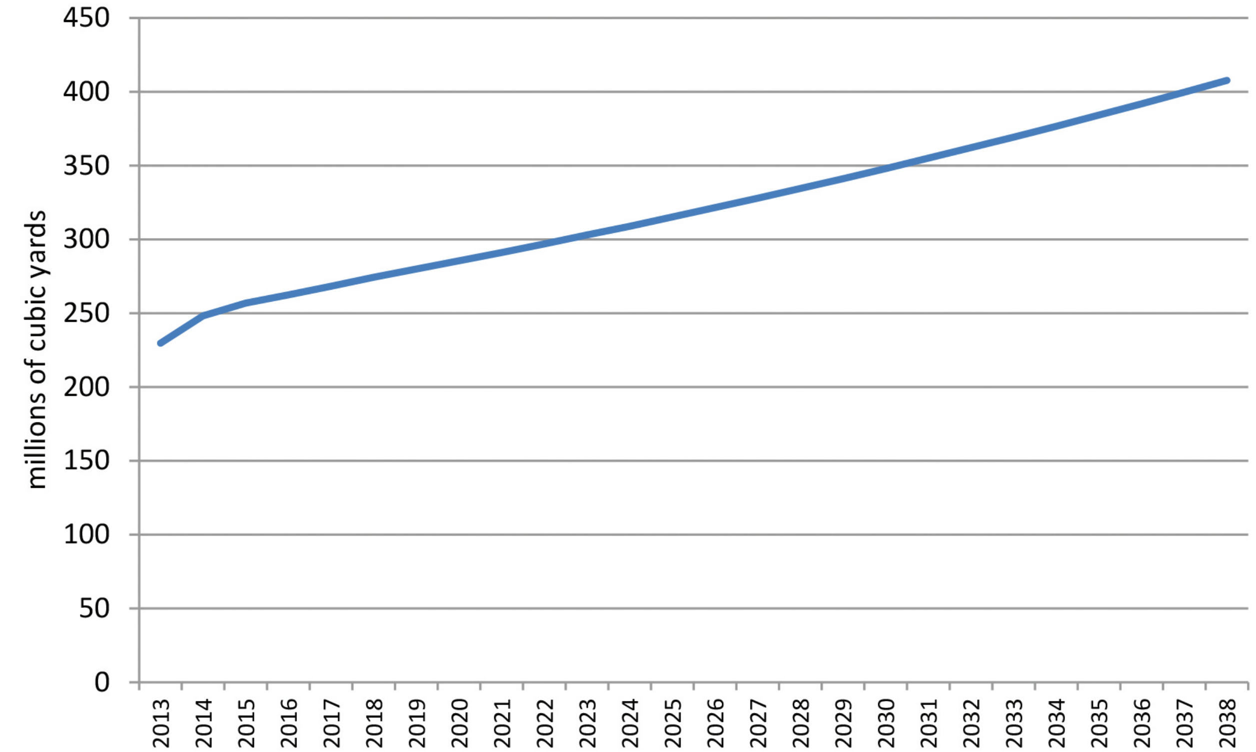
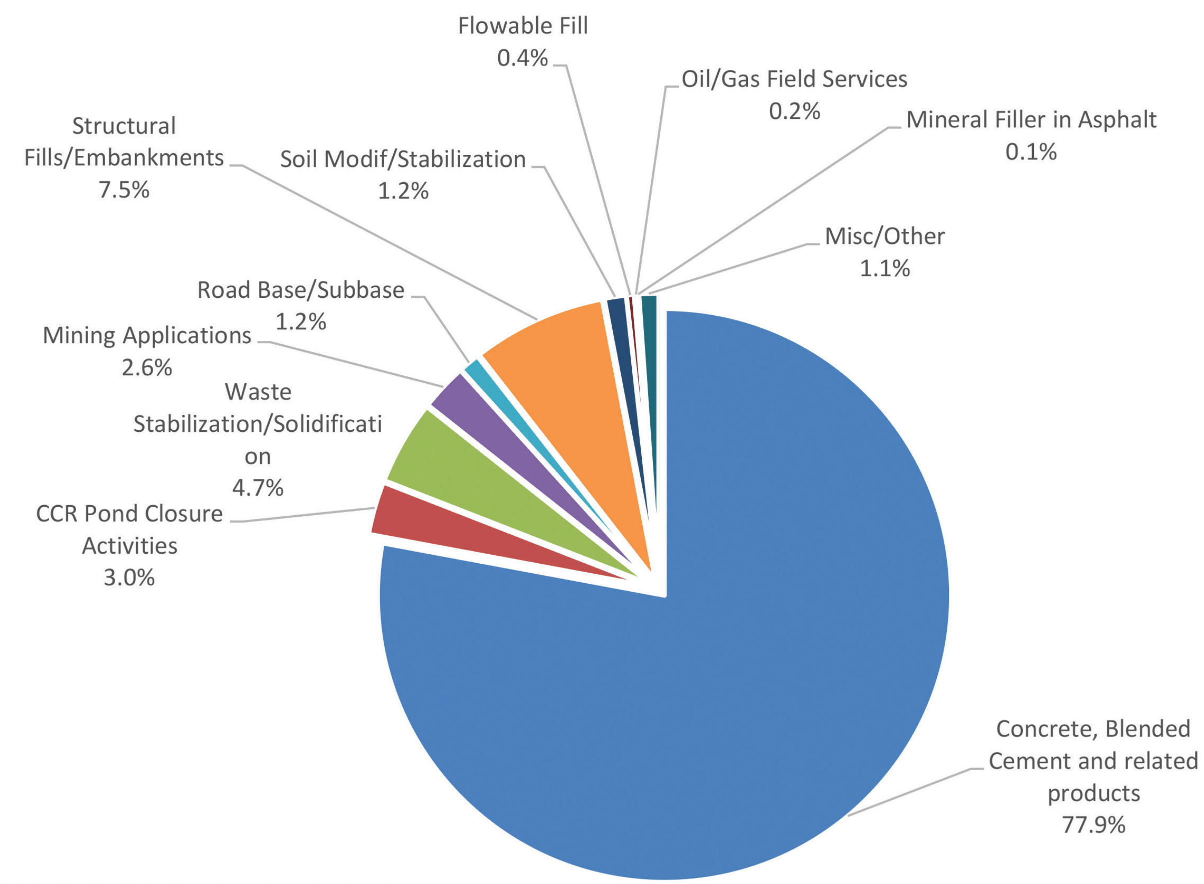


Figure 7. Fly Ash Utilization Rate, 1974 to 2039



Source: ARTBA projection based on historical data from National Ready-Mixed Concrete Association

Figure 8. Projected Demand for Ready-Mixed Concrete Will Help Drive Fly Ash Utilization



ACAA 2018 CCP Production & Use Survey

Figure 9. Fly Ash Utilization by Category

the dynamics of the local construction market and can fluctuate from year to year. About half of all concrete is purchased by state and local governments.[22]

If future growth continued along the historical trend, total ready-mixed concrete production would increase from 280 million cubic meters in 2019 to nearly 416 million cubic meters in 2039.

High-Volume Fly Ash Applications

New concrete mixtures with higher volumes of fly ash have significant potential to reduce costs, reduce energy content, reduce CO_2 emissions, and improve long-term performance when used for highway and bridge construction.[23 24 25] Some studies have shown that mixtures in which 50 percent or more cement is replaced with fly ash have produced "sustainable, high-performance concrete mixtures that show higher workability, higher ultimate strength, and high durability."[26]

Transportation and Logistics

The implementation of improved management practices for the beneficial use of fly ash and other CCPs will help support their growing utilization. These include such factors as "corporate policies, financial decisions, [and] subsidizing reuse," among others.[27] Improved storage facilities would help control the supply of fly ash during times of lower power demand and routine shutdowns.

The U.S. experienced several regional fly ash shortages in the winter of 2015-16 and the spring of 2016. These were primarily due to unseasonably warm weather, leading to lower power demand; seasonal shutdowns at coal-fueled power plants; lower natural gas prices, which led to economic shutdowns of coal plants; coal plant shutdowns due to environmental regulations; and the increased availability of hydropower due to large snow volumes. Fluctuations in supply such as these increase the likelihood of future shortages, particularly in California and other Western states, where there are fewer coal power plants and fly ash must be transported across longer distances, therefore increasing its price.[28]

Methodology

A series of four individual models were created for this study to forecast values for the production and utilization of fly ash using Box-Jenkins methods.[29] The "high-growth" and "low-growth" production scenarios are included to reflect different forecasts of the total volume of coal-fueled electricity generation in the U.S. Energy Information Administration *Annual Energy Outlook 2019*.

The three-step approach for the Box-Jenkins models includes model identification and selection, estimating parameters, and forecasting. In most cases, the type of models selected were an autoregressive integrated moving average (ARIMA) model or an autoregressive and moving-average model with exogenous variables (ARMAX).

ARIMA models are a special type of regression model in which an independent variable is forecast based on prior values in the time series and errors made by the previous predications.

The following steps and testing methods were used to determine the appropriate model specification and data transformations for the individual production and utilization models:

- **Data Stationarity**: The ACAA data on CCP production and use clearly follow an upward trend over time. The data were transformed to log format to create a stationary time series. The mean, variance, and autocorrelations of a stationary data series are all constant over time.[30]
- **Autocorrelations and Partial Autocorrelation Plots (ACF and PACF)**: The ACF and PACF plots were reviewed to identify evidence of autocorrelation. This means that there is a correlation between a data point and its previous values. The autocorrelations plot can be useful to determine any moving-average specification that could be included in an ARIMA model.
- **Dickey-Fuller Unit Root Test**: Data with a unit root in the series mean that there is more than one trend. The Dickey-Fuller test is commonly used to determine if a data series is stationary.

The independent variables were estimated using an ARIMA or ARMAX model. The models were estimated in growth rates and converted to levels for the final forecast.

The general ARIMA (p,d,q) model forecasts a time series based on the weighted sum of previous values (p), known as the autoregressive term, and the weighted sum of the previous forecast errors (q), known as the moving-average term, where (d) is the total number of differences applied to the series to achieve stationarity. The basic ARIMA (p,1,q) model for independent variable X is presented in the form:[31]

$$X_t = a_0 + \varepsilon_t + \sum_{t=1}^{p} \beta_t X_{t-1} + \sum_{t=1}^{q} \gamma_t \varepsilon_{t-1}$$

Where $X_t = X_t - X_{(t-1)}$, the first difference of the independent variable and a_0 is a constant. The values for p and q are determined using plots from the ACF and PACF plots.

A Dickey-Fuller unit root test was run on the residuals of the model results to test for stationarity. Analysis found that there was a unit root in the logged transformed data, and taking the

[22] Collard-Wexler, Allan. 2013. "Demand Fluctuations in the Ready-Mix Concrete Industry." *Econometrica* 81.3. pp. 1003-1037. http://pages.stern.nyu.edu/~acollard/ecta6877.pdf.

[23] Federal Highway Administration. 2010. "Benefits of High Volume Fly Ash: New Concrete Mixtures Provide Financial, Environmental, and Performance Gains." FHWA-HRT-10-051. http://www.fhwa.dot.gov/advancedresearch/pubs/10051/.

[24] Bentz, Dale, Ferraris, Chiara, and Snyder, Kenneth. National Institute of Standards and Technology, U.S. Department of Commerce. 2013. "Best Practices for High-Volume Fly Ash Concretes: Assuring Properties and Performance." NIST Technical Note 1812. https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=914225.

[25] Malhotra, V.M. and Mehta, P.K. Supplementary Cementing Materials for Sustainable Development, Inc. 2012. *High-Performance, High-Volume Fly Ash Concrete for Building Durable and Sustainable Structures, 4th Edition.*

[26] Aggarwal, Vanita, Gupta, S.M., and Sachdeva, S.M. 2010. "Concrete Durability Through High Volume Fly Ash Concrete (HVFC): A Literature Review." *International Journal of Engineering Science and Technology,* 2.9. pp. 4473-4477. http://www.researchgate.net/publication/50346383_CONCRETE_DURABILITY_Through_High_Volume_Fly_ash_Concrete_%28HVFC%29_A_Literature_review.

[27] Rokoff, Mark, PE, Smith, Sheryl, Masterson, Tara V., and Sutton, Michael E. 2013. *Benchmarking Study for CCP Beneficial Reuse: A View of the Market.* 2013 World of Coal Ash Conference. http://www.flyash.info/2013/070-Rokoff-2013.pdf.

[28] Caltrans. 2016. "Fly Ash: Current and Future Supply: A Joint Effort Between Concrete Task Group of the Caltrans Rock Products."

[29] Box, G.E.P. and Jenkins G.M. 1970. *Time Series Analysis, Forecasting and Control.*

[30] Enders, Walter. 2004. *Applied Econometric Time Series.*

[31] Ibid.

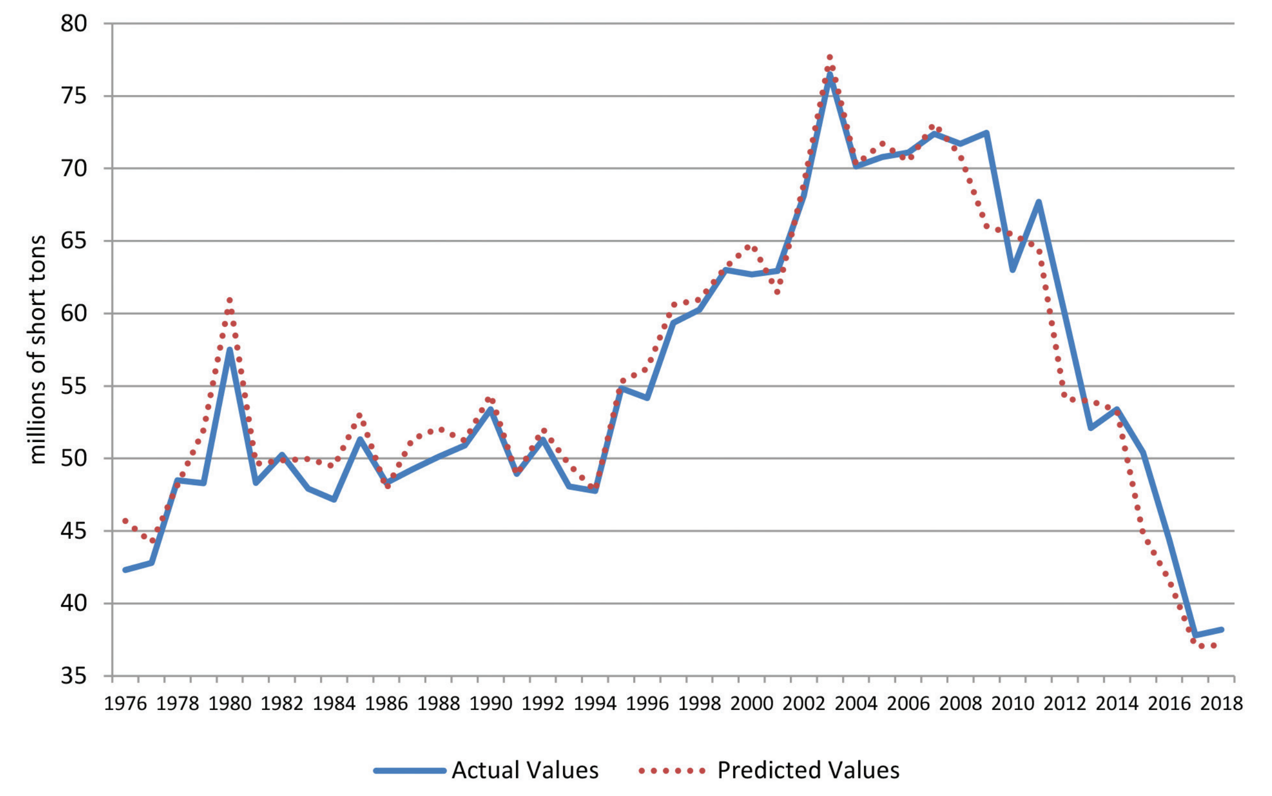


Figure 10. Fly Ash Production Model and Fitted Values

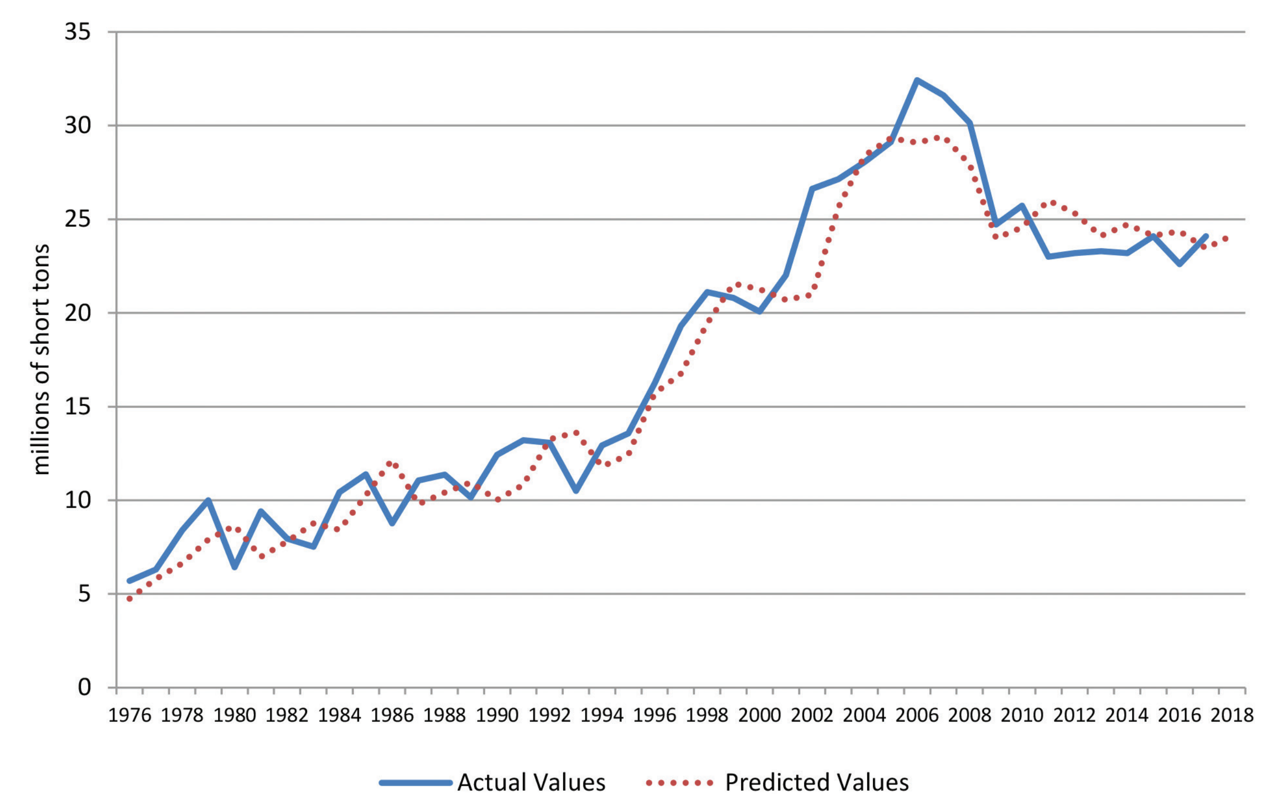


Figure 11. Fly Ash Utilization Model and Fitted Values

first difference of the log was necessary to have a stationary time series for model estimation.

For each individual baseline forecast:

- **Fly Ash Production**: An ARMAX (0,0,1) model where X_t is equal to the first difference of the log of the total volume of fly ash produced from 1974 to 2017. The exogenous input δ is the log of the total volume of coal-generated electricity over the same time period from the U.S. EIA *Annual Energy Outlook 2019* baseline case scenario. The model is in growth rates and converted to levels.

$$X_t = \varepsilon_t + \eta_1 \delta_{(t-1)}$$

For each individual baseline utilization forecast:

- **Fly Ash Utilization**: An ARMAX (1,0,1) model where X_t is equal to the first difference of the log of the total utilization of fly ash from 1974 to 2013. The exogenous input δ is the log of the total volume of U.S. ready-mixed concrete production. Historical values from 1974 to 2013 were provided by the National Ready Mixed Concrete Association. Values for 2014 to 2033 were estimated using the historical average annual growth rate of 3 percent. The model is in growth rates and converted to levels.

$$X_t = \varepsilon_t + \beta_1 X_{(t-1)} + \eta_1 \delta_{(t-1)}$$

Alternative Scenarios: Additional high- and low-growth scenarios are forecasted for the production of fly ash.

The high-growth fly ash production model is an ordinary least squares (OLS) model where the dependent variable is the log of fly ash production and the independent variables are the lagged value of the log of production and the log of megawatt hours of coal-fueled electricity generation.

$$X_t = a_0 + \beta_1 X_{t-1} + \beta_2 \gamma_t$$

In time series analysis, a structural break in the data may make the results of a Dickey-Fuller test biased toward the nonrejection of a unit root.[32] In other words, there may be a one-time change or shock to a time series that would usually be stationary. This shock changes the mean of the series, and the results of the Dickey-Fuller test suggest there may be a unit root when there actually is a structural break.

A visual examination of the data for the production of fly ash suggests that there is a structural break in the data series in the year 1994. The null hypothesis of a Chow test is that all the errors in the model are independent and identically distributed from a normal distribution. Based on the test statistic, we can reject the null hypothesis and conclude that there is a structural break in the model. To account for this break, we can split the data into two sub-samples.

The resulting forecast includes data from the EIA *Annual Energy Outlook 2019* for lower oil and gas resources, known as the "High Oil and Gas Resource and Technology" case. In this scenario, more coal-fueled electricity generation is used to meet energy demand. The recovery cost per well for tight oil, tight gas, or shale gas is 50 percent higher than the baseline case, which means the relative cost of these energy resources is higher.

The low-growth fly ash models are the same as the baseline models, but the forecast for the total megawatt hours of coal-fueled electricity generation was taken from the EIA *Annual Energy Outlook 2019* scenario for increased investment in oil and gas technology. This scenario, known as the "Low Oil and Gas Resource and Technology" case, assumes that the recovery cost per well for tight oil, tight gas, or shale gas is 50 percent lower than the baseline case. This lowers the relative cost of investing in these energy resources relative to the cost of producing coal-generated electricity. Thus, the lower amount of coal consumption by power plants would impact the total production of fly ash.

[32] Ibid.