Energy Efficiency Opportunities in the Stone and Asphalt Industry

Satyen Moray, Nathan Throop, John Seryak, Chris Schmidt, Chris Fisher, Mark D'Antonio, Energy & Resource Solutions, Inc.

ABSTRACT

The highly energy-intensive stone mining and crushing industry, grouped with other mining industries, has been one of the focal sectors of the US Department of Energy's Industries of the Future (DOE-IOF) initiative. In addition to being highly energy intensive, stone crushing currently produces 42% of the total material consumed by weight in the US, which is mainly used as highway aggregates. Based on GDP growth projections, the use of crushed stone could increase at a quicker rate than any other major material use. Given the market size, ample resources and stable growth potential of this industry, the understanding and dissemination of energy efficiency opportunities is paramount for national energy efficiency goals. Further, since there are literally thousands of similar facilities throughout the US (owned by relatively few large holding groups), there is a huge opportunity for replicability of identified energy efficiency measures.

This paper will first review the stone mining, crushing, and asphalt production processes. In this review, we will show that energy use is focused in rock blasting, shot-rock transportation, rock crushing, conveying, and screening. As such, standard building energy efficiency measures such as lighting retrofits and support system optimization have small impacts on overall plant energy use. The identification of energy efficiency opportunities thus relies heavily on system optimization. System optimization not only encourages energy-efficiency, but typically benefits production as well. Coupled with productivity improvements, the economic incentives for energy-efficiency measures in this industry have the magnitude and quick payback that could facilitate industry-wide replication.

The selected case study will feature two plants that manufacture a variety of rock grades for asphalt aggregate, railroad ballast and other uses. These facilities are currently the focus of a US Department of Energy (DOE) Industries of the Future plant-wide assessment. The key findings of the study will be presented, with a critical eye on improvements that are not only applicable to this facility, but to the stone crushing and asphalt industry as a whole.

Overview of the Stone Crushing Industry

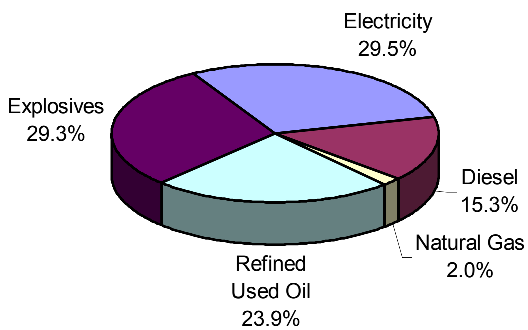
Crushed stone and sand & gravel are the main types of natural aggregate used in the United States. Despite the low value of its basic products, the crushed rock industry is a major contributor to and an indicator of the economic well being of the nation. Industry consolidation is on the rise as large producers buyout the smaller producers. Individual crushed-stone quarries range in size from 50,000 to 10 million tons of product annually.

In 2003, 1,260 companies operating 3,300 active quarries and distribution yards produced 1.5 billion tons of crushed stone valued at $8.6 billion and employing more than 70,000 people. Of the total crushed stone produced in 2003, about 71% was limestone and dolomite; 15%, granite; 7%, trap rock; and the remaining 7% was shared, in descending order of quantity, by sandstone and quartzite, miscellaneous stone, marble, calcareous marl, slate, volcanic cinder and scoria, and shell. Leading states, in order of production, were Texas, Florida, Pennsylvania, Missouri, Illinois, Georgia, Ohio, North Carolina, Virginia, and California, together accounting for 51.8% of the total output (USGS, 2003).

During the past 25 years, production of crushed stone has increased at an average annual rate of about 3.3%. These projections suggest that vast quantities of crushed stone and sand and gravel will be needed in the future and that much of it will have to come from resources yet to be delineated or defined. Further growth will be fueled by new legislation that is allocating significant monetary resources into the construction and repair of highways and bridges in the United States.

Figure 1 below shows the typical cost breakdown of the different resources that are required to operate an aggregate mining operation.

Figure 1: Breakdown of Energy Costs in a Typical Mining Operation



Overview of the Asphalt Industry

Asphalt creation starts with a mixture of sand and small and large rocks (called aggregate), which are combined with heated asphalt cement - thus the name hot mix asphalt (HMA). There are two basic types of plant designs used to manufacture HMA: batch plants and drum plants. There are approximately 3,600 HMA plants in the United States, accounting for a total annual production of 450 to 500 million tons of asphalt paving material. About 2,300 of the HMA plants are batch plants, with the remaining 1,300 are drum mix plants. The asphalt pavement industry employs approximately 330,000 people in the U.S. About 94% of the nation's roads and highways are surfaced with asphalt. (Asphalt Education Partnership, http://www.beyondroads.com/)

Asphalt and asphalt treatment products are petroleum-based. With the cost of petroleum on the rise, costs of manufacturing are also rising, along with the cost to the customer. American Road & Transportation Builders Association (ARTBA) analysts predict that the U.S. highway construction market should grow 4.5% in 2005 totaling $69 billion dollars.

Stone Crushing Process Overview

Stone crushing involves the following processes: mining, processing, crushing, screening and transportation. These processes are discussed in detail below.

Mining

Geological investigations help determine the location, distribution, and nature of potential aggregate in an area. Open-pit mining and quarrying is the common means of extracting rock. Alternately, a small number of locations use underground mines. Mining methods involve removing the overburden to extract the underlying rock deposits. Tricone rotary drills, long-hole percussion drills, and churn drills are used to create the blast holes in the rocks. Blasting in smaller operations may be done with dynamite, but in most medium to large-size operations, ammonium nitrate fuel oil mixture (AN-FO) is used as a low cost explosive. The fractured rock or shot rock is then excavated and loaded onto trucks that either feed portable crushers or stationary crushers for further processing.

The explosive costs represent one of the biggest energy expenses in stone crushing, ranging from 30 to 40% of the total annual energy costs (Figure 1). Therefore, optimizing the impact of explosives in the blasting process is critical in reducing the facility operating costs.

The average blast at a mid size quarry can range from 20,000 tons to 40,000 tons of shot-rock. Optimizing blasts to yield smaller rocks would reduce crusher plant energy consumption. Some of the methods that can be used to improve the shot-rock yields are:

- Increase the blast hole diameter
- Use stemming plugs in the blast holes
- Increase sub-drilling depth
- Use new emerging 3-D imaging technologies to develop the blast patterns

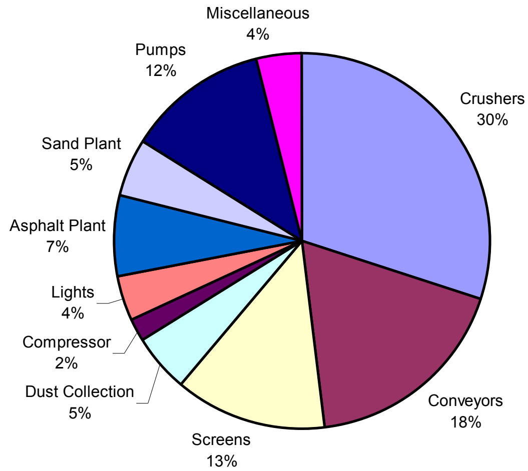
A study in a Pennsylvania quarry in 1999 documented significant benefits using electronic detonators in place of non-electric initiation in production blasts, even without optimizing the blast design. Using a Digital Blasting System from Advanced Initiation Systems, researchers reported the following results (http://www.aggman.com/articles/feb04b.htm):

- 32% decrease in the mean size of rock in the post-blast pile;
- 37% increase in 8-inch minus rock;
- 25% reduction in digging time to excavate the pile; and
- 6-10% savings in primary crushing costs measured by power consumption

Processing

The shot-rock is typically transported to the crushing plants using trucks. The large end users in the crushing plant consist of feeders, crushers, conveyors and screens. Figure 2 below shows the relative significance of the different electric energy users in a typical aggregate rock crushing plant. Figure 2 shows that the crushers are the largest electricity end-use, followed by the conveyors and screens.

Figure 2: Electric Energy Use Breakdown in a Crushing Facility



Crushers

Crushers mechanically break the stone into smaller pieces. Reduction in size is generally accomplished in several crushing stages, as there are practical limitations on the ratio of size reduction through a single stage. Crusher selection is based on rock type, required size reduction, output rock shape and production rate. Details on the different available crusher designs are presented below.

1. **Jaw Crushers.** Jaw crushers are typically used as primary crushers. A jaw crusher consists of a set of vertical jaws, one jaw being fixed and the other moving. The progressive compression by the back-and-forth motion of the moving jaw breaks the stone. Jaw crushers operate best when fully-loaded but not flood-fed.
2. **Gyratory Crushers.** Gyratory crushers are ideally suited for high capacity primary crushing. A gyratory crusher consists of inner and outer vertical crushing cones; the outer cone is oriented with its wide end upward, and the inner cone is inverted relative to the outer with its apex upward. These crushers provide a product of uniform dimensions, can be flood fed, and may be started when fully loaded.
3. **Impact Crushers.** Impact crushers are typically used in the primary and secondary crushing stages, are well suited for softer rocks and can achieve reduction ratios of up to 40:1. Impact crushers tend to wear faster than other crushers because of constant high-velocity collision with the stone.
4. **Cone Crushers.** Cone crushers are a type of gyratory crushers that are well suited for applications that require a reduction ratio of 6:1 and provide a tight control over the rocks leaving the crusher. They are typically applied in the secondary and tertiary crushing stages. For proper reduction and consistent product gradation, cone crushers must be choke fed at all times.
5. **Portable Crushers.** A typical quarry face will recede approximately 45 feet every year. This extra distance increases the work of the haul trucks that feed the primary crushers with the shot rock. Portable crusher plants offer the option of crushing near the blast site and using efficient conveyors to supply the secondary crushing operations. Portable plants are also popular for projects with a limited project life.

Crusher Selection and Application

Table 1 below shows a generic crusher selection guide, as well as unloaded power draw.

Table 1: Selection of Crusher Technologies

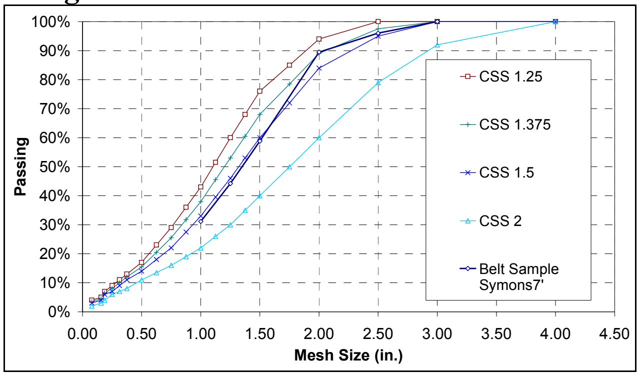
Type	Hardness	Abrasivity	Capacity Range	Reduction Ratio	Use	Unload Power
JAW	Medium hard to very hard	Abrasive	Below 600-700 tph	8/1 to 10/1	Mostly as Primary	Ranges from 40 to 50% of Full Load Power
GYRATORY	Medium hard to very hard	Abrasive	Over 1,000 tph	6/1 to 8/1	Most as Primary	Ranges from 25 to 35% of Full Load Power
CONE	Medium hard to very hard	Abrasive	Flexible	6/1 to 8/1	Secondary & Tertiary	Ranges from 40 to 50% of Full Load Power
Horizontal Shaft Impactors	Soft to medium hard	Slightly abrasive	Flexible	15/1 to 25/1	Primary, Secondary & Tertiary	Ranges from 30 to 45% of Full Load Power
Vertical Shaft Impactors	Soft to medium hard	Slightly abrasive	Flexible	15/1 to 25/1	Primary, Secondary & Tertiary	Ranges from 12 to 40% of Full Load Power

The primary crushing stage is the most economical segment of the aggregate plant in which to make material reduction, after the initial quarry blast. Primary crushing involves reducing shot rock from 40-inch minus to 9-inch minus rock. The secondary and tertiary crushers reduce the stone from 9-inch minus to less than 2-inch rock size. Different stages of crushing are required based on the intended final product size. Typically, a greater number of crushing stages are required to get smaller rock sizes.

The unloaded power consumption of the different crusher designs are derived from the logged power consumption of the crushers. The unloaded power varies from 12% to 50% of full load power. The unloaded power is an indication of crusher friction and inertial load, which the crusher must move at a minimum. As such, the crushers can be used most efficiently when fully loaded. The impact crushers draw lower unloaded power compared with the cone, jaw and gyratory crushers.

All the crushers are designed for a certain gradation output, the information for which can be easily obtained from the crusher manufacturers. Selecting a crusher with the desired gradation output and throughput is critical because this impacts the selection and operation of equipment downstream. The crusher gradation tables predict the size of the stones leaving the crusher based on the closed side setting (CSS). Figure 3 below shows a typical gradation curve for a cone crusher provided by a crusher manufacturer. The gradation curves show the crusher performance at different CSS. The plot shows that for the crusher with a CSS of 1.25-inches, 78% of the rocks will pass the 1.5-inch screen mesh size and for the same crusher with a CSS of 2-inches, only 40% of the rocks will pass the 1.5-inch screen mesh. This indicates that reducing the CSS produces smaller rock, however throughput is reduced.

Figure 3: Cone Crusher Gradation Curve



Potential crusher efficiency improvement include:

- ❑ Run the crushers at or near full load at all times
- ❑ Use premium efficiency motors and cogged V-belts (savings can range from 5 to 15% of existing costs)
- ❑ If possible, achieve greatest size reduction in the primary stage
- ❑ In the secondary and tertiary crushing stages, use crushers that accurately provide the material size required in one pass
- ❑ Minimize/eliminate the re-circulating load circuits and shut off equipment when not needed

Screening

Screening involves passing the stones over a mesh to separate the larger stone from the smaller stone. The selection of a screen is based on the product throughput (tph) and the type of material to be screened. The variables that affect the efficiency of a screen include eccentric throw, frequency (RPM), angle-of-adjustment and throw direction. Adjusting these settings based on the facility requirements can optimize the screening efficiency and thus the plant efficiency. Screening is one of the largest electrical uses and should therefore always be given proper attention. Potential screen efficiency improvement ideas are:

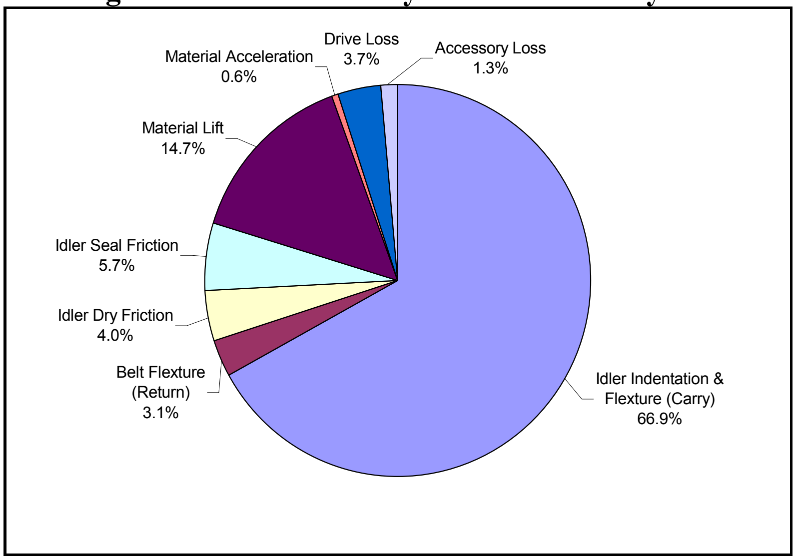
- ❑ Use premium efficiency motors and cogged V-belts (savings can range from 5 to 15% of existing costs)
- ❑ Use light weight screens and shut off equipment when not needed
- ❑ Improve screening efficiency by using efficient designs and settings

Transportation

Truck transportation within and outside of the quarry is the most common method of stone transportation. In-plant, the largest use of diesel is from the haul trucks moving the shot-rock from the quarry to the primary crusher. Diesel fuel costs are significant and can range from 15 to 35% of the facility utility costs. Therefore, careful attention to vehicle maintenance and operation is critical in reducing operating costs. If pits or quarries have access to railroads, rail delivery may be more economical than trucks for outside delivery. If the aggregate shipped annually exceeds 20,000 short tons, or if the aggregate is to be hauled more than 45 miles, rail shipping may be more economical than truck transport.

Most of the bulk movement of rocks in a crushing facility is achieved using electric conveyor belts. Belt-conveyor systems vary in length from a few feet to a number of miles. Conveyor belts connect the crushers, surge piles, screens and storage bins and provide flexibility in plant design. Conveyor belts can account from 20 to 30% of the electrical energy use in facility. Figure 4 below shows the breakdown of the conveyor energy use as published by the Conveyor Equipment Manufacturer's Association (CEMA).

Figure 4: CEMA Conveyor Belt Electricity Use



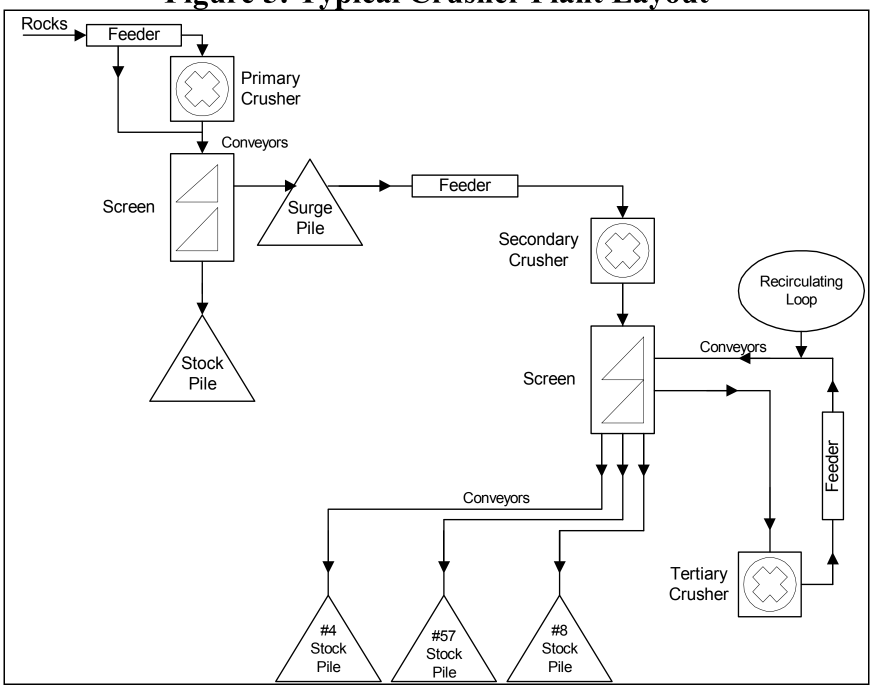
Conveyors use electricity to lift rock, accelerate rock, overcome drive losses, overcome belt and material flexure and overcome friction. In majority of the cases, it is economical to use electric motor driven conveyors compared to haul trucks and should always be considered as an option. Figure 4 above shows that a vast majority of electricity used, approximately 65%, is to overcome flexure caused by idler indentation. The remaining electricity is used to overcome friction are lost in transmission. Potential transportation efficiency improvement ideas are:

- ❑ Reduce the use or travel distance of diesel trucks/front loaders etc.
- ❑ Use electric conveyor belts where possible instead of diesel driven equipment
- ❑ Use premium efficiency motors and cogged V-belts on the conveyor belt motors
- ❑ Conduct regular maintenance and lubricate conveyor belt system to reduce friction losses
- ❑ Increase conveyor belt idler diameter to reduce the idler indentation and flexure losses
- ❑ Reduce the idler seal friction through proper lubrication
- ❑ Reduce the idler dry friction by installing belt cleaners

Rock Crushing Operation Process Flow

Diesel trucks transport shot-rock from the blast site to the primary crusher. Depending on the design of the crusher, a feeder may or may not be required before the primary crusher. The haul trucks load the shot rock into the primary crusher, which feeds the rocks to a primary screen, which directs larger stone to a surge pile and smaller stone to a stockpile. The surge pile acts as a buffer between the primary crushing plant and the secondary crushing plant. Located at the bottom of the surge pile is a tunnel, which feeds the secondary crusher plant. The rocks leaving the secondary crusher are screened in the multiple screen decks, which direct the rocks to different size stockpiles. The larger size rocks from the secondary screen are directed to a tertiary crusher, which in some cases is installed in a closed circuit where the output of the crusher is returned back to the screen. Figure 5 below shows a schematic of a typical rock crushing plant layout.

Figure 5: Typical Crusher Plant Layout

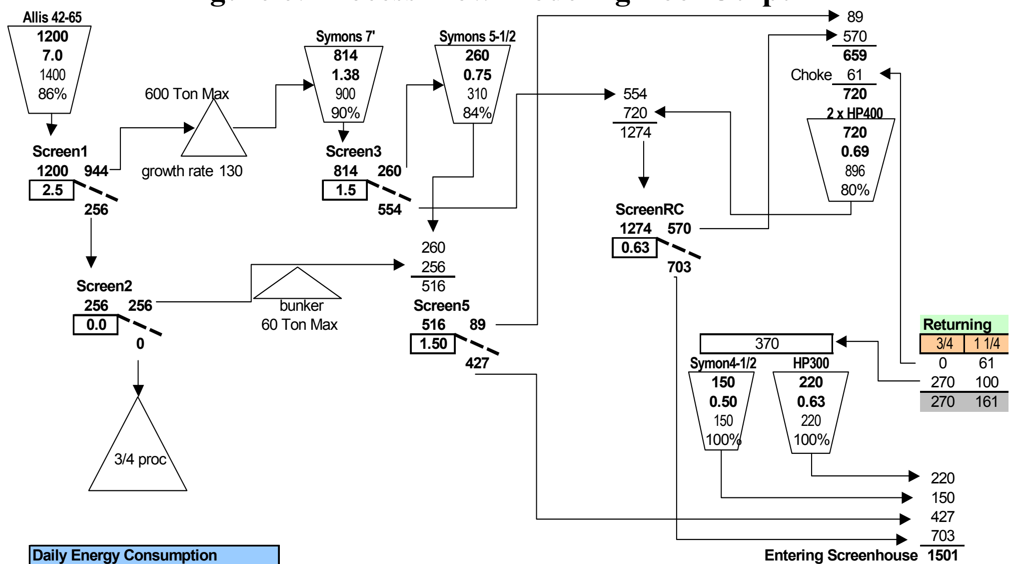


Modeling Rock Crushing Operations

The crusher plant components can be optimized independently only up to a certain limit, beyond which the interaction of the entire crushing plant equipment must be considered. A process flow-modeling tool, which can accurately estimate the impacts of the process changes, is essential. ERS developed a customized modeling tool to simulate various rock crushing operations. Figure 6 below shows the output of a sample rock crushing plant process that was modeled using our spreadsheet tool.

The spreadsheet model is designed to determine the flow rates, gradations, and power consumption based on the given feed rate into the primary crusher. The model breaks down the entire plant into smaller separate units that are interconnected. The surge pile becomes the capacitance between the primary crushing plant and the secondary crushing plant. Since the crushing operations are dynamic, the simulation is set to model a typical day's operation over 15-minute increments. Using the percent load of the equipment, the model derives electricity use during the day. The annual production estimates are extrapolated using the results generated from a typical day's operation. The results of the model are verified with the actual annual production in tons to create a reasonably accurate baseline system.

Figure 6: Process Flow Modeling Tool Output



Daily Energy Consumption		
Run Hours per Day		15.5
Stage	kW	kWh/dy
Primary	240	3,000
Secondary	305	4,526
Tertiary	169	2,539
Screening Stage	27	354
Quaternary	355	5,502
Recrush	709	10,939
Screen House	293	4,465
Total	2,099	31,326

Daily Production	
Product	Tons/dy
3/4 proc	0
1-1/4	231
3/4	1,010
1/2	2,886
3/8	3,977
1/4	2,231
dust	4,665
Total	15,000

Model Notes
The above model represents peak condition.
The feed rates may vary throughout the day.
Free standing numbers represent rock flow in tph.

Annual Extrapolation	
Annual Production (Tons)	2,750,000
15.5 hr Days to reach production	183
Annual Energy Consumption (kWh)	5,743,137
Energy per Ton (kWh/ton)	2.09

Similarly, crusher manufacturers use their own proprietary modeling tools to simulate the crushing plant operations. AggFlow is one example of such a tool that is widely used in the industry.

Asphalt Plant Processes

There are two types of asphalt plants having the following common features:

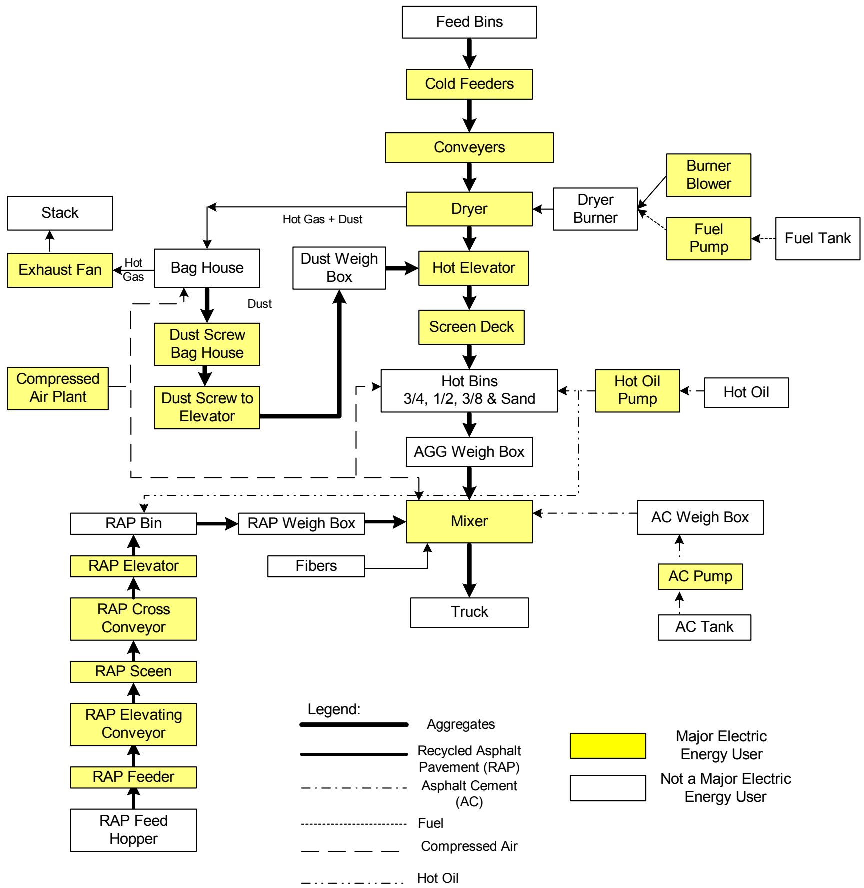
- ❑ Cold feed bins - meter the different aggregates used in the mix to the drying drum.
- ❑ Dryer drum - Dries and heats aggregates by tumbling them through hot air. In a parallel-flow drum, aggregates move in the same direction as the hot air. In a counter-flow drum, aggregates move in the opposite direction.
- ❑ Emission control system - Sometimes called a baghouse, this system traps and removes fine sand and dust particles and returns them to the mix.
- ❑ Storage silos - Drum mix plants must have silos since they produce asphalt continuously. Batch plants do not require a silo, but often have them to increase plant production.

Figure 7 shows a schematic of a typical batch type asphalt plant.

The baghouse exhaust and combustion blowers in the asphalt plant are typically the largest electric users. Asphalt plants contribute 7 to 15% of the total electric consumption and 15 to 25% of the fossil fuel consumption in an aggregate/asphalt facility. Potential asphalt plant efficiency improvements are:

- ❑ Install VFDs on the baghouse exhaust fan and combustion blower
- ❑ Fix compressed air leaks
- ❑ Consider recovering heat from the baghouse exhaust
- ❑ Use premium efficiency motors, cogged V-belts and or direct drives
- ❑ Improve combustion efficiency by using efficient sensors and controls

Figure 7: Schematic of a Typical Batch Asphalt Plant



Other Significant Energy Users-Pumps

Pumps are used for several applications including dewatering collection ponds, stone washing, truck washing and dust suppression. Pumping energy in quarries can range from 12 to 25% of the total electrical consumption, which is significant. Potential pumping efficiency improvement ideas are:

- ❑ Use premium efficiency motors
- ❑ Operate pumps at the best efficiency point (BEP) by matching the required flow, head with a correctly sized pump
- ❑ Reduce system losses by using smooth pipes with large diameters and using less number of bends or pressure drop points
- ❑ Apply smooth polymer coating on the interior pump surfaces

Automation

The decision to automate a plant is necessitated by a desire to achieve consistency and remote operational capabilities, and eliminate human error. Automating crushers can have an immediate impact on operating costs and product yield. Automation can protect from overloads and reduce equipment costs. Automating conveying and stockpiling systems provide opportunities for continuous process improvement and the ability to manage information for manipulation of production rates and scheduling of service intervals.

Advances in Technology

As the mining industry moves towards the twenty-first century, the opportunity to apply emerging technologies to enhance production and resource performance and provide new products are critical to the industry's ability to serve the nation and achieve profitability. Satellite communications systems and information processing technologies are already reducing costs and minimizing environmental disruption associated with reserve characterization and production.

Advances in data acquisition, system modeling and control software will allow for optimized system utilization and quality decision-making and reduction of costs. Downtime can be reduced, service life can be extended, costs of repairs and maintenance can be limited and operator safety can be better assured. Tools that offer life cycle assessment of every aspect of the crushing operations will help make smarter decisions.

New tools that can accurately survey and map 3-D topographical images of pits, quarries, tunnels are available. Such a tool will then be able to provide the blasting engineers with the pertinent information to optimize the blast impact. The system offers a fast and convenient way of quantifying fragmentation.

Case Study-Based on a recent DOE Plant Wide Assessment (PWA)

Introduction

The two facilities selected for the DOE PWA are representative of the hundreds of aggregate mining/ asphalt/sand operations that operate nationwide. For proprietary reasons, we will call the sites Site A and Site B. Site A is a 2.5 MW igneous basalt operation producing 3.5 million tons annually with an on-site asphalt plant. Site B is a newer plant that processes limestone into similar types of aggregate and asphalt products, as well as agricultural lime. Site B has an output of approximately 2 million tons annually, and an electric load comparable to Site A's.

The authors worked with the facility staff to characterize the existing equipment operations and identify energy, waste and productivity measures. Twenty-two measures were identified between the two facilities. Only the key measures in the increasing order of their paybacks for the two sites are presented below.

1. **Increase Productivity by Installing Bigger Crushers.** Based on the existing Site A crusher operations, we investigated replacing the existing tertiary with a higher capacity crusher, increasing the secondary crusher CSS and reducing primary crusher downtime to increase plant throughput and decrease the process energy intensity.

2. **Optimize Compressed Air Systems, Motor Systems, Lights and Pumps.** These measures investigated the cross cutting technologies such the motors, pumps, compressed air and lights.
3. **Optimize Crusher and Equipment Settings.** At Site A, we discovered several conveyors and screens fed by the primary crusher are left running while the primary crusher is off. We recommended shutting this equipment down during these times. At Site B, the logged data for some of the equipment indicated under-loaded operations. We recommended some process changes for the crushers and logistical changes in the conveyors to improve the loading and product distribution.
4. **Install VFDs on Asphalt Plant Combustion Blowers, Baghouse Blowers and Dust Collection Blowers**. The various blowers used in the crushing and asphalt operations have variable loads and can be retrofitted with VFDs to reduce energy consumption.
5. **Optimization of Material Movement**. At Site B, several diesel driven haul trucks transport the shot-rock from the quarry face to the primary crusher. This measure presents the economics of using a conveyor belt system compared with the existing haul trucks.

Project Savings

The combined savings estimates for the two sites associated with the measures described above are presented in the table below.

Table 2: Combined Savings Summary

Energy Efficiency Measure		Electrical Savings (kWh)	Diesel Savings (Gallons)	Annual Cost Savings	Implem. Cost $	Simple Payback years
EM-1	Increase Productivity by Installing Bigger Crushers	-377,233	-18,700	$1,530,064	$1,030,000	0.7
EM-2	Optimize Water Pumping Operations	290,859	0	$18,337	$17,950	1.0
EM-3	Compressed Air System Evaluation	63,969	na	$6,030	$11,175	1.9
EM-4	Optimize Crusher and Equipment Settings	270,417	na	$76,470	$152,500	2.0
EM-5	Install Energy Efficient Motors and Cogged V-belts	159,112	na	$15,791	$36,059	2.3
EM-6	Install VFDs on Asphalt Plant Combustion and Baghouse Blowers	649,146	0	$47,418	$124,770	2.6
EM-7	Install VFDs on the Crusher Plant Dust Collection Blower Motors	50,011	na	$5,001	$17,920	3.6
EM-8	Install High Efficiency Lighting and Lighting Controls	113,569	na	$10,519	$37,281	3.5
EM-9	Optimization of Material Movement	-1,201,301	106,558	$263,661	$1,973,000	7.5
	Total	**18,549**	**87,858**	**$1,973,292**	**$3,400,656**	**1.7**

Replication Potential

Using the total number of aggregate and asphalt operations in US, Table 3 presents the projected corporate and US replication potential for the measures discussed above.

Conclusion

Aggregate quarry and asphalt operations are energy intensive. A significant number of the facilities have older crushers with inefficient controls that present a significant potential for increasing production efficiencies. The application of new technologies, sensors and GPS systems will help provide a real-time status on the different components within a mining operation, resulting in plant optimization and energy savings.

Numerous efficiency improvements exist, including crusher replacement, product flow optimization, pumping opportunities, compressed-air system evaluation, efficient motor and V-belt retrofits, VFD installations and lighting upgrades.

Table 3: Corporate and US Replication Potential

	Projected Corporate Crushing Energy Savings	Projected Corporate Asphalt Energy Savings	Projected US Aggregate Energy Savings	Projected US Asphalt Energy Savings
Energy Efficiency Measure	**Energy Savings (MMBTu/yr)**	**Energy Savings (MMBTu/yr)**	**Energy Savings (MMBTu/yr)**	**Energy Savings (MMBTu/yr)**
EM-1 Increase Productivity by Installing Bigger Crushers	-316,076	na	-1,533,901	na
EM-2 Optimize Water Pumping Operations	135,007	na	917,255	na
EM-3 Compressed Air System Evaluation	16,702	13,755	113,475	159,160
EM-4 Optimize Crusher and Equipment Settings	94,139	na	548,222	na
EM-5 Install Energy Efficient Motors and Cogged V-belts	73,855	na	645,142	na
EM-6 Install VFDs on Asphalt Plant Combustion and Baghouse Blowers	na	217,122	na	2,233,260
EM-7 Install VFDs on the Crusher Plant Dust Collection Blower Motors	20,312	na	78,858	na
EM-8 Install High Efficiency Lighting and Lighting Controls	56,932	1,954	497,319	22,605
EM-9 Optimization of Material Movement	497,379	na	2,413,750	na
Total	**578,249**	**219,076**	**4,183,290**	**2,255,865**

References

U.S. Geological Survey, Mineral Commodity Summaries, January 2004, http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/.

Pit and Quarry Magazine, http://www.pitandquarry.com/pitandquarry/article/articleDetail.jsp?id=17957.

Asphalt Education Partnership, http://www.beyondroads.com/

Argus Asphalt Report (2003), http://www.argusonline.com/wwwroot/pa-html/products/ArgusHome/samples/asphalt.pdf

Rocky Mountain Mineral Law Foundation, http://www.rmmlf.org/SciTech/Lacy/lacy.htm

The National Mining Association, "The Future Begins with Mining", September 1998

McIntosh Engineering, "Hard Rock Miners Handbook Rules of Thumb", www.mcintoshengineering.com

Good Websites:

http://leadstates.transportation.org/

http://www.asphaltalliance.com/upload/focus_lifecycle-PR.pdf

http://www.p2pays.org/ref/13/12842/bd.htm