PLANT EFFICIENCY EVALUATION AT NAVAJO GENERATING STATION

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SRP representatives conducted a high-level review of the Black & Veatch heat rate improvement study and did not identify any revisions to the technical information provided. SRP did provide the following comment and requested that it be added to the report.

“SRP, as operating agent of NGS, has evaluated and implemented numerous upgrades to NGS over its operating life. The NGS participants have considered many of the options presented in this report, performed economic and operational risk evaluations on those options, and have either acted on them to the extent practical or determined them not to be viable in light of operating and economic factors.”

The project team that executed the efforts described in this report engaged NGS Operations Staff on multiple occasions, including a site visit and technical discussions at the NGS plant site. All practical efforts were made to leverage prior work, including review of prior analysis of the heat rate improvement opportunities identified in this report.
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### ACRONYMS AND ABBREVIATIONS

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<tr>
<td>B&amp;V</td>
<td>Black &amp; Veatch</td>
<td>MESA</td>
<td>Mission Execution and Strategic Analysis</td>
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<tr>
<td>Btu</td>
<td>British thermal unit</td>
<td>MW</td>
<td>Megawatt</td>
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<td>DOE</td>
<td>Department of Energy</td>
<td>MM</td>
<td>Million</td>
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<td>DFO</td>
<td>Distillate fuel oil</td>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
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<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
<td>NGS</td>
<td>Navajo Generating Station</td>
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<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
<td>NERC</td>
<td>North American Electric Reliability Corporation</td>
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<tr>
<td>ESP</td>
<td>Electrostatic precipitator</td>
<td>NOx</td>
<td>Oxides of nitrogen</td>
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<td>FD</td>
<td>Forced draft</td>
<td>O&amp;M</td>
<td>Operation and maintenance</td>
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<td>GADS</td>
<td>Generating Availability Data System</td>
<td>O2</td>
<td>Oxygen</td>
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<td>HP</td>
<td>High pressure</td>
<td>PA</td>
<td>Primary air</td>
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<td>HRI</td>
<td>Heat rate improvement</td>
<td>PAC</td>
<td>Powdered activated carbon</td>
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<td>ID</td>
<td>Induced draft</td>
<td>SO2</td>
<td>Sulfur dioxide</td>
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<tr>
<td>IP</td>
<td>Intermediate pressure</td>
<td>SRP</td>
<td>Salt River Project</td>
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<tr>
<td>K</td>
<td>Thousand</td>
<td>U.S.</td>
<td>United States</td>
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<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
<td>VFD</td>
<td>Variable frequency drives</td>
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<tr>
<td>MCR</td>
<td>Maximum continuous rating</td>
<td>°F</td>
<td>Degrees Fahrenheit</td>
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1 INTRODUCTION

The National Energy Technology Laboratory (NETL) and its support contractors (Team KeyLogic and Black & Veatch (B&V)) worked in collaboration with Salt River Project (SRP) plant personnel to conduct a study of the Navajo Generating Station (NGS) to screen for technically and economically feasible heat rate improvement (HRI) options.

B&V scope focused on identifying HRI options, conducting high-level technical and engineering assessments of identified HRI options, and providing screening-level (i.e., order-of-magnitude) estimates for capital and operating costs.

B&V performed the following work scope:

- Reviewed in detail select plant specific-data provided by SRP related to the evaluation of relevant HRI opportunities at NGS.
- Conducted a two-day site visit to NGS to collect data, interview plant engineers and operators, and inspect the site layout and configuration.
- Assessed which potential HRI options might be of the greatest value and feasible for deployment at NGS.
- Estimated the potential heat rate, performance, and other improvements resulting from each of these selected options.
- Where possible, developed an order-of-magnitude cost estimate for each of the HRI options.
2 Existing Plant Description

The NGS consists of three similar pulverized coal-fired generating units, each designed to operate at a maximum continuous rating (MCR) of 810 megawatt (MW) gross and 755 MW net. The units were designed for and currently burn low-sulfur bituminous C (ASTM D388) coal sourced locally from the nearby Black Mesa/Kayenta mine. The three units have similar air pollution control equipment. Emissions control for oxides of nitrogen (NOx) is carried out by combustion controls, low-NOx burners, and an overfire air system. Particulate removal is carried out by hot-side electrostatic precipitators (ESPs), and sulfur dioxide (SO2) control is achieved using a wet limestone scrubber. Mercury removal is carried out through injection of powdered activated carbon (PAC) ahead of the wet scrubber. The NGS is operated with a zero-liquid discharge system and utilizes a brine concentrator and crystallizer to treat cooling tower blowdown and other sources of water for re-use as make-up water within the plant.

Until 2014 the plant operated at a relatively high annual net capacity factor. Recently, annual net capacity factor at the plant has been significantly reduced, largely due to increased cycling and part-load operation relative to most of its prior life. Plant-wide annual net capacity factor over the time period of 2012 to 2016 is illustrated in Exhibit 2-1.

Exhibit 2-1. Navajo Generating Station Annual Average Capacity Factor, 2012-2016 [1], [2]

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*“Net capacity factor” as used here can be considered equivalent to the unweighted pooled Net Capacity Factor as defined by the North American Electric Reliability Corporation (NERC) for use by electricity generators in reporting to the NERC Generating Availability Data System (GADS). [3] For the high-level analysis described here, annual average net capacity factors for the plant were calculated by dividing the sum of the annual electricity generated by the three individual NGS units (as reported to DOE Energy Information Administration (EIA) Form 923 Schedule 3 - Net Generation) by the sum of the calculated potential annual output of the individual units. The potential annual output of each individual unit was calculated as the number of hours in a given year times the average of the individual unit’s Net Summer Capacity and Net Winter Capacity (as reported to EIA Form 860 Schedule 3).*
Over the same time period, the plant-wide annual average heat rate has exhibited a continued worsening trend (e.g., increase in fuel requirement per kilowatt-hour (kWh) of electricity output). Plant-wide annual average heat rate over the time period of 2012 to 2016 is illustrated in Exhibit 2-2.

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"Annual average heat rate" as used here is intended to represent a plant-wide "unweighted pooled" heat rate, conceptually similar to unweighted pooled Net Capacity Factor and is viewed to be a reasonable approach for the high-level analysis described here. The plant-wide "unweighted pooled" annual average heat rate was calculated by dividing annual plant-level Net Generation from EIA Form 923 (the same data used to calculate annual net capacity factor) by the sum of the total annual fuel consumption by all three NGS units. Total fuel consumption was calculated by summing the total annual fuel energy consumption (coal and distillate fuel oil (DFO)) using reported monthly data for physical consumption and energy content (EIA Form 923 Schedule 3 – Quantity for coal, barrels for DFO) and Average Heat Content (MMBtu/short ton for coal, MMBtu/barrel for DFO).

The authors note that publicly available data sources indicate differing trends for heat rate and capacity for the three NGS units. Given the high-level objective of this effort, the authors used the data "as-provided" from the respective data sets. There are numerous factors that could affect unit heat rate and, other than occasional spot-checks for reasonableness, the authors did not independently validate the data or attempt to identify potential factors or influences contributing to the variations in performance across individual units or over time.
3 Evaluation Methodology

This report summarizes a preliminary technical and engineering evaluation intended to identify potential opportunities that, if implemented, could improve the economics of the NGS plant. All recommendations identified in this report would require more in-depth evaluation for site specific applicability, cost of implementation, and efficiency improvements. Before, during, and after the site visit to NGS, many different HRI options were analyzed and discussed. In total, more than 40 potential improvement opportunities were considered.

The evaluation used plant design and performance data collected during the site visit to the maximum extent possible. In cases where plant data were not available, B&V utilized internal data from similarly configured and sized plants and applied engineering judgement. For some options, an HRI range was estimated; in those cases, an average value was used for further evaluation.

The HRI options were identified and evaluated by appropriate disciplines within B&V. The mechanical team addressed fan upgrades; the thermal performance team addressed steam generator and heat rejection upgrades; and the air quality control team evaluated emissions control systems upgrades. Several HRI options crosscut multiple teams, including the steam turbine generator upgrades. The Electric Power Research Institute (EPRI) Vista fuel quality impact model was used to expedite evaluation of HRI options that resulted in modifications to coal properties (i.e., reductions in as-fired moisture and/or ash content). EPRI’s Vista model is a computer program that aids in predicting how changes in fuel quality or fuel sources at a coal-fired power plant will impact plant performance, derates, emissions, maintenance and availability, and economics.

Order-of-magnitude estimates were developed for installed capital costs and additional operation and maintenance (O&M) costs required for implementation of the individual HRI options. Cost estimates are on an overnight basis (exclusive of escalation) and are intended to represent the total capital requirement for each project assuming a turnkey Engineer, Procure, and Construct project execution strategy. Pricing of the individual HRI options was based on direct B&V information of similar projects or use of its internal databases and included contingency of approximately 15 percent.

The economic merit of each HRI option was evaluated as a cost/benefit value based on a combination of installed capital costs and, if applicable, additional O&M costs divided by the incremental improvement to the average annual heat rate of the plant (expressed as British thermal unit (Btu)/kWh), with the resulting “cost efficiency” metric expressed as $/Btu/kWh. Consistent with the nature of a screening-level analysis, simplified methods were used to develop both the cost component of the cost/benefit value (the numerator of the cost efficiency metric) as well as the magnitude of the performance improvement component (the denominator of the cost efficiency metric).

The cost component of the metric was calculated as the sum of the estimated capital cost plus three years of operating costs associated with the specific HRI option. This
approach is intended to approximate the total costs incurred over a three-year period for implementing one or more HRI options, and to provide a high-level metric for use in evaluating near-term costs and benefits of implementing the HRI options.\(^c\)

The performance improvement component is intended to represent the incremental improvement to the plant heat rate and was calculated as the absolute change to the heat rate by applying the HRI (as a point estimate for percentage improvement) to the 2016 plant-wide average annual heat rate of 10,417 Btu/kWh (for example, an HRI option that provides a 1 percent improvement would result in a heat rate decrease of 104 Btu/kWh, or a post-retrofit heat rate of approximately 10,313 Btu/kWh). It should be noted that several of the HRI options that were identified during the analyses described here are likely to provide greater improvement at part-load operations than at full-load operations. However, as this effort was intended to provide high-level insights into the potential for improving the heat rate of NGS, a single point-estimate value was developed for each HRI option, with each point-estimate improvement assumed to be uniformly applicable to each individual NGS unit across its entire load curve.

\(^c\) The three-year summing of capital and operating costs is intended to capture a three-year return on investment for an upgrade at an existing coal plant. This payback period is based on communications between the NETL staff and a handful of owners or operators of existing coal-fueled electric generators. Its use in this analysis was not informed by and should not be considered representative of investment evaluation practices of SRP nor should it be considered as representative of investment evaluation practices of the electric power industry as a whole.
4 Results

Of the total set of potential HRI options identified as part of this study, 23 were considered potentially applicable to NGS, and 20 of those were quantified in terms of HRI and capital and O&M cost impacts. Estimated average improvements for individual HRI options ranged from 0.01 percent to 1.35 percent. Order-of-magnitude capital cost estimates for the individual options ranged from minimal to approximately $20 million/unit. A handful of options, if implemented, would result in a net increase in non-fuel operating and maintenance costs. Of those options that did result in a net increase in non-fuel O&M costs, the magnitude was relatively small and only two options carried annual increased O&M costs of $50,000 per unit per year or greater.

In terms of cost efficiency, the individual HRI options ranged from approximately zero to greater than $1 million/Btu/kWh. The HRI options were ranked based on their relative cost efficiency, and were sorted into four categories:

- HRI Category 1: Options with minimal capital and O&M expenses ("near-zero cost")
- HRI Category 2: Options with cost efficiency \( \leq \$50,000/Btu/kWh \)
- HRI Category 3: Options with cost efficiency \( > \$50,000/Btu/kWh \) but \( \leq \$150,000/Btu/kWh \)
- HRI Category 4: Options with cost efficiency \( > \$150,000/Btu/kWh \).

Exhibit 4-1 shows the potential HRI for options in each cost efficiency category.

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\(^d\) Both the $50,000/Btu/kWh and $150,000/Btu/kWh thresholds are somewhat arbitrary but based on prior B&V experience. Similar to the three-year summing approach described above, this threshold was not informed by and should not be considered representative of investment evaluation practices of SRP nor should it be considered as representative of investment evaluation practices of the electric power industry as a whole.
A discussion of each cost efficiency category follows.

### 4.1 HRI Category 1: Options with Minimal Capital and O&M Expenses (Near-Zero Cost)

Three of the evaluated options could be implemented at near-zero cost through measures as simple as changes to operating procedures. These options include reducing the excess oxygen (O\textsubscript{2}) in the boiler, optimizing the number of cooling tower fans in operation at reduced load and changing ambient conditions, and operating fewer induced draft (ID) fans at reduced load. Operator training and safety impact evaluations would be required, but no capital equipment investment is required, hence the near-zero cost designation. The resulting cumulative average net heat rate reduction is 0.60 percent.

### 4.2 HRI Category 2: Options with Cost Efficiency ≤ $50,000/Btu/kWh

The second category of HRI options considered was one with individual relative cost efficiencies of up to $50,000/Btu/kWh. This category included five options with a cumulative average heat rate reduction of 0.97 percent. Two options comprise 93 percent of the potential HRI: minimizing turbine-side valve leakage and ESP leakage reduction. HRI opportunities that provide lesser impact are ID fan cone extensions and
forced draft (FD) and primary air (PA) fan cone extensions and seals. Total capital costs for options in HRI Category 2 ranged from ~$25,000/unit to ~$330,000/unit.

4.3 HRI Category 3: Options with Cost Efficiency > $50,000/Btu/kWh but ≤ $150,000/Btu/kWh

The third category of HRI options considered was one with individual relative cost efficiencies between $50,000-$150,000/Btu/kWh. This category included seven options with a cumulative heat rate reduction of 3.13 percent. The HRI opportunities in this category include variable frequency drives (VFDs) on the ID, FD, and cooling tower fans as well as the circulating water and condensate pumps, re-tubing the condenser, and high pressure (HP)/intermediate pressure (IP) steam turbine path upgrades and packing seal upgrades. Total capital costs for options in HRI Category 3 ranged from ~$640,000/unit to ~$18 million/unit.

4.4 HRI Category 4: Options with Cost Efficiency > $150,000/Btu/kWh

Five HRI opportunities were identified with individual cost efficiencies greater than $150,000/Btu/kWh. These options include reducing the fuel moisture and ash content, increasing the steam reheat temperature by 50 °F, adding variable frequency drives to the PA fans, and replacing the bottom ash handling system with a submerged chain conveyor. The cumulative impact of these options is a 1.3 percent reduction in net plant heat rate. Although these HRI opportunities show technical merit, their comparatively lower cost efficiency may make them too costly using the presumed three-year payback period.

4.5 Aggregate Heat Rate Improvement Potential

An important goal of this analysis was determining the absolute maximum HRI potential if all non-exclusive upgrades were carried out at the NGS plant. This was analyzed using two different approaches: first, considering all the upgrade options regardless of their cost effectiveness, and second by combining options by cost efficiency threshold. Exhibit 4-2 shows the magnitude of potential HRIs and approximate total costs for application of HRI options as stepwise cumulative combinations of individual cost efficiency categories.
As seen in Exhibit 4-2 the “near-zero cost” options can yield an approximate 0.6 percent average HRI. Implementing all options up to and including those with a cost efficiency of $50,000/Btu/kWh can result in an approximate 1.57 percent average HRI. Setting the threshold at $150,000/Btu/kWh results in a potential HRI of 4.70 percent. If all upgrades were considered regardless of their overall cost, the resulting average HRI would be approximately 6.0 percent.
5 CONCLUSION

This screening study has identified a number of opportunities to improve the heat rate of the existing units at the Navajo Generating Station. Implementation of many of the identified HRI options are anticipated to be relatively low-cost upgrades that may result in decreased operating costs due to reductions in fuel consumption and auxiliary load requirements.

The level of effort conducted for this study allowed only screening-level investigation of identified HRI options. The order-of-magnitude capital and operating cost estimates that were developed as part of this effort carry with them a high degree of uncertainty and are not intended to provide accurate estimates sufficient to inform final implementation decisions. Moreover, the performance estimates described here were approximated as single point-estimate improvement values assumed to be uniformly applicable across the entire load curve of any of the three individual NGS units.

Although similar in design, publicly available operations data indicate subtle differences in the performance of individual NGS units, and application of the HRI options described here may result in different degrees of performance improvements if they were to be implemented at the individual units. Because the applicability and/or magnitude of performance improvement depends on a variety of design and operational factors, more detailed analyses using the most accurate design and operational assumptions are recommended prior to making firm conclusions regarding the merit and costs associated with the implementation of the HRI options described in this report.

The HRI options described in this report, including estimated performance improvements and costs, were shared with representatives of SRP, the operating agent of NGS. SRP indicated that it has evaluated and implemented numerous upgrades to NGS over its operating life. Regarding the specific HRI options identified throughout this report, SRP has indicated that it and other NGS participants have considered many of the options presented in this report, performed economic and operational risk evaluations on those options, and have either acted on them to the extent practical or determined them not to be viable in light of operating and economic factors specific to the NGS facility.
6 REFERENCES


