Improved Accounting of Emissions from Utility Energy Storage System Operation

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Several proposed utility-scale energy storage systems in the U.S. will use the spare output capacity of existing electric power systems to create the equivalent of new load-following plants that can rapidly respond to fluctuations in electricity demand and increase the flexibility of baseload generators. New energy storage systems using additional generation from existing plants can directly compete with new traditional sources of load-following and peaking electricity, yet this application of energy storage is not required to meet many of the Clean Air Act standards required of new electricity generators (e.g., coal- or gas-fired power plants). This study evaluates the total emissions that will likely result from the operation of a new energy storage facility when coupled with an average existing U.S. coal-fired power plant and estimates that the emission rates of SO_2 and NO_x will be considerably higher than the rate of a new plant meeting Clean Air Act standards, even accounting for the efficiency benefits of energy storage. This study suggests that improved emissions "accounting" might be necessary to provide accurate environmental comparisons between energy storage and more traditional sources of electricity generation.

1. Introduction

U.S. Clean Air Act (CAA) regulations are often criticized for their inflexibility and loopholes regarding old, high-emissions sources such as coal-fired power plants. Among the issues insufficiently addressed by the CAA is the coupling of energy storage with these existing power plants. Increased interest in a variety of energy storage technologies, along with several proposals for new large-scale energy storage plants, warrants further examination of the CAA's treatment of emissions that result from the operation of utility-scale energy storage systems.

In the year 2000, a 2700 MW compressed-air energy storage (CAES) facility was proposed for Norton, OH (*1*). State agencies have issued all necessary permits, and the facility may legally be constructed and operated (*2*) (although planned construction has been delayed by a variety of economic factors). The Norton facility represents the first large-scale energy storage system scheduled for construction in the U.S. since 1995, and if successful, it might pave the way for a new generation of utility-scale energy storage systems. By increasing the off-peak demand and reducing the "cycling" of electric power plants, energy storage offers significant potential gains in generation efficiency for both new and existing utilities. By increasing generation from older coal-fired power plants, however, energy storage systems complicate the assessment of air pollution emissions. To date, environmental consequences of energy storage systems have been defined narrowly, ignoring the net impact of increased generation from high-emissions power plants.

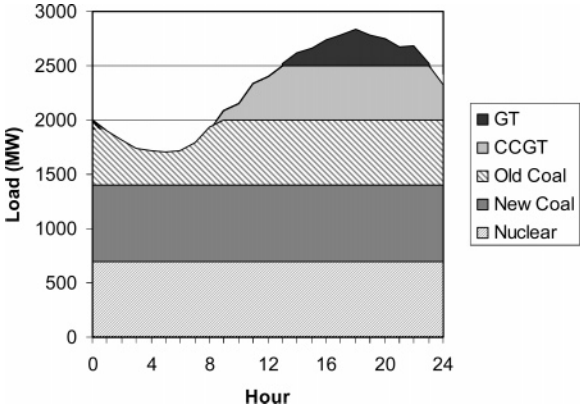

FIGURE 1. Representative daily load profile.

Herein, we calculate the total emissions associated with energy storage, focusing on large-scale CAES systems. These emissions are compared to those of alternative sources of new electricity generation. We begin with an overview of the need for load-following electricity generation and the potential role of energy storage in fulfilling this requirement. We then evaluate the total emissions resulting from the use of existing coal-fired plants with energy storage plants, with an analysis of the proposed Norton facility provided as a case study. We conclude with recommendations to ensure proper evaluation of expected emissions resulting from the use of utility-scale energy storage systems.

2. Load-Following Generation and the Role of Energy Storage

A large fraction of the electricity generated in the U.S. is provided by large "baseload" power plants that are designed to operate at nearly constant output (*3*). Many of the plants, particularly nuclear plants, have a limited ability to respond to the daily variations in consumer demand. Variation in demand is typically met by load-following plants, including intermediate-load coal and gas plants and gas-turbine peaking plants. Figure 1 provides a representative daily load profile for a utility in the U.S., showing the dispatch of various power plants. In this representative scenario, baseload demand is met by nuclear and newer coal plants. Intermediate load is met by an older coal plant and a combined-cycle gas turbine (CCGT). Peak load is met by gas turbines. Any increase in the variable part of the utility's demand or retirement of an existing load-following unit would require the utility to construct a new source of load-following electricity.

Energy storage can provide an alternative to traditional load-following generation technologies by storing electrical energy and releasing it at a later time. Deploying energy

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storage can provide additional benefits to electric power systems, including the ability to quickly respond to changes in electrical demand and provide both "spinning" and standby reserve for conventional electric generators. Energy storage can play a vital role in future energy systems by enabling the increased use of intermittent renewable energy sources such as wind and solar.

Compressed-air energy storage (CAES) is among the most economical energy storage technologies available for large-scale deployment (*4*, *5*). CAES systems are based on conventional gas-turbine technology and utilize the elastic potential energy of compressed air. Energy is stored by compressing air in an airtight underground storage cavern. To extract the stored energy, compressed air is expanded through a high-pressure turbine, which captures some of the energy in the compressed air. The air is then mixed with fuel and combusted, with the exhaust expanded through a low-pressure gas turbine. The turbines are connected to an electrical generator.

CAES is not a pure storage system such as a battery: to effectively utilize all of the energy in the compressed air, CAES requires combustion, making CAES a hybrid generation/storage technology. To deliver 1 kWh of electricity, CAES uses about 0.7 kWh of stored electricity and about 4500 kJ of fuel (*6*). As a result of this hybrid nature, the overall "efficiency" of CAES cannot be precisely defined and depends on the "electrical value" of natural gas; however, a value of 70−75% is a reasonable approximation for comparison with other pure energy storage systems (*6*). CAES is considered technically mature, with a 110 MW facility in operation in the U.S. since 1991 (*4*).

AlthoughCAES has not experienced the utility acceptance previously anticipated (*7*), market conditions, including increased demand for peak energy sources, the high price of natural gas fuel for peaking plants, and increased concerns about grid reliability, have created renewed interest in this technology (*8*). In early 2005, there were a number of active proposals for CAES development in the U.S., including the 2700 MW facility in Ohio (*8*).

Alternative sources of utility-scale energy storage include pumped hydro storage (PHS), advanced batteries, and hydrogen. Virtually all of the utility-scale energy storage currently installed in the U.S. is PHS, with an installed capacity of about 20 GW (*9*). PHS stores hydraulic potential energy by pumping water from a lower reservoir to an upper reservoir, with a typical round-trip efficiency of 70−85% (*6*). Further large-scale development of PHS in the U.S. is unlikely because of environmental concerns and limited availability of new sites (*10*). Advanced batteries and hydrogen have fewer siting restrictions, but are currently more expensive than CAES for large-scale applications (*4*, *11*). For these reasons, this work focuses on CAES, but also briefly considers PHS, which can serve as a proxy for utility-scale battery storage systems.

3. Emission Rates from a New Energy Storage Facility

An energy storage system can be viewed as an alternative source of load-following and peaking electricity, whose "fuel" is off-peak electricity from underutilized baseload power plants. An energy storage system could be built to meet an increase in peak demand, replace retired load-following capacity, or compete in a deregulated market. In any case, a new energy storage system could potentially compete with new conventional generation sources.

To analyze the net air emissions that will result from the use of energy storage, it is necessary to consider the source of electricity that will be stored and analyze the interaction of that electricity generation source with the energy storage system.

3.1. Sources of Electricity for New Energy Storage Facilities. Although studies have indicated that CAES might be particularly well suited for large-scale application with wind energy in the Midwestern U.S. (*12*), in the near term, use of intermittent renewable energy will likely be far too low to require dedicated energy storage. [A possible exception is a planned CAES facility in Iowa (*13*), although the relatively small size of the wind component of this project indicates that most of the stored energy will be derived from traditional sources in the near term.]

One possible source of electricity for new energy storage facilities is underutilized nuclear plants. However, this possibility is limited by the availability of spare capacity in the nation's nuclear fleet. According to the National Electric Reliability Council's (NERC) Generator Availability Data System (GADS), in 2002 and 2003, the average capacity factor of the nation's nuclear fleet was 89.0% and 86.0%, respectively (*14*). In those two years, the average availability was 90.0% and 87.0%, respectively, resulting in a total utilization of about 99% of available nuclear energy. This places significant limits on possibility of using off-peak nuclear energy for new energy storage projects.

Another possible source of off-peak electricity is from spare natural gas plants. For providing energy to storage plants, gas-fired units will have to compete with off-peak coal generation, if available. The current high prices of gas, averaging \$5.46/mmBTU vs \$1.26/mmBTU for coal in 2003 (*15*), produce a fuel cost difference of \$25/MWh between coal- and gas-generated electricity, or roughly a factor of 3, even considering the higher efficiency of a combined-cycle gas plant. This fact, combined with the significant benefits of reduced cycling of thermal steam plants, makes coal the most likely candidate for energy storage, if significant off-peak coal generation is available.

To evaluate the possibility of using underutilized coal plants for energy storage, a power plant survey was performed to identify sources and availability of off-peak coal-based generation in the U.S. This was done by comparing the actual production of the nation's coal plants to their potential output if used at maximum capacity.

Because the bulk of the existing coal generation capacity is in the industrial Midwest and because the largest proposed CAES plant would be located in Ohio, coal plants in the six-state region around Ohio, including Michigan, Indiana, Kentucky, West Virginia, and Pennsylvania, were evaluated. Actual annual production data were derived from the U.S. Energy Information Administration for each plant (*16*). The actual production data were then compared to the maximum potential output, based on average availability for plants in each size class, derived from the NERC GADS database (*14*). The total difference provides an approximate idea of how much spare capacity exists in the coal-fired power plants in this region.

The facilities evaluated were dedicated electric generation facilities and excluded cogeneration facilities, small plants (under 25 MW), and plants with capacity factors of less than 5%.

We identified a total of 108 plants meeting the evaluation criteria, with a total capacity of about 110 GW. In the year 2003, these plants had an overall average capacity factor of 62%. According to the GADS database, the average availability of these plants in the same year was 82−86%, with a capacity-weighted average of about 84%. There is a roughly 215 000 GWh difference between actual and potential annual generation from these plants, equivalent to 29 GW (29 large plants) of "new" baseload generation operating at 84% CF. This unused capacity could provide a significant amount of generation for energy storage in this region.

3.2. Emission Rates from Existing Sources. U.S. Environmental Protection Agency (EPA) data (*17*) for the year

TABLE 1. Emissions Characteristics of Existing U.S. Coal-Fired Power Plants

		representative input-based emissions rates		
plant type	heat rate (BTU/kWh)	CO_2 (lb/MMBTU)	SO_2 (lb/MMBTU)	NO_x (lb/MMBTU)
typical range for existing plants	9500−13 000	205	0.4−3	0.3−0.6
current (2004) NSPS	9000−10 000	205	0.05−0.12	0.08
weighted average (existing plants in six-state region)	10 500	205	1.38	0.4

2003 were used to evaluate emissions from these 108 existing plants, as summarized in Table 1, which includes the range and average input-based emission rates of CO_2, NO_x, and SO_2. Emission rates of CO_2 are included, although CO_2 emissions are currently unregulated. Heat rates (equal to efficiency^{-1}) were derived from the 2000 EPA E-Grid database (*18*). Also included is the estimated performance of a new coal plant meeting 2004 Clean Air Act standards (*19*). Emissions rates for new plants are regulated by the New Source Performance Standards (NSPS) provisions of the CAA (*20*, *21*) and are *input*-based emission standards, expressed as the amount of pollutant allowed per unit of fuel burned. Emissions rates are expressed in English units (pounds and British thermal units), because these are the units used by reporting agencies and codified in federal law.

The CO_2 input-based emission rate is constant for all coal-fired plants because the carbon content of coal is essentially uniform and there is no carbon-capture equipment installed on any plant in the U.S. The considerable variation in the emission rates of SO_2 and NO_x of existing plants is largely a function of the wide range in coal sulfur content, combustion characteristics, and pollution controls among the various plants. The significant ranges in age, combustion technologies, and operating characteristics are also reflected in the wide range of heat rates for the various plants. The emissions standards for new plants reflect the requirements of NO_x combustion controls and postcombustion controls for both SO_2 and NO_x.

3.3. Net Air Emissions from Energy Storage Systems. The net emissions resulting from the operation of an energy storage facility are a function of the emissions from the electricity source and the onsite emissions, particularly for the natural-gas-burning CAES system. The net storage-related emissions factor for a pollutant X ($\mathrm{EF}_\mathrm{S}^\mathrm{X}$) can be calculated using eq 1

$$\mathrm{EF_S}^{\mathrm{X}} = [\mathrm{EF}^{\mathrm{X}}_{\mathrm{gen}}(1 - \eta_{\mathrm{ancillary}})\mathrm{ER}_{\mathrm{net}}] + \mathrm{EF}^{\mathrm{X}}_{\mathrm{op}} \qquad (1)$$

where $\mathrm{EF}^{\mathrm{X}}_{\mathrm{gen}}$ is the marginal emission factor of pollutant X from the electric power plant, $\eta_{\mathrm{ancillary}}$ is the efficiency gain of the power plant due to ancillary benefits of energy storage (including regulation and spinning reserve), $\mathrm{ER}_{\mathrm{net}}$ is the energy ratio of the energy storage system (equal to efficiency^{-1}), and $\mathrm{EF}^{\mathrm{X}}_{\mathrm{op}}$ is the emission factor of X for the storage system itself.

The net emissions rate calculated in eq 1 considers the efficiency increases that result from the use of storage, reflected by the *marginal* emission rate of the power plant. A new coal-fired power plant that runs at optimal load at all times can consume about 10 000 BTU of heat input for each kilowatt-hour generated. This heat rate will increase as the plant is used to follow load. As it ramps up and down, the plant will operate at different efficiencies. In addition, startup and shutdown result in lost heat energy. The same plant used to follow load might average 10 500 BTU/kWh. The issue for energy storage is the heat rate of the next, or additional, unit of energy produced for energy storage. This will typically be much lower than the average heat rate, as illustrated in Figure 2, which presents estimated average and marginal heat rate curves for a proposed coal-fired power plant (*19*).

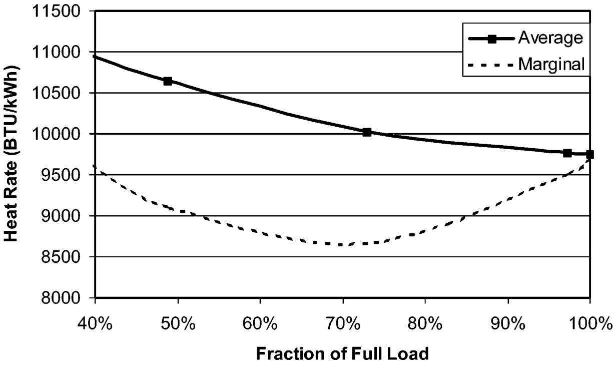

FIGURE 2. Average and marginal heat rates as a function of load for a coal-fired power plant.

Figure 2 illustrates that, although the average heat rate drops from 10 500 to under 10 000 BTU/kWh, the heat rate of any and all energy produced when operating between 50% and 100% of load is substantially below the lowest average heat rate. If this plant could increase its load from 50% to 100% using energy storage, it could produce this incremental energy at a heat rate of only ~9000 BTU/kWh. (This number actually represents the *average* marginal heat rate, which is the average heat rate of all electricity produced raising the power plant from partial to full load.) This efficiency gain is realized only because of the decreased power plant cycling and increased plant optimization that results from the use of energy storage and can potentially produce lower emission rates from existing sources, particularly compared to relatively inefficient load-following alternatives.

Both the average and marginal heat rate curves can be represented as continuous functions, based on a polynomial that represents a theoretical input−output curve for a steam boiler (*22*). An input−output curve represents the fuel consumption rate as a function of output power, whereas the average heat rate curve is fuel consumption per unit of energy as a function of output power. The marginal heat rate is the rate of change of fuel consumption per unit energy as a function of output power. The three equations that characterize power plant input−output rate, average heat rate, and marginal heat rate are as follows

input−output ratio (BTU/h): $$y = Ax^3 + Bx^2 + Cx + D \qquad (2)$$

average heat rate (BTU/kWh): $$y/x = Ax^2 + Bx + C + D/x \qquad (3)$$

marginal heat rate (BTU/kWh): $$\mathrm{d}y/\mathrm{d}x = 3Ax^2 + 2Bx + C \qquad (4)$$

In these three equations, y is fuel consumption (BTU/h); x is output power (kW); and A, B, C, and D are constants determined by a curve fit to known values of y and x. For example, in Figure 2, the heat rate curves were based on four known instantaneous heat rate points.

Whereas heat rate curves for individual power plants are generally not available, average and instantaneous heat rate data are available from publicly accessible sources, including EPA emissions monitoring data. A set of heat rate curves were derived for a subset of the Midwestern coal-fired power plants identified earlier using instantaneous heat rate data fit to eqs 3 and 4. These curves were combined to generate the performance of an "average" coal-fired power plant, and it was then assumed that this average plant could be optimally loaded by using energy storage, moving its heat rate from average conditions to maximum efficiency. The base-case estimate used in this study for the average marginal heat rate of a coal plant feeding a new energy storage plant is 9100 BTU/kWh, representing an approximately 13% improvement in power plant efficiency attributable solely to the use of energy storage. Included in this value is the benefit of running the plant at optimal load at all times, which includes eliminating plant cycling and dynamic benefits of ancillary services. This value will vary considerably from plant to plant, and there is considerable uncertainty in this value, so a wide range of marginal heat rates was considered for the emissions calculations presented in this work.

Using the power plant marginal heat rates and the emission rates from Table 1, the average emission rate for an energy storage system coupled with an existing coal plant can be calculated by applying the net energy ratio for each storage technology. This assessment assumes an ER_{net} value for CAES of 0.7 and a fuel consumption of 4300 BTU for each kilowatt-hour generated (*6*). Also evaluated is a pumped hydro system with an ER_{net} value of 1.33, which is roughly equal to the round-trip efficiency (75%) of a utility battery system (*6*).

To compare the emission rates of different energy storage system configurations as well as conventional generation, a number of different systems were considered. The conventional fossil generation (nonstorage) systems include a new coal plant operating at a heat rate of 10 500 BTU/kWh and a new CCGT operating at an efficiency of 8500 BTU/kWh. These plants are "derated" to consider inefficiencies of following load and providing ancillary services. The storage plants analyzed include CAES coupled to three generation sources: an existing average coal plant with characteristics determined in the previous section, a new baseload coal plant meeting current NSPS, and a "zero-emissions source" such as wind or nuclear energy. The results for PHS are shown only for the two coal plants, because emissions from this pure storage system are zero when coupled to a zero-emissions source. The results for the energy storage cases are based on a marginal heat rate of 9100 BTU/kWh, with a range of 8500–10 000 BTU/kWh used to account for the large range and uncertainty of plant marginal heat rate estimates. In all cases, only point-source emissions are included, ignoring "life-cycle" components including construction, O&M, etc. Results of the CO_2, SO_2, and NO_x emissions analysis are shown in Figures 3–5, respectively.

Because of the "fuel-switching effect" of the hybrid storage–generation CAES system, this storage technology can produce significantly lower net CO_2 emissions than a new higher-efficiency coal plant, even when coupled to existing fossil generation with much lower efficiency. In addition, CAES coupled to a zero-emissions source (labeled Nucl./Ren. in Figures 3–5) has much lower emissions than a relatively low-emission gas plant. Solely on the basis of its emissions of CO_2, CAES demonstrates positive environmental performance, even when coupled with older plants.

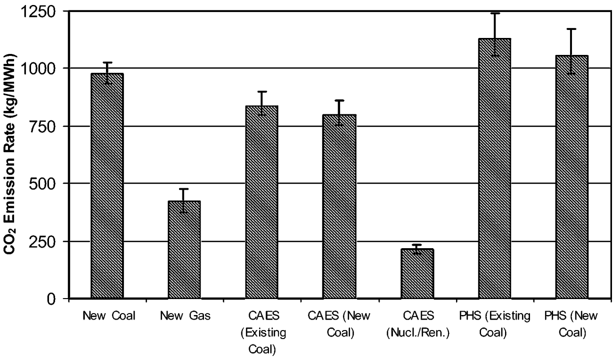

FIGURE 3. Point-source CO_2 emission rates from new sources of load-following electricity.

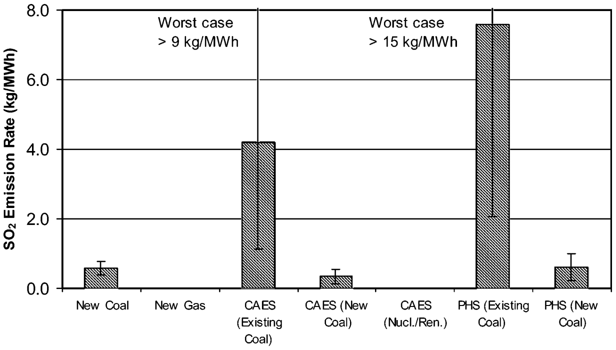

FIGURE 4. Point-source SO_2 emission rates from new sources of load-following electricity.

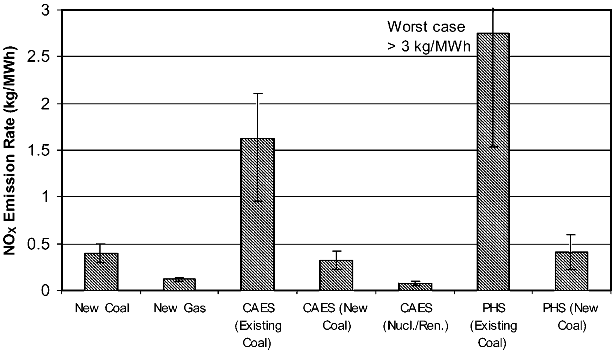

FIGURE 5. Point-source NO_x emission rates from new sources of load-following electricity.

Although there is significant variation in the levels of SO_2 and NO_x emissions resulting from the use of energy storage with existing coal plants, the net emissions of SO_2 and NO_x from a new storage plant will almost certainly exceed the emissions levels of any new generator. The lack of SO_2 and NO_x emissions controls on current plants overwhelms the environmental benefits of increased efficiency made possible by the use of energy storage.

The "effective" emissions produced by the use of energy storage plants pose a potential dilemma for regulators and public officials. If a new energy storage plant is proposed, should the potential impact of upstream emissions be considered? More specifically, should these upstream emissions be considered when comparing a new energy storage facility to a new generation alternative? An accurate environmental comparison of competing new sources of load-following and peaking energy, such as a new storage plant compared to a new conventional generator, requires consideration of upstream emissions. Without this consideration, a new storage plant might seem dramatically cleaner than a new generation alternative.

3.4. Case Study of the Emissions from a Proposed Energy Storage Plant Compared to New Generation Alternatives. When any new major emissions sources are proposed, preconstruction permits must first be obtained from the state permitting authority, which oversees the requirements of the federal CAA standards (*23*). Application for a permit must be accompanied by a technical evaluation of the projected emissions from the plant, including models of possible distributions of pollution concentration and qualifications of other potential impacts on human health and the environment (*24*). These models provide information to regulators and the general public about the potential impacts from the proposed facility.

An important consideration for regulators and the public is how the emissions from a proposed energy storage plant compare to alternatives. An example might be an emissions comparison between the proposed Norton CAES facility and a new gas or coal plant. The various application documents from the Norton CAES project meet all of the extensive CAA requirements by providing estimates of the emissions from the CAES turbines; these documents also discuss the significant potential advantages of energy storage in increasing the operational efficiency of existing baseload plants (*25*). However, it is difficult to perform a direct comparison between the proposed plant and a new generation alternative, because no estimation of the overall emissions resulting from storage plant operations is required by the state permitting agency.

To facilitate better understanding of the actual impacts of CAES, as well as provide a more equitable comparison between competing sources of new load-following and peaking generation, it would be beneficial to estimate the total emissions that would result from storage plant operation.

The following analysis provides an estimate of the emissions rates and annual emissions that could result from the operation of the Norton CAES facility. These emissions were then compared to the emissions from alternative new sources that meet NSPS. These alternatives include CAES coupled to a coal plant that meets NSPS and two nonstorage alternatives: the combination of an intermediate-load NSPS coal plant and a simple-cycle gas-turbine peaking plant and the combination of intermediate-load combined-cycle and simple-cycle peaking gas turbines.

The estimated emissions for the proposed plant are based on the previous assumptions made about current emissions rates from existing coal fired power plants. Therefore, there is significant uncertainty about these estimates, but they do provide a basis for comparing a new CAES plant with new generation alternatives. This analysis assumes that the 2700 MW CAES facility will serve as an intermediate-load and peaking plant operating at an annual capacity factor of 25%, producing about 5900 GWh annually. This capacity factor is based on the project application (*26*) and the current use of U.S. PHS facilities (*27*). Table 2 lists the total emissions that would result from each of six systems that provide this equal amount of electricity. The first row provides the reported emissions, which result only from the operation of the CAES turbines. This is also equal to the total emissions that would result if the plant were coupled exclusively to emissions-free sources of electricity. The next five rows provide the total system-wide emissions for the storage and nonstorage cases providing an equivalent amount of energy. In each case, the total fuel consumed is equal to the total electricity produced multiplied by the heat rate. The total emissions for each technology is the product of the total fuel consumed and the fuel input emissions rate, which is provided in Table 1 for the coal plants. The first CAES/coal case assumes that all stored energy is derived from a mix of coal plants with the average emissions rate calculated in the previous section. The next case assumes a mix of coal and nuclear energy. This case assumes that the 18 GW of installed nuclear capacity within 500 km of the proposed plant could increase their output by 1% (based on the NERC GADS data discussed previously) and that all of this electricity could be used by the storage plant. This extra output would provide about one-third of the annual energy requirements, with the remaining two-thirds derived from existing coal plants. Also included is a case in which CAES is coupled to a new coal plant meeting current emissions standards.

TABLE 2. Point-Source Emissions from New Load-Following Electricity Generators Providing 5900 GWh Annually

	annual fuel consumption and emissions for a 2700 MW plant operating at a 25% CF			
	fuel consumed (billion BTU)	CO_2 (million tons)	SO_2 (tons)	NO_x (tons)
CAES turbines alone[a]	25 400	1400	<100	500
CAES with Average Existing Coal Plant				
CAES turbines	25 400	1400	<100	500
coal plant	37 700	3900	26 000	9400
total	63 100	5300	26 000	9900
CAES with Mix of Existing Coal (2/3) and Nuclear (1/3)				
CAES turbines	25 400	1400	<100	500
coal plant	25 100	2600	17 300	6300
total	50 500	4000	17 300	6700
CAES with Coal Plant Meeting NSPS				
CAES turbines	25 400	1400	<100	500
coal plant	35 200	3600	2100	1400
total	60 600	5000	2100	1900
NSPS Coal and Gas Turbine				
coal plant	31 500	3200	1900	1300
gas turbine	32 000	1800	<100	600
total	63 500	5000	1900	1900
NSPS Gas				
CCGT	25 500	1400	<100	500
GT	32 000	1800	<100	600
total	57 500	3200	<100	1100

[a] Ignoring upstream emissions.

The nonstorage cases include an NSPS coal plant acting as an intermediate-load plant with an average heat rate of 10 500 BTU/kWh, producing 3000 GWh annually, with a simple-cycle gas turbine producing the remaining 2900 GWh with a heat rate of 10 500 BTU/kWh. Also included is a natural gas case with 3000 GWh produced by an intermediate-load combined-cycle gas turbine with a heat rate of 8500 BTU/kWh and the remainder produced by a single-cycle gas turbine. In all cases, the input emissions rates for gas are 118 lb/mmBTU for CO_2, 0.6 lb/billion BTU for SO_2, and 0.04 lb/mmBTU for NO_x (*28*).

Table 2 demonstrates that the “reported” emissions (emissions that can be estimated from the project application) are only a small fraction of the total emissions that could actually result from the operation of a new CAES facility. If the Norton CAES facility is coupled to an existing coal plant, the total net emissions of SO_2 and NO_x will almost certainly be much higher than the emissions from legally allowable new sources of intermediate-load and peaking energy. Coupled to the average coal-fired power plant evaluated in the previous section, the CAES plant would effectively produce at least 10 times more SO_2 and 5 times more NO_x than the alternative plants that can legally be constructed. Using potentially available nuclear capacity in the region reduces the emissions significantly, but emissions of SO_2 and NO_x still greatly exceed those of a new plant.

Operating at a 25% capacity factor, the CAES plant coupled to an existing coal-fired plant will annually consume in excess of 37 trillion BTU of coal, roughly equivalent to the annual consumption of a 500 MW baseload coal power plant. A new generation plant providing this energy would be required to meet environmental performance standards established by the New Source Review (NSR) provisions of the Clean Air Act.

4. Discussion: Existing and Potential Policies to Account for Emissions from the Use of Energy Storage

4.1. Legal Basis for the Use of Energy Storage. As indicated by Table 1, emissions from most existing coal plants in the U.S. greatly exceed standards for new plants. When originally implementing the Clean Air Act, policy makers recognized that requiring immediate retrofitting of all of the nation's generation facilities, especially those in areas that already meet air-quality standards, would be economically disruptive (*29*). Congress decided that existing facilities in areas with relatively clean air would be allowed to continue to emit at their existing emissions rates until the facilities were upgraded or otherwise modified, at which point they would be considered new sources and be required to meet NSR rules. New construction or major upgrades provide the most economic opportunity for installation of new pollution equipment, so NSR is triggered for existing plants at the time of a major modification. This rule, referred to here as the "change rule", states that NSR shall be triggered by

> "any physical change in, or change in the method of operation of, a stationary source which increases the amount of any air pollutant emitted by such source or which results in the emission of any air pollutant not previously emitted" (*30*).

To guide utilities and establish clear rules, terms such as "physical change" and "method of operation" must be more specifically defined. Further definition of these terms is the responsibility of the administering agency (*31*), in this case the U.S. Environmental Protection Agency (EPA).

The EPA's attempts to further define the terms physical change and method of operation have been extremely contentious and have resulted in many lawsuits by utilities, states, and environmental organizations. As of July 2005, the change rule is defined only by what it is *not*, established by a number of exemptions (*32*). Major exemptions to the change rule include: (1) routine maintenance, repair, and replacement; (2) an increase in production rate, if unaccompanied by capital expenditure; (3) an increase in the hours of operation; (4) use of alternate fuels; and (5) installation of new pollution control equipment.

The most important of these exemptions for energy storage is the hours-of-operation exemption, which establishes the legal use of energy storage without triggering New Source Review. An energy storage facility can store off-peak power from an older coal plant in an area currently meeting federal air-quality standards, substantially increasing the hours of operation of this plant and, consequently, its air emissions. As long as local air-quality standards are not exceeded, the increase in emissions that results from the use of energy storage is allowed through the hours-of-operation exemption.

There has been some question as to whether a "universal" application of the hours-of-operation exemptions is justifiable (*33*). The hours-of-operation exemption appears reasonable in many cases, especially considering the highly variable, largely uncontrollable, and somewhat unpredictable changes in electricity demand. Although utilities can roughly estimate the expected annual increases in electricity demand, it would be impossible for them to predict exactly how much a generator will need to produce from year to year, especially considering the effects of weather-related demand.

It might be possible, however, that this exemption is less justifiable for a long-term, planned, and controllable increase in plant operation, and therefore emissions. In the case of energy storage, for example, the use of this technology can involve significant planning, long-term purchase contracts between the generator and storage facility, and other strategic decisions that result in changing an intermediate-load plant into a baseload plant. In other words, the generator would know ahead of time that a significant change in power plant operation, and resulting increase in emissions, was anticipated. As one legal scholar has noted,

> "when a utility makes a long-term, strategic decision to increase the utilization of a power plant from 30% on average to 60% on average over an extended period, it is hard to understand why this is not an 'operational change'. Such a change, if accompanied by a significant emissions increase, would appear to require the NSR under the statutory definition of 'modification'." (*33*).

It should be noted that NSR is only one of many laws that regulate emissions at planned and existing power plants. Other regulations, such as the 1990 CAA (*34*), which introduced a national cap on SO_2 emissions, and the recent Clean Air Interstate Rule (*35*), which significantly lowers the cap on SO_2 and introduces a cap on NO_x from stationary sources in the eastern U.S., apply to all of the generators likely to supply energy to the Norton CAES facility. As a result of these provisions, the actual emissions resulting from the operation of CAES estimated earlier could be significantly lower in the future as emissions caps are lowered over time.

Despite the legal use of energy storage with existing plants, and the potential restrictions on increased emissions at existing plants due to other existing CAA regulations, new energy storage facilities still challenge accurate comparison of new competing sources of load-following generation.

4.2. Improving Emissions Assessment of Energy Storage Systems. Energy storage provides unique opportunities for electric power systems to increase the flexibility and use of baseload generators. It is clear that energy storage technologies such as CAES could represent a significant tool for improving air quality when coupled with zero-emissions sources, or even new coal plants, as CAES coupled with a new baseload coal plant produces energy with a net lower NO_x and SO_2 emissions rate than a new load-following coal plant. However, the low or zero point-source emissions from CAES limits the ability of regulators and the public to understand potential air-quality impacts compared to conventional alternatives.

In the near term, the likely sources of electricity for energy storage in the U.S. include older coal-fired power plants with high rates of emissions. The combination of energy storage and an older coal-fired plant creates a new source of intermediate-load and peaking power with emissions that might exceed the maximum allowable emissions rate for a generation source that could be legally constructed.

It appears that there are significant opportunities to improve the ability of regulators and the public to make fair and accurate comparisons between competing new sources of intermediate-load and peaking power, given the unique characteristics of energy storage.

To provide the public and regulators with sufficient information to evaluate energy storage as a source of load-following and peaking power, a more complete accounting of emissions resulting from energy storage would be necessary. Required documents, such as environmental impact statements, could provide at least a range of estimates of the emissions that will result from expected power purchases. Such disclosures should, of course, estimate and report the substantial environmental benefits of storage, including increased plant efficiency, reduced spinning reserve requirements, and any other advantages unique to energy storage. Although it would be unreasonable (and impossible) to expect precise calculation of the origin of all power purchase and resulting emissions, some bounded estimates are possible, as demonstrated by the analysis herein. Full accounting would improve the ability of public officials and citizens to equitably compare competing sources of load-following and peaking energy. This would allow better understanding of the environmental costs and benefits of utility-scale energy storage technologies.

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