Life-Cycle Air Emissions from Utility-Scale Energy Storage Facilities: Comparative Analysis and Policy Implications

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Introduction

Among the numerous benefits of energy storage are two that are unique to large utility-scale storage systems. The first is the ability to provide backup for intermittent energy sources such as wind and solar photovoltaic (PV) systems. The second is to provide alternatives to conventional load-following sources such as gas turbines and reciprocating generators. This second application also allows energy storage systems to purchase inexpensive off-peak electricity, and sell it at periods of higher demand and prices.

Concerns about the emissions of greenhouse gases and other potentially harmful pollutants warrant examination of the emissions resulting from the operation of energy storage systems. To fully evaluate the net emissions that result from the use of energy storage, a "life-cycle" approach must be used. Life-cycle analysis allows for the complete accounting of emissions that result from construction, operation, and decommissioning of an electricity generation system.

Using life-cycle assessment, metrics for the calculation of greenhouse gas (GHG) emissions from utility energy storage systems were developed and applied to three storage technologies: pumped hydro storage (PHS), compressed air energy storage (CAES), and advanced battery energy storage systems (BESS) using Vanadium and Sodium Polysulphide electrolytes. The use of these technologies with renewable and fossil sources is examined in detail. In addition, the compatibility of these sources with existing U.S. Clean Air Act regulations is considered.

Energy Storage Life-Cycle Analysis

Only a few energy storage technologies are currently viable for large, multi-MW applications. Pumped hydro is a proven technology with over 90 GW installed worldwide.[1] CAES is currently in use at two facilities in the U.S. and Germany, and there is interest in developing at least three new facilities the U.S, representing a substantial increase in nationwide storage capacity.[2] CAES is a hybrid storage/generation system that requires natural gas fuel. Advanced battery systems, such as flow-cell batteries, are currently being installed in several locations. Among the most suitable for large application are the Vanadium-Redox Battery (VRB) and the Polysulphide Battery (PSB.)[3]

Each technology was evaluated from a life-cycle perspective to estimate the net GHG emissions from manufacturing and operation. GHG emissions are generally reported in terms of CO_2-equivalent emissions per unit of electricity delivered (kg CO_2e./MWh), and include non-CO_2 greenhouse gasses such as methane. Table 1 provides a summary of the emission characteristics of the four evaluated storage technologies.

Table 1: Life-Cycle Emissions Parameters for Utility-Scale Energy Storage Systems

Parameter	PHS	CAES	VRB BESS	PSB BESS
Estimated Plant Life (years)	60	40	20	20
Estimated Capacity Factor (%)	20	20	20	20
Generation Emission Multiplier (Energy Ratio)	1.35	0.735	1.33	1.54
Construction and O&M Related Emissions Rate (kg CO_2e./MWh)	6	4	40	33
Fuel Related Emissions Rate (kg CO_2e./MWh)	0	288	0	0

In terms of emissions not related to stored electricity, CAES demonstrates the highest emissions due to the combustion of natural gas, followed by BESS systems, which require energy intensive manufacturing. PHS demonstrates the lowest emissions due to a number of factors, including long-lived components.

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Evaluation of Dispatchable Renewable Energy Systems

The limitations of intermittent renewable sources such as wind and solar PV systems are well known. While researchers have demonstrated the feasibility of wind penetration rates to 20% of a region's total energy demand and a non-zero capacity credit for spatially diverse wind turbine sites, utilities may be unwilling to develop the necessary forecasting systems necessary for this level of use and require backup in the form of energy storage.[4,5] Moving beyond a 20% penetration rate will require the use of energy storage.

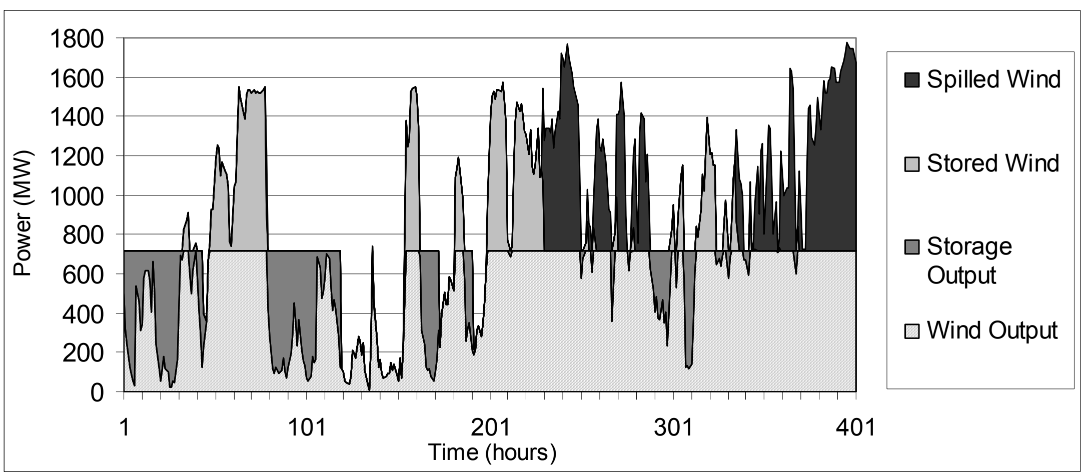
To examine the emissions consequences of renewable energy used with storage, a "dispatchable renewable" energy system model was developed. This model combines renewable energy generation, energy storage, and in certain cases, long distance transmission. Three scenarios were investigated: wind/CAES, wind/PHS, and solar PV/BESS. Given the limited economic viability of existing solar PV/BESS systems, the work focused on wind energy systems.

For wind energy systems, the model provides an output which approximates that from a conventional baseload power system, with an overall capacity factor in excess of 80%.[6] Furthermore, the model attempts to provide a constant output during most of its operation, to reflect the economic use of a dedicated transmission system. As an example, a wind farm with a peak output of 1000 MW and a capacity factor of 35% will produce, on average, 350 MW. If this wind farm were coupled to a 100% efficient storage system, with an unlimited storage capacity, it could produce a *constant* output of 350 MW. When the wind farm output exceeds 350 MW, energy will be stored, and when output drops below 350 MW, energy is delivered from storage.

The model incorporated hourly wind energy data from existing wind turbines, including data collected by the National Renewable Energy Laboratory from a large wind power plant in the Midwest. Storage vessel sizes were based on economic and geologic constraints of CAES and PHS systems; the model typically used a storage capacity of 24 hours at full load.

Figure 1 provides a sample output for a 400-hour period of time for a simulated wind/CAES system located in North Dakota. The rough envelope represents the total wind farm generation, while the flat line is the desired level of constant output.

Figure 1: Output from a Wind/CAES system in North Dakota



The constant output level of the wind farm can be adjusted up or down to arrive at a desired capacity factor. This determines the net energy balance of the system, including the amount of energy lost in storage, and the amount of energy "spilled" due to limitations of the storage system capacity.

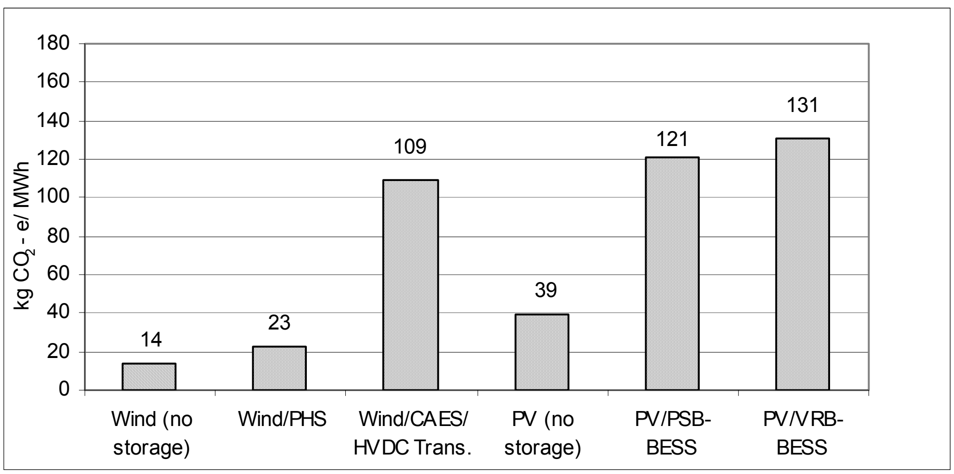
In this example shown in figure 1, the combination of wind and storage can provide a net yearly capacity factor of 84%, and delivers the desired full output 77% of the time. Due to the limitations of storage, about 15% of the wind farm output must be spilled. Capacity factors much greater than 85% lead to excessive spillage rates, unless storage times can be significantly increased. While a capacity factor of 84% is less than well run nuclear or coal plants, it is high enough to be considered a baseload source. During periods of low wind, utilities could potentially purchase off-peak power to replenish the storage reservoir. This is analogous to a nuclear power plant refueling outage, but instead of a month long outage every 18 months, the wind/storage system has frequent, short duration "refueling" outages.

The wind/CAES system is of particular interest due to the availability of significant wind resources and suitable geology in the Midwest. From this model, the amount of fuel usage can be determined for each delivered unit of electricity. The model found an effective heat rate for the wind/CAES system of 800-1000 BTU/kWh, compared to 7200 BTU/kWh for a modern natural gas combined cycle system.

Similar models were developed for wind/PHS and PV/BESS. The wind/PHS system was assumed to be located in California, and provided an output similar in nature to the wind/CAES system. Several different PV/BESS systems were considered. While off-grid PV/BESS systems require 24-hour coverage, grid-connected PV systems would not be used in this manner. One possible use of storage for PV systems is load shifting. There is a significant time difference between solar output peak at noon, and thermal (demand) peak, which generally occurs around 4:00 pm. A BESS system could be used to store PV output and deliver it at peak times. This assumption was the basis for the model used in this study.

Example results for the three cases are provided in figure 2. In general, the use of energy storage with renewable electricity generation substantially increases the total greenhouse gas emissions. The net emissions vary depending on solar and wind resources. The emissions from a wind/PHS system are the lowest of any dispatchable renewable, and only a modest increase over wind systems not using storage. Due to natural gas combustions, the wind/CAES system shows a substantial increase in GHG emissions. The large level of emissions associated with BESS systems, combined with the large storage requirements of PV systems, showed the highest level of GHG emissions. Despite these increases in emissions due to storage, the life-cycle GHG emission rates from dispatchable renewable energy systems are substantially lower than from fossil fuel-derived electricity sources.

Figure 2: Life Cycle GHG Emissions from Renewable Energy/Storage Systems



Evaluation of Storage Systems used with Fossil Energy Sources

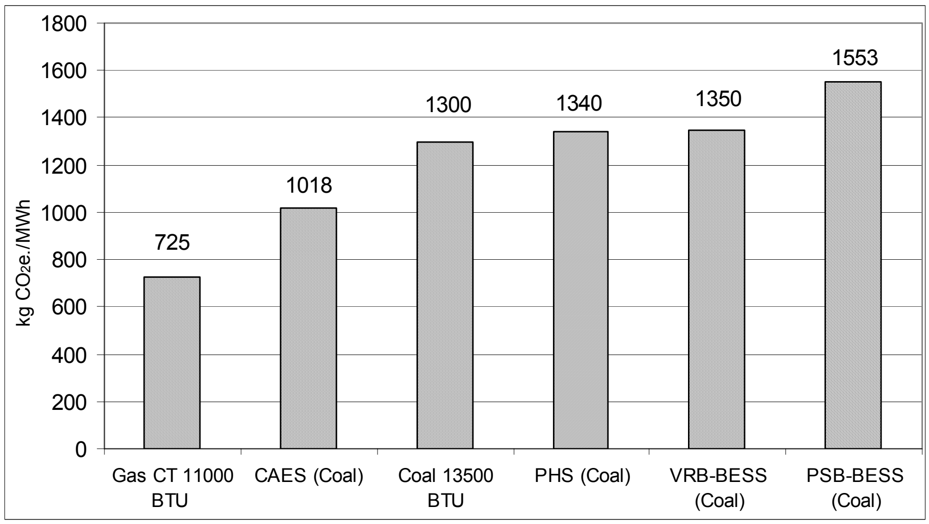
While the combination of storage and low-carbon energy sources such as nuclear and renewable energy produce far less GHG emissions than from fossil sources, such use is unlikely in the U.S. in the foreseeable future. Rising baseload energy demand has eliminated any significant spare capacity from nuclear plants, and wind energy production remains far too low to require the use of energy storage. Most storage plants built in the U.S. in the near future will likely be powered by fossil sources (particularly coal), so the potential use of energy storage systems with these sources is examined in detail.

An energy storage system can be considered a stand-alone load-following or peaking plant, whose fuel is off-peak electricity, or electricity plus natural gas. The net emissions are the combination of emissions from electricity generation, CAES fuel combustion, and other life-cycle effects such as plant construction and O&M. Particularly for the storage-only systems (PHS and BESS), the emissions are dominated by fossil generation.

One difficulty in determining the net storage-related emissions is the effect on generation efficiency. Storage plants may increase the net efficiency of thermal plants by increasing their load to the design point, or reducing their spinning reserve requirement. This impact is discussed in more detail in the next section.

The net emissions from a storage plant can be estimated by choosing an appropriate generation source. This model assumes that electricity is generated from a baseload coal-fired power plant, with a heat rate of 10,500 BTU/kWh, resulting in emissions of 974 kg CO_2e./MWh. Figure 3 provides the results of this analysis. Emissions from each storage plant are shown, along with alternatives for load following, including a gas turbine and an older intermediate-load coal plant.

Figure 3: Life Cycle GHG Emissions from Fossil Energy/Storage Systems and Fossil Generation Alternatives*



*Heat rates (BTU/kWh) are abbreviated as BTU.

When coupled with fossil-generation, CAES produces significantly lower net GHG emissions than PHS or BESS. This difference is essentially due to the "fuel-switching effect" of the hybrid storage-generation nature of CAES. Despite the inefficiencies associated with storage, emissions from coal-powered CAES can be competitive with conventional load-following power sources. Emissions from a CAES/coal system can be 20% less than an inefficient load-following coal plant. Simple-cycle gas turbines generally have lower emissions than CAES/coal systems; the break-even point for a gas turbine is around 16,000 BTU/kWh. Emissions from BESS and PHS coupled with coal are generally higher than most other sources, including load-following coal. Polysulphide-BESS has particularly unfavorable results due to its low storage efficiency. From a greenhouse gas perspective, the use of PHS and BESS with coal is undesirable, unless substantial thermal plant efficiency gains can be achieved.

Compatibility of Energy Storage with the U.S. Clean Air Act Regulations

While energy storage has the potential to increase the efficiency of existing fossil sources, this application may have certain undesirable results.

The U.S. has a number of environmental regulations to limit the emissions of harmful pollutants from electric power generation. Among these are the New Source Review (NSR) provisions of the Clean Air Act.[7] New plants constructed in the U.S. are required to meet certain standards established by the New Source Performance Standards (NSPS) for criteria pollutants such as SO_2, NO_x, and others. Plants constructed before adoption of the NSR rules were not required to retrofit; however, plants making modifications that result in increased emissions must bring emission controls up to current standards.[8] The intention of this law is that as older plants retire, or are upgraded, the national average emission rates will decrease. Unfortunately, the lack of retrofit requirements has created a disincentive to remove older plants from service.

The U.S. currently has a large number of old coal-fired power plants which have emission levels that greatly exceed the current NSPS. Many of these plants operate as intermediate-load plants, meaning they are only partially loaded during some parts of the day. Energy storage plants may purchase off-peak power, when prices are low, and re-sell the electricity during periods of higher demand. The net emissions from this operation are the base generation emissions, plus the net effect of efficiency losses and gains from the storage process. The total emissions vary depending on power plant load, but the net emission rate from the operation of the storage plant in many cases will exceed NSPS. Since the NSR allows for increased output at older plants due to increased demand, New Source Review will not be triggered if a power plant increases output due to the use of energy storage. (It is unclear, however, whether addition of an on-site storage facility would represent a plant modification and trigger NSR.) As a result, energy storage is a new source of power that while legal in this application, appears to violate the *intention* of New Source Review.

For example, a utility desiring a new, peaking facility can choose from a variety of options, including a gas turbine, or a new energy storage facility to be coupled to an existing intermediate-load coal plant. The gas turbine would require the use of emission controls, to ensure the emission rate meets NSPS. The storage system (perhaps a battery) would produce no point source emissions, possibly requiring no environmental impact statement, and no review of its impact on air emissions. In reality, the net emissions produced by electricity delivered by the battery would greatly exceed that of the gas turbine, and likely exceed NSPS. However, since just increasing output at an existing facility does not trigger New Source Review, the storage system can effectively exploit this loophole.

The energy storage industry can be proactive in demonstrating compliance with both the NSR legal requirements and its intentions. The first step would be to provide a full accounting of emissions resulting from energy storage. Required documents, such as environmental impact statements, should provide 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.

More importantly would be a requirement that the net emissions from energy storage facilities meet the actual requirements of NSPS. As with proper disclosure, the net emissions would capture the emission reductions resulting from storage plant operation. Flexible purchase agreements could also help storage plants meet NSPS requirements. Such requirements would encourage the development of cleaner sources of primary power, and remove a loophole allowing increased output at older, high emission rate power plants.

Conclusions

A greenhouse gas life-cycle analysis was performed on three energy storage technologies: pumped hydro, compressed air, and batteries using Vanadium and Polysulphide electrolytes. When coupled with low-emission renewable sources, the resulting dispatchable renewable energy system produces significantly less greenhouse gas emissions than any fossil source. Wind/PHS systems produce very low levels of GHG emissions, while wind/CAES and PV/BESS systems produce higher levels. The worst case renewable/storage system produces GHG emissions at a rate less than one third that of a highly efficient combined-cycle gas turbine. When coupled with fossil sources for load following and peaking power, CAES produces significantly lower GHG emissions than PHS or BESS. CAES/coal also produces less emissions than an old coal plant running inefficiently due to load following conditions. PHS and BESS, however, produce emission levels equal to or greater than the inefficient coal plant, and appear to produce an undesirable level of emissions when coupled to coal. Further analysis is required to determine whether the efficiency gains in primary production resulting from storage offset the inefficiency of the storage process. A new storage system coupled to an old coal fired plant produces a new peaking source with net emissions that may be higher than allowed by the New Source Performance Standards of the Clean Air Act. Since the Clean Air Act does not consider storage, this usage is legal, but appears to violate the intention of the NSPS. The energy storage industry may consider methods to demonstrate its ability to use energy storage in such a way as to produce net emission levels at or below levels required by the NSPS.

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[7] 42 U.S.C. 7470(1).

[8] 42 U.S.C. § 7411(a)(4), as incorporated in the NSR program by 42 U.S.C. § 7479(2)(C), 7501(4).