

Comparison of Vehicle-to-Grid versus Other Grid Support Technologies

A Master's Project submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in the Nicholas School of the Environment of Duke University.

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Submitted On:
April 2012

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Acknowledgements

I would like to express my gratitude to the General Electric Company (GE) and the following professionals from GE, who kindly served as my clients and provided invaluable resources and guidance to the development of this project:

Ms. Beth Comstock, Senior Vice President and Chief Marketing Officer, GE

Ms. Debora Frodl, Chief Strategy Officer, GE Capital Fleet Services

Dr. Matthew Nielsen, Electrical Technologies and Systems, GE Global Research

I would also like to thank Dr. Dalia Patino-Echeverri, Gendell Assistant Professor of Energy Systems and Public Policy at the Nicholas School of the Environment, for her invaluable guidance to the communication of the analysis results of this project.

1 Executive Summary

With the accelerating adoption of electric vehicles, using the batteries in the existing vehicle fleet to discharge to the power grid when needed (vehicle-to-grid, V2G) provides a potential alternative for supplying grid support. While many studies have suggested V2G to be highly competitive in providing regulation service, a segment of grid support, it is necessary to compare V2G versus other available grid support technologies before its actual competitiveness can be determined.

This master project focused on the often-overlooked side of V2G, the energy efficiency, and compared V2G versus other grid support technologies in terms of their efficiencies and emissions. Given V2G is most suitable for regulation service, other available technologies serving regulation were selected for the comparison. These technologies fit into two groups: generation-based and storage-based. Fast-ramping gas turbines were chosen to represent the generation-based technologies. For storage-based technologies, hydroelectric pumped storage, battery banks, flywheels, and V2G were analyzed.

The project adopted a *fuel-to-grid* scope when conducting the comparison among different grid support technologies, meaning the efficiency at which fuels are converted into final grid support, along with the associated emissions, were analyzed and compared.

The comparison led to three major findings: (1) energy storage-based technologies achieve a lower fuel-to-grid efficiency than gas turbines do; (2) V2G is less efficient in delivering grid support than grid-dedicated battery banks and flywheels; (3) storage-based technologies, especially V2G, would significantly increase CO₂, SO₂, and NO_x emissions.

However, opportunities still exist for the commercialization of V2G given its great mobility in supplying power at load as well as the lower financial burden to utilities. To address the lower efficiency and increased emissions associated with V2G, the electric power sector should rely more on clean and efficient power generation mechanisms, such as natural gas and renewables.

2 Introduction

Electric vehicles (EVs), also referred to as electric drive vehicles (EDVs), with an electric-drive motor powered by batteries, a fuel cell, or a hybrid drivetrain, have been widely recognized as a key pathway to enhance national energy security, mitigate greenhouse gas emissions, and promote economic growth. In his 2011 State of the Union address, President Obama called for putting one million electric vehicles on the road by 2015. This goal represents not only a milestone in transforming our national vehicle fleet, but a challenge as well as an opportunity for the electric power system.

With a minimum battery capacity of 4 kWh (defined by IEEE), *gridable* electric vehicles, such as plug-in hybrid electric vehicles and battery-electric vehicles, have the ability to discharge their batteries and send electricity back to the power grid when they are parked and connected to an electrical outlet. The electricity flowing from electric vehicles to the power grid is then called “vehicle-to-grid” power, or V2G.

V2G provides a potential alternative for supplying grid support. Studies have always looked at the economic implications of V2G. Among the ancillary services for grid support, V2G is suggested to be highly competitive for the most expensive regulation service. However, the energy efficiency (the ratio of the energy delivered to that consumed) of V2G for regulation should be analyzed before the economics of V2G for regulation can make sense.

This project focuses on comparing the efficiency and emissions of V2G versus other grid support technologies, covering conventional generation-based and storage-based technologies. Chapter 3 introduces the concepts of ancillary services, regulation, and V2G, followed by a brief summary of opposing opinions about the application of V2G. Chapter 4 evaluates each grid support technology individually. Chapter 5 explains the methods used in the quantitative analysis while Chapter 6 presents the comparison results. Conclusions and recommendations are provided at the end of the report in Chapter 7.

3 Ancillary Services, Regulation, and V2G

3.1 Ancillary Services

Managed by the Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), ancillary services support the reliability of an electric power system. The Federal Energy Regulatory Commission (FERC) defines the ancillary services as "those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system".

Ancillary services differ in their control method, response time, duration of power dispatch, contract terms, price and terminology. The Oak Ridge National Laboratory distinguishes the ancillary services into regulation, spinning reserve, supplemental reserve, replacement reserve, and voltage control based on their different response timeframes. Table 1 summarizes the features of the timeframes of the five key ancillary services.

With the restructuring of the electricity industry, ancillary services that used to be bundled in the generation of vertically integrated utilities are now provided by various industry participants, ranging from generation to the demand. In market-based systems, separate markets are usually created to trade these services. The PJM Interconnection (mid-Atlantic and mid-West), for instance, currently operates two markets for ancillary services: Synchronized Reserve and Regulation. The Synchronized Reserve market supplies electricity when an unexpected power shortage occurs. The Regulation corrects for short-term changes in electricity such as frequency and voltage. PJM makes the remaining ancillary service, Black Start service, compulsory. Nationwide, ancillary services account for 5-10% of the annual electricity cost, or \$12 billion, of which 80% goes to regulation and spinning reserve services [1].

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Table 1. Definitions of key ancillary services. Adapted from *Frequency Regulation Basics and Trends* (p. 3) by Oak Ridge National Laboratory, 2004.

Service	Service Description		
	<i>Response Speed</i>	<i>Duration</i>	<i>Cycle Time</i>
Regulation	Power sources online, on automatic generation control, that can respond rapidly to system-operator requests for up and down movements; used to track the minute-to-minute fluctuations in system load and to correct for unintended fluctuations in generator output to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Reliability Council (NERC 2002)		
	<i>~1 min</i>	<i>Minutes</i>	<i>Minutes</i>
Spinning reserve	Power sources online, synchronized to the grid, that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 min to comply with NERC's Disturbance Control Standard (DCS)		
	<i>Seconds to <10 min</i>	<i>10 to 120 min</i>	<i>Days</i>
Supplemental reserve	Same as spinning reserve, but need not respond immediately; units can be offline but still must be capable of reaching full output within the required 10 min		
	<i><10 min</i>	<i>10 to 120 min</i>	<i>Days</i>
Replacement reserve	Same as supplemental reserve, but with a 30-min response time; used to restore spinning and supplemental reserves to their pre-contingency status		
	<i><30 min</i>	<i>2 hours</i>	<i>Days</i>
Voltage control	The injection or absorption of reactive power to maintain transmission-system voltages within required ranges		
	<i>Seconds</i>	<i>Seconds</i>	<i>Continuous</i>

The importance of ancillary services stems from their potential to deliver or withdraw electric power or other resource upon request. Consequently, the value of ancillary services must be measured by their ability to respond when needed, for instance, the response time. In practice however, ancillary services are usually compensated for based on the clearing price and the bidding capacity. Such a discrepancy in service performance and compensation mechanism should be corrected.

3.2 Regulation

Regulation, or frequency regulation, is one type of ancillary services that fine-tunes the grid to maintain the frequency at a stable level (60 Hz in the U.S., 50 Hz in the Europe). It is designed to handle rapid fluctuations in load and unintended small changes in generation. In the PJM

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example, generation and demand resources willing to perform regulation must be able to provide as small as 0.1 MW of regulation capacity [2].

Online generation, storage, or load that is equipped with automatic generation control (AGC) and that can change output quickly (within minutes) is capable of providing regulation. However, generation-based technologies, such as natural gas-fired power plants and hydropower plants, prevail in the regulation service. When the load exceeds the generation, causing frequency to drop, a regulation control signal calling for a positive correction will be sent to the generators, requiring them to “regulation up” their generation. When excessive generation increases the frequency, a signal calling for a negative correction will be sent to ask for “regulation down”.

Large frequency deviations are harmful and may lead to a collapse of the power system. Since electricity generators are designed to operate within a relatively narrow range of frequencies, when the frequency falls too low, protection devices will disconnect the generators from the grid to prevent potential damages. Such disconnections exacerbate generation deficit, causing the frequency to further drop and more generators to be disconnected.

Figure 1 illustrates that frequent imbalances existing between load and generation are balanced by regulation service. The smooth blue curve on the top shows the total generation ramping up from below 3,600 MW to above 4,000 MW over a three-hour period from 7 to 10 a.m. Overlying the smooth blue is a jagged green curve representing the continuously fluctuating demand for electricity. At the bottom, a jagged red curve illustrates the minute-to-minute imbalances between the generation and load using a scaled up representation.

Despite being widely used, thermal generators like gas-fired power plants are still not ideal power sources for grid balancing. First, they respond “slowly” (in minutes) to a regulation control signal, contributing to a large Area Control Error (ACE) that is measured on a per-minute basis. Second, they exhibit significant efficiency losses while providing regulation, which then translates into higher operating costs and increased emissions. Today, with an increasing amount of electricity being produced by renewable sources (such as wind and solar) with variable power outputs, the need for more and better balancing power sources grows.

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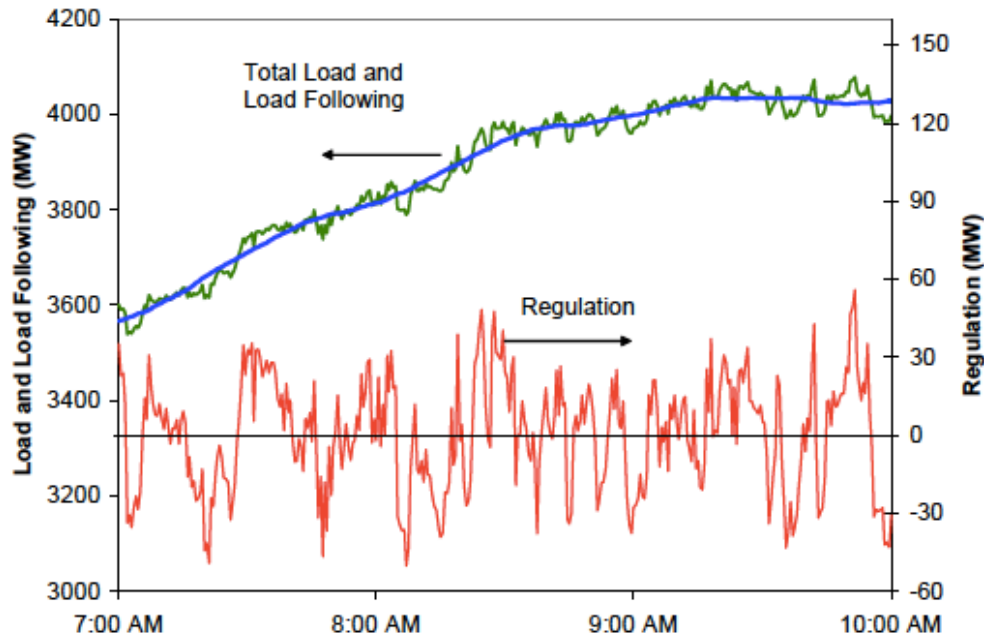


Figure 1. Regulation compensates for minute-to-minute imbalances between load and generation. Adapted from *Frequency Regulation Basics and Trends* (p. 5) by Oak Ridge National Laboratory, 2004.

Some energy storage-based technologies however, including solutions based on lithium-battery technology, have emerged as technologically and environmentally superior to traditional generation-based technologies for regulation. Since regulation represents keeping short-term grid fluctuations in balance, it neither generates nor consumes energy over a measurable amount of time, enabling an energy storage system with a finite capacity to accomplish regulation service successfully. In addition, energy storage can respond virtually instantaneously (in milliseconds) and precisely without the wear and tear or efficiency loss associated with performing regulation. As a result, more generators can be relieved from performing regulation, improving asset utilization. The table below summarizes the key requirements for an energy storage technology to perform regulation.

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Table 2. Energy storage characteristics required to perform regulation. Adapted from *Frequency Regulation Basics and Trends* (p. 19) by Oak Ridge National Laboratory, 2004.

Cycle Life (20-year)	500,000
Round-trip Efficiency	High
Response Time	1 – 10 minutes
Energy Delivery Duration	10 – 15 minutes
Service Duty	Continuous
Potential Technologies	Flywheels, battery banks, V2G

3.3 V2G Power

The fundamental concept of vehicle-to-grid (V2G) power is using *gridable* electric vehicles to provide electric power to the grid while they are parked and properly connected. The electric vehicles can be fuel cell vehicles, plug-in hybrids, or battery-electric vehicles. Most vehicles are parked an average of 95 percent of the time a day, the electrochemistry energy stored in their batteries are therefore, able to provide electricity to power grid when connected, with economic benefits both for the utilities and the vehicle owners [3].

To be able to provide V2G power, the vehicle must have three required elements [4]: (a) a connection to the grid for electric energy flow, (b) control or logical connection necessary for communication with the grid operator, and (c) controls and metering on-board the vehicle.

In contrast to the traditional one-way trip from grid to the vehicles, the electricity now flows two-way between the grid and the connected vehicles as needed. Illustrated in Figure 2, the electric power system operator (labeled ISO, Independent System Operator) sends out a control signal wirelessly, requesting for electricity. The signal can go directly to each individual vehicle (upper right of Figure 2), or to a fleet manager controlling a fleet of parked vehicles (lower right of Figure 2), or through a third-party aggregator managing dispersed individual vehicles' power (not shown in figure).

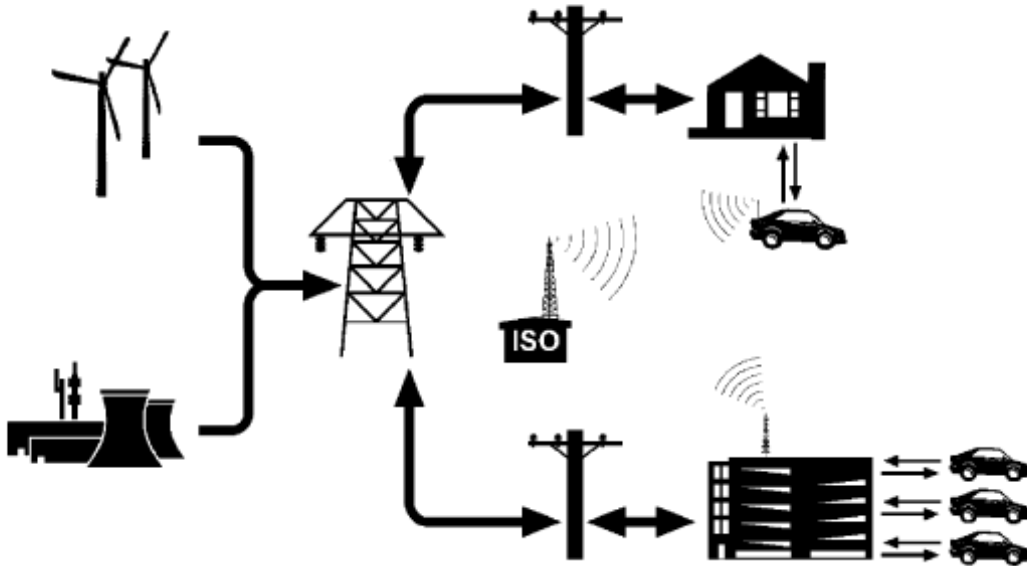


Figure 2. Illustrative schematic of power line and wireless control connections between vehicles and the electric power grid. Adapted from *Vehicle-to-grid Power Fundamentals: Calculating Capacity and Net Revenue* (p. 269) by W. Kempton, & J. Tomić, 2005.

3.4 V2G for Regulation

As discussed earlier, energy storage-based technologies are considered technically superior to traditional generation-based technologies for regulation. Generally, there are two reasons. First, an energy storage system with a finite capacity can accomplish regulation because regulation is a “zero-energy” service – it neither generates nor consumes energy over a measurable amount of time. Second, energy storage can respond virtually instantaneously and provide the power asked for precisely without significant efficiency losses associated with performing regulation.

V2G emerged as a side product with the introduction of electric vehicles to transportation. It is considered highly competitive for regulation by some researchers. Three reasons are presented in supporting V2G to be suitable for regulation by Tomić and Kempton in their study: (a) regulation service has highest market value for V2G, (b) stresses on battery are minimized, and (c) battery-electric vehicles are well suited to provide regulation services [5]. Their study suggests that “large profits come from providing V2G for regulation up and down” while admitting the estimated \$290 annual net income may be too small to justify transaction costs [6].

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Some other analysts have questioned the economic merits behind V2G based on the fact that the profit depends on the efficiency of battery systems and the difference in peak and off-peak electricity prices. First, if the efficiency works for V2G, then the grid-dedicated battery storage systems like battery banks would be more suitable for grid support. Second, with the mass adoption of EVs to provide V2G power, the price of grid balancing would eventually fall and thus make V2G no longer profitable.

The price issue is not within the scope of our analysis. However, a brief understanding of how the regulation prices are determined in a market-based power system is necessary. In practice, the opportunity costs associated with maneuvering generation assets performing regulation are driving the high market prices. First, to be able to perform regulation, the generator has to operate at a reduced power output instead of the rated output. Second, when a generator is required to regulation down, it further incurs an opportunity costs for being unable to sell more electricity. There is also an opportunity cost for regulation-performing generators to keep running at minimal capacity even if the electricity prices are lower than their marginal costs. Lastly, regulation requires frequent ramping up and down; the increased cost of wear and tear and reduced efficiency must also be compensated for.

It is not yet clear about the long-term effects of using V2G for regulation on battery's cycle life (typically defined as the number of times a battery can be charged and discharged before its capacity falls below 70 to 80 percent of its original capacity or nameplate energy). However, unlike thermal generators, battery-electric vehicles already have energy storage that is designed for large and frequent power fluctuations over short time periods, making V2G a strong candidate for supplying grid-balancing power. Interestingly, it was noted in a demonstration project of V2G for regulation in California that the battery capacity increased by about 10% during the testing [7].

4 Grid Support Technologies

4.1 Generation-based Technologies

In the U.S., about one percent of the total generation capacity is used to correct frequency deviations. Traditionally, fast-ramping generators such as natural gas-fired power plants and hydropower plants are called upon to provide grid balancing. In areas where the balancing capacity of natural gas and hydro is insufficient, coal-fired power plants would also be employed, even though they are more suitable for supplying base load given their design for steady outputs and lower fuel costs.

Because the construction of a hydropower plant is limited by geological requirements, cold, quick-starting, fast-ramping gas-fired power plants are taken as the primary generation-based technology for regulation service in the analysis. Two types of gas-fired power plants are widely commissioned for generation in the U.S., open-cycle gas turbine (OCGT) plants and combined-cycle gas turbine (CCGT) plants. OCGT plants are used to meet peak-load demand with efficiency of between 35% and 42% at full load. CCGT plants are similar to OCGT except that gas turbine exhaust is reused in a heat recovery steam generator (HRSG) to improve the overall efficiency, which currently falls within the range 52%–60% [8].

Table 3 below summarizes the average efficiency of electricity generation reported at full load conditions by power plant type in the U.S. These efficiencies represent the status quo of the entire electricity generation sector instead of the performance of a few newly installed generating units. The average efficiency is used because of the stronger incentives for the less efficient and less economical power plants to participate in the expensive regulation market. According to the table below, the most efficient use of fossil fuels is to put natural gas through a combined cycle plant (CCGT), converting nearly 45% of the energy embedded in natural gas into the form of electricity. However, when providing regulation to grid with high ramp rates, CCGTs may have to operate as OCGTs because their heat recovery steam generators would be damaged by the “frequent, rapid, high amplitude balancing” [9]. In our analysis, the 29.44% efficiency for gas turbine (OCCT) is used instead of the 44.78% for combined cycle.

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Table 3. Average generation efficiency by energy source and prime mover. Converted with data from *Electric Power Annual 2010*, updated in Nov. 2012, U.S. EIA.

Power Source	Prime Mover	Efficiency	Net Summer Capacity (MW)
Coal	Steam turbine	33.64%	316,800
	Combined cycle	W	
Natural Gas	Steam turbine	32.76%	407,028
	Gas turbine	29.44%	
	Internal combustion	34.41%	
	Combined cycle	44.78%	
Petroleum	Steam turbine	33.29%	55,647
	Gas turbine	25.49%	
	Internal combustion	32.72%	
	Combined cycle	32.58%	

Note: Efficiency is converted from heat rates that are reported at full load conditions for electric utilities and independent power producers. W = Withheld to avoid disclosure of individual company data.

4.1.1 Efficiencies of Gas Turbines

Gas turbines are most efficient at their rated outputs. To be able to ramp up and down quickly, they must operate at reduced outputs. Such reduced outputs impose heat rate losses with the significance depending on the ratio of the reduced output to rated output. According to Willem Post's study [9], gas turbines running at 80%, 50%, and 20% of the rated output have an average heat rate (equivalent to efficiency) degradation of 5.3%, 17.6%, and 81.8%, respectively. Therefore, gas turbines rarely operate below 40% of the rated output given the huge degraded heat rates. In addition, fast ramping up and down would further incur wear and tear on the generator and losses in heat rate. According to a study by KEMA Inc. [10], gas turbines performing regulation exhibit increased fuel consumption on the order of 0.5% to 1.5%. In this report, a 0.7% increase in fuel consumption (equivalent to efficiency) is assumed as KEMA did in their study. The table below presents the corrected efficiency for natural gas turbines providing regulation at an average 80% and 50% of rated output, respectively.

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Table 4. Corrected efficiencies for natural gas turbines performing regulation.

Prime Mover	At 100% of Rated Output	At 80% of Rated Output	At 50% of Rated Output
Gas Turbine	29.44%	27.76%	24.86%

These efficiency losses would then translate into higher operating costs and increased emissions. Such situation is worsened now as the electricity generation is being mandated to include more renewables across the nation through the renewable portfolio standards (RPSs) [11], increasing the demand for gas turbines to balance the variable power output of renewables. Therefore, energy storage technologies with high efficiency, fast response, and great cycle life seem to be a better fit for the ancillary services, especially regulation.

4.1.2 Emissions of Gas Turbines

Even though natural gas is the cleanest fossil fuel, as evidenced by the emission level comparison in Table 9, burning it still releases large quantities of gas emissions into the atmosphere. Large-scale emission preventative technology, Carbon Capture and Sequestration (CCS), has been developed to address carbon emissions from a conventional power plant. However, the commercialization of CCS is expensive and limited by geological formation to safely store carbon dioxide. Therefore, this project assumes no CCS is applied to a gas turbine in the analysis. The estimated emission levels for gas turbines are presented in Table 5 below.

Table 5. Emissions of Gas Turbines (lbs. per MWh).

Pollutant\Efficiency	29.44% (rated output)	27.76% (80% output)	24.86% (50% output)
Carbon Dioxide	1,356.030	1,437.895	1,605.854
Nitrogen Oxides	1.066	1.131	1.263
Sulfur Dioxide	0.012	0.012	0.014

4.2 Storage-based Technologies

Storage-based technologies do not directly generate electricity from fuels. Instead, they store electricity from the grid and send it back when needed. The term *round-trip efficiency* is usually used to describe the efficiency of storage systems. It is the ratio of electricity recovered from system to the electricity consumed for storage. Although the operation of storage-based technologies alone is almost emission-free, the electricity they consume and store is produced with a mix of fuels that are not free from emissions. As discussed in detail in Chapter 5, the reason for including the electricity generation, transmission and distribution into the analysis for storage-based technologies is due to the fuel-to-grid scope adopted in this project. In the U.S., the transmission and distribution losses average about 7% of the output according to U.S. EIA's estimate [12].

4.2.1 Hydroelectric Pumped Storage

Hydroelectric pumped storage (HPS) is the only conventional, mature commercial grid-scale electricity storage option available to date. Its use however, is strictly limited by the geographical requirements. Many of the best sites today have been taken already. Pumped storage represents the largest capacity versus other grid electricity storage options in the U.S., with an installed capacity of 20,538 MW in 2010 (U.S. EIA). This technology stores energy by pumping water to a high storage reservoir during off-peak hours, using excess baseload capacity from the grid. During peak-hours, the stored water is released through turbines to produce electric power.

Pumped storage comes online very quickly, typically within seconds, and provides hundreds to thousands of megawatts in a single facility, making them highly efficient in smoothing out transient fluctuations in generation and load. Their ramping rate can exceed hundreds of megawatts per minute. Built between 1976 and 1982 at Dinorwig, North Wales, the pumped storage project there has the world's fast response time, able to provide 1320 MW in 12 seconds [13].

The round-trip efficiency of hydroelectric pumped storage varies with plants. An old-fashioned pumped storage can have a round-trip efficiency (the ratio of electricity generated over the electricity consumed for pumping water) lower than 60%. To date, the Federal Energy

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Regulatory Commission (FERC) has authorized a total of 24 pumped storage projects that are constructed and in operation. Most of them were authorized more than 30 years ago. According to Electricity Storage Association (ESA), the round-trip efficiency for a current pumped storage project using a closed-loop system falls within the 70% to 85% range.

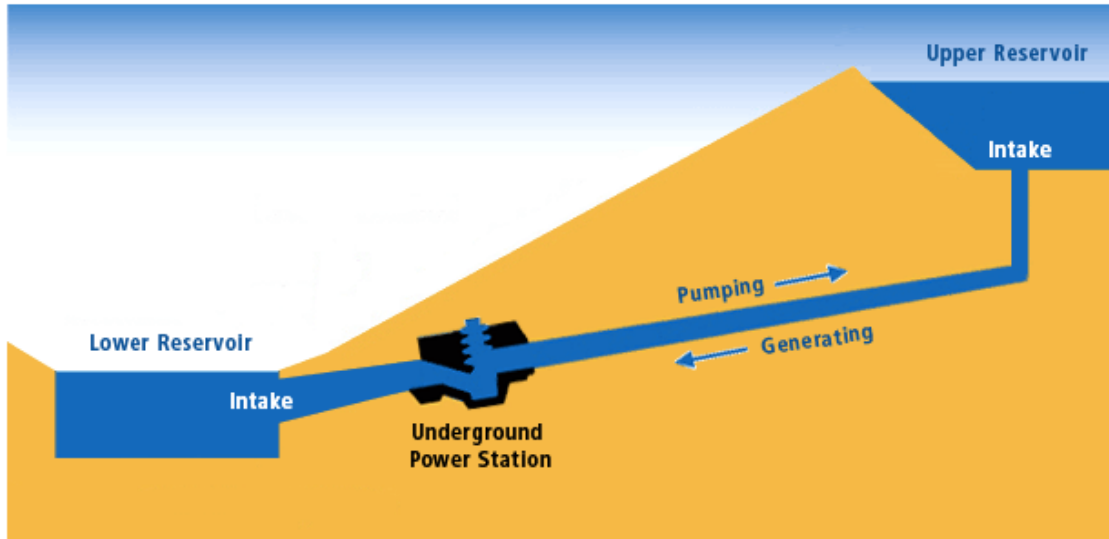


Figure 3. Illustrative schematic of a hydroelectric pumped storage project. Adapted from Federal Energy Regulatory Commission.

The environmental impact of pumped storage is usually considered relatively small for two reasons. First, the pumped storage requires a much smaller water reservoir than that of a conventional hydroelectric power station. In addition, the typical design life of a pumped storage station is 80-100 years. As a result, the environmental impact of pumped storage construction and operation is very low.

Table 6. Key features about a hydroelectric pumped storage project.

Round-trip Efficiency	75% (nominal, by IEEE)
Life	80 – 100 years
Response Speed	Within seconds
Power	Hundreds to thousands of MW

4.2.2 Battery Banks

With the technological advances in battery technology and the unlimited mobility in contrast to pumped storage, battery banks have been utilized for maintaining the grid's reliability for a few years. The world's largest installed battery bank is the 27 MW 15 minute nickel-cadmium battery bank in Fairbanks, Alaska, switched on in 2003. Earlier this year however, a 36 MW battery storage project was launched in China, using ferrous battery technology from a domestic solar and auto company, BYD.

The battery storage usually suffers from three drawbacks: (1) large upfront and maintenance costs, (2) a limited lifespan, and (3) a small capacity size (especially compared to pumped storage). However, researchers from Stanford University have developed a new electrode that can withstand 40,000 charging/discharging cycles in the laboratory. Even after the test this electrode could still return to more than 80% of its original capacity [14].

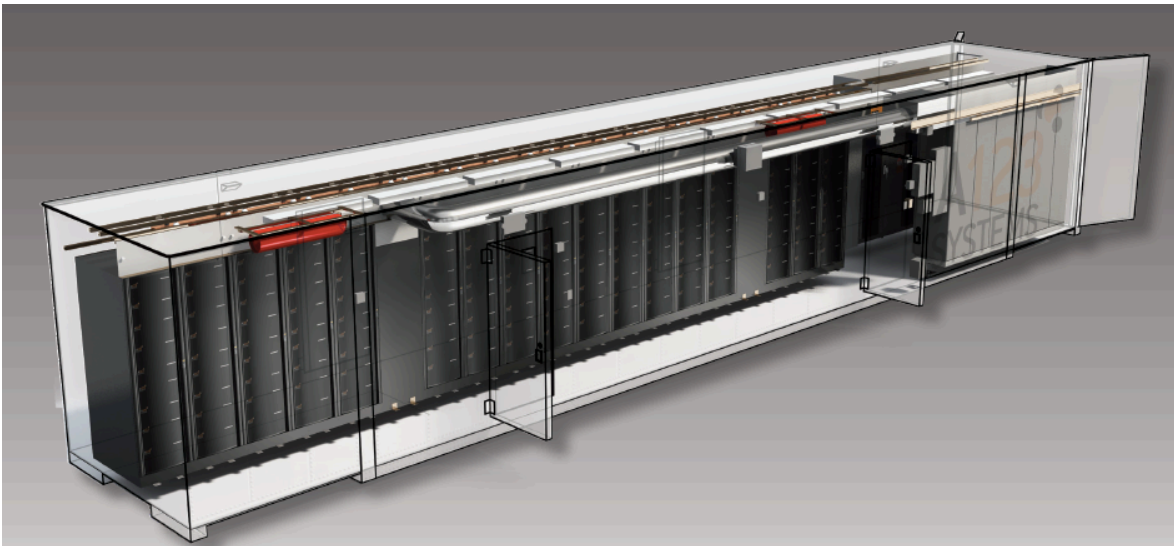


Figure 4. A single container of A123's Smart Grid Stabilization System (SGSS). Adapted from A123 Systems.

The round-trip efficiency (the ratio of the amount of electricity supplied to that consumed) of battery banks can be very high. The current lithium-ion battery bank produced by A123 Systems for grid energy storage claims to be 90% efficient, with a 2 MW output for each container. The table below summarizes the key features about A123's battery-based energy storage system.

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Table 7. Key features about a single container of A123's Smart Grid Stabilization System (SGSS™). Data extracted from *Grid Stability Battery Systems for Renewable Energy Success* by Charles Vartanian from A123 Systems.

Round-trip efficiency	90%
Cycle life	10,000 – multiple 100,000 depending on actual energy throughput
Response Speed	20 milliseconds
Energy Delivery Duration	15 minutes (at maximum power output)
Power	2 MW
Capacity	500 kWh

Like pumped storage, the operation of battery banks itself does not generate any emissions. However, electrochemical energy stored in the battery comes from the grid, which in turn comes from a mix of fossil fuels, nuclear and renewables. Besides, improper disposal of batteries can be very harmful to the environment. Appropriate regulation needs to be enforced to make sure the battery banks will be properly disposed when they are retired in the future.

4.2.3 Flywheels

A flywheel is a mechanical cylindrical assembly, or rotor, that stores energy as rotational energy. When absorbing energy, the motor connected to the flywheel draws power from the grid to spin the rotor at a high speed. When discharging, the motor switches to a generator mode and converts the inertia energy of the rotor back to electric power. In other words, the flywheel system is a kinetic, or mechanical battery, spinning at very high speeds to store energy that can be instantly available when needed. Friction must be kept minimum to prolong the storage duration, which is often achieved by placing the flywheel in a vacuum and using magnetic bearings, tending to make this method expensive. Another cost contributor is the strong material such as steel or composite materials required by high flywheel speeds.

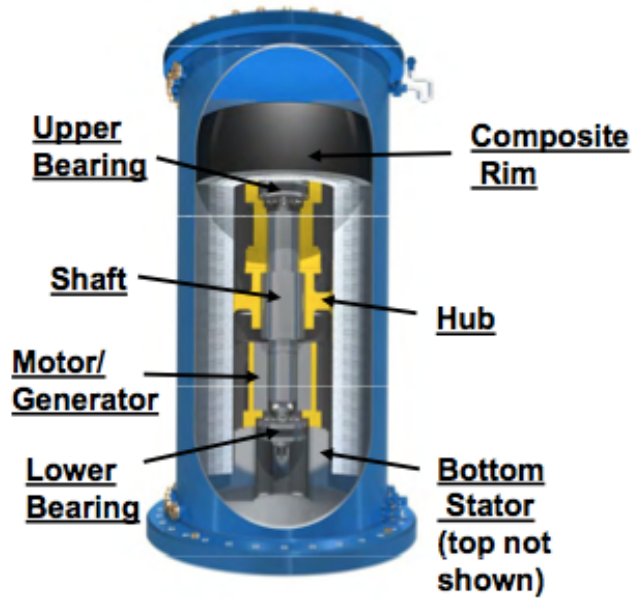


Figure 5. A single Smart Energy 25 Flywheel. Adapted from Beacon POWER.

A flywheel energy storage system can achieve a round-trip efficiency level as high as 85% [15]. Beacon POWER, a leading company in the flywheel-based energy storage solutions for grid-scale frequency regulation services, claims that “for the frequency regulation application, flywheel mechanical efficiency is over 97 percent, and total system round-trip charge/discharge efficiency is 85 percent”. The table below summarizes the key features about Beacon POWER’s flywheels.

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Table 8. Key features about a single Smart Energy 25 Flywheel produced by Beacon POWER.
Data extracted from *Fact Sheet: Frequency Regulation and Flywheels* by Beacon POWER.

Round-trip efficiency	85%
Cycle Life	Over 150,000 (full charge/discharge cycles at a constant full power charge/discharge rate; 6,000 – 8,000 effective cycles per year)
Response Time	< 4 seconds
Energy Delivery Duration	15 minutes (at 16,000 rpm, maximum)
Power	100 kW (at 16,000 rpm, maximum)
Capacity	25 kWh (at 16,000 rpm, maximum)

4.2.4 V2G

Essentially, the technology of V2G is similar to that of battery banks. They both use batteries to store electric power. For vehicle batteries to store and supply electricity to grid, the electric power first goes through a conversion from alternate current (AC) to direct current (DC) before it is later stored as electrochemical energy and stored in the battery. On its trip back to the grid, the electrochemical energy is converted to DC power and eventually AC. The whole process can add up to 20% or more losses of energy. Since V2G is still in its very early testing phase (only one single EV has been tested for V2G to date in PJM [16]), the information on V2G is limited. For the analysis, 80% is suggested by our project client *General Electric* and therefore assumed as the round-trip efficiency for V2G.

5 Analysis Methods

This project applies a fuel-to-grid scope to the analysis. For each grid support technology, their fuel-to-grid efficiencies are calculated based on the efficiency of each process involved within the scope. The emissions are then derived. The rest of this chapter gives a general introduction to the methods used for the analysis while efficiency data have been presented in Chapter 4.

5.1 Fuel-to-grid Scope

To compare storage-based technologies to generation-based technologies, a fuel-to-grid scope is adopted for the efficiency analysis. In other words, the efficiency at which fuels are converted to grid support is analyzed and compared. The efficiency comparison model in Figure 6 illustrates the steps taken by each technology to convert fuels into grid support. For gas turbines, the grid support directly comes from the natural gas they burn. For storage-based technologies, the grid support comes from electricity on the grid, which is generated with a mix of fossil and renewable fuels and has to go through a storage process.

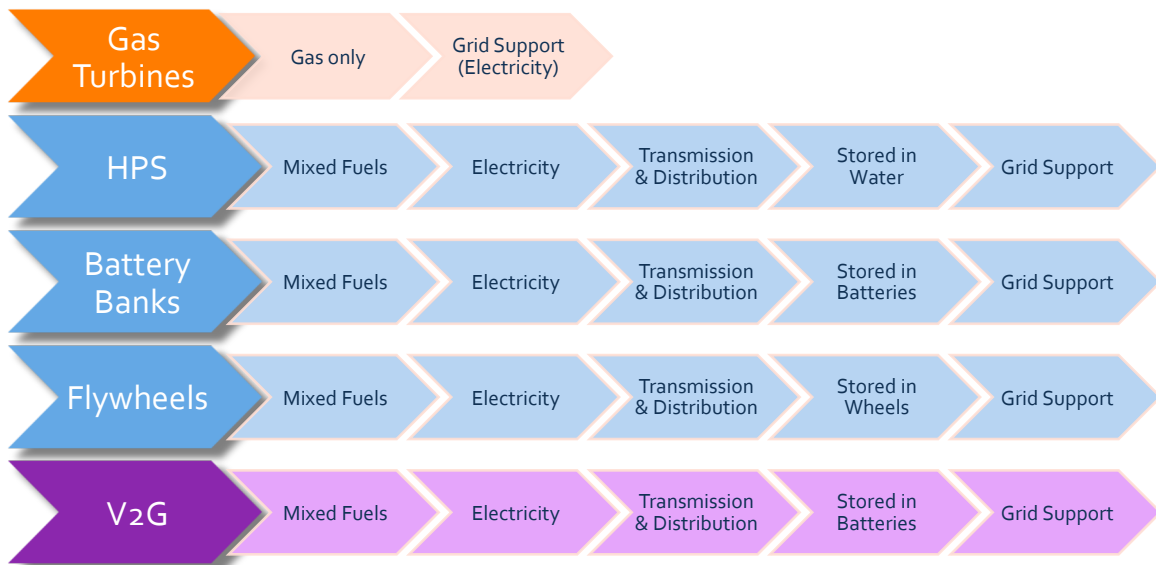


Figure 6. Efficiency comparison model.

5.2 Obtaining Efficiency

A few assumptions are made for calculating the efficiency of generation-based technologies.

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First, open-cycle natural gas turbines are picked to represent the generation-based technologies; and their industry average heat rate (generation efficiency) is used as basis. Second, the efficiency for gas turbines is adjusted to efficiency losses that are caused by providing regulation. Third, Carbon Capture & Sequestration (CCS) is excluded from the scope of our analysis. The calculation uses U.S. EIA 2010 data as input.

For storage-based technologies, including HPS, battery banks, flywheels, and V2G, their efficiencies are obtained through public information. In particular, for HPS, a nominal efficiency rate by IEEE is used. For battery banks and flywheels, efficiencies of their current commercialized products are used. For V2G, its efficiency is estimated based the nature of this technology.

5.3 Calculating Emissions

For gas turbines, their emissions are calculated based on their efficiency and the emission levels for natural gas (Table 9). However, for storage-based technologies, since their energy input is electricity on the grid, their emissions are calculated based on the round-trip efficiencies and the emission levels of electricity. The emission levels for grid electricity are calculated with net generation and total emissions in U.S. EIA 2010 report, presented in Table 10.

Table 9. Fossil Fuel Emission Levels (lbs. per billion BTU of energy input). Adapted from *Natural Gas Issues and Trends 1998*, U.S. EIA. Data still current as of 2010.

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591

Table 10. Average emissions for U.S. electricity generation in 2010. Calculated with data from *Electric Power Annual 2010*, revised Jan 2012, by U.S. EIA.

Emissions	Lbs. / MWh
Carbon Dioxide	1,276.611
Sulfur Dioxide	2.887
Nitrogen Oxides	1.331

6 Efficiency and Emission Comparisons

6.1 Efficiency Comparison

Table 11 below summarizes the efficiencies for different grid support technologies. It is clear that storage-based technologies have much higher efficiencies by themselves. This is mostly due to their technological nature of storing *already-tapped* energy instead of generating from the fuels. Among the storage-based technologies, battery banks rank number one with 83.70% efficiency while V2G is nearly 10% less efficient. Therefore, if efficiency is the only measure, V2G seems to be an inferior option to battery banks for supplying regulation.

Table 11. Efficiency by grid support technology.

Grid Support Technology	Efficiency
Gas turbines, 80%	27.76%
Gas turbines, 50%	24.86%
HPS	75.00%
Battery Banks	90.00%
Flywheels	85.00%
V2G	80.00%

To be able to compare generation-based technologies with storage-based technologies from a fuel-to-grid perspective, the efficiency of electricity generation must be known. Unfortunately it is unclear that how efficient the electricity is produced when the fuels include renewables. There is no measure on energy inputs for renewables. However, it is clear that the fossil fuels are converted into electricity at an average efficiency of 33% (which remained the same all the way back to 1957 [17]). If 33% is used to represent the electricity generation efficiency, the resulting fuel-to-grid efficiencies are still good enough for comparison purpose. The calculated fuel-to-grid efficiencies are then presented in Table 12 and compared in Figure 7. From the comparison it seems only battery banks are efficient enough to compete with gas turbines, assuming fossil fuels are the only source for electricity generation. However, since highly efficient natural gas generators and fossil fuel-free renewables are being added to generation, the lower efficiencies of other grid support technologies can be considerably mitigated and may eventually become irrelevant.

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Table 12. Fuel-to-grid efficiency by grid support technology, assuming electricity on the grid is generated with fossil fuels only.

Grid Support Technology	Fuel-to-grid
Gas turbines, 80%	27.76%
Gas turbines, 50%	24.86%
HPS	23.02%
Battery Banks	27.62%
Flywheels	26.09%
V2G	24.55%

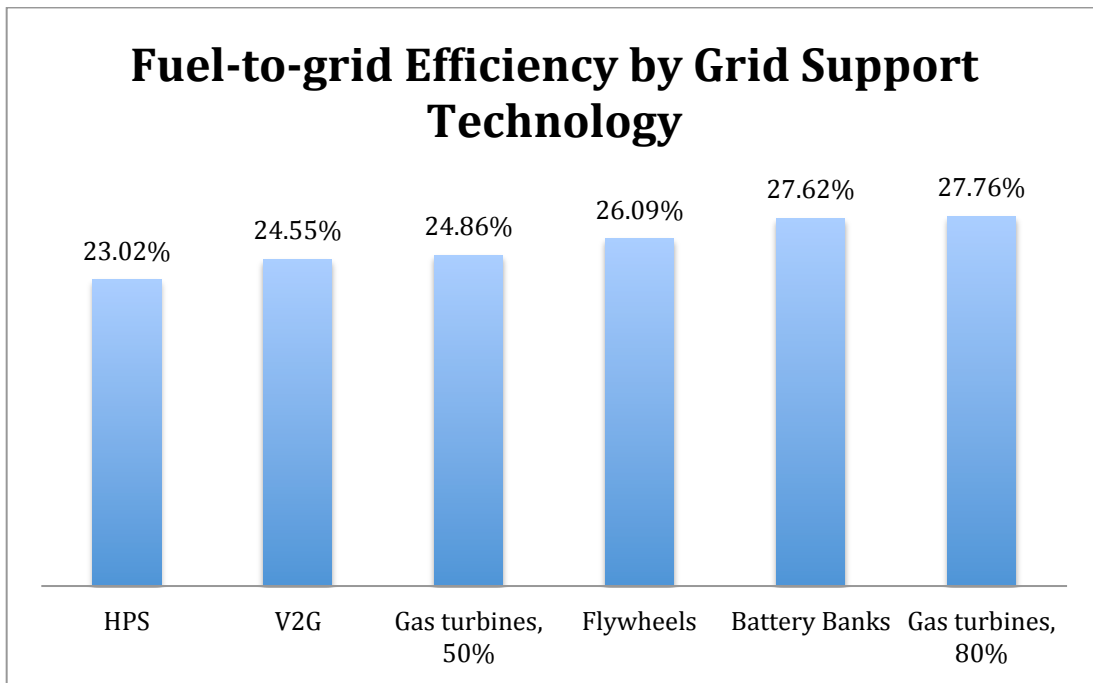


Figure 7. Fuel-to-grid efficiency comparison by technology, assuming electricity on the grid is generated with fossil fuels only.

6.2 Emission Comparison

Based on emission and efficiency information discussed in previous chapters, Table 13 exhibits the emissions caused by each grid support technology in lbs. to provide 1 MWh of grid-supporting electricity. One general pattern can be observed from the table when comparing generation-based to storage-based technologies – all of the storage-based technologies have caused higher CO₂, SO₂, and NO_x emissions.

Table 13. Emissions to provide 1 MWh of electricity for grid support in lbs. (Emissions for storage-based technologies come from the grid electricity they consume, which in turn comes from mixed fuels.)

Technology \ Emissions	Gas turbines, 80%	Gas turbines, 50%	HPS	Battery Banks	Flywheels	V2G
Carbon Dioxide	1,438	1,606	1,830	1,525	1,615	1,716
Sulfur Dioxide	0.012	0.014	4.138	3.449	3.652	3.880
Nitrogen Oxides	1.131	1.263	1.909	1.591	1.684	1.789

The different emission levels of fossil fuels may explain the observation above. Table 9 shows burning natural gas instead of coal will lead to a 43% reduction in CO₂, 80% in NO_x and almost 100% in SO₂. In other words, generating electricity exclusively through natural gas is much cleaner than that from a portfolio primarily consisting of coal and natural gas. Consequently, storage technologies that consume grid electricity will increase the emissions. Figure 8, 9 and 10 illustrate the percentage changes in the amounts of emissions caused by grid support technologies to provide 1 MWh of electricity for grid support in lbs. The baseline here is the original amounts of emissions for 1 MWh of electricity on the grid (Table 10).

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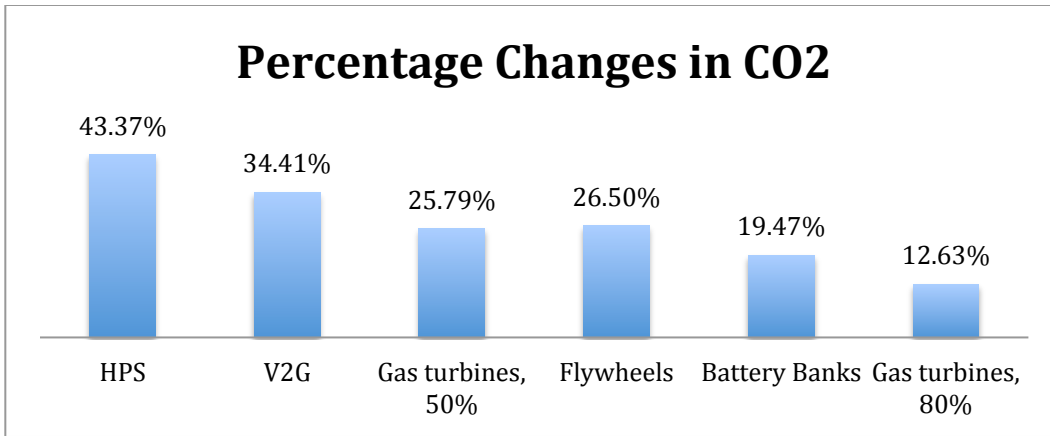


Figure 8. Percentage changes in CO2 emissions compared to original emissions of producing 1 MWh of electricity.

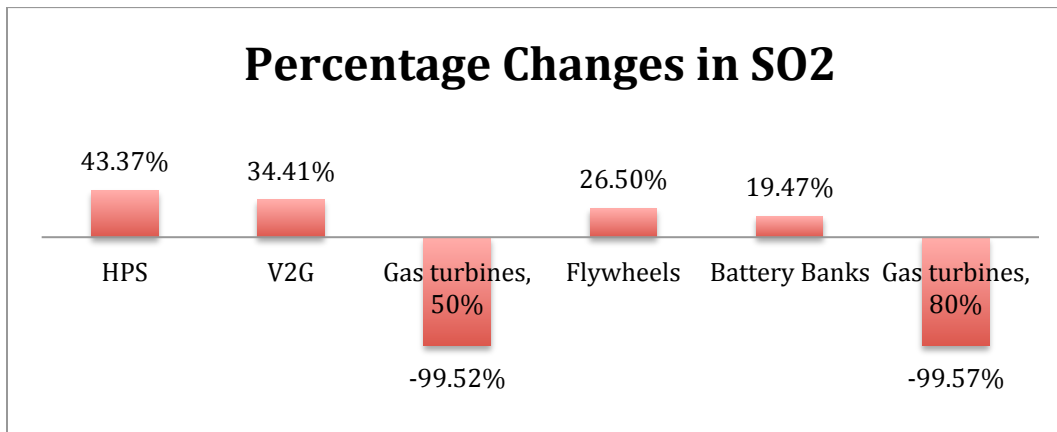


Figure 9. Percentage changes in SO2 emissions compared to original emissions of producing 1 MWh of electricity.

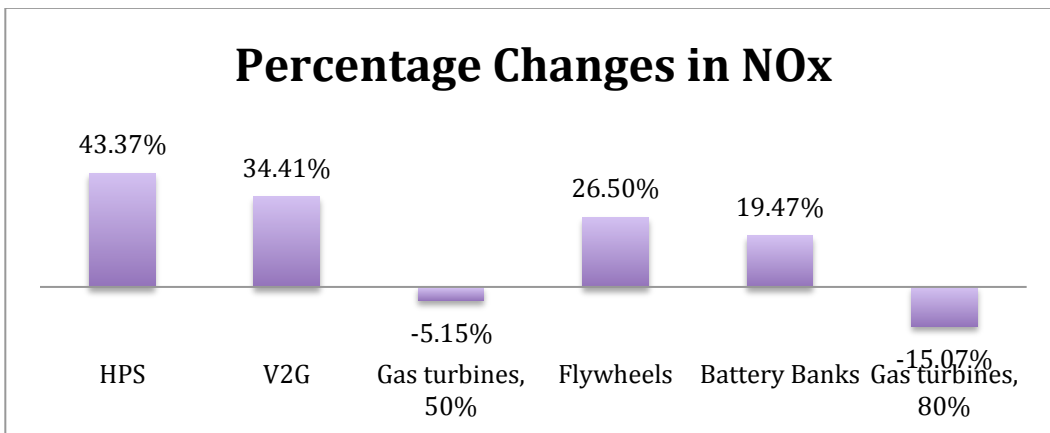


Figure 10. Percentage changes in NOx emissions compared to original emissions of producing 1 MWh of electricity.

7 Conclusions

Energy storage can relieve power generators from supplying grid support and hence improve their performance. As the electricity generation is shifting towards more renewables, energy storage can also help balance the variable power output of renewables, making them a more reliable power source. When selecting the most suitable storage-based technology for grid support or power balancing, the efficiency and emissions play an important role in the decision-making process.

Three general conclusions can be drawn from the analysis of this project given the current U.S. generation efficiency and fuel mix. First, energy storage-based technologies achieve a lower fuel-to-grid efficiency than conventional gas turbines do. Second, V2G is less efficient in delivering grid support than grid-dedicated battery banks and flywheels. Finally, storage-based technologies, especially V2G, would significantly increase carbon dioxide, sulfur dioxide, and nitrogen oxides emissions.

The application of V2G would seem unfavorable from an efficiency and emission perspective. However, further studies on the technical feasibility and financial implications of large-scale V2G application will be necessary before any firm conclusions can be made. Opportunities still exist for the commercialization of V2G given its great mobility in supplying power at load as well as the lower financial burden to utilities.

In order to address the efficiency and emission issues associated with V2G and other storage-based technologies, the electricity generation efficiency must be improved and the fuel mix become cleaner. In the short-term, old and inefficient power plants, especially coal-fired power plants can be retired and replaced with both natural gas and renewables. Over the long run, a significant shift towards renewables in electricity generation would be ideal for achieving an efficient and environment use of electricity.

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