CPS Energy *Flex*POWER Bundle Request for Information (RFI)

Alternative Storage Technologies Overview

CPS ENERGY

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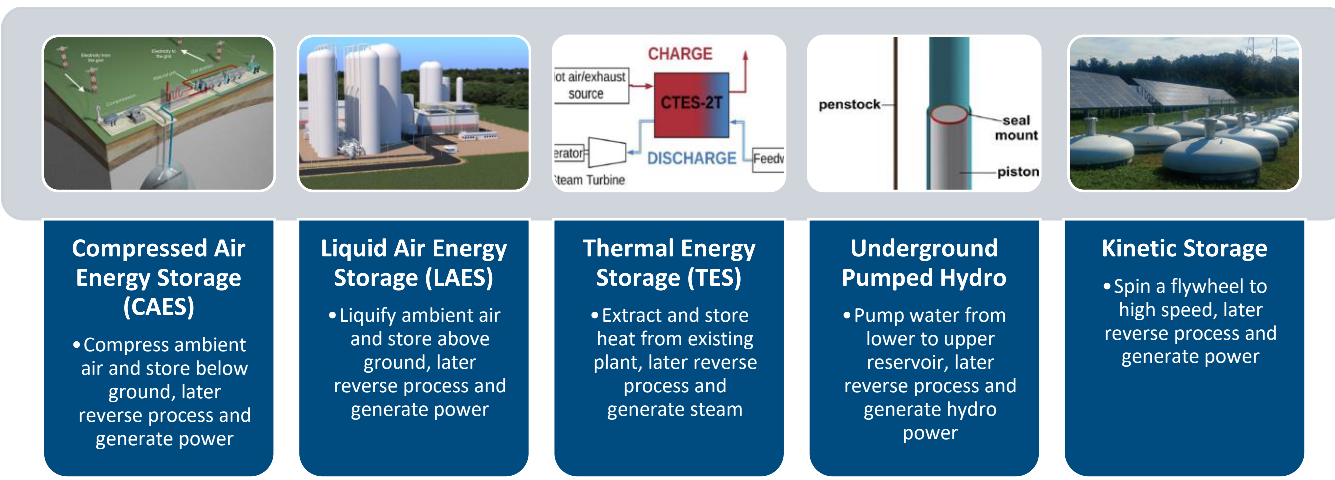
Summary

This document summarizes the review performed by the ***Flex*POWER Bundle** Team of the interesting alternative technologies that companies have described in their responses to the ***Flex*POWER Bundle** RFI (RFI). The majority of these are energy storage technologies.

Energy storage has become a vital new component for electric utilities in their quest to integrate high levels of renewables. Battery energy storage is the leading technology in this space, using the now familiar lithium ion chemistry that we see all around us today in automobiles, cell phones and the latest utility scale battery storage projects. However, the sheer volume of lithium ion-based storage needed by the power industry to integrate the large amount of renewables planned has spurred advancement in other storage technologies. In addition, as more solar resources are added to the grid, there is a greater need for larger and longer duration energy storage to better handle the resulting larger intermittency impacts.

The alternative energy storage technologies described in the RFI responses are summarized in the figure below.



Compressed air energy storage involves compression of ambient air for storage below ground, with subsequent reversal and expansion of the air through a turbine to generate power. Liquid air energy storage involves liquefaction of ambient air to extremely low temperatures, with subsequent reversal and gasification of the air through a turbine to generate power. Thermal energy storage is an integrated storage approach, where heat is extracted from a host plant or process, with subsequent reversal to extend the performance of the host process such as a steam power plant. Underground pumped hydro is an adaptation of the common hydro pumped storage technology where water is pumped uphill and then subsequently reversed and released downhill for power generation. With the underground technology the reservoirs are located underground and man-made allowing for smaller and simpler projects. Finally, kinetic storage involves using power to spin a flywheel with later reversal to generate power.

The following sections provide more detail on each of these technologies, their relative advantages and disadvantages, and some information about the relevant responses received. The table below summarizes information about each technology. Information in the sections below and in the table is generalized from the responses so as not to reveal specific confidential information. Some of the information is from publicly available sources as noted.

Comparison Table

	Compressed Air Energy Storage (CAES)	Liquid Air Energy Storage (LAES)	Thermal Energy Storage (TES)	Underground (UG) Pumped Hydro	Kinetic	Flow Battery	H2 Bromide
Nominal Duration (hours)	4-48	4-12	4-14	4-16	0.25	4-6	undetermined
Round trip efficiency	70%	50-60%	78-90%	84%	70-80%	68%	67%
Response Time	3-10 minutes	< 1 minute claimed	15 minutes	20 seconds	< 1 second	< 1 second	undetermined
Heat Rate (Btu/kwh)	4,200-4,300	n/a	undetermined	n/a	n/a	n/a	undetermined
CO2 emissions rate (lbs. CO2/MWh)	475-525	n/a	undetermined	n/a	n/a	n/a	undetermined
Max Cycles or Lifetime	1x daily/30 years	undetermined	undetermined	undetermined	200,000, 20+ years	10,000, 15 years	undetermined
Degradation factor	About 4- 5% every 24,000 hours	undetermined	undetermined	undetermined	undetermined	undetermined	undetermined
Limitations of depth of discharge	unknown	undetermined	undetermined	undetermined	undetermined	undetermined	undetermined
*Capital Cost ($/kW)***	1,700 (2018)[1]	undetermined	undetermined	undetermined	2,400 (2018)[2]	2,600 (2018)[3]	undetermined

[1] Energy Storage Technology and Cost Characterization Report, July 2019, Pacific Northwest National Laboratory PNNL-28866, tables ES-1 and ES-2.
[2] Energy Storage Technology and Cost Characterization Report, July 2019, Pacific Northwest National Laboratory PNNL-28866, tables ES-1 and ES-2.
[3] Energy Storage Technology and Cost Characterization Report, July 2019, Pacific Northwest National Laboratory PNNL-28866, tables ES-1 and ES-2.

Compressed Air Energy Storage (CAES)

DESCRIPTION

CAES storage technology involves using electrically-driven compressors and low-cost off-peak power from the market (for example, during nighttime periods) to compress ambient air and store the air in a large vessel or underground cavern. During peak demand periods (for example, during sunset) the flow is reversed, and the air is expanded through a gas-fired power turbine that generates power for sale to the market. Net revenue is generated due to the price difference between peak and off-peak power (price arbitrage) and the sale of ancillary services to the transmission operator (regulation up/down and frequency responsive reserves (also known as spinning reserves), non-spinning reserves, and black start service).

TECHNICAL PARAMETERS

CAES plants are typically sized for large storage capacities and durations. .

CAES plants that do not utilize heat exchange between the compression and expansion cycles (known as diabatic CAES) have a round trip efficiency of 40-50 percent. The two existing operating CAES plants (one in Alabama and one in Germany) utilize diabatic CAES. New plants propose to use heat transfer, or adiabatic CAES, and have reported round trip efficiencies in the 70 percent range.

The response/discharge time is similar to that of conventional gas-fired combustion turbine resources, responding within 3 minutes for regulation up/down and spinning reserve, and within 10 minutes for non-spinning reserve service.

Market information indicates a carbon dioxide (CO_2) emissions rate of approximately 500 lbs. CO_2/MWh assuming a heat rate of approximately 4,300 Btu/MWh and a CO_2 intensity rate for natural gas of approximately 120 lbs. CO_2/MMBtu. This CO_2 emissions rate of approximately 500 lbs. CO_2/MWh is about 32 percent less than that of a new combined cycle power plant, which is approximately 735 lbs. CO2/MWh.

With respect to maximum cycles and lifetime, projects are typically designed with the ability to cycle once a day for a lifetime of 30 years. However, salt cavern life is impacted by the frequency and amplitude of pressurization (storage) cycles and geo-mechanical studies must be performed to estimate the range of frequency and amplitudes that are acceptable to mitigate damage (micro fracturing) of the salt and achieve this performance.

Performance degradation is similar to that for conventional gas-fired combustion turbine resources, losing approximately four to five percent of capacity and two percent of efficiency for every 24,000 hours of operation. Some of this loss is restored with each combustion turbine major overhaul.

With respect to depth of discharge, there is no readily available information. Depth of discharge would be determined through the aforementioned geo-mechanical studies.

The deployment of CAES tends to be geographically limited to areas with known existing underground salt bodies such as East Texas, Louisiana and western Alabama. However, CAES can also be developed using depleted gas and oil fields which are far more common across the US (e.g., West Texas, Colorado, Oklahoma) although well fields are generally more porous and therefore relatively poor for holding pressurized air.

With respect to safety, beyond the normal power plant safety issues such as fuel leakage and equipment failure, it is possible that the underground formation holding the air under relatively high pressure could break down due to failure of the overlying rock up to the surface; sudden failure of the sealing membrane outward to other formations, and failure of the valving closing the cavern. We are unable to find reports of such failures in the public domain.

RELATIVE ADVANTAGES:

Advantages of this technology relative to other storage technologies include:

- Very large scale (several hundred MW) and long duration (multiple days) storage is possible due to economies of scale of mining large caverns or adapting large well fields.
- The compression and generation technology are a developed technology, using conventional equipment with decades of operating history.
- The compression and generation are highly flexible and can provide a broad range of ancillary services to the system such as regulation up/down, spinning reserves, non-spinning reserves and black-start service.
- The generator is a rotating mass providing synchronous inertia, voltage support and short circuit power benefits to the ERCOT grid as opposed to Li-ion and flow batteries which are not rotating devices.

RELATIVE DISADVANTAGES

The disadvantages of this technology relative to other storage technologies includes:

- Natural gas is burned, resulting carbon and other emissions. Natural gas is injected into the return air stream to prevent icing due to the expansion and to boost power generation.
- Cavern preparation is time consuming – it may take one to two years to solution mine the cavern with water.
- A byproduct of the cavern solution mining is a large volume of brine. The brine needs to be removed and disposal can be expensive and time consuming.
- Only two utility scale plants are in operation worldwide.

ENVIRONMENTAL IMPACTS

Environmental impacts include air emissions from natural gas combustion including carbon. Mining of the underground cavern will require significant amounts of water and will result in significant amounts of brine that need to be handled and disposed of properly so as not to impact water resources. End of life impacts include disposal of the generating equipment and sealing off the subsurface structures.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

CAES technology is a technology currently in operation as evidenced by two large scale plants that have been in utility operation for many years, a 290 MW plant in Huntorf Germany and a 110 MW plant in McIntosh Alabama.

RESPONSES RECEIVED

Responses concerning this technology included:

- A detailed response for the traditional CAES approach described above.

- A description of a technology using compressed natural gas storage. Storage tanks can be above ground. No capital cost is indicated.
- A response with technology using purpose-built underground storage, which promises faster development, a smaller foot print and less environmental impact than solution-mined caverns. No capital cost is indicated.
- Two responses with technology adding a thermal energy storage system. Heat is removed from the air after compression, stored, and then added back to the air during expansion to avoid the use of natural gas. No capital cost is indicated.

Liquid Air Energy Storage (LAES)

DESCRIPTION

LAES is a long duration energy storage process based on existing air liquefaction and power recovery cycles. The system charges from the grid using an electrically-driven industrial air liquefier. Air is chilled until it changes phase into a liquid, storing energy during the process. The energy is stored in the form of liquefied air held at low temperatures in thermally insulated vessels. Upon system demand, the energy (liquid air) changes phase back into a gas as it is released from the tanks and expanded through a steam-derivative turbine expander to drive a synchronous generator and supply energy to the grid. Heat from the refrigeration process can also be stored and used to enhance energy recovery.

TECHNICAL PARAMETERS

LAES plants have been sized for moderate storage capacities and durations. Two responses to the *Flex*POWER Bundle RFI indicate capacities between 10-100 MW and durations between 4 and 12 hours.

LAES systems have a round trip efficiency of approximately 50-60 percent. Additional waste thermal streams can be incorporated to further increase performance.

LAES system benefits include no additional air emissions or additional water usage. The technology produces no waste discharges or emissions into the atmosphere, resulting in little to no environmental impacts.

Compared to existing compressed air energy storage systems that require below ground storage, LAES systems store the liquified air in steel tanks above ground. The first respondent states that their proposed LAES facility requires a small footprint of approximately 2.5 acres for a 50 MW system, which includes the charging module, storage tanks, discharge unit and all other required auxiliary systems and noise abatement enclosures.

LAES uses relatively established technology for the pressure vessels. The components and processes used are derived from industrial gas and power generation, which contribute to its safe operation and design life.

With respect to response/discharge time, the first respondent indicates startup or shutdown of the LAES can be accomplished in less than 1 minute. However, starting from a long-term shutdown (>1 day long) will likely take longer due to the time required to prepare the vaporization process.

There are no CO_2 emissions associated with this technology, other than emissions that might be attributed to the electric energy from the grid used for the liquefaction process.

With respect to maximum cycles and lifetime, no information is available.

With respect to performance degradation, no information is available, but we expect it is similar to that for conventional air liquefaction and vaporization processes.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, there are no significant restrictions. LAES can be located in isolation as a standalone storage facility or in close proximity and integrated with an existing power plant to provide electricity or heat to the LAES process.

With respect to safety, no information is available.

RELATIVE ADVANTAGES:

- There are no local combustion or air emissions. The emission footprint from the charging energy would need to be assessed.
- No underground mining or excavation is required.
- The required footprint is relatively small, and multiple trains can be added in a modular approach to achieve multi hundred megawatt storage capacities.
- The liquid air is valuable in itself, and can be extracted for further processing for industrial gasses.
- Systems typically use off the shelf products with long life cycles.

RELATIVE DISADVANTAGES

- Round trip efficiency is 50-60 percent which is significantly below that for battery storage, adiabatic CAES and pumped hydro technologies. Air liquefaction is less efficient than air compression due to the refrigeration requirement.
- There are no known utility scale plants in operation.

ENVIRONMENTAL IMPACTS

As stated above, the LAES technology is a no-combustion process and produces no additional air emissions. In addition, there are no water requirements. The first respondent states that this will likely result in low permitting requirements given the relatively small footprint, no fuel supply, zero water requirements and air emissions.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

There is a 5MW/15MWh pilot plant at a landfill facility in the United Kingdom, which started operating in June 2018. No capital cost is indicated.

RESPONSES RECEIVED

The second respondent's response indicated technology similar to first respondent, except that second respondent does not incorporate thermal energy storage for improved efficiency.

Thermal Energy Storage

DESCRIPTION

Thermal energy storage (TES), can be considered an indirect storage technology since it extends the performance of an existing host process or plant. It extracts heat from a host process or plant, which is stored in some manner to be used for power generation process at a later time. This is similar to adding battery energy storage to a solar plant, which allows generation from the solar plant to extend beyond sunset.

TECHNICAL PARAMETERS

Six responses to the *Flex*POWER Bundle RFI were received in this category of which only two responses provided detailed information, including a complete generation solution. We also reviewed the technical parameters for these TES systems.

Thermal energy storage typically involves the use of a medium to store heat generated either from a host process or by using energy from the grid. Thermal energy storage can be achieved in many ways. Of the two complete responses, the first respondent's system utilizes a common material as the medium to store heat energy, while the second respondent's system utilizes a less common material as the heat storage medium. Both respondents' systems may be utilized to completely replace preexisting heat recovery systems or supplement the same in order to realize better overall system performance and reduce dependence on heat recovery systems.

TES facilities have been sized for moderate storage capacities and durations. The responses indicate capacities of up to 40 MW and durations up to 14 hours.

The round-trip efficiency for a TES system will depend on the technology utilized. The first respondent states its system's round-trip efficiency is expected to be around 78 percent, which will fluctuate with change in ambient temperature and pressure. The second respondent states its system's round-trip efficiency is expected to be around 90 percent depending on the efficiency of the associated steam turbine generator.

With respect to response/discharge time, TES systems may allow for reduced response times due to preheating capabilities. The first respondent's system can achieve hot response times of under 15 minutes. Discharge times vary and depend on the technology utilized but appear to typically range between 4 to 14 hours.

CO_2 emissions associated with this type of technology can vary depending upon the technology and fuel used for the host. However, no specific information for CO_2 emissions are available.

The useful life of the host plant producing heat energy may be improved, leading to longer life and avoidance of new plant capital expenditures. This is because the host plant is expected to run less on account of storing the heat energy. However, it is not clear how much expected life of the host plant can be extended by using this type technology. There is also no information available regarding the useful life of the storage system as these storage systems are relatively new.

With respect to performance degradation, no specific information is available.

With respect to maximum cycles, no information is available.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, TES must be located in close proximity and integrated with an existing power plant to provide electricity or heat to the TES process.

With respect to safety, no information is available.

RELATIVE ADVANTAGES:

- Relatively low-cost technology and low-cost equipment and materials can be used.
- The life and performance of the host plant are improved, leading to longer life and avoidance of new plant capital expenditure.

RELATIVE DISADVANTAGES

- Applications must be customized to suit the size and type of the host plant.
- Siting is not flexible - it must be built at or very near the host plant site.
- There are no known utility scale plants in operation.

ENVIRONMENTAL IMPACTS

No information was provided for the technologies indicated.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

No information was available for the technologies provided.

RESPONSES RECEIVED

Currently, the first respondent is working on a pilot program and has indicated that a pilot project can run anywhere between six to 12 months while a full-scale demonstration can be done between 12 and 18 months. The technology is comprised of a storage medium installed near the host system that functions like a heat recovery steam generator (HRSG) but with energy storage capabilities that allow for a maximum of four-hours without charging or the host being in operation.

The second respondent’s technology involves an electric resistance heating of a storage medium insulated within a steel container. A closed-loop circulates an inert gas mixture through the medium and conducts heat to an application-specific heat exchanger delivering steam, hot water or thermal oil at the temperature and pressure matching the customer’s requirements. In addition, units will be able to charge with AC or DC power, eliminating the need for inverters, and to simultaneously charge and discharge, providing an edge in ancillary markets.

When paired with any thermal generation stations that have a steam turbine generator, these technologies can help optimize performance through preheating, maintain vacuum seals on equipment, increase output during peak production, and increase duct firing capacity. They can also be connected to wind or solar facilities and absorb curtailed and clipped energy.

Underground Pumped Hydro Storage

DESCRIPTION

Underground pumped hydro is a novel adaption of the traditional above ground pumped storage technology. With the underground technology the reservoirs are located underground and man-made. Out of three responses to the ***FlexP*OWER Bundle** RFI, the first respondent's technology stores energy by using energy from the grid to pump water down and hydraulically lift a massive piston inside a shaft. The process is then reversed to allow the piston to drop and force the water back up through the same pump serving as a generator, much like in standard above ground pumped storage applications. The second respondent's technology pumps water at high pressures into underground rock formations. The third respondent's technology utilizes a sealed pressurized geomembrane which is placed in a basin and covered with soil such that the weight of the overlaying soil creates a gravity-imposed pressure on the water corresponding to the height difference (app. 30-50 m) in traditional pumped hydro systems (PHS). Water is released from the system and a turbine and a generator regenerate the electric energy with an efficiency of 75-85 percent.

TECHNICAL PARAMETERS

Underground pumped hydro facilities have been sized for large storage capacities and durations. The first respondent's response indicates capacities up to 400 MW and durations up to 16 hours.

Round trip efficiency is reported at 80 percent by the DOE.

With respect to response/discharge time, no information is available. DOE reports a response time for traditional above ground pumped storage ranging from five seconds to five minutes so this same performance may be possible from underground pumped storage.

With respect to CO_2 emissions, there are no CO_2 emissions associated with this technology other than emissions that might be attributed to the power source used to pump or pressurize the water.

With respect to maximum cycles and lifetime, no information is available.

With respect to performance degradation, no information is available.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, the first respondent's technology can be located in isolation as a standalone storage facility or in close proximity and integrated with an existing power plant to absorb/discharge electricity to the process. The second respondent's technology relies on existing geologic reservoirs and is therefore less geographically flexible.

With respect to safety, no information is available.

RELATIVE ADVANTAGES:

- The reservoirs can be custom sized and modular, allowing deployment of smaller projects or groups of projects in urban environments

- The reservoirs are located below ground resulting in less surface disturbance and potential impact on surface lakes and streams
- The water is "private", meaning that it is not owned by the government but rather by a private landowner and therefore permitting and water rights complexity is low.

RELATIVE DISADVANTAGES

- For the first respondent's technology, the shaft and piston seals must be designed and constructed to a relatively high precision to ensure both adequate sealing and ease of travel. This is challenging in underground construction.
- The second respondent's technology is highly dependent upon sub-surface geology and therefore the risk of degradation and performance loss is relatively high.
- There are no known utility scale plants in operation.

ENVIRONMENTAL IMPACTS

Due to the underground nature of all three technologies, the environmental impacts may be low. The closed loop and closed reservoir layout for each of the technologies results in a much lower use of water. Overall, the environmental impacts for all three projects appear to be low compared to conventional technologies.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

All three technologies are in the conceptual or demonstration phase. None have yet achieved commercial operation. As a result, the maturity of this technology is in the early stages of research and development.

- Respondent 1 – This technology is in the demonstration phase. The technology does not yet have data on cost, efficiency, or ability to scale the technology for commercial operation. This technology relies on underground construction resulting in potentially lower environmental impacts.

- Respondent 2 – A demonstration project is underway in Texas with funding from a grant. As with the other two technologies in this category, there are no operating projects so questions of efficiency, cost and ability to scale to commercial operations remain open.

- Respondent 3 – This technology appears to be further behind the other two in that a demonstration project does not appear to be in construction. As with the other technologies in this category, no data yet is available to determine cost, efficiency or scale to commercial operation.

RESPONSES RECEIVED

<u>Respondent 1</u>: Deep underground water storage shaft. The technology stores energy by hydraulically lifting a piston. Once the piston is lifted, it can be released, forcing water through a shaft to the turbine, which generates energy. Plants are built by local engineering, procurement, and construction contractors with local labor and materials, such as concrete and steel. The plant life span is expected to be in excess of 80 years.

<u>Respondent 2</u>: Geo-mechanical Pumped Storage (GPS) stores energy as high-pressure water in the subsurface. Storage is charged by pumping water down a well into a confined rock "storage lens" using surplus or off-peak power. When power is required, this storage lens is discharged by allowing the stored pressure to force the water up the well and through a generator. THE GPS is modular (1-10 MW per well) with scalable durations (10+ hours).

Respondent 3: This technology utilizes a sealed pressurized geomembrane, which is placed in a basin and covered with 15-25 meters of soil. The weight of the overlaying soil creates a gravity-imposed pressure on the water, corresponding to the height difference (approximately 30-50 meters) in traditional PHS systems (average soil density is around 2.0 kg/m3 compared to water with a density of 1.0 kg/m3). Water is pumped into the reservoir during periods with surplus of electric energy. When required, the water is released from the system and a turbine and a generator regenerate the electric energy with an efficiency of 75-85 percent.

Kinetic Energy Storage

DESCRIPTION

Kinetic energy storage systems (KESS) are mechanical in nature. Typically, a precision flywheel is constructed and operated in a vacuum with special bearings to allow it to operate in a near frictionless state. An electric motor is used to spin it up to very high speed (16,000 rpm is not unusual). The process is then reversed with the motor reversed to a generator and power produced by the flywheel for discharge. KESS can be paired with solar systems to store excess energy during periods where production may exceed demand and deploy the energy during times of increased demand.

TECHNICAL PARAMETERS

KESS plants are typically sized for relatively small storage capacities and durations. The DOE indicates 20 MW of generating capacity and 15 minutes of storage. However, Amber Kinetics has announced a project it is developing in California with a four-hour duration.

Round-trip efficiencies for KESS are typically between 70 and 80 percent.

Flywheel installation has little effect on the environment given that KESS do not use any hazardous materials or produce any emissions.

The KESS technology usually includes some type of containment system for safety and performance purposes. The containment usually involves submerging the flywheel underground, with access above ground, and enclosing it in a thick steel vessel surrounding the rotational components. The configuration ensures that parts or fragments remain contained within the system and do not damage bystanders or other equipment.

With respect to response/discharge time, KESS typically have a response time of less than one second and a discharge time of up to one hour.

There are no CO_2 emissions associated with this technology or water usage requirements.

With respect to maximum cycles and lifetime, the DOE indicates up to 200,000 cycles and a life of greater than 20 years.

With respect to performance degradation, it is highly dependent on monitoring and maintenance practices. Degradation can be mitigated by properly maintaining the system.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, there are no significant restrictions. KESS can be located in a number of areas due to their relatively small footprint and are typically paired with existing power plants to provide generation storage.

With respect to safety, systems are integrated into the KESS installation that provide the necessary safety for operation.

RELATIVE ADVANTAGES:

- Highly modular in nature, with multiple flywheels controlled in combination to operate as a larger storage resource.
- Small with high power density, allowing the technology to sit at existing electrical plants, substations and loads.
- Self-contained and occupying a small footprint, allowing for fast deployment and re-deployment as necessary.
- Although degradation is the primary cause for damage to a flywheel or KESS technology, the overall life cycle is generally greater than other energy storage systems, sometimes exhibiting over 100,000 full charge-discharge cycles. Proper maintenance and monitoring are required for long life cycle operation.

RELATIVE DISADVANTAGES

- Relatively high cost due to precision machinery and electronics. Changes to the precision machinery may impact performance. These changes usually result in mechanical vibration over time and lead to damage.
- KESS systems also have relatively high degradation due to degradation in vacuum seals, cooling, friction and other support systems. The most common failure mode often observed is rotor cracking. Adequate system monitoring is required to ensure that performance and system operation is consistent.
- Duration is relatively short (15 minutes to 4 hours). To achieve 10 hours duration would require from four to 40 flywheels discharging in series.
- There are no known utility scale plants in operation.

ENVIRONMENTAL IMPACTS

As stated above, KESS produces no air emissions and has no water requirements. Additionally, the footprint of a system is typically small but can easily be scaled up by adding additional flywheels.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

Flywheel and KESS technology are sold as an alternative to typical battery storage. While typical flywheel installations typically have a smaller capacity, there have been applications with larger capacities upwards of one to 10 MW. KESS units have been installed and operating for approximately 10-15 years.

RESPONSES RECEIVED

Only one response was received, and the information provided was very limited.

Flow Battery

DESCRIPTION

Vanadium redux flow batteries are a type of flow battery whereby two electrolytic solutions are pumped through a cell that contains an ion-selective membrane and a set of electrodes that capture and release electrons during charge and discharge cycles. The electrolyte solution is comprised of a vanadium and sulfuric acid mixture and pumped, as needed, to the cells.

TECHNICAL PARAMETERS

Flow battery facilities are typically sized for relatively small storage capacities and durations. The DOE indicates up to 30 MW of generating capacity. One respondent indicates up to 6 hours of storage.

Systems are rated to approximately 20,000 cycles.

VRB units have a round-trip efficiency of approximately 68 percent according to DOE.

VRB installations are scalable and are dependent on the amount of electrolyte and cells. The electrolyte and cells are typically enclosed in a standard storage container and can be sized up with additional containers.

VRB units are unique compared to other battery solutions given that the electrolyte and chemistry are non-flammable and are safer to operate.

With respect to response/discharge time, KESS typically have a response time of less than on second and a discharge time of up to four to eight hours.

There are no CO_2 emissions associated with this technology or water usage requirements.

With respect to maximum cycles and lifetime, the typical life is approximately 20 years.

With respect to performance degradation, no information is available.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, there are no significant restrictions. VRB units can be located in a number of areas due to the relatively small footprint and operating temperature requirements of -10°C to 60°C.

With respect to safety, VRB systems and the materials included in the system are safe and can be operated remotely.

RELATIVE ADVANTAGES:

- There are no local combustion or air emissions.
- Materials that are used are relatively safe and non-flammable when compared to other battery solutions.

RELATIVE DISADVANTAGES

- When decommissioning a VRB unit, the cell membranes may be highly toxic, requiring a more complex disposal process.
- There are no known utility scale plants in operation.

ENVIRONMENTAL IMPACTS

When decommissioning a VRB unit the cell membranes may be highly toxic, requiring a more complex disposal process.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

The sole respondent has recently finalized the third generation of its product and has multiple installations completed with varying capacities from 5kW/20kWh to 260kw/1.54MWh.

RESPONSES RECEIVED

The sole respondent's technology charges and discharges as the positive and negative electrolytes circulate through the cell stack and back into their respective tanks. Both electrolytes are comprised of an aqueous solution that contains sulfuric acid and vanadium ions in different valence states. Each cell contains a carbon felt electrode. The half cells are separated by a proton exchange membrane. When the system charges and discharges, redox reactions take place at each electrode. Typical electrolyte cell battery unit inside an onsite container. The electrolyte is 30-60 percent of the total capex but retains residual value at the end of the battery life cycle.

Hydrogen Bromide Electrolysis

DESCRIPTION

Hydrogen bromide electrolysis storage technology utilizes organic waste materials reacting with aqueous bromine to produce hydrobromic acid (HBr) which is then used in an electrolysis process to produce hydrogen. The hydrogen is then stored, and the process is reversed to produce HBr and release electricity. The process can use renewable electricity to facilitate electrolysis and produce cleaned water, CO_2, concentrated nutrients, and thermal energy in addition to the principal hydrogen product.

TECHNICAL PARAMETERS

Given the fact that the technology requires the continuous supply of organic waste feedstocks, it is technically a thermochemical conversion process rather than an electrical energy storage technology. The process appears to require only 16 kWh of electrical energy per kilogram of hydrogen produced for HBr electrolysis compared to the approximately 55 kWh/kg that a traditional water electrolyzer requires. The technology may be scalable from 100 to 10,000 kg/day of hydrogen production, processing about 4,000 dry tons per year of organic waste and producing around 400 metric tons of hydrogen per year.

The information provided by the sole respondent to the ***Flex*POWER Bundle** RFI does not include sufficient data to discern key technical parameters, such as process efficiency and/or cycle time. However, information available outside of the RFI process suggests that the technology has an energy efficiency of approximately 67 percent, which presumably is based on the hydrogen and thermal energy outputs divided by the organic waste and electrical energy inputs. Electricity may then be produced from hydrogen to enable an 80 percent roundtrip efficiency; however, we believe this will be closer to 25 percent roundtrip efficiency.

With respect to response/discharge time, no information is available.

There are no CO_2 emissions associated with this technology or water usage requirements.

With respect to maximum cycles and lifetime, no information is available.

With respect to performance degradation, no information is available.

With respect to depth of discharge, no information is available.

With respect to geographic flexibility, no information is available.

With respect to safety, no information is available.

RELATIVE ADVANTAGES:

- Good ability to process organic waste materials into energy products.
- Production of co-products, including cleaned water, CO_2, concentrated nutrients, and thermal energy (heat).
- Lower electrical energy consumption for HBr electrolysis than traditional water electrolysis.
- Use of closed loop process with reactant (aqueous bromine) recycling.

RELATIVE DISADVANTAGES

- Requirement for continuous supply of organic waste.
- Unclear project economics if tipping fees associated with organic waste feedstocks are less favorable than pondered by the respondent.
- Feedstock pre-processing and product hydrogen purification requirements do not appear to be well understood and are not discussed in literature from the respondent.
- The size of the system that would be required to store any appreciable amount of electrical energy, including feedstock requirements and hydrogen power generation system (e.g., reciprocating engine or fuel cell), is likely to be quite large and expensive relative to traditional electrical energy storage devices.
- There are no known utility-scale plants in operation.

ENVIRONMENTAL IMPACTS

Although the HyBrTec process would consume potentially polluting organic waste materials, thereby preventing them from entering the environment or having to be disposed of in less environmentally-conscious ways, the process does produce CO_2 on a continuous basis. Traditional water electrolysis systems used in hydrogen energy storage applications do not produce greenhouse gases when utilizing renewable energy.

STAGE OF MATURITY AND EXPECTED COMMERCIALIZATION

Based on the documentation provided by the sole respondent, it appears that the technology has been demonstrated at a lab scale and the respondent is preparing to demonstrate the technology at a pilot scale. Because the specific process is well-established and the commercial technology has been used in chloro alkali applications, this may help accelerate the development process.