The Solar Duck Curve and Sustainable Storage Options: A Policy Recommendation

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Abstract

Before the rise in renewable energy, few people considered the consequences of adding large amounts of intermittent power onto the grid. As renewable energy has become more prevalent, utility companies must adapt their business practices to accommodate these unique sources of power. This is leading to challenges on how best to manage a grid with large amounts of renewable power.

Arizona Public Service (APS), the largest electricity provider in the state of Arizona, has more than 70,000 distributed solar customers on their grid and the number of solar customers increases every day. With this increase in distributed solar customers comes the solar duck curve—the phenomenon whereby solar produces energy during times of low demand. However, with the use of storage, the duck curve problem may be mitigated.

This project examines the sustainability of three storage options: pumped hydro energy storage, compressed air energy storage, and lithium-ion batteries. Using several sustainability indicators, this project makes a policy recommendation to APS on the most sustainable choice for large-scale energy storage.

This project found that compressed air energy storage was the most sustainable option for APS. This considered the impacts of compressed air on the environment, communities, and the costs of this storage option. One important aspect to acknowledge regarding this technology is that in its current form, it does emit some carbon emissions. However, the carbon emissions may have less of an impact if this storage facility can allow APS to use its renewable energy assets most efficiently and continue to use energy from Palo Verde, the nuclear facility in Arizona.

Table of Contents

Abstract 1

Introduction 3

Problem Context in Arizona 5

Storage and Renewable Energy 6

Sustainability Implications 7

The Three Storage Options 8

- Pumped Hydro Energy Storage 8
- Compressed Air Energy Storage 10
- Lithium-Ion Batteries 13
- Seasonal Storage Capability 16

Current Storage Projects in the Project Area of Arizona 17

- Pumped Hydro Energy Storage 17
- CAES 17
- APS Pilot Projects 18

Sustainability Matrix: Comparing the Three Options 19

- Planet/Environment 19
- Profit/Costs 20
- People/Communities 21
- Summary 22
- Limitations 24

Policy Recommendation 25

Future Steps 26

Conclusion 27

References 28

Introduction

Electricity generation is a key contributor to carbon emissions, accounting for almost 30% of all greenhouse gas emissions in the U.S. (Sources of Greenhouse Gas Emissions, 2015; Ameli & Brandt, 2015). If the world wishes to minimize the impacts of climate change, the electricity sector will need to rapidly transition to low- and zero-carbon sources of energy. Utility companies are not the only entities that can choose low-carbon energy options. Businesses, nonprofit organizations, schools, and homeowners can all play a role in this transition through options like the installation of rooftop solar systems.

Due to the significant drop in the price of solar panels in recent years, there are now 1.3 million photovoltaic solar systems in the U.S. (Munsell, 2017). The dramatic drop in the price of solar, along with creative financing options and an attractive tax credit, have enabled homeowners to install PV solar systems on their homes. This means that homeowners can now provide some of their own power instead of simply relying on their utility company for all their electricity needs.

While there are few, if any, reasonable and factual arguments against electricity generated from solar panels, the fact that homeowners can now generate electricity from their roofs is changing the business model for the utility company. Previously, electricity generation was a one-way street. Electricity flowed from the utility company's power plants to the customer's home. For every kilowatt hour consumed at the home, the utility company charged a set rate and received an expected payment from the customer each month. Now that customers can generate some of their own electricity, the one-way street has become a two-way street. Customers with solar can now generate their own energy, thereby reducing the amount of energy purchased while selling electricity back to their own utility company for use by other customers. The utility companies' 100-year-old business model must adapt to these changes. These changes also offer significant opportunities for the utility company, customers, and planet to collectively benefit.

As distributed solar generation became more popular, the excess generation that comes from solar panels during the middle of the day became a challenge for utility companies. Solar generation occurs during the day when electricity demand is low. When people start returning home after work, demand for electricity starts to increase, especially in the summer months in Phoenix due to the heavy reliance on air conditioners to cope with extreme heat. Simultaneously, solar generation sharply decreases because the sun is much lower in the sky. This mismatch between the demand for electricity and solar generation is often called the duck curve.

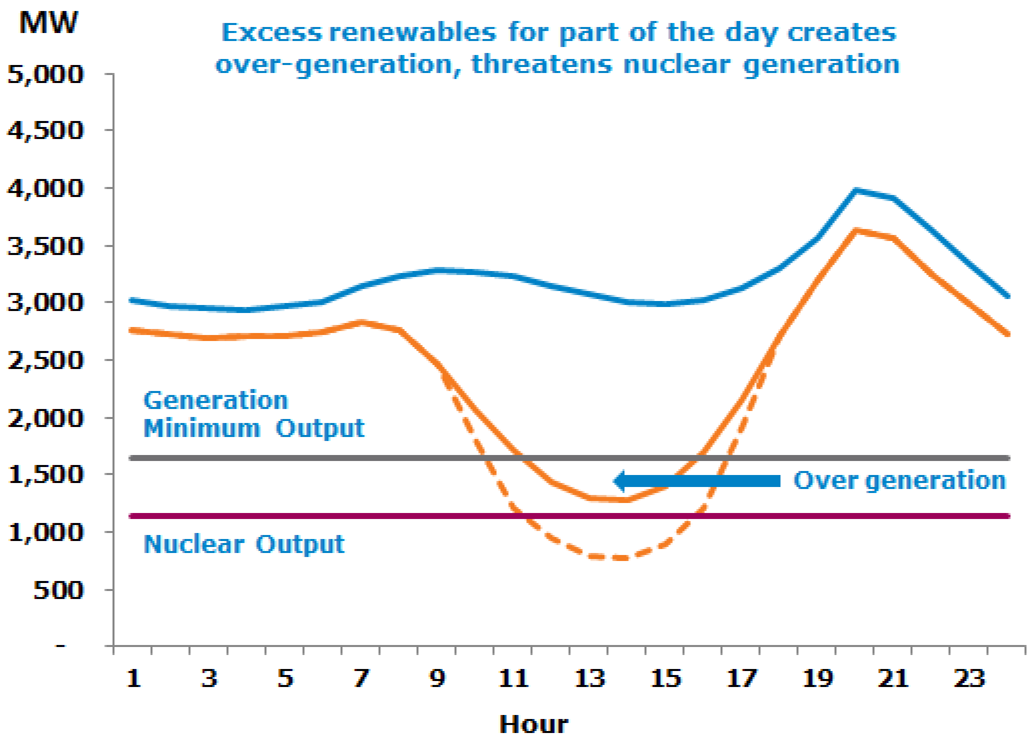


Figure 1 (APS, 2018)

Distributed generation is more of a technical challenge for utility companies than large, utility-scale wind or solar farms, because distributed resources are not controlled by the utility. Since utility companies have no control over these sources of energy, they cannot turn these energy sources off when there is too much energy on the grid. When there is too much energy, the utility company needs to look at the resources it owns or controls to determine the best option for energy curtailment.

The duck curve is becoming a threat to the future of baseload power resources owned or operated by Arizona Public Service (APS), which stands at about 3,000 MW. There is so much excess energy generation in the middle of the day during winter months that there is an incentive for APS to reduce baseload power generation assets. These are usually large power plants, like Palo Verde, that run all day, every day. Another option for dealing with the problem of excess energy is energy storage which would allow APS to continue to use its baseload powerplants while also using energy from renewable sources during times of high demand.

This project will focus on creating a policy recommendation of the most sustainable option for energy storage. It will examine pumped hydro energy storage, compressed air energy storage, and lithium-ion batteries and evaluate which ones will be best for APS, customers of APS, and the environment. Instead of a typical cost-benefit analysis, the storage options will be evaluated through the lens of sustainability. The impacts on the environment, costs, and communities will be examined as they apply to the storage options. For environmental impacts, the project will examine the carbon emissions, impact on the surrounding environment, and the materials needed. The cost analysis will look at the estimated construction/maintenance costs, lifetime, and reliability. Finally, the impacts on communities will be determined by the potential for displacement, change to the natural area, and the need for new transmission lines. The information provided in this matrix will then be used to determine what would best serve APS and its customers.

Problem Context in Arizona

APS is the largest electricity provider in Arizona and has different needs than other utility companies around the country. The weather in many parts of APS' territory greatly changes the electricity demanded from APS. There are two seasons in many parts of Arizona; summer is extremely hot, and the fall, winter, and spring are much milder. These two seasons require vastly different energy resources, with especially high demands in the summer for air conditioning homes and other buildings. According to estimates from APS, the electricity demand in their territory goes from about 3,000 megawatts (MW) in non-summer months to about 7,500 MW in summer months, specifically June through September. APS needs to manage its energy resources to provide electricity for the high demand in the summer months.

In addition to the unique energy needs due to Arizona's weather, APS has many more distributed solar systems compared to other utility companies in the U.S. APS has over 70,000 solar customers in its territory with rooftop solar systems generating electricity. These 70,000 systems total about 700 MW in total nameplated capacity—that is, the total capacity available from these distributed systems. However, during the middle of the summer, solar panels only provide about 235 MW of energy during the hours of 12 p.m. – 2 p.m. Yet the high summer demand occurs much later in the evening, between 6:00 p.m. – 7:00 p.m. These distributed solar systems are simply not helping to provide APS power when it needs power the most.

The low energy demand in Phoenix due to the mild weather in spring, fall, and winter means that APS does not need to have all of its available power plants producing electricity. It only needs baseload power plants running to meet the low demand. However, the distributed generation systems on the grid are still producing energy during this time of low demand, thus creating an excess of energy on the grid. This excess energy threatens the future of some baseload power plants

Excess energy for a utility company sounds like a beneficial thing considering they are occasionally worried about having enough supply to meet customers' demand for electricity. However, excess energy does not benefit the grid, and it has the potential to increase carbon emissions for APS. Because APS has so many distributed solar systems that are producing energy at times of low demand, APS is worried about the future of the Palo Verde Generating Station, the largest power producer in the United States (Arizona Emergency Information Network, 2015). Palo Verde provides APS with baseload power that is running constantly. This is because nuclear power plants are not easily ramped up or down. They operate at relatively the same levels unless there is a scheduled maintenance or another reason for a temporary shutdown.

Also, despite the criticism of nuclear power, it is a low-carbon source of energy. With a goal to reduce the amount of carbon emissions worldwide, nuclear is a good option for electricity generation, especially since it operates very similarly to fossil fuel plants in that it does not rely on nature to operate. If this low-carbon source of energy for Phoenix is forced offline and replaced by natural gas peaking plants to help smooth the fluctuating nature of renewable energy, specifically solar here in Arizona, then carbon emissions will likely increase. This is precisely the opposite intended outcome of increasing the amount of renewable energy on the grid. Therefore, APS is interested in looking at storage options to help with the excess energy on the grid while maintaining the benefits of the baseload power coming from Palo Verde.

Storage and Renewable Energy

While renewable energy has had tremendous growth, there is overwhelming consensus that without the ability to store energy, renewable energy cannot be the main source of energy for the grid. That is because renewable energy is often intermittent. Wind and solar, the two major renewable energy sources, only work when the wind is blowing, or the sun is shining.

One of the biggest challenges of deployment of large-scale renewable energy is storage. Better, more advanced renewable energy technologies will likely happen. However, this is not nearly as important as storage (Bullough, Gatzen, Jakiel, Koller, Nowi, & Zunft, 2004). The intermittency of wind, sun, and other similar sources renewable energy, causes problems for the electrical grid. The grid's design depends on the supply of electricity always matching demand (Bullough et al., 2004).

The intermittent nature of renewables causes problems and uncertainty for the grid and grid operators (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010). With higher percentages of renewables on the grid, there is less predictability and lower control over the supply of energy (Bullough et al., 2004; Swider, 2007). Additionally, intermittency interferes with energy generation and load balancing (Luo, Wang, Dooner, & Clarke, 2015). Renewable energy sources "can rarely provide immediate response to demand as these sources do not deliver a regular supply easily adjustable to consumption needs," (Ibrahim, Ilinca, and Perron, 2008).

Additionally, intermittent sources of power are not flexible and therefore cannot be adjusted to meet differing power demands (Yang & Jackson, 2010). Because of the inflexibility of these sources of power, along with their unpredictable nature, renewable energy plants are simply turned off when there is too much energy on the grid. When the traditional baseload sources of power are operating close to or at their minimum load, wind and solar plants are curtailed. Since traditional power plants are not easily ramped up or down quickly, it is the wind and solar power plants that are taken offline when there is excess energy (Foley, Leahy, Li, McKeogh, and Morrison, 2015).

Wind, solar, and other renewables will only be able to reduce carbon emissions from electricity generation in significant amounts and make the electricity grid more sustainable if these generation sources can replace baseload power plants. In order to accomplish this, storage for these renewable sources is critical (Succar & Williams, 2008; Evans et al., 2012; Hadjipaschalis, Poullikkas, & Efthimiou, 2009). There are a variety of storage options available to utility companies now, and the unique needs of each utility company will determine the storage options pursued. In addition to the individual needs of APS, there are other decision factors when it comes to choosing a storage option, like the sustainability of each of these choices, that should be incorporated into any decision made by APS.

Sustainability Implications

While sustainability is becoming more common in everyday advertising, many people still do not have a working definition of the word. Because sustainability is a complex topic, it encompasses a variety of disciplines with several acceptable definitions for sustainability. For this project, the best definition is the original definition of the word - "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). As most of the world is increasingly concerned about climate change, and there are many initiatives to improve the health and wellness of all communities, sustainability is more prevalent and important. Incorporating sustainability into both small, every day choices as well as larger, long-term choices is imperative to preserving the planet for future generations.

Sustainability is not simply about the environment. While the impacts on the environment are pertinent when it comes to sustainability, outcomes on communities and economies due to an activity or decision are imperative, too. These three topics, environment, communities, and economies, which are sometimes referred to as the pillars of sustainability, must be carefully evaluated and analyzed before declaring whether something is truly sustainable.

Often, businesses and companies use a traditional cost-benefit analysis to determine the best option. However, simply looking at the costs and benefits leaves out important aspects, namely the impacts on the environment and communities. This is problematic because ignoring the consequences of a decision on these two areas does not consider the true cost of a product or decision. Using sustainability as a factor allows for a more holistic decision-making process.

The issue of the duck curve, especially here in Arizona, is a sustainability problem in itself. While excess energy on the grid and the difficulty of quickly ramping up electricity generation are experienced by other utility companies with significant solar PV resources, Arizona may be unique in that it is home to Palo Verde. If the duck curve becomes significant enough to force the retirement of this powerplant, there will be a few negative sustainability outcomes.

If Palo Verde is taken offline, then the energy must be replaced with another resource, most likely a carbon resource. This would lead to increases in carbon emissions from the generation of electricity in Arizona. The irony of this would be that renewable energy leads to increased carbon emissions. Carbon emission increases are not the only problem if Palo Verde is shutdown. Palo Verde employs 2,600 people regularly, and an additional 800 people twice a year during re-fueling (APS, 2017). With the closure of Palo Verde, all these employees would be without a job which would negatively impact thousands of families around the state. And finally, the state would lose a large source of economic activity with the plant closure. Through taxes, salaries to employees, and services it uses, Palo Verde's annual economic output is about $1.8 billion (APS, 2017). Additionally, it is the state's largest taxpayer, paying around $50 million in taxes annually (APS, 2017). The closure of Palo Verde could then be used by those who are against the deployment of renewable energy to demonstrate that renewables should not be pursued because they cause economic problems for the state.

The Three Storage Options

Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is one of two viable options when it comes to large-scale utility energy storage. PHES works in a very similar way to traditional hydroelectric power plants. When there is excess energy on the grid or when energy prices are low, water is pumped uphill to a reservoir where the water is stored. When energy is needed, like during peak demand hours, water is released from the reservoir and passes through a turbine to create electricity. This water is then stored in a reservoir downstream (Evans et al., 2012; Ibrahim et al., 2008; Yang & Jackson, 2010; Deane et al., 2009; Steffen, 2012; Rehman et al., 2015; Uria, Martinez, O'Connor, Johnson, 2015). The cycle repeats whenever there is excess energy on the grid.

PHES is not a new technology; PHES has been in use around the world for almost 100 years (Foley et al., 2015; Evans et al., 2012; Ma et al., 2014). In fact, Germany's first PHES was completed in the 1920s (Steffens, 2012). Since PHES has been around for many decades, it should come as no surprise that it is not only a predictable technology, but it is also the most common form of energy storage technology in the world (Deane et al., 2009; Steffen, 2012; Yang & Jackson, 2010; Dunn et al., 2011; Evans et al., 2012; Foley et al., 2015; Ma et al., 2014). Worldwide, there are 127,000 MW of PHES capacity compared to compressed air energy storage, the second most common form of energy storage, which only has 440 MW of capacity (Dunn et al., 2011).

PHES has a variety of benefits, both in terms of energy storage as well as services it can provide to the electricity grid. One of the biggest benefits of PHES is that due to its long and proven history, it is both a stable and reliable form of energy storage (Evans et al., 2012; Ibrahim et al., 2008). In addition to its reliability it also has a long lifespan. PHES plants are expected to last anywhere between 50-100 years (Dunn et al., 2011; Evans et al., 2012; Deane et al., 2009). PHES has a fast ramp time which is another one of the reasons utility companies find it an attractive option for energy storage (Yang, Makarov, Desteese, Viswanathan, Nyeng, McManus, & Pease, 2008; Deane et al., 2009; Evans et al., 2012; Rehman et al., 2015). PHES can also be turned on and off quickly, help stabilize voltages on the grid, balance supply and demand, and shift loads (Rehman et al., 2015; Evans et al., 2012; Deane et al., 2009; Uria et al., 2015). Because of its flexibility, it has comparable benefits to other sources of energy that are used as back-up power such as peaker plants or gas turbines (Deane et al., 2009). Peaker plants are resources used by utility companies when demand is particularly high, and they can be turned on and off relatively quickly. The price for this electricity is often much higher than baseload power because it comes from resources that are only used at times of high demand.

PHES also has a high efficiency. It operates somewhere between 70-85% efficiency (Evans et al., 2012; Deane et al., 2009). While this efficiency is important, it means that PHES is also a net consumer of energy (Evans et al., 2012). Therefore, it is imperative that the PHES system drives water uphill at times of low demand and then releases the water at times of high demand to make the plant economically feasible (Evans et al., 2012). A PHES system addresses the duck curve problem by using the excess energy in the middle of the day, a period of low demand, to move the water uphill to the higher reservoir to be used later at times of high demand.

With any storage option, cost must be examined closely. Utility companies want “cost-effective” storage options because storage has the potential to help alleviate problems faced by the electricity sector. However, these storage technologies come at a cost that must be paid by the utility company. For PHES, there is no set industry cost per kilowatt (kW) stored because PHES systems are extremely site specific (Deane et al., 2009; Foley et al.; Evans et al., 2012). However, there are some estimates for an average PHES plant. Estimates vary anywhere between $600-$3,300 per kW depending on the date of the study and the location (Evans et al., 2012; Foley et al., 2015; Deane et al., 2009). This large price discrepancy demonstrates that for an accurate price estimate, an assessment of the proposed PHES site must be done by a company with knowledge of this type of energy storage. While PHES can be expensive to build, there are low operation and maintenance costs for the plant (Deane et al., 2009; Dunn et al., 2011).

Since PHES is a proven technology and has been used globally for decades, why is it not utilized? To begin, storing energy is a difficult task which requires equipment that is bulky, expensive, or both (Ibrahim et al., 2008). As a result, utility companies opt to build more generation instead of investing in energy storage technologies (Dunn et al., 2011). Also, PHES has some specific characteristics that make it infeasible for many locations.

First, PHES requires particular site conditions (Evans et al., 2012; Ma et al., 2014; Yang et al., 2008; Deane et al., 2009). There need to be two locations to hold water and reliable access to water (Deane et al., 2009**)**. Additionally, the reservoirs must be large enough to accommodate the amount of water that will need to travel uphill and downhill and they must also be at different altitudes. These requirements are important as PHES has low energy density (Rehman et al., 2015).

The site-specific requirements of PHES also mean that long transmission lines may need to be built as the site may be located far from centers of high demand (Evans et al., 2012). Building new transmission lines have their own problems, including high cost, long construction time, incredible size, and the fact that they impact wildlife areas (Personal interview, Marc Romito, February 21, 2018). Additionally, these lines usually must pass through both public and private land which requires cooperation between many different entities. In Arizona, the issue is compounded even more by the fact that a great deal of land that would be needed for the transmission lines is on Native American Reservations (Personal interview, Marc Romito, February 21, 2018).

PHES gives rise to environmental concerns, similar to regular hydroelectric power plants (Evans et al., 2012; Yang, et al., 2008; Ma et al., 2014). Regular hydro power negatively impacts riparian ecosystems and fishing resources by permanently changing the river system (Kosnik, 2010). These environmental concerns apply to PHES as well. Many experts point to these environmental concerns as barriers to the more widespread adoption of PHES both in the U.S. and globally. For example, Yang and Jackson explored several proposed PHES projects in the U.S. and found that opposition by environmental groups played a significant role in the termination of most of the proposed projects before they started (2010). However, they also note that engaging with all stakeholders, including environmental groups, increased the ease of proposing and developing PHES projects (Yang & Jackson, 2010).

Historical events, both nationally and globally, have had a negative impact on PHES development over the last 30 years. PHES was a very popular option for new energy development in the 1960s during the height of the nuclear energy era (Yang & Jackson, 2010; Deane et al., 2009; Uria et al., 2015). The oil crisis during this period, especially in the U.S., increased the development of nuclear energy. With the increase in nuclear power, there was also an uptick in the development of PHES facilities as a complementary component to nuclear energy. Since nuclear power cannot easily or quickly ramp up or down to meet demand, PHES was often paired with nuclear facilities to provide the ability to quickly provide power during times of high demand (Yang & Jackson, 2010; Deane et al., 2009).

However, the slowdown in nuclear power development in the 1980s lead to a concomitant decline in PHES development (Yang & Jackson, 2010; Deane et al., 2009). As natural gas became much cheaper in the 1980s, utility companies chose natural gas instead of PHES to be used as peaking power plants (Yang & Jackson, 2010; Deane et al., 2009; Uria et al., 2015). This is because PHES competes directly with natural gas turbines as they provide very similar benefits to the electrical grid.

Finally, the electricity sector in the U.S. underwent a deregulation transformation in the 1980s and 1990s. The utility industry transitioned to one where generators of electricity separated from those who owned the transmission lines used to transport energy. Since energy storage does not neatly fit into either of those categories, development of PHES slowed (Yang & Jackson, 2010; Deane et al., 2009).

With the difficulties of storage outlined above, and the vastly different price estimates for PHES plants, there is nonetheless increased demand for PHES because of the new goals for renewable energy deployment in both the U.S. as well as other countries. With more renewable energy mandates, there is an increased need for some way to store the energy from these low-carbon sources of energy. Additionally, there is an increased need for energy and peak power, both of which PHES can also provide (Yang & Jackson, 2010). Much of this proposed new development of PHES in the U.S. is occurring in the western part of the country where many of the states have higher renewable portfolio standards (Deane et al., 2009). Germany is another place where there is a new interest in PHES due to their renewable energy targets (Steffens, 2012).

Compressed Air Energy Storage

Compressed air energy storage (CAES) is the other major viable large-scale energy storage technology today (Chen, Zhang, Liu, & Tan, 2013; Chen et al., 2009; Succar & Williams, 2008; Abbaspour, Satkin, Mohammadi, Ivatloo, Cotfi, and Noorollahi, 2013). The two plants in the world using this technology are both diabatic CAES, or known as D-CAES, plants. There are other theories about how CAES can work, but since these technologies have not been deployed by a utility company anywhere in the world, there is no information on their viability. This project will therefore discuss D-CAES and its benefits and concerns. The mechanism of CAES is not complex. During off-peak periods, electricity is turned into potential energy by compressors which pressurize air. This air is then stored underground in a cavern. When energy is needed, especially during times of high demand, the pressurized air is released and expanded in a turbine. To expand the air, a fuel source like natural gas, is used to heat the air. The turbine converts the stored energy into electricity (Budt, Wolf, Span, and Yan, 2016; Bullough et al., 2004; Greenblatt, Succar, Denkenberger, Williams, and Socolow, 2007; Simmons, Barnhart, Reynolds, and Son, 2010; Swider, 2007; Succar & Williams, 2008; Fertig & Apt, 2011; Beaudin et al., 2010; Chen et al., 2013; Ibrahim et al., 2008; Lund, Salgi, Elmendgaard, and Andersen, 2008; Abbaspour et al., 2012; Luo et al., 2015; Chen et al., 2008; Lund & Salgi, 2009; Fthenakis, Mason, and Zweibel, 2008).

CAES is a relatively new technology. Research into compressed air as a form of storage began in the late 1960s, and the first plant was built in 1978 (Budt et al., 2016). The motivation behind CAES was similar to the increase in PHES deployment. In the 1960s and 1970s, due to a variety of factors including the oil crisis and an increase in nuclear energy, interest in storage options started to boom (Succar & Williams, 2008). Similar to PHES, CAES was explored as a potential form of storage due to the prevalence of baseload power, mainly from coal and nuclear power (Budt et al., 2016). With the baseload power provided by coal and nuclear power, utility companies have an incentive to store energy from off-peak times for later use during peak times (Budt et al., 2016). Many viewed storage, including CAES, as economically useful to utility companies because it could improve the use of expensive baseload power plants (Sharma, Chiu, Ahrens, Ahluwalia, & Ragsdell, 1979).

In the 1970s, northern Germany needed storage but PHES was not possible in this part of the country due to the geography in the area. However, CAES was a possibility in the region, and the first CAES plant in the world was built near Huntorf, Germany in 1978 (Budt et al., 2016). The Huntorf plant spurred interest in CAES research in the U.S., but the first and only CAES plant in the U.S. was not built until 1991 (Budt et al., 2016).

This first CAES plant was built with a capacity of 290 MW and about 2 hours of storage using a salt dome as its gas reservoir (Budt et al., 2016; Bullough et al., 2004; Greenblatt et al., 2006; Succar & Williams, 2008; Fertig & Apt, 2011; Beaudin et al., 2010; Ibrahim et al., 2008; Chen et al., 2013; Abbaspour et al., 2013; Lund et al., 2008; Luo et al., 2015; Chen et al., 2008; Simmons et al., 2010; Fthenakis et al., 2008). The Huntorf plant is currently used for leveling the variable energy on the grid in Germany, even though it was not specifically designed with that function in mind (Greenblatt et al., 2006). The plant helps with peak shaving and assists with filling the gaps left by plants that are slow to start, like coal and nuclear (Succar & Williams, 2008; Fertig & Apt, 2011). Additionally, Huntorf has the ability to blackstart, which means that there is no wait time for the plant to provide power (Budt et al., 2016; Luo et al., 2015). The Huntorf plant also helps with variable wind power in Germany, an increasing source of energy (Fertig & Apt, 2011). There have been some repairs and adjustments to the original plant, but the facility has been extremely reliable (Budt et al., 2016; Chen et al., 2008; Beaudin et al., 2010).

The other CAES plant is located near McIntosh, Alabama. The plant was constructed in 1991 and is slightly smaller than the Huntorf plant at just 110 MW of capacity. This plant is also located in a salt dome and works in the same way as the Huntorf plant (Bundt et al., 2016; Bullough et al., 2004; Greenblatt et al., 2007; Simmons et al., 2010; Succar & Williams, 2008; Fertig & Apt, 2011; Beaudin et al., 2010; Ibrahim et al., 2008; Chen et al., 2013; Abbaspour et al., 2013; Luo et al., 2015; Chen et al., 2008; Fthenakis et al., 2008). The McIntosh plant can provide 100MW of energy in 14 minutes and it burns about one-third the natural gas that similar gas turbines would burn (Power South, n.d.). This plant is also considered to be extremely reliable source of power (Budt et al., 2016; Beaudin et al., 2010).

Through improvements on the design of CAES, the McIntosh plant is about 25% more efficient than Huntorf (Budt et al., 2016; Beaudin et al., 2010; Luo et al., 2015; Chen et al., 2008). Additionally, the McIntosh plant was designed for weekly load shifting by taking cheap baseload power at night and storing it until peak times when energy is expensive, while Huntorf was designed for reserve power (Budt et al., 2016; Fertig & Apt, 2011).

These two CAES plants are located underground, though an above ground design is believed to be possible. There are a number of potential types of underground caverns that are considered acceptable locations for CAES: mined salt caverns, spent natural gas caverns, hard rock cavities, and aquifers (Budt et al., 2016; Greenblatt et al., 2007; Simmons et al., 2010; Succar & Williams, 2008; Sharma et al., 1979; Ibrahim et al., 2008; Chen et al., 2013; Luo et al., 2015; Chen et al., 2008). However, mined salt caverns are the only option in use today. Natural gas has been stored in a similar manner in this type of cavern, so there is a greater understanding of how pressurized gas behaves in that environment (Budt et al., 2016). There is some discussion of using aquifers as acceptable locations for a CAES cavern; however, it has not been used in a commercial plant yet (Budt et al., 2016; Succar & Williams, 2008). While above ground is an option, in theory, it would likely be much more expensive than storing compressed air in an already developed cavern underground because a container for storing the air would need to be built (Greenblatt et al., 2007).

The similarities between CAES and PHES explain why they are the only two commercially viable large-scale energy storage technologies (Chen et al., 2013; Chen et al., 2008; Succar & Williams, 2008; Abbaspour et al., 2013). These two technologies have high efficiencies, large capacities, long storage times, and the ability for quick ramp times (Succar & Williams, 2008; Beaudin et al., 2010; Abbaspour et al., 2013; Fthenakis et al., 2008; Fertig & Apt, 2011; Chen et al., 2008).

While CAES appears to be a promising storage option, PHES has historically been a much more popular choice for energy storage. since PHES has been in operation since the late 1920s and is often seen as a proven technology (Luo et al., 2015). Nonetheless, many developed countries no longer have any more PHES options available (Bullough et al., 2004).

If large-scale storage is needed, CAES may be the best option when PHES is not possible and batteries are cost prohibitive (Swider, 2007). CAES does not have the same limitations or severe environmental concerns like PHES. CAES has similar size capabilities as PHES, and it does not have the geographic restrictions presented by PHES (Bullough et al., 2004). In fact, it is estimated that 75% of the area in the U.S. is suitable for CAES, including spots in Arizona (Fthenakis et al., 2008; Beaudin et al., 2010 Simmons et al., 2010). CAES also has fewer environmental concerns than PHES (Chen et al., 2008). CAES uses little land area as much of it is underground. Because of the little land necessary for CAES, it has a smaller impact on the land and surrounding ecology, especially when compared to PHES (Succar & Williams, 2008; Beaudin et al., 2010).

Similar to PHES, estimating the cost of CAES is difficult as there are only two plants from which cost data to build such a system can be obtained. The varying cost estimates for CAES which may be attributed to the available caverns to store the compressed air. Estimates range from $400-$800 per kW of energy storage capacity (Beaudin et al., 2010; Chen et al., 2013; Chen et al., 2008). Because CAES can be built in caverns that already exist, capital costs can be lower compared to other energy storage options (Succar & Williams, 2008).

While CAES may have certain characteristics that make it more attractive or feasible than PHES, it also has some drawbacks. CAES needs a secondary form of energy when discharging the stored energy to heat up the air (Budt et al., 2016). With the two existing plants using fossil fuels to help power CAES, this inevitably means that there are carbon emissions coming from this technology, which may make CAES a less attractive form of energy storage (Chen et al., 2013). However, these plants use about one-third the fuel that regular turbines use and thus have one-third the carbon emissions (Power South, n.d.). It is important to note that there is research on how to reduce, or possibly eliminate, the carbon emissions from CAES which would help improve the environmental impact of using CAES (Succar & Williams, 2008).

The salt caverns used for both existing CAES plants in the world cause environmental issues as well. To create the dome or cavern, the salt must be dissolved which produces brine (Simmons et al., 2010). This process not only requires large amounts of water, but then the briny water must be disposed as it cannot be released into fresh water.

Finally, there are a lack of new CAES facilities. Many of the available papers discuss future CAES projects, but all but one project in the U.S. have been abandoned so far. The only potential project is a project located in Texas. The cancellation of many of these projects is discouraging. However, CAES may start experiencing a comeback in the U.S. due to the increase in renewable energy and the subsequent need to balance out these intermittent sources of power (Budt et al., 2016; Succar & Williams, 2008).

Lithium-Ion Batteries

APS has several pilot projects underway to increase their storage capacity. Many of these projects involve lithium-ion batteries. To fully compare the sustainability aspects of CAES and PHES with the APS pilot projects, a review of lithium-ion batteries is necessary. While there are a few articles outlining how these batteries work, their benefits, and the costs associated with this technology, many of the articles available now outline the tested improvements to this technology. Some news stories about using large lithium-ion batteries as storage provided more information than academic articles, especially for the context of this project.

Under the right conditions, batteries for storage can help with the challenges presented by solar and other renewable energy sources (Hill, Such, Gonzalez, Grady, 2012). Batteries have fast ramp rates and can provide voltage support and stability to the system. Therefore, batteries can help with the variability challenges that come from solar generation (Chen et al., 2008; Hill et al., 2012).

Batteries are the oldest form of energy storage, dating back over a century (Chen et al., 2008). Due to the changes in the energy sector, as well as the transportation industry, batteries are quickly becoming a more popular way to store energy. In 2015, 95% of all new energy storage installed was in the form of batteries (D'Aprile, Newman, Pinner, 2016). This may be due to flexibility in location of batteries as well as short construction times (Luo et al., 2014). However, the use of lithium-ion batteries by utility companies for large-scale storage is a new phenomenon (Chen et al., 2008).

While everyone uses some sort of battery daily, many of these same people may not understand the mechanics of how batteries operate. There is an anode, the negative electrode, and the cathode, the positive electrode. There is also an electrolyte in the battery as well which allows for the transfer of electrons between the anode and cathode (Hadjipaschalis et al., 2009; Luo et al., 2015; Chen et al., 2008; Dunn et al., 2011). In lithium-ion batteries, often referred to as Li-ion batteries, a lithium metal oxide is used for the cathode and graphite is the anode. The electrolyte in the battery is a liquid usually containing lithium salt (Luo et al., 2015; Scrosati & Garche, 2010). In this battery, the lithium-ion moves between the anode and cathode to create electricity (Evans et al., 2012; Diaz-Gonzalez, Sumper, Gomis-Bellmunt, Villafafila-Robles, 2012).

Li-ion batteries are used for many applications today, but the most popular use is in portable technology like cell phones, cameras, laptops, and iPads (Diaz-Gonzalez et al., 2012; Dunn et al., 2011; Beaudin et al., 2010; Hadjipaschalis et al., 2009; Lindley, 2010). In the early 1990s, Sony was the first to commercially produce Li-ion batteries, and the technology has only improved since then (Dunn et al., 2011; Beaudin et al., 2008; Chen et al., 2008). In fact, Li-ion batteries have improved since the publication of these articles. Some of the older articles mention that Li-ion batteries may be used for electric vehicles or hybrid vehicles. Today, the auto industry has a variety of electric vehicles on the market that can power the vehicle for a couple hundred miles on one charge.

There are a variety of characteristics of Li-ion batteries that make them attractive for energy storage, specifically for utility companies. They have high energy densities (Diaz-Gonzalez et al., 2012; Dunn et al., 2011; Beaudin et al., 2010; Chen et al., 2008). Li-ion batteries have fast charge and discharge rates (Diaz-Gonzalez et al., 2012). This means that batteries can either absorb or dispatch power quickly, which is a benefit to utility companies that need storage to quickly respond to the needs of the grid. Li-ion batteries also have high efficiency rates, around 95% (Diaz-Gonzalez et al., 2012; Chen et al., 2008). In fact, Li-ion batteries have a higher energy density and efficiency than lead-acid and nickel batteries (Hadjipaschalis et al., 2009). Another benefit of Li-ion batteries is that they have low self-discharge rates, that is the amount of energy lost due to processes inside the battery (Evans et al., 2012; Hadjipaschalis et al., 2009).

In addition to these benefits, Li-ion batteries are easily scalable and are very versatile which makes them attractive for storage (Larcher & Tarascon, 2015).

Li-ion batteries, unlike the other two forms of storage discussed above, can be placed anywhere on the grid. There are no geographic limitations for the placement of batteries. This is hugely beneficial to the utility company because it means that batteries can be used by utilities that need storage in any location. Also, since batteries can be placed anywhere, construction of new transmission lines can be avoided.

The cost of large-scale Li-ion batteries has been the biggest barrier to the deployment of more battery storage. In fact, the cost of these batteries makes it an unattractive option in many scenarios (Evans et al., 2012; Beaudin et al., 2010; Chen et al., 2008; Lindley, 2010; Scrosati & Garche, 2010). Currently, Li-ion batteries cost about $500 per kilowatt (Roberts, 2017; Baidwai, 2017). One reason for this is that Li-ion batteries need to be managed by some device or computer to ensure that they are not fully discharged as this would negatively impact the lifetime of the battery (Luo et al., 2015; Hadjipaschalis et al., 2009). This monitoring system adds to the cost of using a large battery for storage.

While there are many benefits to Li-ion batteries, there are some concerns about this type of energy storage. The biggest concern is safety and the possibility of fires due to the use of lithium salt as it can become flammable (Diaz-Gonzalez et al., 2012; Beaudin et al., 2010; Lindley, 2010). There are also concerns about available reserves of lithium worldwide as it is a finite resource (Dunn et al., 2011; Larcher & Tarascon, 2015; Scrosati & Garche, 2010). Environmental concerns, especially in the manufacturing of the battery, are important to consider when using Li-ion batteries. Li-ion require huge energy inputs during manufacturing (Larcher & Tarascon, 2015. This means that unless the batteries are made using electricity from renewable sources, there are significant carbon emissions just from the manufacturing process alone.

In addition to the available sources of lithium in the world, there are also concerns about the extraction process of lithium. While lithium mining is not the same as mining for other metals, like copper, it still causes some environmental impact. The majority of the world’s lithium comes from Australia and South America. In South America, there are concerns by the indigenous communities near lithium mines over the large amount of water needed to process lithium (Merchant, 2017).

There are issues with temperature and Li-ion batteries. High temperatures mean that the Li-ion batteries age more quickly (Hadjipaschalis et al., 2009). This is important to remember considering the hot summer temperatures in the Phoenix area as well as other areas within APS service territory. Additionally, Li-ion batteries have a shorter lifetime than either CAES or PHES. These batteries have a lifetime varying from 5-16 years (Diaz-Gonzalez et al., 2012; Evans et al., 2012). This short lifespan means that the utility will need to procure more batteries in the future when the current batteries are at the end of their useful life.

Recent literature on Li-ion batteries focuses on how to improve batteries, while reputable news organizations fill in the gap by providing information on new Li-ion battery systems installed around the world. In the last nine months, there have been two large installations of Li-ion batteries, one in California and one in Australia. In September 2017, the largest Li-ion battery in the U.S. went live in southern California. This battery, built for San Diego Gas & Electric, can dispatch 30 MW of power in seconds and was constructed in less than six months (Spector, 2017). This system was built in response to a gas leak in Southern California in 2015 that lasted more than four months (Spector, 2017). The utility company wanted a technology that could provide power immediately but also exist in dense urban areas. More traditional options, like gas peaker plants or hydro plants, were not possible in populated areas, like San Diego (Spector, 2017). Therefore, the utility company decided to utilize Li-ion batteries. This system behaves like a gas peaker plant, but it does not emit air pollution or greenhouse gas emissions while in use. Additionally, it is much quicker to build a battery system than a gas plant (Spector, 2017). This battery system is being used as a test for large-scale Li-ion batteries for the grid (Spector, 2017).

Shortly after the construction of this battery, a much larger Li-ion battery came online in Australia. In December 2017, a 100 MW battery was built by Tesla in Southern Australia in less than 100 days (BBC, 2017). This battery system is connected to a wind farm in the area, and it is used to “support and stabilise (sic) existing electricity supplies,” (BBC, 2017). Tesla said that its experience with Li-ion batteries for its vehicles helped it build this system, even though the batteries used for storage are slightly different than those used in their electric vehicles (BBC, 2017).

McKinsey, a large consulting firm in the U.S., sees potential for batteries to become more prominent in the short-term. McKinsey predicts that battery prices will fall, which is imperative for more widespread use of this technology. They expect batteries will cost $200 per kilowatt hour in 2020, which is half the cost of these batteries in 2016, and $165 per kilowatt hour, or less, by 2025 (D-Aprile et al., 2016). Additionally, researchers continue to work to improve Li-ion batteries. As batteries improve, in terms of cost, lifespan, and material extraction, there is hope that renewable energy sources could provide a significant portion of the energy needs in the U.S.

Seasonal Storage Capability

The weather in many parts of APS service territory gives the utility company unique energy demands. Because of the extreme heat in the summer, APS must build enough generation to fulfill this demand. This power is extremely expensive, both for the utility company and the consumer as the costs are passed on.

The mild fall, winter, and spring means that the excess energy from distributed solar is an even greater threat to baseload power during these seasons. The utility does not need as many sources of power because demand is low. The difference in demand in the summer compared to the other three seasons provides an interesting case for seasonal storage.

Seasonal storage is an idea that has not been put to practical use. However, due to the characteristics of different storage technologies, some storage options are better suited for the possibility of seasonal storage. Due to size, storage ability, and other characteristics, both CAES and PHES are possible options for seasonal storage (Beaudin et al., 2010; Luo et al., 2015; Simmons et al., 2010; Succar and Williams, 2008).

Current Storage Projects in the Project Area of Arizona

These three storage options were chosen because all three are possible in Arizona. Below are details on potential future projects or research that indicates how best each particular storage option can be implemented in the state.

Pumped Hydro Energy Storage

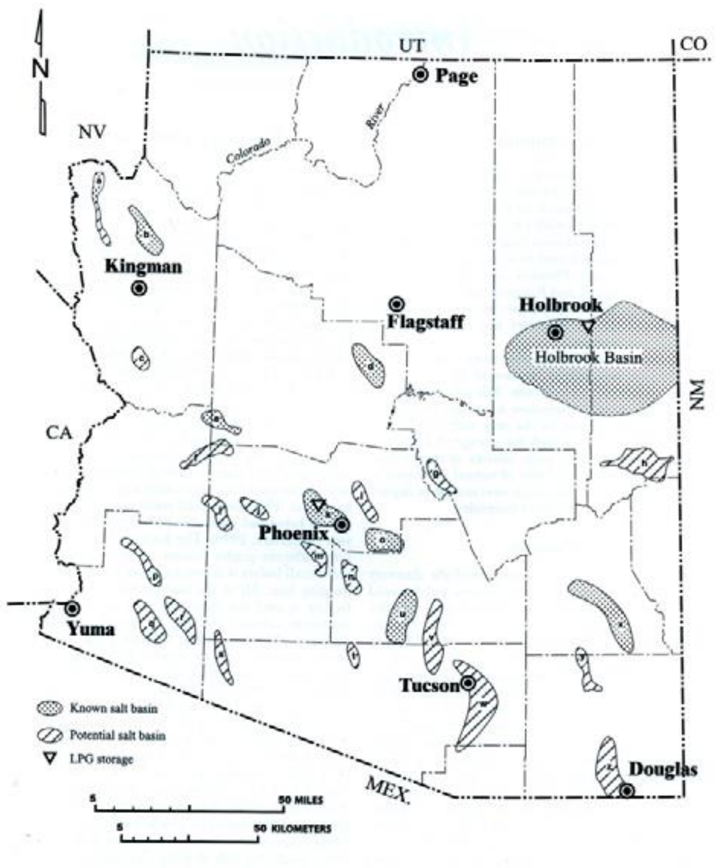
Currently, there is an active preliminary permit for a PHES facility in the Chino Valley. This project was filed in October 2017 with the Federal Energy Regulatory Commission (FERC). The 2,000 MW project proposes pumping water from the Big Chino aquifer, the same aquifer that supplies water to the residents of parts of northern Arizona as well as the Verde River. In the filing, this project looks to compliment the growth in renewable energy in the region (Ciampoli, 2017). The proposal states that it will explore options to reduce the impact on regional water use (Ciampolo, 2017).

Upon the filing of this permit, the town of Clarkdale filed a motion to intervene on the project. Their main concern is the water that will be used for the project will negatively impact the water the town uses. In fact, the town of Clarkdale states that the amount of water needed for this project, estimated to be 19,000-acre feet, is equal to more than 40 years of water use by the residents and businesses in Clarkdale (Motion to Intervene, Town of Clarkdale, Arizona, 2017). Additionally, Clarkdale is concerned that this project will negatively impact the Verde River and the surrounding riparian ecosystem (Motion to Intervene, Town of Clarkdale, Arizona, 2017).

The concerns put forth by Clarkdale, and possibly other cities or towns, are legitimate concerns. Water is a precious resource, especially here in Arizona. Additionally, there are valid concerns when it comes to the health of riparian areas where PHES plants exist. However, working with all stakeholders, including city governments, citizens, and environmental groups may help ease the worries of the small cities and towns that rely on the Big Chino aquifer for their water. Without buy-in from the local communities, the proposed Big Chino Valley PHES plant will likely face an expensive, lengthy, and contentious battle before it even gets approved for construction.

CAES

There are a couple of studies published that demonstrate that Arizona has potential locations for CAES around the state (Simmons et al., 2010; Neal & Rauzi, 1996) There are at least two salt caverns in APS territory, one in west Phoenix and one in Pinal County. These are both large caverns which means that they have the potential to store large amounts of energy. As discussed above, the availability of underground caverns means that APS would not need to include the cost of building a structure to the already high costs of energy storage.



Map of known and potential salt caverns in Arizona (Simmons et al., 2010)

APS Pilot Projects

The idea for this project came from investigating what APS was doing to alleviate the duck curve problem. Right now, the main strategy for APS is to try several different pilot projects and see which one, if any, can make a significant impact with the problem. In September 2017, APS announced that they were in the process of developing more programs to help the utility save energy when it needed to most and helping customers save money at the same time. Some of these new programs will be available to APS customers beginning in the summer of 2018. These programs include smart thermostats and smart water heaters. The intent of these programs is help absorb the excess energy on the grid in the middle of the day from solar.

In addition to the programs listed above, APS will also have two programs that include Li-ion batteries for residential customers free of charge. These projects are in addition to the other battery experiments APS has carried out throughout its territory. The first program, the Solar Innovation Study–75, gives customers a variety of energy equipment, like rooftop solar systems, pool pumps, load controllers with a home energy management system, and batteries. The program will study how customers manage their own energy without guidance. There will be 10 homes with a battery designed to charge during the day and then discharge between APS’ peak hours, 3p.m.-8p.m. They are 2-kilowatt, 5-hour batteries, or 10 kilowatt-hours of storage total.

For the homes that have batteries, they will also have rooftop solar systems (Personal interview, John Pinho, March 16, 2018).

The second program is part of APS' rewards program. APS will install 50 batteries in homes that do not have rooftop solar systems. Similar to the Solar Innovation Study – 75, the batteries are 2-kilowatt, 5-hour batteries and will come with a critical load panel. These batteries are also designed to charge during off-peak times and discharge during the peak. APS has specific locations throughout their territory that have high solar penetrations and want to place the batteries in these areas. For this program, they have allocated $3 million for the purchase and installation of the 50 batteries. Applications for this program will state in early summer 2018 (Personal interview, John Pinho, March 16, 2018).

Sustainability Matrix: Comparing the Three Options

The storage options detailed above can all help APS in terms of storing excess energy from solar. However, the different characteristics of each storage option impact the sustainability of each of the technologies. The sustainability matrix below helps detail the sustainability assessment of each storage option.

The three pillars of sustainability are often referred to as planet, people, and profit. For each of the pillars, there are three aspects that will help determine the sustainability score for each storage option. For the planet section, CO_2 emissions, impacts on surrounding environment, and materials needed for constructed are evaluated. The cost section examines the cost to build and/or maintain, lifetime of the storage option, and reliability. Finally, the last pillar, people or communities, will evaluate the risk of displacement, transmission line construction, and negative impacts to natural space enjoyment.

The metrics are evaluated quantitatively using the information provided in both the literature review as well as discussions with professionals and academics involved in the energy storage industry. The matrix has a minus sign (-) showing negative aspects of the technology, a plus sign (+) representing positive aspects, and no symbol indicates the impact is neutral.

Planet/Environment

Impacts on the environment must be carefully evaluated for any sustainability decision. Any storage option will have some impact on the environment. However, energy storage is necessary to continue to expand the role of renewable energy technologies into the APS generation portfolio.

The use of PHES does not have any CO_2 emissions, which is a major benefit of this type of storage. However, PHES, like regular dams, can cause issues on the surrounding riparian ecosystems. Dams change the nature of the river and can cause harm to both wildlife as well as plants in the area (Kosnick, 2010). PHES also requires a lot of materials, and these construction materials can have their own impact on the environment. For example, concrete is a major contributor to carbon dioxide emissions globally.

CAES, while it can be used for large-scale storage like PHES, it differs greatly from PHES in terms of environmental issues. For one, CAES does create carbon emissions. In a world that is looking to greatly reduce carbon emissions as quickly as possible, the carbon emissions from this type of energy storage are problematic. However, CAES has little impact on the surrounding environment. CAES facilities are located underground and can use existing caverns. There is a possibility that creating these underground caverns may create other environmental issues. If the salt must be removed from the caverns, briny water is produced. The disposal of this water can cause other environmental problems. However, the salt from the caverns may be extracted and processed by salt companies. If the briny water is disposed of properly or if the salt can be used in a commercial application, the environmental issues with the salt may not be a problem.

Li-ion batteries also impact the environment. Like PHES, Li-ion batteries do not emit carbon emissions while in use. Li-ion batteries do not necessarily negatively impact the surrounding environment either. However, for Li-ion batteries to provide enough storage capacity, they must be large battery installations. This means that undeveloped desert landscape must be transformed to accommodate a large battery installation. The construction and subsequent battery system could disrupt this ecosystem. And finally, the materials needed for Li-ion batteries are problematic due to the mining of precious metals necessary for the batteries. Additionally, Li-ion lifespans are somewhere between 5-16 years (Diaz-Gonzalez et al., 2012; Evans et al., 2012). Therefore, the disposal of these batteries must be considered when analyzing the environmental sustainability of batteries.

Profit/Costs

The cost of any of the storage options is an important aspect to consider because APS ratepayers will ultimately pay for any of these options, much like they would pay for new generation plants. Externalities must also be part of the cost discussion for any new technology. Externalities are not explicitly discussed in this section; however, the externalities of the storage technologies are encapsulated in the entire sustainability matrix.

Determining a potential cost for PHES may be difficult due to the extreme variability in costs for this type of project. As outlined in the literature review, costs vary from $600-$3,300 per kW. (Foley et al., 2015; Evans et al., 2012). This includes the construction as well as the maintenance of the system. Compared to the other options, PHES is one of the most expensive storage options. With PHES, a major benefit of this storage technology is that the operation and maintenance costs are very low. And finally, PHES has a long lifetime. Conservative estimates put the lifetime at 40-50 years, but other sources say these plants last up to 100 years (Dunn et al., 2011; Evans et al., 2012; Deane et al., 2009). This is important because unlike batteries, this system can be used for decades without the need to be completely replaced. PHES is an extremely reliable storage technology. It is not only the most common form of energy storage globally, but it also has set the requirements for energy storage (Larcher & Tarascon, 2015).

The costs for CAES can vary greatly as well because of the specifics of the sites to be used for the plant. However, for this exercise, we will assume that the plant will use caverns underground as Arizona has caverns available. This is a slightly cheaper option as a structure above ground that can tolerate compressed air will not need to be constructed. Costs for CAES range from $400-$800 per kW (Beaudin et al., 2010; Chen et al., 2013; Chen et al., 2008). CAES is also a long-term asset. The plant in Germany was built in 1978 and is still in use 40 years later. The plant in Alabama is a bit newer, but it has been in operation for almost 30 years. These two plants are also extremely reliable (Budt et al., 2016; Chen et al., 2008; Beaudin et al., 2010). One thing to consider with CAES is the need to purchase fossil fuels, most likely natural gas, to run. The fuel is used to heat the gas after it has been depressurized and needed to create electricity. This is an on-going cost for any CAES plant.

Cost is one of the most talked about problems with batteries, though these batteries are cheaper than CAES and PHES. The cost of batteries is more straightforward than either PHES or CAES. Right now, batteries cost about $500 per kW (Roberts, 2017; Baidawi, 2017). There is also optimism that battery costs will fall as technology either changes or improves. The increasing popularity of electric cars, which use a similar Li-ion battery, may help reduce the costs of Li-ion batteries for storage in the future. Unlike, PHES or CAES, Li-ion batteries are not a long-term asset as they must be replaced. Utility companies would need to consider the purchase of batteries in the future as an additional cost in terms of battery deployment. While Li-ion batteries are reliable in small portable electronics, using these batteries as large-scale storage is a new application of this technology. Reliability of this type of storage will need to be evaluated over the next several years as batteries become more popular.

People/Communities

The impact on communities from any storage option needs to be considered as well. Often, the impacts to communities are not fully considered when decisions are made by large companies or corporations. However, all communities must be acknowledged when a decision may impact them, either directly or indirectly.

With PHES, there is the issue of displacement of communities due to the construction of the two reservoirs. The most convenient location for PHES may be in locations where people live. In the case of the Big Chino Valley PHES proposal, communities may not be displaced due to the location of the reservoirs. However, there is concern that the amount of fresh water needed for the storage could negatively impact the livelihoods of people living in communities near this project. PHES could also negatively impact people's enjoyment of natural areas. Constructing a large PHES facility would alter the natural environmental significantly. The characteristics of rivers, streams, and small ponds are likely to change, and there would be the addition of the mechanisms that move the water from one reservoir to another. These would all alter the landscape in ways that may impact the abilities of communities to enjoy nature. Finally, due to the geographic specifications of PHES, there would likely be new transmission lines needed. As described above, these transmission lines are large, unsightly, and can impact the natural environment.

The location of the available CAES sites in Arizona do not necessarily have the same displacement impact communities compared to PHES. One of the sites considered in Phoenix is located near Luke Air Force Base. Construction of a plant on this property would not require communities to move. Due to the geographic limitations of CAES, this storage option is like PHES in that it may require the construction of new transmission lines. However, because CAES locations may be closer to areas of large energy demand, new transmission lines are not a given. And finally, both CAES plants in the world use underground caverns. There are parts of the plant do require space aboveground, which may impact the enjoyment of the natural area around the site depending on the location of the plant. Although it is less dramatic than PHES, this is a point to consider for this storage technology.

Picture of McIntosh CAES plant (www.wired.com)

Since batteries can be located anywhere, the chances of displacement are extremely small. Batteries can be placed adjacent to renewable energy farms, at the substation, or even at distribution feeders. This means that the location is already developed, and communities would not need to be moved from these locations. The flexibility of location also indicates that transmission lines do not necessarily need to be built for this storage option. The downside with batteries in terms of communities is the size of batteries needed for the duck curve in Arizona. A battery system would have to be large and this could negatively impact enjoyment of the natural environment. These batteries are large square boxes and would not improve the natural aesthetic of an area.

Summary

Using the information above, CAES is deemed the most sustainable storage option for APS even though it has some carbon emissions. This is because it outweighs the other two options in the three pillars of sustainability. CAES it has less of an impact on the environment than batteries or PHES, has moderate costs compared to PHES, and its impact on communities is not as drastically negative as PHES. Additionally, it is one of only two options that has the potential to be used for seasonal storage which makes this option even more attractive to APS. This is not to say that the other two options do not have their own benefits. Li-ion batteries came in a close second to CAES as a sustainable storage option for APS. These batteries have much less of a potential impact on communities, produce no carbon emissions while in use, and the costs for the batteries are falling. PHES came in third even though it is a zero-carbon source of energy. This is because of the negative impacts it poses to both riparian ecosystems and surrounding communities.

Storage Technology	Environment	Economics	Communities
PHES* possible for seasonal storage application	+ Zero-carbon energy storage system - Damage to riparian ecosystems - Many materials needed for construction	- High cost ($600-$3,300 per kW) + Long lifetime (50-100 years) + Low maintenance costs	- Potential displacement of communities for construction of reservoirs - Change in how communities can enjoy the natural area - Need for new transmission lines
CAES* possible for seasonal storage application	- Emits some carbon emissions (about one-third those of a regular gas turbine) + Little impact on surrounding environment Briny water: disposal of water may be issue; however, salt may be extracted and used (neutral)	+ Moderate costs ($400-$800 per kW) + Long lifetime - Moderate maintenance costs (must purchase natural gas)	+Potential CAES sites would not require displacement of communities - Change in how communities can enjoy the natural area - Potential for new transmission lines
Li-ion batteries	+ Zero-carbon energy storage system - Large, aboveground installations - Concern over precious metals used in battery	+ Moderate price ($500 per kW) with prices expected to fall - Must be replaced due to short lifetime Potential reliability issues (neutral)	+ Negligible change of displacement + Need for new transmission lines unlikely - Change in how communities can enjoy natural area

Limitations

With any decision, and especially with a large decision like energy storage, there are inherent risks with each possible choice. While risks were not included in the sustainability matrix above, they should be considered when making a decision for the best storage option. There are both internal and external risks for the three storage options. Some internal risks that could have a negative impact on the storage options include issues with supply chains for Li-ion batteries, intense legal battles for PHES, and unsuitability of cavern sites for CAES. Additionally, there are external risks, like climate change, complete change in utility structure, or a radically new energy storage technology, that could also negatively impact any one of the storage options above. It is difficult to predict which, if any, of these risks may occur. However, understanding risks and creating a risk management tool will assist APS to prepare for these potential risks.

Policy Recommendation

APS' vision is to "create a sustainable energy future for Arizona." With sustainability a part of APS vision, decisions regarding new energy sources and the long-term plans for their energy portfolio must include aspects of sustainability. APS is the largest electric provider in the state of Arizona with resources that other utility companies may not have access to in their territories. This allows APS to be a leader when it comes to renewable energy and storage projects.

A recent proposal put forth by Andrew Tobin, an Arizona Corporation Commissioner, calls for Arizona to significantly increase its renewable energy portfolio and storage capacity. The announcement suggested a plan for Arizona to have 80% clean energy by 2050 and 3,000 MW of storage by 2030 (Spector, 2018). This plan also seeks to improve the reliability of the grid in Arizona and bring down consumer costs for electricity (Spector, 2018). Tobin's plan was big news, not just for energy storage but for Arizona as well. If the Arizona Corporation Commission (ACC) approves this proposal, Arizona would be ahead of any other state in terms of energy storage.

To meet these targets, especially the storage target, utility companies like APS will need to quickly develop more storage options. While batteries for energy storage are in use today, they tend to be smaller in terms of capacity. If Arizona plans to have 3,000 MW of energy storage in 12 years, large-scale storage must be examined. For APS to pursue its own vision, it must consider the sustainability aspects of storage technologies as well as new renewable energy power plants.

APS' business plan for 2018 incorporates solutions to the duck curve. The seriousness of this problem requires APS to put significant resources towards a solution. The changing landscape of the utility business is not only occurring in Arizona. In fact, the duck curve is an issue in many other parts of the country that have experienced a boom in renewable energy. Many states, like California and New York, are placing an emphasis on storage to complement their renewable energy assets. Storage not only helps renewables compete with baseload power, but as shown above, it provides other benefits to the grid.

The information from the literature reviews, along with discussions with experts in the field of energy storage, demonstrate CAES to be the best sustainability option for dealing with the duck curve. It is large enough to be a utility-scale storage option, it is feasible in the state of Arizona, it has a variety of benefits including grid support, and is a reliable technology. Also, it can be constructed relatively quickly, does not cause the same environmental problems as PHES, and is a long-term asset for the utility.

This is not to say that CAES is a perfect solution with no drawbacks. As a society concerned about CO_2 emissions, any technology that emits carbon emissions should be carefully vetted. However, CAES would enable APS to use its renewable sources of energy to their fullest potential. The ability to store and then use energy from zero-carbon sources would help reduce carbon emissions from the production of electricity in Arizona. Also, it would allow APS to pursue more renewable energy power plants as they would now have a tool to store energy from these intermittent energy resources. Perhaps most importantly, a large-scale storage solution would allow Palo Verde to continue to provide Arizona with zero-carbon energy for many years to come.

CAES does come at a cost to APS, a cost that will be passed onto customers of APS. However, this kind of project could help APS in managing its grid better and has the potential to improve the image of APS and their commitment to renewable energy. Committing to a serious and innovative storage technology will allow APS to be a role model for other utility companies around the country by demonstrating that large-scale storage can benefit the environment, its customers, and the company.

Future Steps

As is widely recognized, sustainability is an incredibly complex topic. There is no one answer that will completely transform the electricity grid into a sustainable energy grid overnight. As outlined above, all choices for storage presented in this project have benefits and costs to the environment and the community. In addition, these storage options are not free; in fact, they are quite expensive. However, if the utility company wants to use its renewable assets to the fullest and continue to reduce carbon emissions from the electricity sector, storage is imperative. Using sustainability factors, the utility can make the most sustainable storage decision, even if that option is not perfect.

Since storage is becoming more popular with the increase in renewables, there are a variety of future projects that can use this current project as a starting point. Potential future projects are as follows:

- This project only analyzes three storage options. However, literature regarding storage indicates that there are many other options when it comes to energy storage. Two innovative and interesting storage concepts are desalination and electrolysis. For desalination, excess energy is used to create drinking water from salt water. This is particularly interesting since one of the biggest problems with desalination is the amount of energy needed. Electrolysis also requires large amount of energy to create hydrogen. The excess energy during the middle of the day could be used to create hydrogen which can be used as a fuel or an additive to gasoline. A future report could analyze the feasibility of both in Arizona.
- A student could analyze the carbon emissions from CAES versus the carbon emissions if Palo Verde were shutdown. It would be interesting to see which would cause more carbon emissions for the state.
- APS has pilot projects that include both batteries as well as other technologies. Some of these technologies require customer participation. A future student could put together an informational brochure on best practices for including customers in utility programs.
- Another student could also work with APS on some of their pilot projects to analyze how the programs are operating and then propose best practices on how to improve customers' participation in such programs.
- An analysis of Andrew Tobin's proposal in terms of its sustainability is another project option for a future student.

Conclusion

The issue of storing electricity is one of the main obstacles renewable energy must overcome to provide more electricity to the grid. However, the recent uptick in research into different storage options may allow renewables to provide most of our electricity. If these storage ideas can be put to use in real-world applications and help renewable energy provide more of our nation's energy, then our grid will be part of the solution to create a more sustainable future.

If APS is serious about both solving the duck curve and its commitment to sustainability, then CAES provides the best option when it comes to energy storage. Using CAES will not only help APS in improving its grid; CAES provides both indirect and direct benefits to the community and the environment. Also, APS has the potential to become a pioneer in the utility industry by using sustainability in their decision making regarding energy storage for renewable energy. With the deployment of CAES, Arizona can become a leader in both renewable energy and storage.

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