MODELING & OPTIMIZATION OF A RENEWABLE ENERGY SUPPLY CHAIN WITH A FOCUS ON ENERGY STORAGE

A Thesis

by

SHERRALYN SNEEZER

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENERGY

Chair of Committee,	Stratos Pistikopoulos
Committee Members,	Styliani Avraamidou
	Mahmoud El-Halwagi
	Sergiy Butenko
	Valentini Pappa
Head of Department,	Efstratios Pistikopoulos

August 2021

Major Subject: Energy

ABSTRACT

The demand for energy has grown and will continue to grow due to factors such as climate change and population growth. As climate change fuels the need for higher energy usage, this demand for energy will be met, in part, with fossil fuels, which would continue the cycle. In order to both meet energy demands and mitigate the effects of climate change, renewable energy technologies must be used to generate a greater amount of energy. Unfortunately, wind and solar energy, in particular, are intermittent sources of energy, and they are not able to provide energy when the sun is not shining, or when the wind is not blowing. Moreover, these renewable energy sources risk the possibility of over-generation when they are available, so other sources of energy must be cut during this time, resulting in the Duck Curve. To address both problems, energy storage can be used to store energy from renewable energy sources when there is excess energy to use later when these sources of renewable energy are no longer available. This paper examines a renewable energy system with the intent to integrate an energy storage system using available energy storage technologies. The goal is to design and optimize an energy storage system for the renewable energy storage system with the focus on cost and environmental impact minimization.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Styliani Avraamidou [advisor], Stratos Pistikopoulos [chair], and Professor Mahmoud El-Halwagi of the Department of Chemical Engineering and Professor Sergiy Butenko of the Department of Industrial and Systems Engineering.

The model was analyzed by Styliani Avraamidou. Rahul Kakodar assisted with model implementation in Python.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

No funding was received for this thesis.

NOMENCLATURE

CAES	Compressed Air Energy Storage
CCUS	Carbon Capture Utilization and Storage
EIA	Energy Information Administration
kW	Kilowatt
kWh	Kilowatt Hour
LCA	Lifecycle Assessment
MILP	Mixed Integer Linear Programming
MW	Megawatt
NREL	National Renewable Energy Laboratory
NSRDB	National Source Resource Database
PNNL	Pacific Northwest National Laboratory
PSH	Pumped Storage Hydro
SMES	Superconducting Magnetic Energy Storage
VRB	Vanadium Redox (Flow) Battery
WEC	World Energy Council

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Electricity has become a vital component of the way people live their lives, and the electricity demand continues to grow along with the global population. Moreover, energy demand is expected to grow due to the effects of climate change by 25% to 58% in 2050 (van Ruijven et al., 2019). In addition, the Energy Information Administration (EIA) predicts that the global energy demand will increase by 50% in 2050 which will be led by Asia as economic growth would be the driving force (Kahan, 2019). With the expected increase in energy demand, there will be a greater need for energy throughout the world, which could be satisfied with a greater use of fossil fuels or renewable energy. Increasing the usage of fossil fuels may worsen the effects of climate change, so the use of renewable energy will be an integral part of meeting the increasing energy demand in a sustainable manner (Mitsos et al., 2018). Unfortunately, the one of the most pressing issues with renewable energy is the intermittency problem; therefore, the need for energy storage has grown in order to meet the future demands of energy. There are several types of energy storage technologies that may be used in conjugation with renewable energy systems. This paper aims to model and optimize a renewable energy system with a focus on energy storage using information and data from NREL's National Source Resource Database (NSRDB) as well as scientific articles concentrating on energy storage (Sengupta et al., 2018).

1.1 Motivation

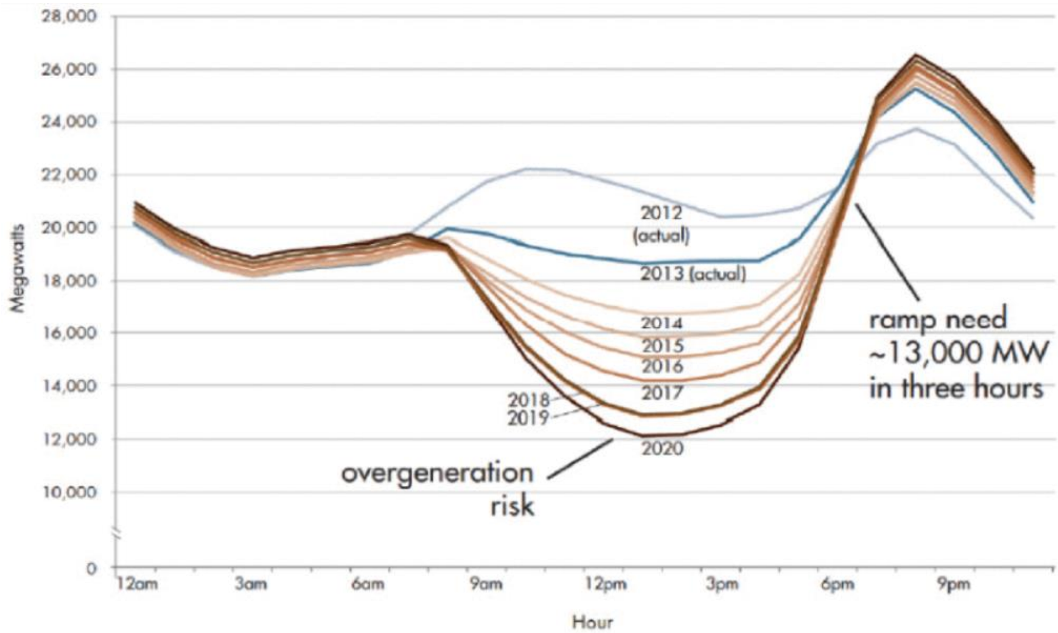

Figure 1. The Duck Curve. Reprinted from Wong et al., 2020.

In addition to the growing energy demand, there is another related issue known as the "Duck Curve" which can be seen in **Figure 1.** There are different issues associated with the Duck Curve, and the prevention of the Duck Curve will be an important issue that energy storage can solve or mitigate. Basically, the Duck Curve is an issue of supply and demand. When examining the Duck Curve in **Figure 1**, the graph depicts the net load for a spring day, so the amount of electricity being generated by solar PV, energy supply, is considerable during the day (Wong et al., 2020). Thus, the other sources of energy generation, fossil fuels generating stations, can operate at a reduced capacity as solar PV can adequately meet the energy demand. Not to mention, there is the risk of over-generation damaging energy infrastructure (Wong et al., 2020). As the sun sets, the demand for energy increases while the energy generated by solar PV decreases, which explains the steep incline which forms the neck of the duck (Wong et al., 2020). This becomes a problem as other sources of energy generation would need to significantly increase their production in a short period of time to meet the increasing demand for energy, which would require more sources of generation to be turned on or shut down to meet the energy demand (Wong et al., 2020). Therefore, this process becomes inefficient for the operation of generators throughout the day since they are operating at a reduced capacity and then need to significantly increase their production capacity to meet demand (Wong et al., 2020). Energy storage systems implemented into renewable energy systems will be able to store the excess energy generated during the day with or without the decrease in other sources of generation, so that the increased energy demand can continue to be met with energy generated by renewable sources. It is important to note that solar energy is the only form of renewable energy impacted by the Duck Curve since the shape of the Duck Curve is made by the energy supply of solar PV throughout the day (Jones-Albertus, 2017). So, diversifying the types of renewable energy utilized with solar energy may also help mitigate the effects of the Duck Curve. The issue of over generation and increasing energy demand while solar PV generation decreases will be addressed with energy storage to ensure that the Duck Curve is prevented.

2. LITERATURE REVIEW

Due to the intermittent nature of certain renewable energies, wind and solar energy, energy storage is needed to supply electricity when these renewable energies are not generating electricity on a daily or seasonal scale. Devising energy storage systems for renewable energy supply chains is a complex process due to the numerous energy storage types and technologies available. Each type of energy storage has advantages and disadvantages that serve as indications for the suitable applications that these technologies can and should be utilized. Therefore, these technologies are not exclusive, and they can be used in conjunction with other energy storage technologies to increase the overall efficiency of the energy system. Energy storage technologies can be categorized by their forms of stored energy: electrical and magnetic, mechanical, chemical, and thermal (Sørensen, 2015; Ding et al., 2015). An additional form of categorization is coupled and decoupled energy storage systems which focus on the relationship between the storage technology and the energy generation technology (Sørensen, 2015; Ding et al., 2015). Moreover, energy storage technologies being used today are pumped storage hydropower (PSH), compressed air energy storage (CAES), thermal energy storage, batteries, hydrogen fuel cells, flywheels, capacitors, and superconducting magnetic storage (SMES) (Breeze, 2018; Zablocki, 2019). Each of these energy storage types has different installation and operational costs that also impact the economic feasibility of integrating energy storage into a renewable energy system. There are different scales and durations over which these energy storage technologies can operate, so the energy storage technology used depends on the energy system.

Technology	Max Power Rating (MW)	Discharge Time	Lifetime	Energy Density (Wh/liter)	Efficiency (%)	Round-Trip Efficiency (%)	Form
PSH	100-2500	4 h - 16 h	30-60 yrs	0.2-2	70-85	75-90	Mechanical
CAES	10-1000	2 h - 30 h	20-40 yrs	2_6	40-70	65	Mechanical
Molten Salt	1-150	hours	30 yr	70-210	80-90		Thermal
Li-ion Battery	0.05-100	1 min - 8 h	1000-10000 cycles	200-400	85-95	75-90	(Electro)Chemical
Lead Battery	0.001-100	1 min - 8 h	6 - 40 yr	50-80	80-90	75-90	(Electro)Chemical
Flow Battery	0.1-100	hours	12000-14000 cy	20-70	60-85	90	(Electro)Chemical
Hydrogen	0.01-100	min - week	5-30 yr	600 (@ 200 bar)	25-45		Chemical
Flywheel	0.001-20	sec - min	20000-100000 cy	20-80	70-95	80	Mechanical
Supercapacitors	0.01-1	ms-min	10000-100000 cy	10_20	80-95	90	Electrical
Superconducting Magnet	0.1-1	ms-sec	100000 cy	6	80-95	90	Magnetic

Table 1. Relevant data for energy storage technologies. Adapted from World Energy Council, 2016; Sørensen, 2015; Ding et al., 2015; Breeze, 2018.

Changes in climate conditions vary on a daily, weekly, and seasonal basis which affects the amount of energy generated by renewable sources of energy that depend on these climate conditions like solar energy and wind energy. It is for this reason that energy storage technology must address these varying climate conditions by storing energy on a daily to seasonal scale (Sørensen, 2015; Ding et al., 2015). Depending on the type of energy storage technology, they may be better suited to operate on a daily or seasonal scale (Sørensen, 2015; Ding et al., 2015). At a daily scale, lithium-ion and lead-acid batteries can be used since they are able to store energy for several hours (World Energy Council, 2016). Additionally, other energy storage technologies suited for daily storage are flow batteries, thermal storage (molten salt), supercapacitors, and SMES (WEC, 2016). A few of these energy storage technologies can only be used for term operation, so they can be used to assist with changes in generation sources when renewable sources of energy are not available (WEC, 2016). Pumped-storage hydro energy storage as well as compressed air energy storage could also be used on a daily basis, but they also have the potential to be used on a weekly to seasonal scale (WEC, 2016; Sørensen, 2015; Ding et al., 2015). A balanced energy storage system will have more than one energy storage technology that can be used at a daily to seasonal scale to ensure optimal operation (Sørensen, 2015; Ding et al., 2015). The change in seasonal climate conditions will affect the amount of energy generated in the summer compared to the winter, so seasonal energy storage technologies like fuel storage are needed to make up for lost energy generation (Sørensen, 2015; Ding et al., 2015).

As mentioned previously, there are different methods of categorizing energy storage technologies, and there are two main types that this paper focuses on, forms of stored energy and coupled or decoupled energy storage (Sørensen, 2015; Ding et al., 2015). To begin, the forms of stored energy are broadly grouped into four categories: mechanical, chemical, electrical and magnetic, and thermal (Sørensen, 2015; Ding et al., 2015). Briefly, mechanical energy storage relies on storing kinetic and potential energy through a mechanical medium, namely flywheels and pumped-storage hydro (Kalaiselvam & Parameshwaran, 2014; Sørensen, 2015; Ding et al., 2015). Then, there is chemical energy storage that stores energy within a chemical medium which uses energy generated during chemical reactions to reproduce the energy stored like batteries (thermochemical) and hydrogen fuel (Kalaiselvam & Parameshwaran, 2014; Sørensen, 2015; Ding et al., 2015). Electrical and magnetic energy storage both store electricity directly using either magnetic fields or electrostatics, and supercapacitors as well as superconducting magnetic energy storage are both examples of these types of stored energy (Kalaiselvam & Parameshwaran, 2014; Sørensen, 2015; Ding et al., 2015). Lastly, thermal energy storage uses heat or cold temperatures to store energy, and this will be discussed in detail in later sections (Sørensen, 2015; Ding et al., 2015). While this categorization focuses on the form of energy stored, coupled and decoupled energy storage examines the relationship between the charging devices and the energy storage (Sørensen, 2015; Ding et al., 2015). Thus, coupled energy storage is energy storage that is integrated with the charging devices like flywheels and rechargeable batteries (Sørensen, 2015; Ding et al., 2015). Decoupled energy storage is energy storage that can be separated from the charging devices such as pumped storage hydropower and hydrogen fuel storage (Sørensen, 2015; Ding et al., 2015).

2.1 Pumped Storage Hydropower

Renewable energy systems can range from distributed power generation to utility-scale power generation, and these different systems need energy storage technologies that will complement them. Knowing when a specific energy storage technology can be used is important for building an efficient energy system that includes energy storage. PSH is suitable for longer term storage, since it relies on storing water in a reservoir when demand is low and releasing the potential energy of the water when there is a high energy demand. The released water flows downward to a turbine to produce electricity using the kinetic energy of water, and water is collected in a reservoir after it flows through the turbine (Zablocki, 2019). The electricity generated by PSH is proportional to the height distance from the higher reservoir and the lower reservoir, and the greater distance between the two, the more electricity generated (Kalaiselvam & Parameshwaran, 2014). PSH has been limited to mountainous geographical locations with rivers, but it can also be used in other areas with the caveat that the costs of creating the infrastructure needed may be significantly higher (Breeze, 2018). When there is excess electricity or a low energy demand, water can be pumped from the lower reservoir back to the higher reservoir in a closed loop system (Breeze, 2018). PSH is the most widely used form of energy storage, and it has been implemented in different locations around the world with a global deployment of 169,557 MW (Mongird et al., 2019). In terms of life expectancy, PSH systems are operational from 30 to 50 years with a round-trip efficiency of 60% to 95% (Breeze, 2018; Kalaiselvam & Parameshwaran, 2014). Furthermore, PSH can store energy for 10 hours, and developments in technology have increased efficiency through the creation of adjustable speed technology (Zablocki, 2019; Sørensen, 2015; Ding et al., 2015).

2.2 Compressed Air Energy Storage

Similar to PSH, CAES is geographically limited to locations with large underground caverns like aquifers, mines, and salt caverns (WEC, 2016). If there are not any caverns available, then above ground pressure vessels are used to store the compressed air (WEC, 2016). CAES works by pumping compressed air in the underground caverns when energy demand is low, and then releasing the compressed air to generate electricity when demand is high (Sørensen, 2015; Ding et al., 2015). Although CAES is a relatively well-known form of energy storage, there are only two facilities in the world that are utilizing CAES, and new CAES projects have been canceled (Sørensen, 2015; Ding et al., 2015). This may be due to the low round-trip efficiency of CAES, ranging between 40% to 54%, or the need to be used with a gas turbine plant (Sørensen, 2015; Ding et al., 2015; Kalaiselvam & Parameshwaran, 2014). There are many advantages associated with CAES, such as the 40-year lifespan and cost effectiveness (Kalaiselvam & Parameshwaran, 2014). In addition, CAES has a low self-discharging rate (Kalaiselvam & Parameshwaran, 2014). One report estimates that in 2018, there were 407 MW of CAES deployed globally (Mongird et al., 2019). New technology is being developed to make CAES more efficient and a more viable option for energy storage in the future (Sørensen, 2015; Ding et al., 2015).

2.3 Batteries

One of the most well-known forms of energy storage are batteries, and there several different types of batteries. For this paper, the only types of batteries that will be evaluated are lithium-ion, lead acid, and flow batteries. Batteries work by storing chemicals that generate chemical reactions to create energy that produces electricity, and they are typically used in small-scale energy storage like phones and electric vehicles (WEC, 2016; Breeze, 2018). Since batteries, particularly lithium-ion and lead acid, began as storage for small devices, the challenge has been how to use batteries for large-scale energy storage in utility-scale solar PV systems or other renewable energy systems. Flow batteries can hold more energy, because it stores the chemical reactants in separate tanks which are usually large and releases the reactants depending on the energy needed (Breeze, 2018). Furthermore, flow batteries have a medium energy density and a long life, and 72 MW of flow batteries energy storage have been deployed across the world (Mongird et al., 2019; Breeze, 2018). Recently, lithium-ion batteries have been used for larger energy storage applications that range from 2 MW to 30 MW, and they have a high energy efficiency and energy density (Kalaiselvam & Parameshwaran, 2014). However, lithium-ion batteries are quite expensive, and their life cycle is shortened by deep discharges (Kalaiselvam & Parameshwaran, 2014; Breeze, 2018). Despite the high cost of lithium-ion batteries, it is the most widely used form of battery storage around the world with 1,629 MW deployed (Mongird et al., 2019). While lithium-ion and flow batteries have promising futures for energy storage, lead-acid batteries, although cheap, have low life cycles and energy density, so they would not be suitable for long-term storage, and they have been used for large-scale storage in the past. In 2018, there were 75 MW of lead acid batteries being used around the world (Mongird et al., 2019.). Unfortunately, one facility was only operational for 5 years, so they are best used for short time periods at a smaller scale (Kalaiselvam & Parameshwaran, 2014; Breeze, 2018).

2.4 Hydrogen Fuel

Hydrogen is another form of energy storage that can be used in conjunction with renewable energy systems to address the intermittency issues. Using hydrogen as energy storage works through the electrolysis of water which produces hydrogen and oxygen when electricity demand is low (Zablocki, 2019). On the contrary, when electricity demand is high, electricity can be produced by combining hydrogen and oxygen (Zablocki, 2019). Hydrogen can be produced by biogas, ethanol, or hydrocarbons; however, the use of hydrocarbons would release carbon emissions into the atmosphere. If using pure hydrogen, the only byproduct of this process would be water, so it can be a great way to reduce carbon emissions in the energy industry depending on the materials used and process of forming hydrogen (Zablocki, 2019). Another advantage of hydrogen is the high energy density, and the ability to transport the hydrogen created to another location for usage (Zablocki, 2019). To store hydrogen, it can be stored as a liquid or a gas, and if stored as a gas it can use natural gas infrastructures in place (WEC, 2016). Unfortunately, hydrogen is an expensive form of energy storage since it requires the use of platinum in the process, but hydrogen is already being used for backup energy for different facilities (Zablocki, 2019).

2.5 Flywheel

While hydrogen takes advantage of chemical energy, the flywheel utilizes kinetic energy to store energy that can be converted into electrical energy. The flywheel has a rotating part that uses magnetic levitating bearings to reduce material degradation and friction along with low pressure to also reduce wind or shear disturbances (Kalaiselvam & Parameshwaran, 2014). Furthermore, the shape of the rotating part and the effects of inertia determine the amount of energy stored by the flywheel (Kalaiselvam & Parameshwaran, 2014). When storing energy, the flywheel spins at high speeds through the use of an electric motor, and the flywheel maintains this speed until energy is needed. When discharging energy, the kinetic energy is used to return energy to the electric motor which then acts as an electric generator. In order to determine the amount of energy that can be stored by a flywheel, the kinetic energy is proportional to the mass of the flywheel and its rotational speed; therefore, the strength of the flywheel material determines the maximum energy storage density (Kalaiselvam & Parameshwaran, 2014). There are two different types of flywheels with one being more suitable for a continuous supply of power for a short period of time. Flywheels have a lifespan between 15 to 20 years, and they are able to quickly charge and discharge quite efficiently. On the other hand, flywheels are made from expensive materials, and they are not suitable for long-term storage with a high self-discharge rate.

2.6 Thermal Energy Storage

Thermal energy storage is a category of energy storage technologies that depend on heat or cold to store energy generated with electricity which is converted back into electrical energy when it is needed (Sørensen, 2015; Ding et al., 2015). There are different types of thermal energy storage which focus on sensible heat, latent heat, and thermochemical reactions (Kalaiselvam & Parameshwaran, 2014). As mentioned previously, thermal energy storage does not only rely on heat to store energy but also cold temperatures in which one example is cryogenic energy storage (Kalaiselvam & Parameshwaran, 2014). Cryogenic energy storage stores liquid air or nitrogen when there is an excess of renewable energy generation, and the liquid air or nitrogen is heated to be converted into energy when there is a demand for electricity. The benefits of cryogenic energy storage are the high energy density, long-term storage ability, and relatively low cost of electricity (Kalaiselvam & Parameshwaran, 2014). On the other hand, heat can store energy through high temperatures to heat an object such as molten salt which can be used in conjunction with concentrated solar power (Kalaiselvam & Parameshwaran, 2014; Sørensen, 2015; Ding et al., 2015). Steam can be produced using molten heat to turn a steam turbine like conventional fossil fuel power plants (WEC, 2016). While molten salt is quite efficient, 80% to 90%, cryogenic energy storage is less than 60% efficient, indicating research and development must be done to increase the efficiency (WEC, 2016; Sørensen, 2015; Ding et al., 2015).

2.7 Supercapacitors and Superconducting Magnetic Energy Storage

Lastly, supercapacitors and superconducting magnetic energy storage are additional energy storage options that are both able to store the energy for a short period of time with a swift response time (WEC, 2016). Supercapacitors are quite expensive as they cost more than batteries for energy storage, but they have a longer lifespan since they are able to charge and discharge up to 100,000 cycles (WEC, 2016). Similar to supercapacitors, superconducting magnetic energy storage has a life span of 100,000 charge and discharging cycles (WEC, 2016). In terms of its energy storage process, superconducting magnetic energy storage stores DC energy in superconducting coil cables within a magnetic field, so there is not a conversion to another form of energy (Kalaiselvam & Parameshwaran, 2014). The material used for the coil cables must be kept at low temperatures, so a cryogenic cooling system is needed to reduce electrical losses (Kalaiselvam & Parameshwaran, 2014; WEC, 2016). Supercapacitors are also able to store electrical energy by using two metal plates separated by a medium that is either insulated or a conductor (Kalaiselvam & Parameshwaran, 2014). Once a DC charge is applied to one of the metallic plates, this causes the other metallic plates to become charged with an opposite nature (Kalaiselvam & Parameshwaran, 2014). This process depends on the size of the metallic plates, medium's material, and the distance between the two plates (Kalaiselvam & Parameshwaran, 2014). One disadvantage of supercapacitors is the low energy density, which can be improved with a larger design; however, that would be quite expensive (Kalaiselvam & Parameshwaran, 2014). Similarly, superconducting magnetic energy storage is expensive, so the development of this type of storage has been limited (Kalaiselvam & Parameshwaran, 2014). Both of these types of energy storage are not typically used due to high costs, so they will not be used in the model.

2.8 Cost

As mentioned throughout the section, the cost of these energy storage technologies varies depending on the materials and scale as well as other factors. The capital cost is the cost of the different components of energy storage technology or the part that make up the actual energy storage device (Mongird et al., 2019). For example, this includes electrolytes and separators that go into making a battery or the reservoirs and pumps for PSH, and they are measured in $/kWh or $/kW (Mongird et al., 2019). The cost of the power conversion system must also be considered, and it is the cost of inverters or other components of the inverter for battery energy storage systems, and it is measured in $/kW (Mongird et al., 2019). Another component of cost is the balance of plant which accounts for the cost of wiring and ancillary equipment, and this is also measured in $/kW (Mongird et al., 2019). The construction and commissioning costs encompasses the cost of site design, equipment, labor, and other costs associated with construction; moreover, this cost is measured by $/kWh (Mongird et al., 2019). Fixed operations and maintenance costs ($/kW-yr) are the fixed costs of operating the energy storage system throughout its life (Mongird et al., 2019). Lastly, the variable operations and maintenance costs are the fluctuating costs incurred during the operation of the energy storage system for its lifetime, so this cost is measured in $/kWh-yr (Mongird et al., 2019).

2.9 Infrastructure Planning for Renewable Energy Systems

There are different approaches to designing an energy storage system for a renewable energy system as well as what these approaches prioritize in designing the system. When designing an energy storage system, there are different methods of modeling the energy system, and different forms of optimization are among those methods. For example, Haas et al. examines a 100% renewable energy system in Chile and prioritizes environmental factors related to energy storage that are not typically considered such as hydropeaking and externalities associated with transmission lines while utilizing a multi-objective optimization approach. In addition to environmental factors, reliability in renewable energy systems is important for meeting the energy demand when utilizing intermittent sources of energy such as wind and solar energy (Abdulgalil et al., 2018). For this approach, stochastic optimization was used to account for uncertainty in a microgrid system using an algorithm in a two-phase optimization approach (Abdulgalil et al., 2018). Similarly, Wu et al. examined a microgrid system, but particle swarm optimization algorithm was used to minimize the cost of the microgrid system with a reliability constraint to ensure demand is met. In addition, chance-constrained optimization is used to consider stochasticity; however, the complexity of a chance-constrained optimization problem is difficult to solve, so a reformulation of the problem is solved instead (Geng et al., 2020). This approach examined only two energy storage technologies, batteries and hydrogen fuel, as well as heating, gas, wind energy, and solar energy to create an isolated energy hub (Geng et al., 2020). Each of these approaches utilized different optimization methods and prioritized different objectives when designing their energy systems to account for issues they deemed were most important for their context.

3. METHODOLOGY

To create the model, data was collected on each energy storage technology incorporated into the optimization model. The required data was categorized into three sections: technical, economic, and environmental.

3.1 Technical

First, the technical data was composed of response time, energy density, power density, energy efficiency, daily self-discharge, self-discharge time, and storage capacity. The response time can be described as the amount of time needed for the energy storage technology to provide the needed energy to meet load demand (Zafirakis, 2010). Furthermore, the response time is inherent to the system, so technologies with shorter response times may be best utilized to meet energy demand instantaneously while the technologies with longer response times will meet energy demand once they have been sufficiently ramped up (Zafirakis, 2010). Energy density is given by the ratio of energy storage capacity to the volume or mass of the system (Zafirakis, 2010). Similarly, the power density is the ratio of rated power to volume or mass of the system (Zafirakis, 2010). Both energy and power density place an emphasis on size of the system, so it is important to clearly define the system boundaries (Zafirakis, 2010). The energy efficiency of an energy storage device measures the amount of energy leaving the system compared to the amount of energy put into the system for one cycle or charge to discharge (Zafirakis, 2010). This formula for energy efficiency changes depending on whether self-discharge is considered negligible or significant (Zafirakis, 2010). Self-discharge is the energy lost during storage, which determines the maximum amount of time energy can be stored by a specific energy storage technology (Zafirakis, 2010). Therefore, the daily self-discharge is the amount of energy lost during storage daily, and it is related energy dissipation (Luo et al., 2015). It is important to know the self-discharge time of energy storage devices since it determines the suitable storage duration (Luo et al., 2015). The energy storage capacity is the parameter that determines the size of the storage, and it relies on the discharging time, efficiency, and depth of discharge (Zafirakis, 2010). These parameters give an overall description of the different energy storage technologies and how they compare to one another. From there, a literature search was done to gather information about the parameters for eight different energy storage technologies.

Energy Storage Technology	Technical						
	Response Time	Energy Density (Wh/L)	Power Density (W/L)	Energy Efficiency %	Daily self-discharge %	Self-Discharge time %	Capacity
PSH	Minutes [36]	1.10 [1]	1.00 [36]	77.50 [1]	0 [6]	0 [6]	Max: 3600 MW Min: 1.14 MW [17, 49]
CAES (large)	Minutes [38]	4.00 [1]	1.25 [53]	55.00 [1]	0 [6]	0 [6]	Max: 500 MW [38]
Li-ion Battery	Seconds [38]	350.00 [36]	5750.00 [36]	90.00 [1]	0.2 [6, 30]	0.19 [6]	Max: 100 MW Min: 1 kW [38, 58]
Lead Battery	Seconds [38]	65.00 [6]	205.00 [36]	85.00 [1]	0.2 [36]	0.3832 [6]	Max: 5 MW [38]
Flow Battery VRB	ms – seconds [36]	25.50 [36]	1.25 [53]	75.00 [36]	0 [19]	0 [6]	Max: 30 MW Min: several kW [38]
Hydrogen	Seconds [36]	1750.00 [36]	500.00 [36]	35.00 [1]	0 [32]	0 [32]	Max: 100 MW [39]
Flywheel	Seconds [38]	50.00 [36]	1500.00 [36]	82.50 [1]	74.6 [6, 36]	74.6 [6]	Max: 20 MW [38]
Supercapacitor	Seconds [38]	15.00 [1]	100000.00 [36]	87.50 [1]	22.5 [36]	25.115 [6]	min 250 kW max 2 MW [38]

Table 2. Technical data collected for the parameters of the model. It should be noted that energy density, power density, and self-discharge time were not incorporated into the model. Adapted from WEC, 2016; Behabtu et al., 2020; Donalek, 2020; *Flow Batteries*, (n.d); Kalaiselvam & Parameshwaran, 2014; Kharel & Shabani, 2018; Luo et al., 2015; Mongird et al., 2019; Mongird et al., 2020; Soha et al., 2017; Venkataramani et al., 2016; Zablocki, 2019.

3.2 Economic

After the technical section, economic considerations are also important for determining whether the system with energy storage is economically feasible. Economic data is composed of operation and maintenance costs, energy capital cost, power capital cost, capital cost, and the lifetime of the energy storage technology for each energy storage technology which can be seen in **Table 2**. The operation and maintenance costs (O&M costs) can be separated into two categories of fixed and variable costs (Mongird et al., 2019). Fixed O&M costs are the costs incurred at a fixed rate, which do not change due to energy usage, to keep the energy storage system functioning throughout its lifetime (Mongird et al., 2019). The variable O&M costs are similar to fixed O&M costs except they are not incurred at fixed rate, so they may depend on energy usage, size, or other factors (Mongird et al., 2019). Furthermore, fixed O&M costs are measured in $/kW-year while variable O&M costs are measured in $/kWh-year (Mongird et al., 2019). The O&M cost data used in this paper is assumed to be fixed the O&M costs for each energy storage technology. Lifetime of an energy storage device can either be measured in the number of cycle or the number of years, and this depends on the discharge characteristics, specifically depth of discharge (Zafirakis, 2010). Deep discharges reduce the lifetime of an energy storage device (Zafirakis, 2010). It is important to note that these values collected from different reports are based on different assumptions made by the authors of the articles or reports. For example, Mongird et al., 2020 calculated the fixed O&M costs of bidirectional hydrogen energy storage to be $28.51/kw-year based on a 100 MW system with 10 hours storage.

Energy Storage Technology	Economic				
	O&M Costs ($/kW-yr)	Energy Cost ($/kWh)	Power Cost ($/kW)	Capital Cost ($/kW)	Lifetime (cycles)
PSH	3 [12]	5-100 [36]	2000-4300 [36]	2638 [38]	20000 [36]
CAES (large)	22 [12, 39]	2-120 [36]	400-1000 [36]	1669 [38]	10000 [36]
Li-ion Battery	4.455 [12, 39]	600-3800 [36]	900-4000 [36]	271 [38]	5500 [36]
Lead Battery	5.9 [12, 39]	50-400 [36]	200-600 [36]	260 [38]	1000 [36]
Flow Battery VRB	70 [12, 39]	150-1000 [36]	600-1500 [36]	555 [38]	13000 [36]
Hydrogen	28.51 [39]	15 [36]	500-3000 [36]	2823 [39]	20000 [1]
Flywheel	20 [12]	1000-14000 [36]	250-350 [36]	2400 [38]	60000 [36]
Supercapacitors	6 [12]	300-2000 [36]	100-450 [36]	400 [38]	55000 [36]

Table 3. Economic data for each energy storage technology with the references. Power cost and energy cost were not utilized in the model. Adapted from WEC, 2016; Dehghani-Sanij et al., 2019; Luo et al., 2015; Mongird et al., 2019; Mongird et al., 2020.

3.3 Environmental

The objective of the model is to balance the economic and environmental aspects of energy storage technologies to find the optimal solution. To assess the environmental impact of the energy storage technologies, raw material, recycling, local impact, pollution, toxicity, and greenhouse gasses (GHG) data were collected for each energy storage technology which is shown in **Table 4.** The GHG emissions were estimated using different lifecycle assessment (LCA) techniques, namely ReCiPe 2008 and 2016 (Dekker et al., 2020; Florin & Dominish, 2017). When collecting information about the environmental impacts of energy storage technologies, it was particularly difficult to find information for flywheels as well as supercapacitors. Furthermore, the environmental impacts of energy storage throughout its lifetime is a difficult task, and it may not be accurately captured by minimizing GHG emissions emitted throughout the lifetime of an energy storage technology. In the cases of PSH, the process of constructing a reservoir or dam destroys the natural environment along with habitat for wildlife; however, that may not be accurately reflected by solely focusing on GHG emissions. However, the GHG for each energy storage technology will be used in the model to minimize the GHG emissions released throughout the lifetime of an energy storage technology. This should include all the processes from extracting the material used to make the energy storage technology to the disposal of the energy storage technology after it has served its purpose. The optimization model will be a multi-objective optimization problem that minimizes both cost and GHG emissions.

Energy Storage Technology	Environmental					
	Raw Material	Recycling	Local Impact	Pollution	Toxicity	GHG
PSH	construction materials (build dam, reservoir), water (river, reservoir) [8]	able to recycle water (closed loop) [41]	construction process may cause destruction of trees, animal life [33]	reduced water quality [22]	Non-toxic [33]	18.5 gCO^2-e/kWh [26]
CAES (large)	salt caverns, natural gas, aluminum, copper, iron [7, 18, 36]	material inputs recyclable, long lifetime [18]	CO2 emissions, low impact on landscape (assume natural storage) [18]	Generates CO2 emissions [33]	not toxic [18]	292, 10-750 gCO2e/kWh [15]
Li-ion Battery	lithium, graphitic carbon, copper [36, 42]	expensive but feasible, limited <3% [12]	mining effects, battery disposal, fire risk [12]	copper, lithium mining, PM, 70 kg CO2/kWh [12, 42]	battery disposal toxic to humans, treated as hazardous waste [12, 33]	25 kgCO2e/MWh [18]
Lead Battery	lead, sulfuric acid [36]	95% effective, required to reduce impacts [12]	lead fumes, particulates, mining effects [12]	disposal of lead smelter, PM [42]	toxic to humans [12]	25 kgCO2e/MWh [18]
Flow Battery VRB	sodium, bromine, sulfate, zinc, vanadium [36]	technically recyclable but pathways under development [18]		lowest GWP/MWh [18]	toxic remains/waste [33]	20 kgCO2e/MWh [18]
Hydrogen	Water, natural gas [8]	low [18]	may emit CO2 but no significant environmental impact [8]	depend on hydrogen production - may/ may not emit CO2 [8]	not toxic [8]	0 (using water) 1-5 (using nat. gas & CCUS) [5]
Flywheel	steel-based, graphite, carbon fiber, boron [9]		no disposal issues [33]	noise, environmentally benign [8]	no chemical management [33]	
Supercapacitors	graphene, activated carbon, nitrogen, phosphorus, oxygen [10, 23, 57]	recycle graphene - reduced environmental impact [10]	relatively small [8]	relatively small [8]	waste supercapacitors class as hazardous [33]	

Table 4. Environmental Impact of Energy Storage. Adapted from Florin & Dominish, 2017; Luo et al., 2015; Dehghani-Sanij et al., 2019; Bartlett & Krupnick, 2020; Bouman et al., 2013; Breeze, 2018; Conteh & Nsofor, 2016; Cossutta et al., 2020; Denholm & Kulcinski, 2004; Heidari et al., 2020; Huang et al., 2019; *International Hydropower Association,* (n.d.); Khawaja et al., 2019; Normyle & Pittock, 2020; Oliveira et al., 2015; Wu et al., 2017.

3.4 Model

To begin modeling the system, I created a basic superstructure to represent the system which can be seen in the **Figure 2** below. The energy sources will be coming from both solar PV and electricity, and it will be used to meet the electricity demand at each time interval in a 24-hour period. Any excess electricity generated by the solar PV system will be stored in any one or a combination of the energy storage technologies in the middle column. When solar PV can no longer generate electricity, the stored energy will be discharged to meet the electricity demand. Ideally, electricity will not be used to meet the electricity demand if the demand can be met by both direct solar PV as well as energy storage. This model assumes that smaller processes, such as converting electricity to either AC or DC, that will take place within the superstructure are included in the generation or storage processes. The solar PV system converts the outgoing power to AC. The arrows represent the flow of energy or electricity to either storage or demand.

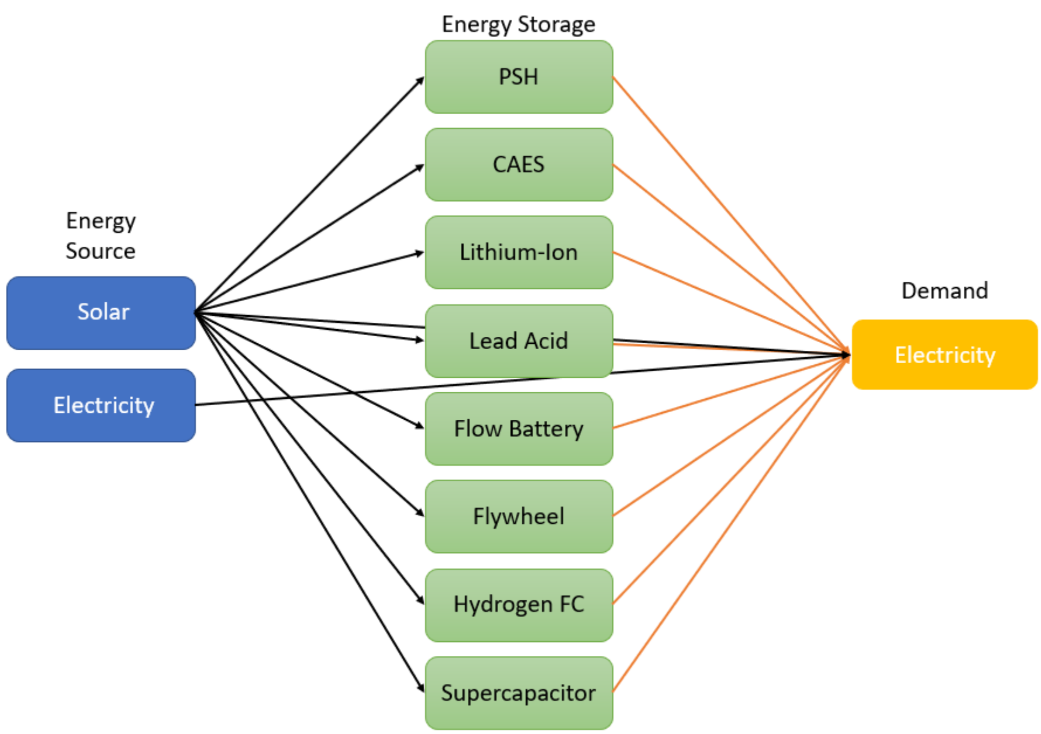

Figure 2. The superstructure created to represent the energy storage system.

Building the mathematical model, I used Demirhan et al., 2021 as a guide when creating the parameters, variables, and constraints for this system. The model is a mixed-integer linear programming (MILP) model, so the constraints are expressed in terms of linear relationships with binary variables for decision-making processes. The computer programs used to create the models were Python and Gurobi using Jupyter Notebook. For my parameters, I created a parameter for each technical aspect of the different energy storage technologies such as efficiency, self-discharge, and the other technical aspects which can be seen in **Table 5**. The "i" is one of the energy storage technologies out of all the energy storage technologies that are a part of this model in Figure 2, which make up the set "I". Furthermore, the "t" refers to a time interval belonging to the set "T".

Parameters	
$Demand_t$	demand for electricity
$Efficiency_i$	efficiency of storage technology i
$CapCost_i$	capital cost of storage technology i
$O\&MCost_i$	O&M costs of storage technology i
$Cost_i^{Total}$	total costs of storage technology i
Cap_i^{Max}	max storage capacity for storage i
Cap_i^{Min}	min storage capacity for storage i
$Self\_Discharge_i$	loss of energy while stored in storage technology i
$EnergyResource_t$	total solar energy resource at time t
$ResponseTime_i$	response time of storage technology i
$EnergyDensity_i$	energy density of storage technology i
$PowerDensity_i$	power density of storage technology i
$GHG\_emissions_i$	GHG generated throughout lifetime of storage tech i

Table 5. Parameters used for the model along with a brief description.

To determine the solar PV energy resources going into the model, I first had to use pvlib to create a modelchain (Holmgren et al., 2018). The solar data used for the modelchain was downloaded from NREL's National Solar Radiation Database (NSRDB), and it was the PSM v3 5-minute 2019 data in 5-minute intervals to get the best data resolution (Sengupta et al., 2018). Thus, there are 288 time intervals in this models for each 5-minute interval in a 24-hour period. Furthermore, the modelchain was created using the simple modelchain example shown on the pvlib python website with the new data acquired from NREL (Holmgren et al., 2018; Sengupta et al., 2018). The power output from the modelchain was integrated into the optimization model as the generated solar PV resources either went into storage or directly to meet the electricity demand. Moreover, the model was created to examine energy storage technologies for a single day or 24-hour period, but it could be used for a longer time period with some slight adjustments. The day selected for the model was January 1, 2019, and the time period falls in the winter where it can be assumed the solar resources are reduced.

Once the modelchain was completed, the parameters for the technical aspects of the energy storage model were created using the dataframe function. The technical aspects used in the dataframe were energy density, power density, efficiency, self-discharge, maximum capacity, minimum capacity, capital cost, O&M cost, maximum lifecycle, and electricity demand. After the parameters were created, variables were made for the different parts of the system that needed to be determined by the model. The variables created are listed in Table 6.

Variables	
$Capacity_{i,}$	storage capacity of storage technology i
Store $Inlet_{i,t}$	solar resource going to storage i at time t
Store $Outlet_{i,t}$	solar resource leaving storage i at time t
$Stored_{i,t}$	solar resource stored in storage i at time t
TotalCost	total cost of the energy storage system per year
y_i	equals 1 if storage technology i is selected
z_t	equals 1 if Energy_Resource less than demand at time t
$Source_t^{Direct}$	solar resources going to demand at time t

Table 6. Variables created for the model with a description.

General equations were created to model the relationships between the parameters and variables along with the energy balances throughout the system. These equations are used as constraints for the optimization model to ensure the system is accurately portrayed. The more central constraints are listed below, and they either illustrate an energy balance or binary constraint. The binary constraints are used along with the binary variables to determine whether an energy storage technology will or will not be used in the optimal solution. Binary variables can be thought of as a “switch” to either turn on or turn off the energy storage technologies. The equations are linear to simplify the model. Many of the equations are simplified and still need to be multiplied with the appropriate parameters.

$$Capacity[i] \geq Capacity\ Min\ [i] * y[i] \qquad \text{Equation 1.}$$

Equation 1 states that the capacity of the energy storage technology should be greater than the minimum capacity of the energy storage technology. If it is not greater than the minimum energy storage capacity, then the binary variable “y” will turn off the capacity.

$$Capacity[i] \leq Capacity\ Max\ [i] * y[i] \qquad \text{Equation 2.}$$

Capacity of the energy storage technology “i” should be less than or equal to the maximum capacity of the energy storage technology. If it is greater than the maximum energy storage capacity, then the binary variable “y” will turn off capacity.

$$Stored[i,t] = Store\ Inlet[i,t] - Store\ Outlet[i,t] + Stored[i,t-1] \quad \text{Equation 3.}$$

The energy stored in each energy storage technology at time interval “t” is equal to the incoming energy minus the outgoing energy as well as the energy that remains from the previous time interval.

$$\Sigma Store\ Outlet[i,t] * (efficiency)[i] + Source\ Direct[t] + Electric[t] \geq Demand[t] \quad \text{Equation 4.}$$

The sum of the energy leaving the energy storage technology at time interval “t” multiplied by the efficiency of the energy storage technology plus the solar energy directly meeting demand and the electricity meeting demand should be greater than the demand at time interval “t”.

$$Store\ Outlet[i,t-1] - Store\ Outlet[i,t] \leq 0.5 * Capacity[i] \quad i = 1,2 \quad \text{Equation 5.}$$

This equation reflects the response time of an energy storage technology. In this case, storage technologies 1 and 2 are PSH and CAES, and they need approximately 10 minutes to respond and operate at full capacity. So, they operate at half capacity after 1 time interval “t”.

$$Store\ Outlet[i,t-1] - Store\ Outlet[i,t] \leq 1 * Capacity[i] \quad i = 3:8 \quad \text{Equation 6.}$$

Similar to Equation 5, this equation reflects the response time of energy storage technologies 3 through 8, which are able to almost instantaneously operate at full capacity at time interval “t”.

$$Energy\ Resource[t] = Store\ Inlet\ [i,t] + Source\ Direct[t] \quad \text{Equation 7.}$$

The energy resource at time interval “t” is equal to the energy going into energy storage technology “i” at time interval “t” and the solar energy going directly to demand at time interval “t”.

$$Store\ Inlet[i,t] \leq Capacity[i] \quad \text{Equation 8.}$$

The energy going into the energy storage technologies should be less than or equal to the capacity of the energy storage technology as determined by the model.

$$Store\ Inlet[i,t] \leq\ 1e7\ *\ y[i]$$ Equation 9.

This equation should turn off any energy going into the energy storage technology if the binary variable is 0.

$$Stored[i,t] \leq\ Capacity[i]$$ Equation 10.

Energy that can be stored in energy storage technology “i” at time interval “t” is less than or equal to the capacity of energy storage technology “i”.

$$\Sigma Capital\ Cost[i] * Capacity[i]\ +\ OM\ Cost[i] * Capacity[i]\ * 1\ year\ +\ 0.11 * Electricity[t]$$

Equation 11.

This equation is the objective function for the model that focuses on minimizing cost, and it based on the capacity/size of the energy storage technology being used in the model. In addition, the cost of electricity is included since electricity may need to be purchased to meet demand.

In the process of creating this optimization model, several assumptions were made to simplify the model. One of the main assumptions is that there is a constant electricity demand throughout all time periods. As mentioned earlier, the data for this model is for an entire year; however, the model only utilizes the data for one 24-hour period in winter. In terms of energy storage technologies, hydrogen energy storage is assumed to be produced from electrolysis, so there is not any natural gas or other materials used to produce hydrogen. Moreover, the technical data used for the model is an average of ranges found in the literature about different energy storage technologies. For example, a 2016 report from the World Energy Council listed the energy density of pumped-storage hydro to between 0.2 - 2 Wh/L, so the value used for the model is 1.1 Wh/L since it is the average of the two numbers. This was done for all the values that had a range of data listed in the literature. For the minimum capacity of energy storage technologies, the minimum capacities that could not be found in the literature were estimated to be 0 while the minimum capacity values that could be found were used for the other technologies. When downloading NREL's NSRDB data, the location used was College Station, TX, so the solar data is specifically for this location.

4. RESULTS AND DISCUSSION

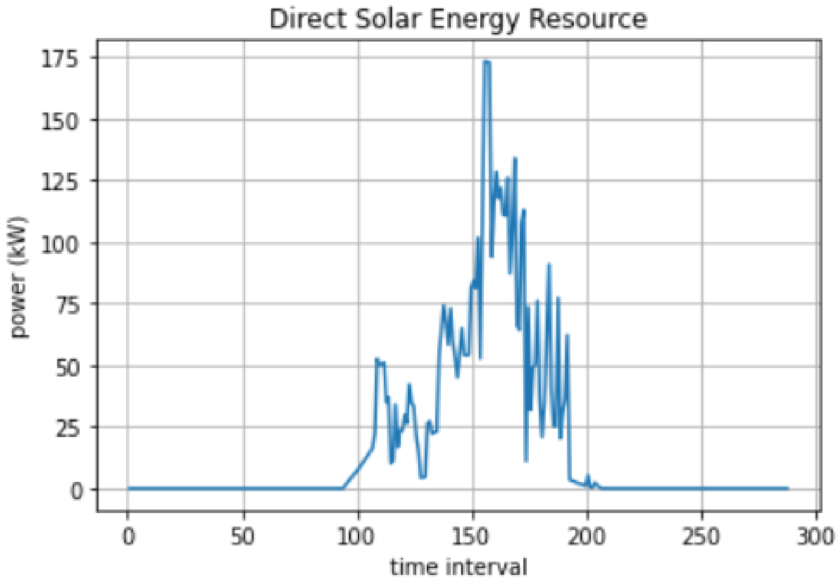

Figure 3. Solar energy directly meeting demand at each time interval.

The first part of the model utilized pvlib to create a power source coming from solar energy over the 288 time intervals to either feed into the energy storage technologies or meet directly without any storage. In addition to solar energy, electricity from the grid was used to also meet demand with the expectation that it would only be utilized when solar energy could not meet demand either directly or indirectly through energy storage. **Figures 3** and **4** illustrate the solar power going directly to meeting demand, and the electricity purchased from the grid to meet demand. I assumed a constant demand and used 50 kW per time interval. The solar energy going directly to meeting demand and the total solar energy resource from the pvlib model are the same. In other words, the model is not storing any energy in the energy storage technologies as it prefers to purchase electricity from the grid. **Figure 5** show that there is not any energy being stored in lithium-ion batteries and PSH, which is the same for the rest of the energy storage technologies. There are a few different interpretations of this result: electricity is cheaper, demand is too small to justify energy storage, and the time period is too short for the model.

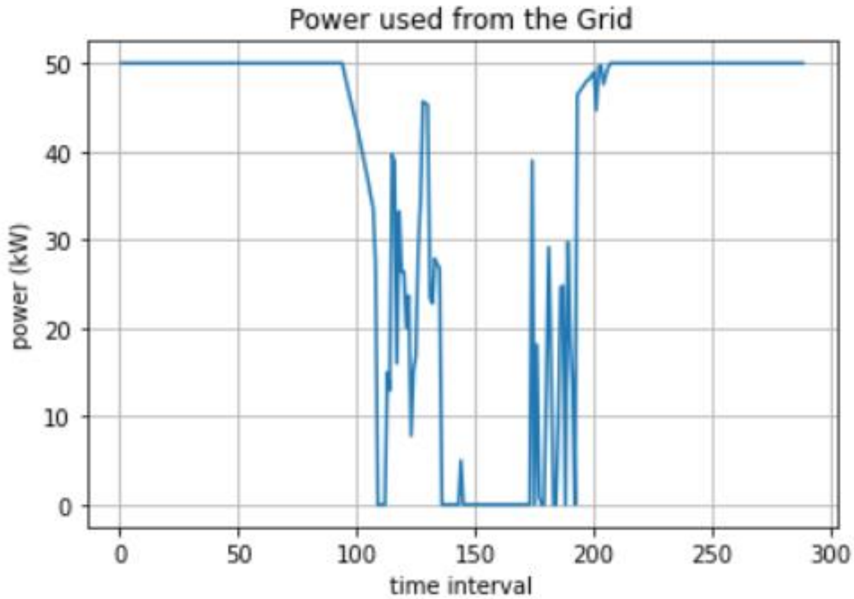

Figure 4. Electricity purchased from the grid to meet demand.

The first interpretation of the results makes the most sense since the model is focused on minimizing cost, and I first estimated the cost of electricity to be 11 cents per kW. Furthermore, the costs of the energy storage technologies are based on the capacity/size of the energy storage technologies. This results in the capacity of energy storage technologies being 0, so none of the energy storage technologies are being utilized while the demand is being met by solar energy directly as well as electricity purchased from the grid. While this makes sense, I also tried changing the cost of electricity to $100 per kW to see if there is any difference in the results, and there was not any difference. Since there was not any change in the results, I changed the price of electricity again to $100,000 per kW, and there not a difference in the results. So, I concluded there must be another factor that has led to none of the energy storage technologies being utilized.

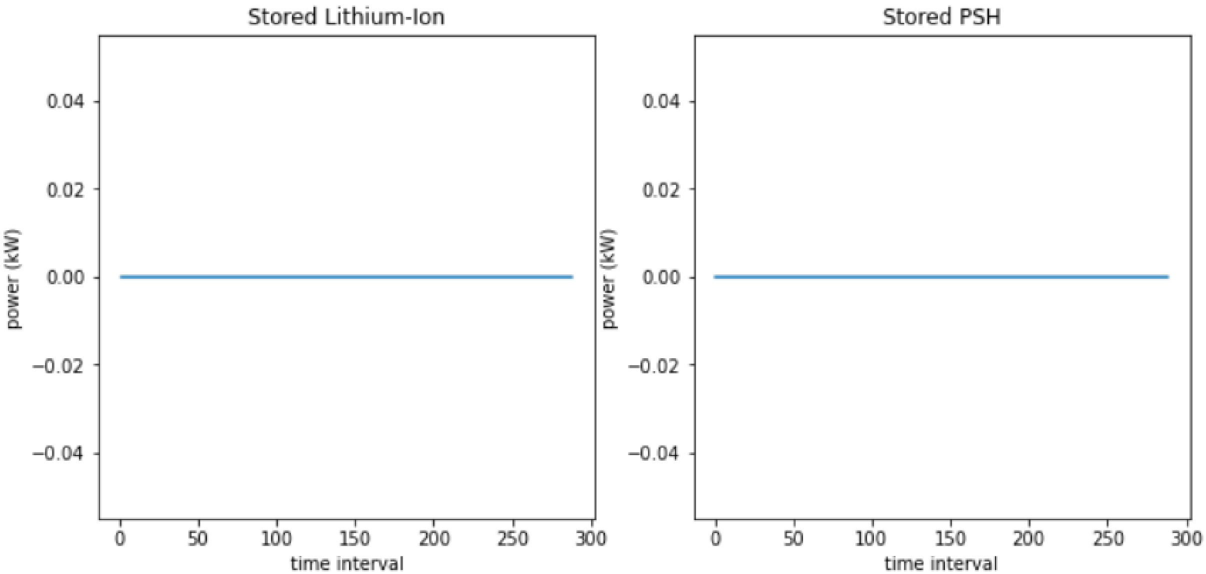

Figure 5. Zero energy stored in any of the energy storage technologies.

Next, I looked at the size or capacity of the system and how that worked with the current demand of 50 kW per time interval. The model has minimum capacity constraints on PSH, lithium-ion batteries, VRB, and supercapacitors, so they cannot be utilized below their minimum capacity. For example, PSH cannot be utilized below 1 MW since it is not practical to build a PSH facility at such a small scale. However, the demand is only 50 kW per time interval for a 24-hour period, so it is very unlikely that most of the energy storage technologies with minimum capacities would be utilized in this model. However, this does not quite explain why the energy storage technologies with a minimum capacity of 0 are also not being utilized in this model. In order to make it feasible for energy storage technologies such as PSH to be utilized, the demand was increased to 1000 kW or 1 MW. However, the significantly increased demand presented a challenge in that there was no need for energy storage at all since there was not any excess solar energy from the pvlib model. In other words, all the solar energy went to meeting demand directly, and the rest of the electricity was purchased from the grid since demand could not be met otherwise.

Part of the issue becomes that the time period of the model is too short for energy storage technologies to store large amounts of energy. However, increasing the model time period may make it difficult to find the errors that are present in the model which presents additional challenges to fix those errors. For example, there was a “hole” in model where energy coming from solar energy would go into the energy storage technologies, but there was not any energy leaving the model. This error resulted in an energy imbalance in the model, and it has since been corrected. Additionally, before the minimum capacity constraint was introduced, all the energy storage technologies were being in small amounts (1 to 10 kW). The minimum capacity constraints on PSH, lithium-ion batteries, VRB, and supercapacitors caused all the energy storage technologies to not store any energy. Therefore, there may also be an error with the model choosing only one or a couple of energy storage technologies rather than choosing all the energy storage technologies.

The energy storage model created incorporates energy storage technologies that cannot store energy for a long period of time such as flywheels and supercapacitors. While I initially decided it would be best to create a comprehensive model with all major energy storage technologies regardless of their storage duration, I realized that the technologies with shorter storage would not be the best-suited technologies to meet demand. Yet, I included them in the model to make sure that the assumptions I made were correct and allowed the model to decide which storage technologies would be the optimal solution. In addition, PSH and CAES are geographically oriented energy storage technologies, but this model did not consider those geographic constraints. In terms of best energy storage technologies regardless of geographic location, lithium-ion, lead-acid, or vanadium redox flow batteries may be the best solution, but these battery storage technologies will be costly. Additionally, batteries may have a greater environmental impact by producing more GHG emissions as well as issues with disposal if they are not recycled than any of the other energy storage technologies.

4.1 Challenges

Finding the errors in the model has been the most challenging part of building this model since they are not easy to find, and they could either be caused by coding issues or a fundamental misunderstanding of how to correctly model the system. Before I added another objective function to my model, I wanted to make sure my model was correct with only one objective function which was minimizing cost. Therefore, I was unable to add minimizing greenhouse gasses as another objective function for my model. Furthermore, it was challenging figuring out what parameters I needed to use in my constraints. For example, energy and power density were not used in the constraints while some information needed for the objective function or constraints is difficult to find. The GHG emissions for flywheel and supercapacitors throughout their lifetime have been difficult information to uncover as the literature on their lifecycle analysis is slim compared to the other energy storage technologies. Discerning what information is useful for building an energy storage model becomes a challenging task when collecting data since it is better to collect more data than having too little data for the model. However, the variation in data and general lack of information have made the data collection process time-consuming. Additionally, many newer energy storage technologies have less data about them which makes it difficult to incorporate these energy storage technologies into an energy storage model since there is less research available about these specific technologies. While data collection has presented some challenges, the implementation process has also been a trial-and-error process. Since I am new to Python and Gurobi, implementing the model into python presents new challenges such as understanding syntax, indices, and dataframes.

5. CONCLUSION

The need for energy storage has grown tremendously due to increasing energy demands of the future. Climate change is one of the pressing factors for usage of intermittent sources of renewable energy, requiring the implementation of energy storage to meet electricity demands regardless of when these renewable energy sources are not producing electricity. Utilizing data from NREL's NSRDB to model a renewable energy storage system in Texas will allow insight into designing and operating an energy storage system for a renewable energy system that will determine feasibility of creating such a system in real life as well as the costs of doing so. Since climate change is a pressing issue, this model sought to minimize GHG emissions as well as cost to determine the best energy storage technology economically and environmentally. Often times, companies or organizations are only concerned with finding the lowest cost solution, however, these solutions may come at the greater cost of increased GHG emissions that only continue to exacerbate climate change. It is important to also ensure sound energy storage systems that prioritize environmental concerns. With some additional revisions, this model can be applied to different renewable energy systems with the caveat that it will need to be modified to correctly capture the new system. Energy storage is essential for meeting future energy demands through the usage of renewable energy, which would be important for mitigating climate change.

5.1 Future Work

Assuming constant demand does not consider issues that the Duck Curve poses, but the integration of energy storage technologies into a renewable energy system can help avoid those issues. More work must be done to adjust the model, so that it can be applied to different situations that may change the time duration, demand, and other model aspects. In addition, the constraints of the model need more work, so that they can accurately reflect the system and eliminate any errors in present in the model. However, the code runs smoothly and changing some of the constraints leads to different results in which all the energy storage technologies are being utilized. This indicates that the model has potential to be useful with some additional corrections, and this model can be added onto to create a more robust model that can decide which energy storage technology would be best suited for a particular system. Changes in the system can affect the model output. It is important to decide the scale of the system, utility scale or household, and whether this system is grid-tied or isolated. The model I created was for a grid-tied system that could get additional electricity from the grid to meet electrical demand if it could not be met by solar energy or stored solar energy. This model also attempted to determine the optimal sizing of the selected energy storage devices to meet the electricity demand.

More research must be done to determine the best usage for energy storage technologies and address any gaps in research, especially related to newer energy storage technologies. When collecting data for each energy storage technology in the model, there was a noticeable gap in lifecycle assessment data for flywheel and supercapacitors to determine the amount of GHG emissions have been released throughout the lifetime of these technologies. Understandably, it may be more difficult to obtain information about their lifecycles since these technologies are not quite as common as lithium-ion or lead-acid batteries. In addition, there is significant variation about different energy storage technologies that make it difficult to determine which sources of information to use for modeling. There are many factors or assumptions that have led to this variation in data such as publication year, size of energy storage device, and others. More research may help lead to a better picture of what data for different energy storage technologies is more accurate or finding acceptable variations in data that still accurately portray these technologies. Additionally, new energy storage technologies are emerging while current technologies are being upgraded, so more research will need to be done in the future to ensure all available technologies are being used to their best potential.

REFERENCES

1. "World Energy Resources E-Storage 2016," World Energy Council, https://www.worldenergy.org/assets/images/imported/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf
2. Abdulgalil, M. A., Alharbi, H. S., Khalid, M., & Almuhaini, M. M. (2018). Reliability Assessment of Microgrids with Multiple Distributed Generations and Hybrid Energy Storage. *2018 IEEE 27th International Symposium on Industrial Electronics (ISIE)*, 868–873. https://doi.org/10.1109/ISIE.2018.8433614
3. Abdulgalil, M. A., Khalid, M., & Alismail, F. (2019). Optimal Sizing of Battery Energy Storage for a Grid-Connected Microgrid Subjected to Wind Uncertainties. *Energies (19961073)*, *12*(12), 2412. https://doi.org/10.3390/en12122412
4. Allen, R. C.; Baratsas, S. G.; Kakodkar, R.; Avraamidou, S.; Powell, J. B.; Heuberger, C. F.; Demirhan, C. D.; Pistikopoulos, E. N. (ADCHEM 2021). An Optimization Framework for Solving Integrated Planning and Scheduling Problems for Dense Energy Carriers. Proceedings of the 11th IFAC International Symposium on Advanced Control of Chemical Processes.
5. Bartlett, J., & Krupnick, A. (2020, December). *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions*. Resources for the Future. https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/
6. Behabtu, H. A., Messagie, M., Coosemans, T., Berecibar, M., Anlay Fante, K., Kebede, A. A., & Mierlo, J. V. (2020). A Review of Energy Storage Technologies' Application

Potentials in Renewable Energy Sources Grid Integration. *Sustainability*, *12*(24), 10511. https://doi.org/10.3390/su122410511

7. Bouman, E., Øberg, M. M., & Hertwich, E. (2013). LIFE CYCLE ASSESSMENT OF COMPRESSED AIR ENERGY STORAGE (CAES). *The 6th International Conference on Life Cycle Management in Gothenburg 2013*. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.895.6480&rep=rep1&type=pdf
8. Breeze, P. (2018). *Power System Energy Storage Technologies*. Elsevier Science & Technology. http://ebookcentral.proquest.com/lib/tamucs/detail.action?docID=5399303
9. Conteh, M. A., & Nsofor, E. C. (2016). Composite flywheel material design for high-speed energy storage. *Journal of Applied Research and Technology*, *14*(3), 184–190. https://doi.org/10.1016/j.jart.2016.04.005

10. Cossutta, M., Vretenar, V., Centeno, T. A., Kotrusz, P., McKechnie, J., & Pickering, S. J. (2020). A comparative life cycle assessment of graphene and activated carbon in a supercapacitor application. *Journal of Cleaner Production*, *242*, 118468. https://doi.org/10.1016/j.jclepro.2019.118468

11. Das, C. K., Bass, O., Kothapalli, G., Mahmoud, T. S., & Habibi, D. (2018). Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. *Renewable and Sustainable Energy Reviews*, *91*, 1205–1230. https://doi.org/10.1016/j.rser.2018.03.068

12. Dehghani-Sanij, A. R., Tharumalingam, E., Dusseault, M. B., & Fraser, R. (2019). Study of energy storage systems and environmental challenges of batteries. *Renewable and Sustainable Energy Reviews*, *104*, 192–208. https://doi.org/10.1016/j.rser.2019.01.023

13. Dekker, E., Zijp, M. C., van de Kamp, M. E., Temme, E. H. M., & van Zelm, R. (2020). A taste of the new ReCiPe for life cycle assessment: consequences of the updated impact assessment method on food product LCAs. *The International Journal of Life Cycle Assessment*, *25*(12), 2315–2324. https://doi.org/10.1007/s11367-019-01653-3

14. Demirhan, C. D., Tso, W. W., Powell, J. B., & Pistikopoulos, E. N. (2021). A multi-scale energy systems engineering approach towards integrated multi-product network optimization. *Applied Energy*, *281*, 116020. https://doi.org/10.1016/j.apenergy.2020.116020

15. Denholm, P., & Kulcinski, G. L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. *Energy Conversion and Management*, *45*(13), 2153–2172. https://doi.org/10.1016/j.enconman.2003.10.014

16. Ding, Y., Li, Y., Liu, C., & Sun, Z. (2015). Chapter 2 - Solar Electrical Energy Storage. In B. Sørensen (Ed.), *Solar Energy Storage* (pp. 7–25). Academic Press. https://doi.org/10.1016/B978-0-12-409540-3.00002-5

17. Donalek, P. J. (2020). Pumped Storage Hydro: Then and Now. *IEEE Power and Energy Magazine*, *18*(5), 49–57. https://doi.org/10.1109/MPE.2020.3001418

18. Florin, N. and Dominish, E. (2017) Sustainability evaluation of energy storage technologies. Report prepared by the Institute of Sustainable Futures for the Australian Council of Learned Academies.

19. *Flow Batteries*. (n.d.). Retrieved June 19, 2021, from http://www.eseslab.com/ESsensePages/FlowBatt-page

20. Geng, S., Vrakopoulou, M., & Hiskens, I. A. (2020). Optimal Capacity Design and Operation of Energy Hub Systems. *Proceedings of the IEEE*, *108*(9), 1475–1495. https://doi.org/10.1109/JPROC.2020.3009323

21. Haas, J., Nowak, W., & Palma-Behnke, R. (2019). Multi-objective planning of energy storage technologies for a fully renewable system: Implications for the main stakeholders in Chile. *Energy Policy*, *126*, 494–506. https://doi.org/10.1016/j.enpol.2018.11.034

22. Heidari, A., Esmaeel Nezhad, A., Tavakoli, A., Rezaei, N., Gandoman, F. H., Miveh, M. R., Ahmadi, A., & Malekpour, M. (2020). A comprehensive review of renewable energy resources for electricity generation in Australia. *Frontiers in Energy*, *14*(3), 510–529. https://doi.org/10.1007/s11708-020-0671-6

23. Huang, S., Zhu, X., Sarkar, S., & Zhao, Y. (2019). Challenges and opportunities for supercapacitors. *APL Materials*, *7*(10), 100901. https://doi.org/10.1063/1.5116146

24. Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, *12*(5), 1221–1250. https://doi.org/10.1016/j.rser.2007.01.023

25. Immendoerfer, A., Tietze, I., Hottenroth, H., & Viere, T. (2017). Life-cycle impacts of pumped hydropower storage and battery storage. *International Journal of Energy and Environmental Engineering*, *8*(3), 231–245. https://doi.org/10.1007/s40095-017-0237-5

26. *International Hydropower Association*. (n.d.). Retrieved June 19, 2021, from https://www.hydropower.org/factsheets/greenhouse-gas-emissions

27. Jones-Albertus, B. (2017). *Confronting the Duck Curve: How to Address Over-Generation of Solar Energy*. Energy.Gov. Retrieved December 21, 2020, from

https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

28. Kadiyala, A., Kommalapati, R., & Huque, Z. (2016). Evaluation of the Life Cycle Greenhouse Gas Emissions from Hydroelectricity Generation Systems. *Sustainability*, *8*(6), 539. https://doi.org/10.3390/su8060539

29. Kahan, A. (2019, September 24). *EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia - Today in Energy*. U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=41433

30. Kalaiselvam, S., & Parameshwaran, R. (2014). *Thermal Energy Storage Technologies for Sustainability*. Academic Press. https://learning.oreilly.com/library/view/thermal-energy-storage/9780124172913/

31. Kapila, S., Oni, A. O., Gemechu, E. D., & Kumar, A. (2019). Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. *Energy*, *170*, 592–603. https://doi.org/10.1016/j.energy.2018.12.183

32. Kharel, S., & Shabani, B. (2018). Hydrogen as a Long-Term Large-Scale Energy Storage Solution to Support Renewables. *Energies*, *11*(10), 2825. https://doi.org/10.3390/en11102825

33. Khawaja, M. K., Alkhalidi, A., & Mansour, S. (2019). Environmental impacts of energy storage waste and regional legislation to curtail their effects – highlighting the status in Jordan. *Journal of Energy Storage*, *26*, 100919. https://doi.org/10.1016/j.est.2019.100919

34. Lin, W., Ma, Z., Ren, H., Gschwander, S., & Wang, S. (2019). Multi-objective optimisation of thermal energy storage using phase change materials for solar air systems. *Renewable Energy*, *130*, 1116–1129. https://doi.org/10.1016/j.renene.2018.08.071

35. Liu, M., Li, W., Wang, C., Polis, M. P., Wang, L. Y., & Li, J. (2017). Reliability Evaluation of Large Scale Battery Energy Storage Systems. *IEEE Transactions on Smart Grid*, *8*(6), 2733–2743. https://doi.org/10.1109/TSG.2016.2536688

36. Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, *137*, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081

37. Mitsos, A., Asprion, N., Floudas, C. A., Bortz, M., Baldea, M., Bonvin, D., Caspari, A., & Schäfer, P. (2018). Challenges in process optimization for new feedstocks and energy sources. *Computers & Chemical Engineering*, *113*, 209–221. https://doi.org/10.1016/j.compchemeng.2018.03.013

38. Mongird, K., Fotedar, V., Viswanathan, V., Koritarov, V., Balducci, P., Hadjerioua, B., & Alam, J. (2019). *psh* (PNNL-28866). Pacific Northwest National Laboratory.

39. Mongird, K., Viswanathan, V., Alam, J., Vartanian, C., Sprenkle, V., & Baxter, R. (2020). *2020 Grid Energy Storage Technology Cost and Performance Assessment*. 117.

40. Murrant, D., & Radcliffe, J. (2018). Assessing energy storage technology options using a multi-criteria decision analysis-based framework. *Applied Energy*, *231*, 788–802. https://doi.org/10.1016/j.apenergy.2018.09.170

41. Normyle, A., & Pittock, J. (2020). A review of the impacts of pumped hydro energy storage construction on subalpine and alpine biodiversity: lessons for the Snowy Mountains pumped

hydro expansion project. *Australian Geographer*, *51*(1), 53–68. https://doi.org/10.1080/00049182.2019.1684625

42. Oliveira, L., Messagie, M., Mertens, J., Laget, H., Coosemans, T., & Van Mierlo, J. (2015). Environmental performance of electricity storage systems for grid applications, a life cycle approach. *Energy Conversion and Management*, *101*, 326–335. https://doi.org/10.1016/j.enconman.2015.05.063
43. Oró, E., Gil, A., de Gracia, A., Boer, D., & Cabeza, L. F. (2012). Comparative life cycle assessment of thermal energy storage systems for solar power plants. *Renewable Energy*, *44*, 166–173. https://doi.org/10.1016/j.renene.2012.01.008
44. Pellow, M. A., Ambrose, H., Mulvaney, D., Betita, R., & Shaw, S. (2020). Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues. *Sustainable Materials and Technologies*, *23*, e00120. https://doi.org/10.1016/j.susmat.2019.e00120
45. Pellow, M. A., Emmott, C. J. M., Barnhart, C. J., & Benson, S. M. (2015). Hydrogen or batteries for grid storage? A net energy analysis. *Energy & Environmental Science*, *8*(7), 1938–1952. https://doi.org/10.1039/C4EE04041D
46. Pham, T. T., Kuo, T.-C., & Bui, D. M. (2020). Reliability evaluation of an aggregate battery energy storage system in microgrids under dynamic operation. *International Journal of Electrical Power & Energy Systems*, *118*, 105786. https://doi.org/10.1016/j.ijepes.2019.105786

47. Prajapati, V. K., & Mahajan, V. (2021). Reliability assessment and congestion management of power system with energy storage system and uncertain renewable resources. *Energy*, *215*, 119134. https://doi.org/10.1016/j.energy.2020.119134

48. Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., & Shelby, J. (2018). The National Solar Radiation Data Base (NSRDB). *Renewable and Sustainable Energy Reviews*, *89*, 51–60. https://doi.org/10.1016/j.rser.2018.03.003

49. Soha, T., Munkácsy, B., Harmat, Á., Csontos, C., Horváth, G., Tamás, L., Csüllög, G., Daróczi, H., Sáfián, F., & Szabó, M. (2017). GIS-based assessment of the opportunities for small-scale pumped hydro energy storage in middle-mountain areas focusing on artificial landscape features. *Energy*, *141*, 1363–1373. https://doi.org/10.1016/j.energy.2017.11.051

50. Sørensen, Bent. (2015). *Solar Energy Storage.* Elsevier. Retrieved from https://app.knovel.com/hotlink/toc/id:kpSES00002/solar-energy-storage/solar-energy-storage

51. Stecca, M., Elizondo, L. R., Soeiro, T. B., & Bauer, P. (2020). Energy Storage Sizing and Location in Distribution Networks Considering Overall Grid Performance. *2020 IEEE Power Energy Society General Meeting (PESGM)*, 1–5. https://doi.org/10.1109/PESGM41954.2020.9281432

52. van Ruijven, B.J., De Cian, E. & Sue Wing, I. Amplification of future energy demand growth due to climate change. *Nat Commun* 10, 2762 (2019). https://doi-org.srv-proxy2.library.tamu.edu/10.1038/s41467-019-10399-3

53. Venkataramani, G., Parankusam, P., Ramalingam, V., & Wang, J. (2016). A review on compressed air energy storage – A pathway for smart grid and polygeneration. *Renewable and Sustainable Energy Reviews*, *62*, 895–907. https://doi.org/10.1016/j.rser.2016.05.002

54. William F. Holmgren, Clifford W. Hansen, and Mark A. Mikofski. "pvlib python: a python package for modeling solar energy systems." Journal of Open Source Software, 3(29), 884, (2018). https://doi.org/10.21105/joss.00884

55. Wong, L. A., Ramachandaramurthy, V. K., Walker, S. L., & Ekanayake, J. B. (2020). Optimal Placement and Sizing of Battery Energy Storage System Considering the Duck Curve Phenomenon. *IEEE Access*, *8*, 197236–197248. https://doi.org/10.1109/ACCESS.2020.3034349

56. Wu, T., Shi, X., Liao, L., Zhou, C., Zhou, H., & Su, Y. (2019). A Capacity Configuration Control Strategy to Alleviate Power Fluctuation of Hybrid Energy Storage System Based on Improved Particle Swarm Optimization. *Energies (19961073)*, *12*(4), 642. https://doi.org/10.3390/en12040642

57. Wu, Z., Li, L., Yan, J., & Zhang, X. (2017). Materials Design and System Construction for Conventional and New-Concept Supercapacitors. *Advanced Science*, *4*(6), 1600382. https://doi.org/10.1002/advs.201600382

58. Zablocki, A. (2019, February 22). *Fact Sheet: Energy Storage (2019)*. Environmental and Energy Study Institute. https://www.eesi.org/papers/view/energy-storage-2019#1

59. Zafirakis, D. P. (2010). 2 - Overview of energy storage technologies for renewable energy systems. In J. K. Kaldellis (Ed.), *Stand-Alone and Hybrid Wind Energy Systems* (pp. 29–80). Woodhead Publishing. https://doi.org/10.1533/9781845699628.1.29

60. Zeynalian, M., Hajialirezaei, A. H., Razmi, A. R., & Torabi, M. (2020). Carbon Dioxide Capture from Compressed Air Energy Storage System. *Applied Thermal Engineering*, *178*, 115593. https://doi.org/10.1016/j.applthermaleng.2020.115593