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Optimal Sizing and Operation of a Pumped Thermal Energy Storage System

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Optimal Sizing and Operation of a Pumped Thermal Energy Storage System

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Abstract

Current trends in the modern grid are leading to the integration of energy storage technologies (ESSs), such as pumped thermal energy storage to help incorporate more variable renewable energy sources into the grid. This paper analyzes the operation of a pumped thermal energy storage (PTES) system under the grid services of energy arbitrage, regulation services, spinning and non-spinning reserve, resource adequacy, and a combination of them all. Each revenue stream is setup into an optimization problem and solved to find which revenue generating technique would generate the most revenue. The combined revenue stream was found to produce the most revenue and was subjected to a sensitivity analysis to determine if the power transfer limit or energy capacity of the PTES system had a greater effected on its revenue generating capability. The power transfer limit was found to have the greatest effect on the system's revenue generation capability.

Acknowledgements

The Author would like to thank his academic advisor and thesis defense committee for their time and patience during this unprecedented time that this work was completed. A special thanks to Dr. Rui Fan as well, for who's support was instrumental in bringing this work to fruition.

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Introduction

Today's modern power grid is moving away from the conventional energy generation sources such as large coal and natural gas power plants to more distributed variable renewable energy generation sources such as solar and wind energy. As these new variable energy generation sources penetrate the power grid more, grid stability and reliability can become compromised [1]. Since the power grid is based on load following, power generation typically increases or decreases to meet the current power load of the grid. Variable energy generation sources do not allow this as their generation capabilities are governed by factors out of human control. One possible solution to this issue is the implementation of energy storage systems (ESS). Currently used energy storage systems include pumped hydro energy storage (PHES), compressed air energy storage (CAES), and battery systems.

The most widely used energy storage system is PHES, which makes up over 99% of the installed storage capacity in the world [2]. PHES utilizes two water reservoirs at different elevational levels to generate or store electricity. Water is pumped into the higher reservoir during times of excess energy generation, storing energy in the gravitational potential energy of the water. When energy is needed to be generated, the water is allowed to flow utilizing gravity through a turbine and into the lower reservoir. Typically, a PHES system is utilized for leveling the daily energy load or to smooth the power output of variable renewable energy sources as they are characterized with long duration discharging times and quick ramp up times. While PHES systems are widely utilized, they are burdened by high initial capital costs and geographical constraints. The high initial capital costs are mostly associated with the large amount of land that is necessary to build these systems. Furthermore, the land that is used must also have a sufficient elevation difference between the reservoirs that will allow the PHES system to generate acceptable power.

CAES systems are similar to PHES systems except instead of water, air is used as the working fluid. Instead of utilizing gravitational potential energy, energy is stored by pumping air into a storage tank or cavern at high pressures. When energy is needed, the air is released into a turbine transforming the potential energy within the pressurized air into electrical energy. CAES systems are also used similarly in load leveling and smoothing of variable energy generation resources. While PHES is the most widely used, CAES is expected to compete well with PHES as most of the technology utilized in CAES systems is commercialized and share similar characteristics such as long lifetimes, low self-discharge, and quick response times. Though it also suffers from similar constraints as PHES in that they are associated with large initial capital costs, associated with land as well, and geographical constraints, if utilizing underground caverns.

Battery systems are another ESS that is utilized in today’s power grids. These include flow batteries, Li-ion batteries, and lead acid batteries, among others [2]. Unlike the previous two ESSs, battery system does not have geographical constraints which allows them to be utilized closer to urban areas. They also have quick response times and can be designed for various capacities, making them able to provide grid services such as regulation, load smoothing, and energy arbitrage, among others. While battery systems are not held back by the geographical constraints that are experienced by PHES and CAES, they do suffer from limited power output and can become expensive with the utilization of scarce materials.

While these systems are currently adequate for the current power grids' needs, as the penetration of variable renewable energy sources increases, the installed capacity of energy storage will also need to increase. In fact, from Kroposki, we can see that at 70% variable energy generation that the needed energy storage capacity will need to be around 140 GW [1],[3]. With the limitations of application for CAES and PHES, the limited power output of battery systems, as well as high capital costs, other ESSs need to be developed to ensure that future energy storage capacity needs can be met. One developing ESS technology that is coming up is pumped thermal energy storage (PTES). PTES systems do not have limitations in where they can be built and do not have limitations on their power output. This makes it a possible candidate technology that can be add with the other ESS mentioned that can be used for grid applications.

A PTES system utilizes a working fluid (typically argon, air, or carbon dioxide), two thermal reservoirs (hot and cold) filled with a thermal medium, and turbomachinery or reciprocating devices to operate a thermodynamic cycle [5]. Figure 1 shows a simple model of how the PTES works. For storing energy, the PTES system applies work to the working fluid which increase the temperature difference between the two thermal reservoirs. The reverse is done, utilizing the temperature difference of the thermal reservoirs, to generate electricity.

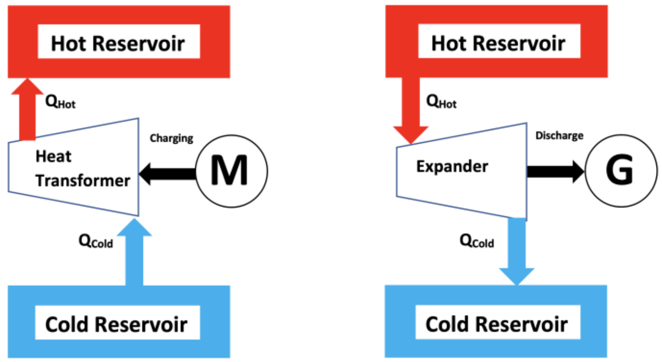

Figure 1: Simple Model of PTES System

PTES systems are not a new concept, in fact the first concept of a PTES system was developed in 1979 but has not been demonstrated at a grid-scale till recently [2], [4]. The first grid-scale PTES system was demonstrated at Newcastle University and able to store 600kWh of energy and output 150kW of power in 2007 with ramp rates in the range of milliseconds during preliminary testing [4]-[5]. Other PTES systems can be designed to operate at values several times larger than these values in the range of a few to hundreds of megawatts [4]. While PTES systems have not been demonstrated in application in partly due to being characterized by large thermal losses and irreversibility, theoretical modeling of these systems has been conducted in literature showing theoretical operating values for power output, efficiencies, energy capacity, and charging/discharging times [2],[4],[6]-[11]. In fact, to help improve PTES systems, research has been done on different configurations that will help reduce the loses and irreversibility that are generally associated with these types of systems. Some PTES system have been utilized for building cooling/heating where waste heat can be used to maintain the working fluids operating temperature and lower the irreversibility of the system while others utilize electric heaters [2],[9]. From these theoretical parameters, it can be possible to utilize a PTES system to generate revenue similar to how other ESS's are used today.

ESS systems are used today to offer grid services that help keep the electrical grid stable. These services include energy arbitrage, regulation services, spinning/non-spinning reserves, and resource capacity among others [12]. In this paper, a PTES system will be analyzed operating under the previously named grid services individually and a combination of them, optimized to maximize the revenue the system can generate. These services will be simulated to be provided to an Independent System Operator (ISO). Furthermore, a sensitivity analysis was done on the system to see which parameters of power and energy capacity have a greater influence over the system's revenue generating capabilities when under the best revenue generating technique.

Modeling and Optimization

In this section, the modeling of a PTES system will be looked at first, covering the parameters selected for this system as well. The optimization models for the revenue streams will next be discussed giving the final optimization setup for each. Pricing data used in the following models was taken from the California ISO (CAISO) energy market and operation data. This data was based on an hour-to-hour timeframe over the course of a year.

PTES System Modeling

The PTES system was modeled similarly to the Generalized Battery Model (GBM) used by Hao et al [13]. This can be done as the PTES system is able to vary its output as well as be able to maintain its output for a period of time [2],[8],[9]. Therefore, the power conversion part of the PTES system can be modeled using the following equations.

$$0 \leq p^{+}(t) \leq p^{+}_{max}, \text{ discharging} \quad (1)$$

$$0 \leq p^{-}(t) \leq p^{-}_{max}, \text{ charging} \quad (2)$$

$$p(t) = p^{+}(t) - p^{-}(t), \text{ power output} \quad (3)$$

In the above equations, p^{+} and p^{-} are the discharging and charging power of the PTES system respectfully and are limited by p^{+}_{max} and p^{-}_{max} which are the maximum discharging and charging power capacity of the PTES system. The difference between the discharging and charging power values then gives the output/input power of the system to/from the grid. It should be noted that the generator convention of using positive power values for injecting power into the grid is being utilized for the PTES system's power value.

Moving from the power conversion side of the PTES system to the energy storage side, we see that the energy level dynamics in the system are governed by the following equations.

$$\frac{de(t)}{dt} = \begin{cases} \frac{p(t)}{\eta^{+}}, & p(t) > 0, \quad Discharging \\ p(t)\eta^{-}, & p(t) < 0, \quad Charging \end{cases} \tag{4}$$

$$e(t) = \frac{de(t)}{dt} t + e_o, \qquad \text{Energy Level Dynamic} \tag{5}$$

$$E_{min} \le e(t) \le E_{max}, \qquad \text{Energy Level Constraint} \tag{6}$$

Here the change in energy level ($\frac{de(t)}{dt}$) is equal to the quotient or product of the PTES's power to the grid and its effeciency for discharging/charging (η^{-}, η^{+}) depending on the value of power output. The energy level of the system ($e(t)$) is then calculated using (5) where $e_o$is the initial starting energy level of the system. Lastly, equation 6 shows that the energy level of the system must stay within the range of values between the minimum and maximum energy levels (E_{min}, E_{max}). E_{min} and E_{max} can be determined from the PTES system's parameters or user specified limits. The following table shows the system parameters being used in this case study. These values were taken from sources [2],[4],[5] as they were derived for commercial use. It should be noted that in (5) the value of time during this case study is equal to one hour. In the following optimization setups this will be implied in the equations but not clearly shown.

Table I: PTES System Parameters

PTES Parameters	
Energy Capacity (E_{max})	16 MWh
Maximum Charging Power (p_{max}^{-})	2 MW
Maximum Discharging Power (p_{max}^{+})	1.6 MW
Recharge Efficiency (η^{-})	81.85%
Discharge Efficiency (η^{+})	81.85%

Energy Arbitrage

Energy arbitrage is the buying and selling of electricity in the wholesale market. To generate revenue, an ESS will buy electricity when prices are low, typically during non-peak hours, and sell it back when the prices are higher, typically during peak hours. Since the prices of electricity in the data are given on a per hour bases, the revenue generated (R_{EA}) can be calculated using the following equation.

$$R_{EA} = \sum P_k^{EA} p_k \quad (7)$$

In (7), P_k^{EA} and p_k is the Locational Marginal Pricing (LMP) price of electricity and the power output of the PTES system at hour k. This equation will now act as the objective function for the optimization problem to find the maximum revenue that the PTES system can generate from energy arbitrage. The following is the optimization problem setup for the PTES system under energy arbitrage operations using equations from the PTES model and system parameters.

Max: $R_{EA} = \sum P_k^{EA} p_k$

Subject to: |

Power Transfer between PTES system and Grid:	$p_k = p_k^+ - p_k^-$
Energy Level Dynamics:	$e_k = e_{k-1} - p_k^{PTES}$
Starting Energy Level:	$e_0 = \frac{E_{max}}{2}$
Ending Energy Level:	$e_K = e_1$
Change in Energy:	$p_k^{PTES} = \frac{p_k^+}{\eta^+} - p_k^- \eta^-$
Discharging Power Constraint:	$0 \le p_k^+ \le p_{max}^+$
Charging Power Constraint:	$0 \le p_k^- \le p_{max}^-$

It should be noted that a PTES system can have the capability of charging and discharging at the same time depending on the system's configuration. In this paper, the PTES system being analyzed does not have this capability. For this reason, an additional check was conducted on the results of the model to ensure that the product of p_k^+ and p_k^- was zero for all data points during energy arbitrage operation.

Regulation Services

The balancing of generation and load levels in the power grid is important to maintaining voltage and frequency levels. Regulation services provided by generators or ESS systems help maintain this delicate balance in near real time by either providing or consuming power. Payment for these services is provided in two parts, payment for the regulation capacity and payment for regulation mileage. Regulation mileage is taken as the sum of absolute value of regulation movement since regulation can be provided by consuming or providing power from or to the grid. Therefore, the total revenue that can be generated from regulation services (R_R) is calculated using the following equation.

$$R_R = \sum \left(P_k^{reg+} + P_k^{mileage+} m_k^+\right) r_k^+ + \left(P_k^{reg-} + P_k^{mileage-} m_k^-\right) r_k^- \quad (8)$$

In (8), $P_k^{reg+}$and P_k^{reg-} are the regulation up/down pricing for the regulation up/down capacity supplied by the system. The milage component of the revenue is add to the regulation capacity pricing through the product of the regulation mileage pricing ($P_k^{mileage+}$, $P_k^{mileage-}$) and the milage multiplier (m_k^+, m_k^-). These prices are designated for every hour in (8) and are multiplied by the regulation capacity up/down values r_k^+ and r_k^- for the hour k. This equation will act as the objective function for the optimization problem to find the maximum revenue the PTES system can generate from regulation services with the starting system parameters discussed in the PTES System Modeling section. The following is the optimization problem setup used to find the maximum revenue generation capability of a PTES system using equations from the PTES system model and parameters.

Max: $R_R = \sum\left(P_k^{reg+} + P_k^{mileage+} m_k^+\right) r_k^+ + \left(P_k^{reg-} + P_k^{mileage-} m_k^-\right) r_k^-$

Subject to:	
Regulation Up Capacity Constraint:	$0 \le r_k^+ \le p_{max}^+$
Regulation Down Capacity Constraint:	$0 \le r_k^- \le p_{max}^-$
Energy Level Constraint for Regulation Up Capacity:	$0 \le e_k - \dfrac{\varepsilon_k^{ru} r_k^+}{\eta^+}$
Energy Level Constraint for Regulation Down Capacity:	$0 \le e_k + \varepsilon_k^{rd} r_k^- \eta^- \le E_{max}$
Power Transfer between PTES system and Grid:	$p_k = p_k^+ - p_k^-$
Energy Level Dynamics:	$e_k = e_{k-1}$
Starting Energy Level:	$e_1 = \dfrac{E_{max}}{2}$
Ending Energy Level:	$e_K = e_1$

In the energy level constraints for regulation up/down capacity, $\varepsilon_k^{ru}$and $\varepsilon_k^{rd}$are the energy reserve per megawatt of regulation up and down service during the k[th] hour. Their respective values were taken to be 0.25 each. Note as well that for the optimization model, the energy level does not change from hour to hour. This is because it is assumed that regulation services will occur multiple times per hour and so the energy used for regulation services will have time to be replaced during the same hour. While in reality this may not be true for every hour, over the course of a year it is possible that the system will return back to its original energy level, so for simplicity it will be assumed that this is experienced by the modeled system.

Spinning and Non-Spinning Reserve

Spinning and non-spinning reserves are required during certain events of a sudden change in the generation and load balance within the grid. For spinning reserve, a PTES system would need to be synchronized to the grid already and able to increase its output immediately and quickly to its maximum output should a generator suddenly go offline. To provide non-spinning reserve, a system that is offline would need to be able to come online and ramp up quickly. The PTES system would be able to provide these services as the system has a quick ramp rate so it can be modeled similarly under both spinning and non-spinning reserve operation. Revenue generated from spinning and non-spinning reserve is formulated as follows.

$$R_{s\&ns} = \sum P_k^{spin} s_k^{spin} + P_k^{non-spin} s_k^{non-spin} \quad (9)$$

P_k^{spin} and $P_k^{non-spin}$ are related to the price for spinning and non-spinning reserve for hour k and s_k^{spin} and $s_k^{non-spin}$ are the reserve values for the system for spinning and non-spinning reserve operations for hour k. Using this equation as the objective function for the optimization problem to find the maximum revenue that can be generated by the PTES system, the following optimization setup was used.

Max: $$R_{s\&ns} = \sum P_k^{spin} s_k^{spin} + P_k^{non-spin} s_k^{non-spin}$$

Subject to:

Spinning Reserve Capacity Constraint: $$0 \leq s_k^{spin} + p_k \leq p_{max}^{+}$$

Non-Spinning Reserve Capacity Constraint: $$0 \leq s_k^{non-spin} \leq p_{max}^{+}$$

Spin and Non-Spinning Power Constraint: $$s_k^{spin} + s_k^{non-spin} + p_k \leq p_{max}^{+}$$

Spinning and Non-Spinning Reserve Energy Constraint: $$0 \leq e_k - \left(\frac{\varepsilon_k^{spin} s_k^{spin}}{\eta^{+}} + \frac{\varepsilon_k^{non-spin} s_k^{non-spin}}{\eta^{+}} \right)$$

Energy Level Dynamics: $$e_k = e_{k-1}$$

Starting Energy Level: $$e_1 = \frac{E_{max}}{2}$$

Ending Energy Level: $$e_K = e_1$$

Similar to regulation in the Reserve energy constraint, ε_k^{spin} and $\varepsilon_k^{non-spin}$ are the energy reserve per megawatt of spinning and non-spinning reserve service at hour k respectfully. Their respective values were taken to be equal to 0.50 each.

Resource Capacity

Resource capacity service is similar to spinning and non-spinning reserve in that the system opting into providing this service is only called upon under specific conditions. In the case of providing resource capacity, the system reserves a set amount of energy for a month that the ISO can use at its discretion. This energy is typically used for peak shaving during peak hours to help keep the cost of electricity low or to supply energy during peak demand events. To calculate the revenue generated by providing resource capacity services, the following equation was used.

$$R_{RA} = \sum P_m^{RA} u_m \tag{10}$$

In (10), P_m^{RA} is the pricing for providing each megawatt of power reserved for resource capacity service for the m^th^ month of the year. u_m is the amount of power in megawatts reserved for resource capacity service by the system during m^th^ month. Similar to the previous revenue generating techniques, (10) is used as the objective function for the optimization problem. The following shows the optimization setup for finding the maximum revenue that the PTES system can generate under resource capacity services.

Max: $R_{RA} = \sum P_m^{RA} u_m$

Subject to:

Resource Capacity Constraint:	$0 \leq u_m \leq p_{max}^{+}$
Energy Level Constraint for Resource Capacity:	$0 \leq e_m - \frac{\varepsilon_m^{ra} u_m}{\eta^{+}}$
Energy Level Dynamics:	$e_k = e_{k-1}$
Starting Energy Level:	$e_1 = \frac{E_{max}}{2}$
Ending Energy Level:	$e_K = e_1$

ε_m^{ra} in the energy level constraint is the energy reserve per megawatt of resource capacity reserve for month m while u_m is the amount of power reserved for resource capacity service during month m. Its value was assumed to be equal to 3.

Combined Revenue Stream

For a combined revenue stream, the optimization problem becomes just a summation of all the previous optimization problem setups. It should be noted that the constraints for the other revenue techniques and the resource capacity constraints will have different summations as the former is every hour of the year and resource capacity is summed every month. This is overcome by converting the monthly data of the resource capacity to hourly data. This is easily done within software used to solve the optimization setups as the data for the other service pricings have data points that contain date information.

Using this information, the summation of the optimization setups becomes simple and takes the form of the following setup.

Max: $\sum_k^K \left[P_k^{EA} p_k + \left(P_k^{reg+} + P_k^{mileage+} m_k^+\right) r_k^+ + \left(P_k^{reg-} + P_k^{mileage-} m_k^-\right) r_k^- + P_k^{spin} s_k^{spin} + P_k^{non-spin} s_k^{non-spin}\right] + \sum_m^M P_m^{RA} u_m$

Subject to:	
Power Transfer between PTES system and Grid:	$p_k = p_k^+ - p_k^-$
Energy Level Dynamics:	$e_k = e_{k-1} - p_k^{PTES}$
Starting Energy Level:	$e_1 = \frac{E_{max}}{2}$
Ending Energy Level:	$e_K = e_1$
Change in Energy:	$p_k^{PTES} = \frac{p_k^+}{\eta^+} - p_k^- \eta^-$
Discharging Power Constraint:	$0 \leq p_k + r_k^+ + s_k^{spin} + s_k^{non-spin} + u_k \leq p_{max}^+$
Charging Power Constraint:	$0 \leq r_k^- - p_k \leq p_{max}^-$
Minimum Energy Constraint:	$0 \leq e_k - \frac{\varepsilon_{ru} r_k^+}{\eta^+} - \frac{\varepsilon_{spin} s_k^{spin}}{\eta^+} - \frac{\varepsilon_{non-spin} s_k^{non-spin}}{\eta^+} - \frac{\varepsilon_{ra} u_k}{\eta^+}$
Maximum Energy Constraint:	$0 \leq e_k + \varepsilon_k^{rd} r_k^- \eta^- \leq E_{max}$

Results

The optimization problem setups for each revenue generating technique were solved within a Juno Integrated Development Environment utilizing the Julia programming language and a linear optimization technique that is contained within its toolbox. Pricing information used was taken from CAISO for all services except for resource capacity. The pricing for resource capacity was derived with the help of my advisor Dr. Fan so that the data would match what would be seen within the energy market. In the following sections, the models will be evaluated, and their results presented.

Energy Arbitrage

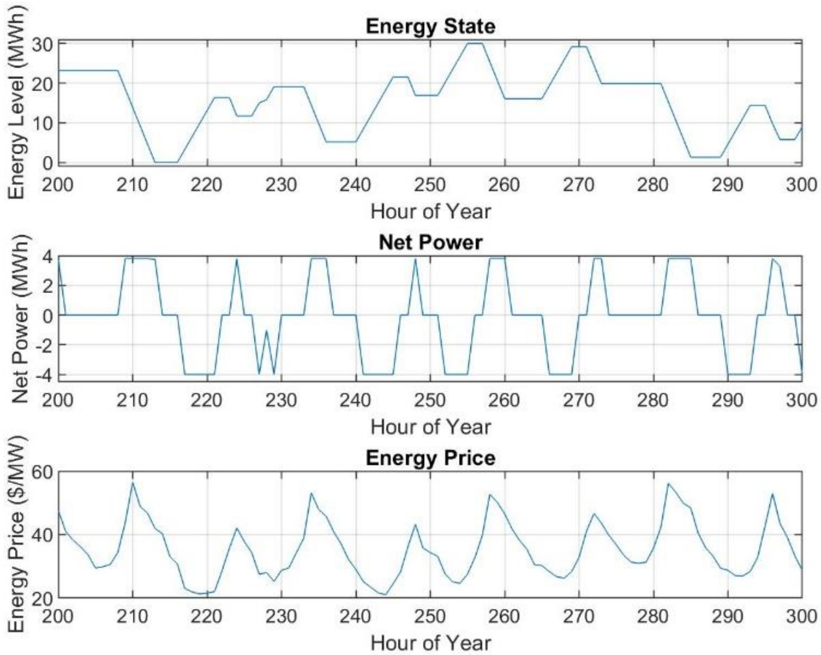

Figure 2: Subplot for Energy Arbitrage Model

Figure 2 displays the subplots for the energy arbitrage model. As shown by the plots, the quantities of energy level, net power stay within their respective constraints. Net power also follows the price of electricity where when the price is low the system is charging and discharges when the price of electricity is high. This means the model is behaving correctly. From the model, a maximum revenue of $232,392.20 was generated.

Regulation Services

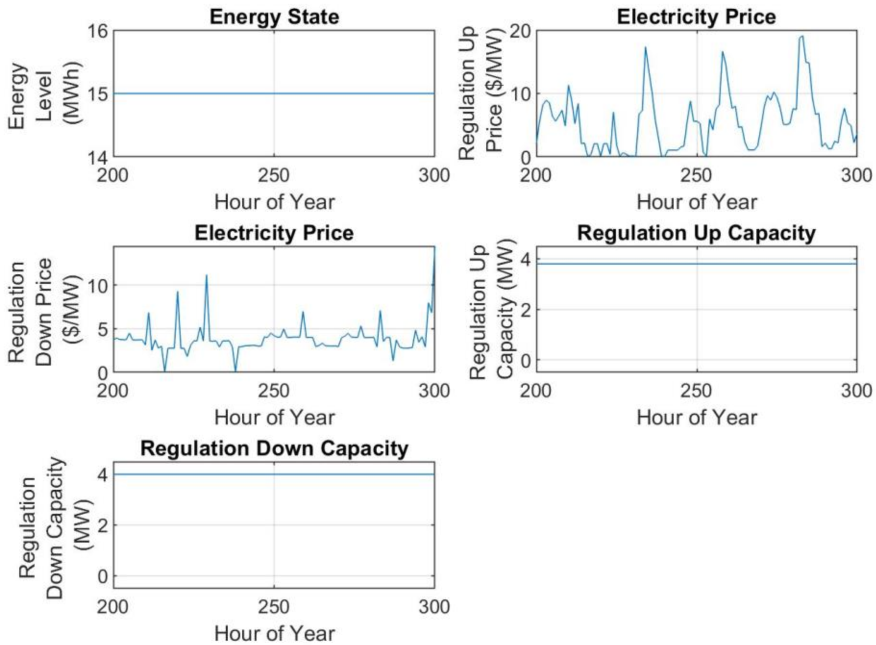

Figure 3: Subplot for Regulation Services Model

Figure 3 shows the subplots for the regulation reserve model. As the plots for energy level and regulation up and down capacity, the model behaves correctly. The values of regulation up and down want to go to there maximum values since neither has anything limiting them from doing this. They can both operate during the same hour as well since it is assumed that in any given hour both operations can take place multiple times. The model gave the result that the maximum revenue under only regulation services was $522,806.10.

Spinning and Non-spinning Reserve

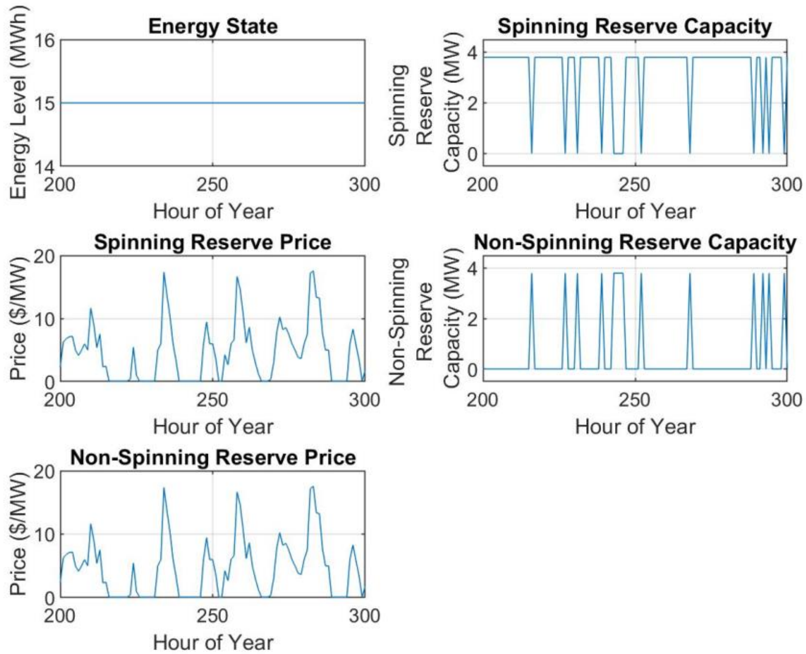

Figure 4: Subplot for Spinning and Non-spinning Reserve Model

Figure 4 shows the subplots for spinning and non-spinning reserve operation. As the plots for energy level and spinning and non-spinning reserve capacity, the model behaves correctly. Unlike regulation services, the spinning and non-spinning reserve capacity values compete with each other for available power output. This means that based on which price is higher, the system will run under either spinning reserve or non-spinning reserve. From the model, the maximum revenue generated was found to be $255,152.50.

Resource Capacity

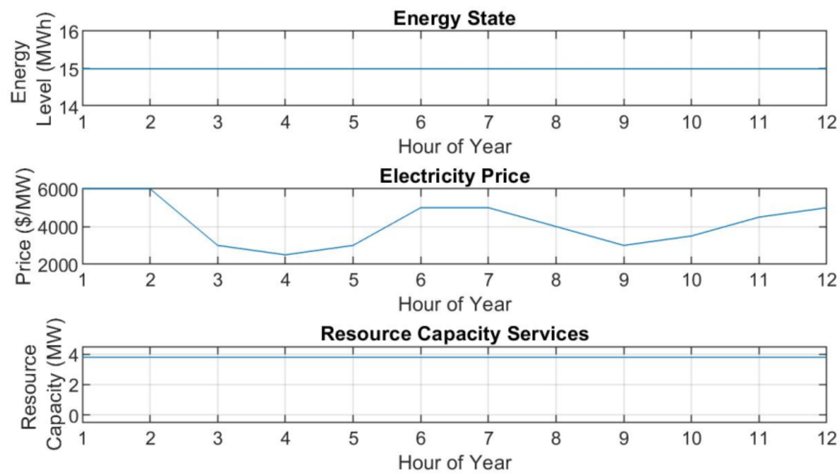

Figure 5: Subplot for Resource Capacity Model

Figure 5 shows the subplot for resource capacity service operation. Similar to regulation services, the resource capacity value wants to go to its maximum value to produce the most revenue. The energy level also remains constant as it was assumed that the system will be able to return to its original energy level after preforming services. This shows that the model is behaving correctly, and the resulting maximum revenue generated was found to be $191,900.00.

Combined Revenue Stream

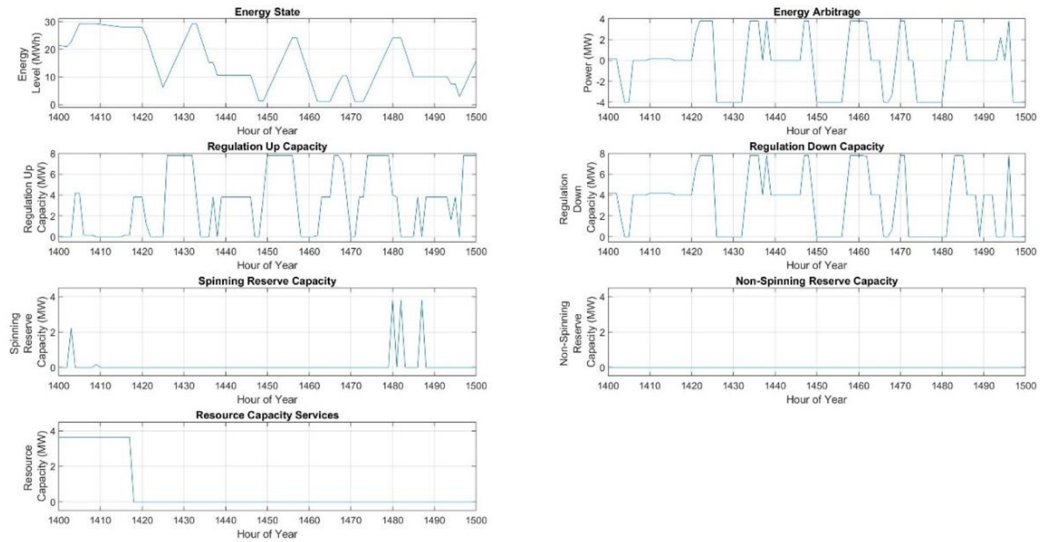

Figure 6: Subplot for Combined Revenue Stream

Figure 6 shows the subplots for the PTES system operating under the combined revenue stream. As the model shows, all the capacity values stay within their respective constraints and the energy level stays with in its limits. For regulation up and down capacities, we can see that since energy arbitrage is being used as well, the limits of these capacities are allowed to increase further but still being limited by the summation of charging and discharging limits and the value of energy arbitrage power. From the model, it was found that the maximum revenue that could be generated was $691,567.30.

Sensitivity Analysis

With all the models evaluated, the maximum revenue generated in each operation is summarized in Table 2. From these values we see that the combined revenue stream produced the most revenue out of all the revenue streams.

Table II: Maximum Revenue Generated for Each Revenue Stream

Energy Arbitrage	$232,392.20
Regulation Service	$522,806.10
Spinning and Non-spinning Reserve	$255,152.50
Resource Capacity	$191,900.00
Combined Revenue Streams	$691,567.30

With the best revenue stream found from all the cases being the combined revenue stream, a sensitivity test was done on the model to see how both power transfer rate constraints and energy storage constraints effect the system while also including costs associated with building and operations. For an ESS, the costs for building and operating the system are divided between power transfer components ($/kW) and the energy storage components ($/kWh) of the system. The costing data and equation were derived from literature and finding a rough medium from the ranges found [4],[14],[15],[17],[18],[20],[24]-[16]. The costs used for the sensitivity analysis are shown in Table 3.

Table III: Cost Data for PTES System

Fixed Cost for Power Transfer Components ($/kW)	743.00
Fixed Cost for Energy Storage Components ($/kWh)	37.00
Variable Costs for Power Transfer Components ($/kW)	.00336
Variable Costs for Energy Storage Components ($/kWh)	14.24

Using this data, we can generate a cost function that takes the form of (11).

$$Cost = c_{FP}p_{max} + c_{FE}E_{max} + \sum c_{VP}p_k + c_{VE}p_k^{PTES} \tag{11}$$

In this cost function, the hourly values of p_k and p_k^{PTES} are still the same values from our previous model but since we will be varying the power transfer capacity of the system, we substitute p_{max} for variables of p_{max}^{+} and p_{max}^{-} in the optimization problem to limit the computing time and complexity of the problem. This means that both the recharge and discharge rates are equal to each other. The new variables introduced are c_{FP}, c_{FE}, c_{VP}, and c_{VE}, which relate to the fixed (c_{FP}, c_{FE}) and variable (c_{VP}, c_{VE}) costs associated with the power and energy storage components. Finally, we just subtract the cost function from the original objective function in the optimization setup to get the new optimization setup for the sensitivity analysis. The following figure and table show the results for this analysis.

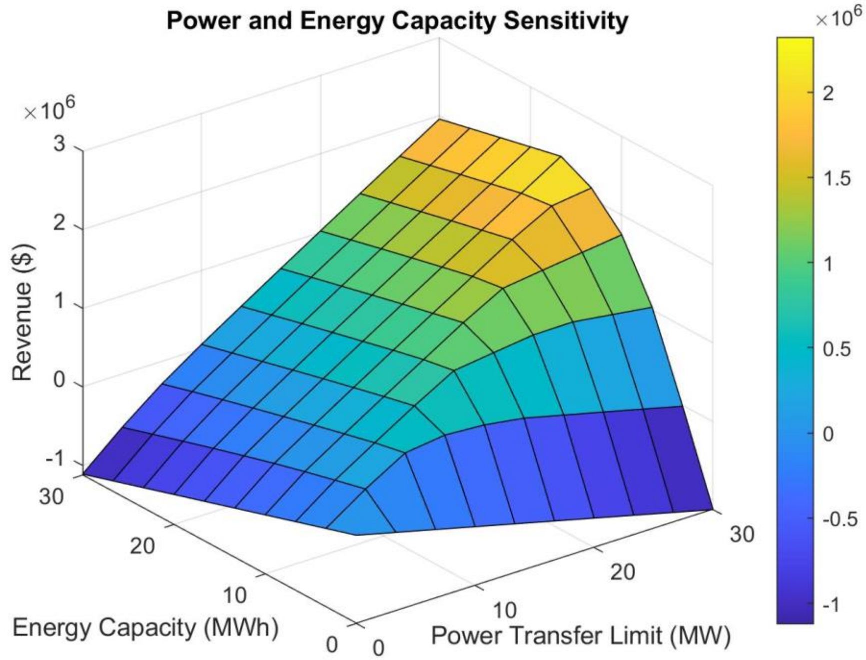

Figure 7: Sensitivity Analysis Surface Plot

Table IV: Sensitivity Analysis Results

	Power Transfer Limit (MW)									
Energy Capacity (MWh)	0	3.33	6.67	10	13.33	16.67	20	23.33	26.67	30
0	0	-$0.12M	-$0.24M	-$0.37M	-$0.49M	-$0.62M	-$0.74M	-$0.87M	-$0.99M	-$1.12M
3.33	-$0.12M	$0.21M	$0.51M	$0.58M	$0.55M	$0.47M	$0.35M	$0.23M	$0.10M	-$0.017M
6.67	-$0.24M	$0.12M	$0.43M	$0.744M	$1.03M	$1.10M	$1.16M	$1.17M	$1.10M	$1.03M
10	-$0.37M	$0.018M	$0.33M	$0.65M	$0.96M	$1.27M	$1.55M	$1.61M	$1.68M	$1.74M
13.33	-$0.49M	-$0.086M	$0.24M	$0.55M	$0.87M	$1.18M	$1.49M	$1.80M	$2.06M	$2.13M
16.67	-$0.61M	-$0.19M	$0.13M	$0.45M	$0.77M	$1.09M	$1.40M	$1.71M	$2.01M	$2.32M
20	-$0.74M	-$0.31M	$0.037M	$0.36M	$0.67M	$0.99M	$1.31M	$1.62M	$1.92M	$2.23M
23.33	-$0.86M	-$0.43M	-$0.065M	$0.25M	$0.58M	$0.89M	$1.21M	$1.52M	$1.83M	$2.14M
26.67	-$0.98M	-$0.55M	-$0.17M	$0.15M	$0.48M	$0.79M	$1.11M	$1.43M	$1.74M	$2.05M
30	-$1.11M	-$0.67M	-$0.28M	$0.056M	$0.38M	$0.70M	$1.02M	$1.33M	$1.65M	$1.96M

As can be seen from Figure 7, the PTES system's revenue generating capability is affected by the power transfer limit and energy capacity. Looking the energy capacity side of the graph, revenue generation becomes linear quickly as we increase energy capacity with steady increases in revenue as the power capacity is increased. In fact, due to this linearity, we see a loss in revenue as energy capacity increases when the power transfer limit is kept the same. The power transfer limit side of the plot does not share this quick linearity but experiences it at a delayed pace. This shows that the power transfer capability of the PTES system effects its revenue generation the greatest. Another thing that can be seen from the graph is a curve that shows what might be a optimal ratio for which the PTSE should be sized. Looking at Table 4, it becomes clearer that at the values colored in orange relate to the optimal sizing of the PTES to ensure the maximum revenue is generated. From this data it was found that the optimal sizing ratio of energy capacity to power transfer limit should be between 1:2 and 3:5.

Conclusion

In this paper, a PTES system was analyzed under several revenue generating techniques. It was found that under a combined revenue generating stream, the maximum amount of revenue generation could be achieved. Furthermore, a sensitivity analysis was conducted on the PTES system operating under a combined revenue stream subjected to fixed and operational costs. From the sensitivity analysis, it was found that the PTES system's revenue generating capability was more sensitive to changes in the power transfer limit of the system than from changes in the energy capacity. This would favor more investment in the power transfer components of the PTES system than to the energy storage components. Furthermore, from the sensitivity analysis, it was found that the sizing of a PTES system should follow a ratio of energy storage capacity to power transfer capabilities should be within the range of 1:2 and 3:5.

It should be noted that this work does not consider different storage vessels geometries. The primary focus of this work was looking at vertical cylindrical storage vessels as illustrated in [3] and [11]. Other storage geometries can produce different cost functions along with different characteristics. As shown in Allen et al., for very large storage vessels, it is more beneficial to have horizontal storage vessels. With the storage component laying on the ground, a different design is needed to consider the thermodynamics experienced within the storage vessel as well as the design of the storage vessel itself [22]. A branch of research that might be worth looking into would be to see which geometries are better suited for which revenue streams. In the case of what was studied in this paper, it would seem that the PTES system analyzed would function well for the combined revenue stream but would need to be made within a certain size as in the results it was found to have a negative revenue generation at some points.

Another point for further research would be to look at the possible reduction in the lifespan of the system due to operating under the combined revenue stream. Most equipment in energy storage systems is given a life span in years based on how many cycles it would normally operate at a certain power output. Under a combined revenue stream, power output and cycle frequency would vary which would affect the expected life span of the system. Research into the limits at which a PTES system can operate at before the benefits of operating under a combined revenue stream are outweighed by the negative effects to its lifespan would also be very beneficial. This could lead to the development of knowledge into how energy storage systems, similar to PTES systems, can be integrated into the grid more effectively while keeping these systems from unexpectedly ceasing function due to the decay of their lifespans.

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