Economic Analysis of a Novel Thermal Energy Storage System Using Solid Particles for Grid Electricity Storage

Preprint

Zhiwen Ma, Xingchao Wang, Patrick Davenport, Jeffrey Gifford, and Janna Martinek

National Renewable Energy Laboratory

Presented at the 15th International Conference on Energy Sustainability (ES2021)
June 16-18, 2021

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5700-79014
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Suggested Citation
Ma, Zhiwen, Xingchao Wang, Patrick Davenport, Jeffrey Gifford, and Janna Martinek. 2021. *Economic Analysis of a Novel Thermal Energy Storage System Using Solid Particles for Grid Electricity Storage: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-79014. https://www.nrel.gov/docs/fy21osti/79014.pdf.

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ECONOMIC ANALYSIS OF A NOVEL THERMAL ENERGY STORAGE SYSTEM USING SOLID PARTICLES FOR GRID ELECTRICITY STORAGE

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ABSTRACT

As renewable power generation becomes the mainstream new-built energy source, energy storage will become an indispensable need to complement the uncertainty of renewable resources to firm the power supply. When phasing out fossil-fuel power plants to meet the carbon neutral utility target in the midcentury around the world, large capacity of energy storage will be needed to provide reliable grid power. The renewable power integration with storage can support future carbon-free utility and has several significant impacts including increasing the value of renewable generation to the grid, improving the peak-load response, and balancing the electricity supply and demand. Long-duration energy storage (10–100 hours duration) can potentially complement the reduction of fossil-fuel baseload generation that otherwise would risk grid security when a large portion of grid power comes from variable renewable sources. Current energy storage methods based on pumped storage hydropower or batteries have many limitations. Thermal energy storage (TES) has unique advantages in scale and siting flexibility to provide grid-scale storage capacity. A particle-based TES system has promising cost and performance for the future growing energy storage needs. This paper introduces the system and components required for the particle TES to be technically and economically competitive. A technoeconomic analysis based on preliminary component designs and performance shows that the particle TES integrated with an efficient air-Brayton combined cycle power system can provide power for several days by low-cost, high-performance storage cycles. It addresses grid storage needs by enabling large-scale grid integration of intermittent renewables like wind and solar, thereby increasing their grid value. The design specifications and cost estimations of major components in a commercial scale system are presented in this paper. The cost model provides insights for further development and cost comparison with competing technologies.

Keywords: Thermal energy storage, renewable energy, long duration energy storage, grid resilience, power cycle

NOMENCLATURE

Roman symbols

C	Cost
c	Unitized Cost
F	Cost Estimation Factor
V	Equipment Volume

Greek symbols

η	Efficiency

Acronyms

TES	Thermal Energy Storage
LDES	Long Duration Energy Storage
ETES	Electric Thermal Energy Storage
CAES	Compressed Air Energy Storage
CSP	Concentrated Solar Power
ABCC	Air Brayton Combined Cycle
GTCC	Gas Turbine Combined Cycle
HRSG	Heat Recovery Steam Generator
sCO_2	Supercritical Carbon Dioxide
TIT	Turbine Inlet Temperature
BEC	Bare Erected Cost
TPC	Total Plant Cost
TOC	Total Overnight Cost
TASC	Total As-Spent Capital
PFB	Pressurized Fluidized Bed
HX	Heat Exchanger
OD	Outer Diameter
ID	Inner Diameter
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
O&M	Operation and Maintenance
CEPCI	Chemical Engineering Plant Cost Index
GTW	Gas Turbine World
DOE	Department of Energy
NREL	National Renewable Energy Laboratory
NETL	National Energy Technology Laboratory

1. INTRODUCTION

The incorporation of renewable energy into the electric grid for low-carbon electricity needs economically firming the electricity supply from variable solar and wind power generators. Energy storage is key to high renewable penetration and bridges the generation gap for high renewable grid integration. The integration of excess renewable power and storage of electricity over time scales of hours or days can expand the renewable energy portion of total electricity generation and improve the peak-load response. Long-duration energy storage (LDES) with storage duration of 10–100 hours can potentially complement the reduction of fossil-fuel baseload generation and coordinate the electricity supply and demand that otherwise would risk grid security when a large portion of grid power comes from variable renewable sources.

Mechanical, chemical, electrochemical, or thermal energy storage (TES) are several energy storage methods that are deployed or under development. The commercialization progress of TES deployment with concentrating solar power (CSP) has been focused on molten-nitrite salt. However, molten salt has shown significant limitations of corrosion, freezing, and high-temperature stability that restrict possible application temperatures and limit operation and performance. A particle-based CSP system was introduced for supporting the U.S. Department of Energy SunShot goal [1] and considered for a Generation 3 CSP system [2]. This paper focuses on solid-particle-based TES to serve the purpose of standalone electric thermal energy storage (ETES). The objective of this paper is to present the component design and cost analysis for particle TES driving an air-Brayton combined cycle (ABCC) power system. The ABCC power system is adopted from a commercial gas turbine combined cycle (GTCC) power system and can leverage the commercial GTCC products to shorten the turbomachinery development cycle as compared to supercritical carbon dioxide Brayton power cycles [3] or emerging pumped thermal energy storage (i.e., Carnot Battery) [4][5].

The ETES system charges using off-peak electricity and stores thermal energy in a TES system. The charging process uses a direct Joule-heating system, which can convert electricity completely to high-temperature heat. The charging efficiency is then reduced only by the component heat loss, which can be low with sufficient and proper insulation for high (>98%) efficiency. The high-temperature heat stored in particle TES can generate power by a high-efficiency power cycle. The standalone ETES for electricity storage has advantages of greater flexibility in site selection than a CSP plant or other large-scale energy storage methods such as compressed air energy storage (CAES) or pumped storage hydropower (PSH).

The ETES economics hinge on developing high-performance, low-cost TES technology that supports the operating conditions, primarily the working-fluid temperature, of high-efficiency thermal-power cycles. Advanced TES technologies are being developed for a low-cost, high-temperature Generation 3 CSP system [2]. The economic analysis in this paper focuses on the standalone ETES system using particle storage media and a high-efficiency ABCC power system for LDES applications. Based on a preliminary storage system configuration, the cost and performance of particle TES was evaluated with respect to key component designs. The ETES costs are potentially significantly lower than both CAES and PSH and can economically serve much longer storage duration than batteries.

2. A CONFIGURATION OF PARTICLE TES FOR GRID-SCALE ELECTRIC STORAGE

FIGURE 1 shows a conceptual ETES system and components using high-temperature, low-cost particle TES integrated with a fluidized-bed heat exchanger to drive high-efficiency ABCC power generation. The system includes an electric charging particle heater, TES modules, a fluidized bed heat exchanger, and the Brayton cycle turbine. The ABCC power capacity in the analysis is set at 135 MW_e and based on a General Electric 7E.03 class turbine.

When electric power is cheapest, electric heaters will charge the storage modules by heating solid particles. When it is time to discharge this energy, the hot particles will move through a heat exchanger to heat a working fluid that drives a high-efficiency Brayton combined cycle attached to an electric generator.

During charging in FIGURE 1, the stored low-temperature particles are transported to the top of the particle heater and heated by the particle heater powered by off-peak electricity. The hot particles are then stored in a containment vessel with minimum thermal losses.

The TES modules consist of four particle containment silos and one spare silo for temporary transfer of particles. Each containment silo stores both hot and cooled particles in a thermocline configuration, thus eliminating half of the storage containment cost compared to separate hot/cold storage. When charging particles fill a TES module, it stores nearly 7 GWh_{th}, or about 25 hours of full-load ABCC operation. Four TES modules contain about 28GWh thermal energy to serve for 100 hours of duration. The TES containment is structured in a concrete silo with an internally insulated layer. The spare silo is used to shift particles if a containment silo is not completely emptied during electric charging.

In the discharging process, the exit gas from the turbine compressor contacts the hot particles inside the fluid bed and is heated up to the turbine-inlet temperature (TIT). The hot gas then flows through the turbine and drives a power generator. The turbine hot exhaust gas is cooled in a heat-recovery steam generator (HRSG) that drives a bottom steam-Rankine power cycle. The system power-conversion efficiency relies on the TIT determined by the particle temperature, and on the relationship between the TIT and power-cycle efficiency that is critical to the roundtrip efficiency of the storage system.

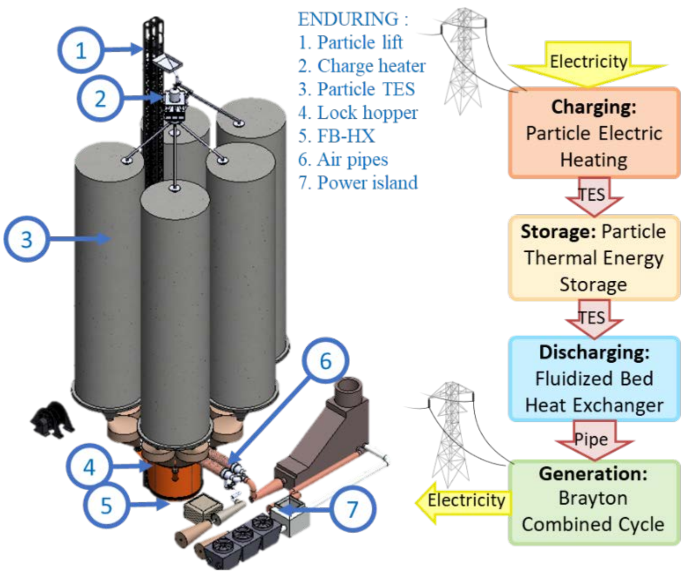

FIGURE 1: A PARTICLE TES SYSTEM INTEGRATED WITH A FLUIDIZED BED AND AN ABCC POWER SYSTEM FOR ELECTRIC-THERMAL ENERGY STORAGE (ETES).

The storage system is designed in a modular configuration, which consists of energy storage components and power-related components. Energy storage uses particle-based TES, and the particles are transported by skip hoists. The power specific components include the power islands and the components for energy conversion including the gas pipeline, the pressurized fluidized bed (PFB) heat exchanger (HX), and gas/particle separation cyclones. Table 1 lists a base case of the designed system operating conditions. All the components are designed at commercial scale derived from heat and mass balances based on the GE 7E.03 turbine combined cycle power capacity of 135 MW_e.

Table 1: SYSTEM DESIGN SPECIFICATIONS AND OPERATING CONDITIONS OF BASE CASE

Specification	Unit	Value
Discharging Power Generation Capacity	MW_e	135
Storage Hours	hr	100
Baseline Round Trip Efficiency	%	50
Cold Particle Temperature	°C	300
Hot Particle Temperature	°C	1200
Particle Type and Mean Diameter	-	Silica Sand, 616 µm

3. DESIGN AND COST ANALYSIS OF MAJOR COMPONENTS

The power plant cost includes several cost levels defined by the National Energy Technology Laboratory (NETL). FIGURE 2 shows the levels of cost from basic equipment, procurement cost, owner cost, and financed total plant cost [6]. The cost estimation depends on the level of project development and financial mechanisms based on the cost estimation methodology for power plants[7][8]. Specifically, the capital cost of the power generation system including the cost of equipment, facilities, and infrastructure to support the plant, as well as construction and/or basic installation costs, is used to perform the cost estimation. The estimation method for the ETES uses the Bare Erected Cost (BEC). The engineering, procurement costs and fees, contingency costs, and other case and/or site-specific costs are not included in the BEC cost analysis. The cost analysis only considers the material usage and component fabrication to derive a BEC of the major components in the storage system. The plant power island is based on the reported costs of a gas turbine plant [9].

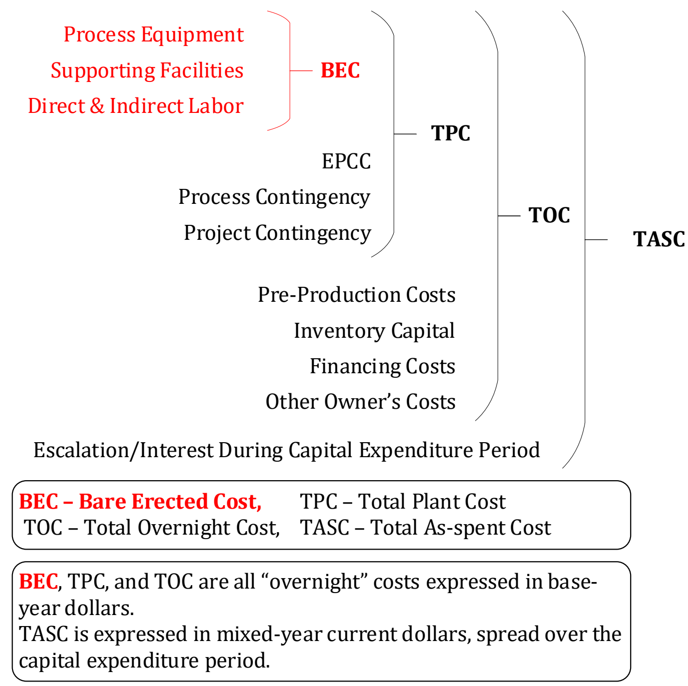

FIGURE 2: CAPITAL COST LEVELS DEFINED BY NETL [6]

3.1 Charging Electric Particle Heater

In this standalone ETES system, charging the particle TES uses an electric charging heater to transfer the off-peak electric power as heat to the particles. High charging temperatures offer the thermodynamic capability of driving high-efficiency power cycles. In an ideal operation with sufficient insulations, the electric charging efficiency can be 100% by Joule heating. Real design considers charging operations and the thermal performance to conserve electricity into heat via thermal management for high charging efficiency (targeted at 98%). Thermal conversion efficiency depends on the heater structure design and insulation effectiveness.

FIGURE 3 shows the schematic design of the electric charging particle heater, which is configured in modules to form the heater unit. In this design, each heater unit is equipped with nine identical heater modules. Each module works at a fixed operating condition and electric charging load. Changes in load are controlled by switching on and off individual modules, and thus nine load steps can be achieved in a heater unit.

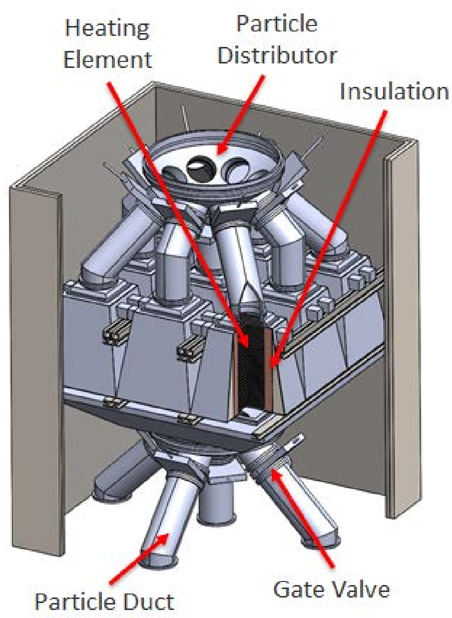

FIGURE 3: MODULAR DESIGN OF THE ELECTRIC CHARGING HEATER TO STORE OFF-PEAK ELECTRIC POWER IN PARTICLE TES.

The material cost of the particle heater consists of three major parts in Eq. (1):

$$C_{heater\_materials} = C_{heating\_wire} + C_{heating\_element\_refactory} + C_{insulation} \quad (1)$$

To calculate the particle heater capital cost. The detailed heater dimensions, structure and insulation designs were performed. Table 2 shows cost estimation based on the design in FIGURE 3 with the consideration of materials fabrication, assembly, and accessories.

Table 2: DESIGN SPECIFICATIONS AND COST ESTIMATION OF PARTICLE ELECTRIC HEATER.

Particle Electric Heater Cost Breakdown		
Categories	***Units***	***Cost Values***
Single Unit Power Capacity	***MW***	***315***
Single Heater Unit Equipment Cost	$	1,316,688
Single Heater Unit Capital Cost	**$**	**2,304,205**
Heater Cost of Unit Power Capacity	**$/kW**	**7.3**

3.2 TES Design

The TES-specific components to contain and handle the particles include particle containment silos and particle lifting skip hoists. They are designed based on the storage capacity, temperature, and solid particle media.

3.2.1 Storage Media

Many solid materials can be considered for particle TES. Silica sand was selected for the current system because it can be obtained from natural reserves with little processing, and is abundant, low cost, and environmentally compatible. The silica sand used for the design contains above 99% pure silica. It is stable at temperatures well above 1,000°C, and compatible with refractory insulation materials at the applicable temperatures [10]. The quoted silica sand cost ranges between 30 and 40 $/Metric Ton.

3.2.2 Particle Containment

Particle containment consists of a concrete silo and an internal insulation layer. Concrete silos are common to hold granular materials and are easy to build. Internal insulation of hot particle storage is unique and can be realized by ceramic materials. This work adopted refractory materials capable of holding particle temperatures above 1,000°C. FIGURE 4 shows the design approach for the TES containment. During charging hot particles fall into the storage silo from the top. The hot particles are discharged through a particle dispenser to a fluidized bed heat exchanger to drive a power cycle for electricity generation. The cooled particles are then lifted by a skip hoist, return to the same containment, and are stored above the hot particles in a thermocline configuration. Thus, one containment vessel can hold both hot and cooled particles and cuts the containment cost by half as compared to a two-tank TES system.

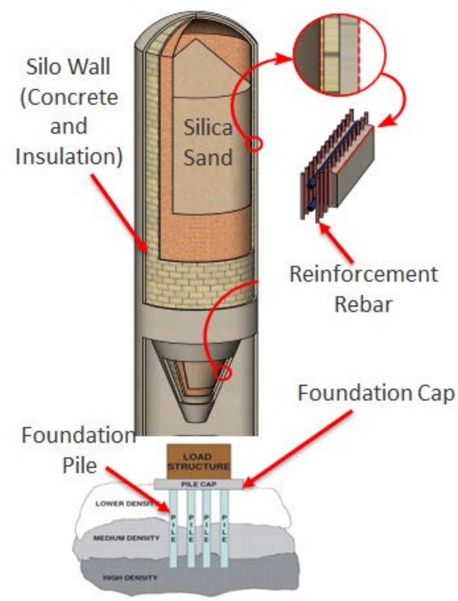

FIGURE 4: TES CONTAINMENT ILLUSTRATION AND PARAMETRIC SPECIFICATIONS FOR COST ANALYSIS.

The silo geometry, silo structure and foundation, as well as the insulation design were determined by following the design approach [11]. TES performance and cost depend on the container and insulation. Transient thermal performance of a well-insulated silo was analyzed to evaluate storage thermal losses [12].

Some key design specification values are shown in FIGURE 4. The containment silo construction cost is estimated in three parts: silo (including foundation), insulation, and storage particles. The containment cost includes both materials and construction labor cost estimation, which can be expressed as:

$$C_{containment,tot} = C_{containment} + C_{particle} = (C_{silo,tot} + C_{foundation,tot} + C_{insulation,tot}) + C_{particle} \quad (2)$$

The required amount of construction and insulation materials can be calculated based on the designed geometries of silo and foundation. The unit prices for insulation and storage particles were provided by material suppliers. The single containment silo cost was estimated from an engineering design and construction estimation [11]. Accordingly, the TES cost including storage media was obtained as $12 million per 6.4 GWht storage unit. For the 405 MW_e ETES plant consisting of three 135MWe modules, 12 storage units are required. The unitized capital cost is 1.96 $/kWh_{th}$ including containment silos, insulation and storage media, which can be found in Table 3.

Table 3: PARTICLE CONTAINMENT SILO DESIGN SPECIFICATIONS AND COST ESTIMATION.

Particle Storage Cost Breakdown		
Categories	***Units***	***Values***
Single Unit Energy Capacity	**GWht**	**6.4**
Silica Sand Weight	ton	22500
Silo size (Diameter X Height)		ϕ20 mX60 m
Single Containment Cost	$	11,731,455
Concrete Silo and Foundation Cost	$	3,857,262
Insulation Cost	$	7,874,193
Single Silo Storage Media Cost	$	771,870
Single TES Total Cost	**$**	**12,503,325**
Containment Cost / Unit TE Stored	**$/kWh$_{th}$**	**1.96**

After adding 0.042 $/kWh skip hoist cost as shown in next section, the total TES cost was estimated around 2 $/kWh_{th}$. This low TES cost can be attributed to the following factors:

- Use of 30–40 $/Ton silica sand and low-cost containment (concrete silo, refractory insulations)
- Large charging/discharging temperature difference of 900 °C with the ABCC power cycle.
- Containment vessels configured to store both hot and cold particles in the same silo.

The low-cost TES is key to achieve large energy capacity and the ETES economic target.

3.2.3 Particle Transport Skip Hoist

A skip hoist has been considered in CSP [13] and can be applied in the particle TES system for bulk granular media transportation. In the ETES system, the skip hoist lifts particles at 300 °C from the bottom of the heat exchanger outlet to the top of the electric charging heater above the particle storage silo. Figure 5 shows the schematic of a skip hoist lifting system. Two skips were driven by one motor with two separate drums on a single axis. Two skips run in opposite directions, i.e., when one skip is rising, the other one is falling. The opposite running directions recover the potential energy from the falling skip to the rising skip and achieve high lifting efficiency. The particle lifting mechanism and the insulation design of the skip were performed for component requirements and operation analysis.

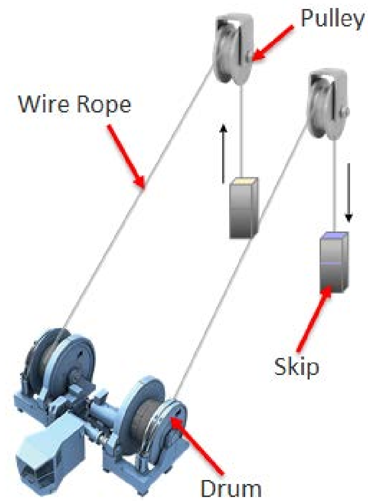

FIGURE 5: THE DESIGN OF SKIP HOIST AND SPECIFICATIONS.

The major components of a skip hoist system include a motor, a drum brake, two hoist drums, two skips, wire rope, and two pulleys as shown in FIGURE 5. The skip hoist is a mature industry product which is also highly modular. Therefore, the basic skip hoist mechanical equipment cost is:

$$C_{skip\_hoist,equip} = C_{motor} + C_{drum\_brake} + C_{drum} + C_{skip} + C_{wire\_rope} + C_{pulley} \quad (3)$$

The equipment cost breakdown is based on a study conducted by Georgia Institute of Technology [14]. In addition, considering installation labor, materials and accessory cost factors, the capital cost of skip hoist can be estimated:

$$C_{skip\_hoist,tot} = C_{skip\_hoist,equip} \times (1 + F_{installation} + F_{parts\&accessories}) \quad (4)$$

where $C_{skip\_hoist,tot}$ - Single unit skip hoist capital cost, $
$F_{installation}$ - Installation factor
$F_{parts\&accessories}$ - Parts and accessories factor

Table 4 lists the cost breakdown for major parts in the skip hoist. Then the skip hoist system unitized capital cost of 0.042 $/kWh_{th}$ for the whole system can be obtained from the design analysis.

Table 4: PARTICLE LIFTING SKIP HOIST COST BREAKDOWN.

Particle Lifting Skip Hoist Parameters and Cost Breakdown		
Categories	***Units***	***Values***
Lifting height	m	125
Particle lifting rate	Kg/s	300
Particle lifting temperature	C	300
Overall Lifting Efficiency	%	78.8
Single Skip Hoist Capital Cost	**$**	**1,074,348**
Skip Host Unitized Capital Costs	**$/kWh$_{th}$**	**0.042**

3.3 Energy Discharging Heat Exchanger

The particle heat exchanger is a key component to connect the TES with the power cycle. Research work for Generation 3 CSP for supercritical carbon dioxide (sCO_2) Brayton power cycle has focused on moving packed-bed (MB) HX. A MB HX is simpler in design and requires less parasitic power for operation; however, the heat transfer between the particles and working fluid may be ineffective due to low heat transfer capability between particles and surfaces, resulting in substantial use of materials and high cost.

For the ABCC power cycle using air as a working fluid, an alternative approach to obtain a high heat-transfer coefficient is through direct gas/particle contact in a PFB HX. The PFB HX allows for direct heat transfer between the hot particles and pressurized gas and eliminates the cost and exergy losses of heating surfaces in indirect, traditional plate or shell-tube heat exchangers. Gas exits the PFB HX at maximum particle temperature to drive a high-efficiency ABCC system. Figure 6 shows the schematic of a direct gas/particle contact PFB HX to drive an ABCC power cycle with a pressure vessel to hold the air pressure.

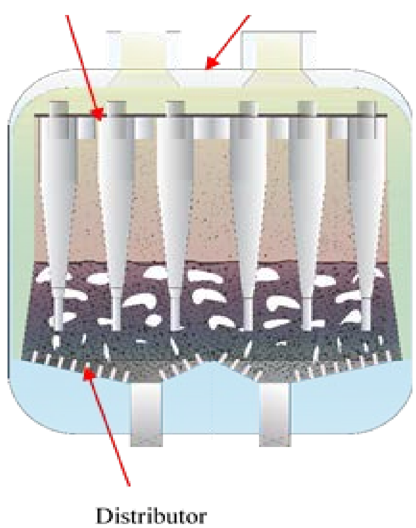

FIGURE 6: A SCHEMATIC OF THE PFB HX DRIVING THE ABCC POWER CYCLE.

The cost of PFB HX consists of a pressure vessel cost, PFB HX cost and particle separation cyclone cost:

$$C_{PFB,equip} = C_{PFBPV,equip} + C_{PFBHX,equip} + C_{cyclone,equip} \quad (5)$$

The pressure vessel is designed according to ASME Boiler and Pressure Vessel code in Section VIII Division 1 to calculate the shell wall thickness [15]. AISI 4340 steel with the relatively high yield strength of 450 MPa at 300℃ is selected to fabricate the inner shell to reduce the amount of material used and the net weight of the pressure vessel. In addition, mineral wool and A36 structure steel are placed outside of the pressure vessel to provide the required insulation capability. The particle separation cyclone costs can be estimated based on the fabrication material costs provided by an industry supplier. The PFB HX cost was based on a PFB combustion boiler to generate steam to drive a steam-Rankine cycle [7], [16]. This PFB combustion boiler was 8.53 m in OD × 23.16 m in height, and Equation 6 is used to scale to the size of the current design by volume:

$$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^{0.6} \quad (6)$$

where C refers to equipment cost and V is the equipment volume [17]. The conversion method of the Chemical Engineering Plant Cost Index (CEPCI) was used to convert the PFB HX cost to the year of 2019. Accordingly, the PFB system capital cost is calculated as 72.00 $/kW.

Table 5: PFB HX COST ESTIMATION BREAKDOWN.

PFB HX Cost Estimation Breakdown		
Categories	***Units***	***Cost Values***
Equipment Costs		
PFB Pressure Vessel Cost	$	2,071,334
PFB HX Equipment Cost (including distributor, baffles, insulation, and other accessories))	$	4,574,561
Particle Separation Cyclone Equipment Cost	$	57,124
Single Unit Capital Cost		
Single PFB System Capital Cost	**$**	**9,719,377**
Gross Capital Cost (3 Units)		
Whole System PFB Capital Cost	**$**	**29,158,132**
Unitized Capital Costs		
PFB Capital Cost per Unit Power Capacity	**$/kW**	**72.00**

3.4 Power generation system

The conversion of thermal energy back to electricity is limited by the thermal-electric conversion efficiency that is capped by the Carnot cycle efficiency. Therefore, one key factor for thermal energy to play a role in electricity storage is to improve thermal-cycle efficiency, which is possible by adopting a high-efficiency ABCC power system that is adapted from a conventional GTCC. With the heat recovery steam generation (HRSG) driving a bottom steam-Rankine power cycle, the BCCP system creates a large temperature difference that increases TES energy density, in addition to a high thermal power efficiency and near-term commercial availability. Thus, the configuration was chosen for the system analysis.

FIGURE 7 illustrates a conventional GTCC plant layout. An extensively cited data source, Gas Turbine World (GTW) Gas Turbine Handbook is used as the baseline to conduct a literature survey to obtain the BEC of essential components of GTCC plants. The total BEC of GTCC plants is broken down into six sections: (1) gas turbine, (2) HRSG, (3) steam turbine, (4) cooling system, (5) generator with electric plant, (6) balance of plant, miscellaneous and control sector.

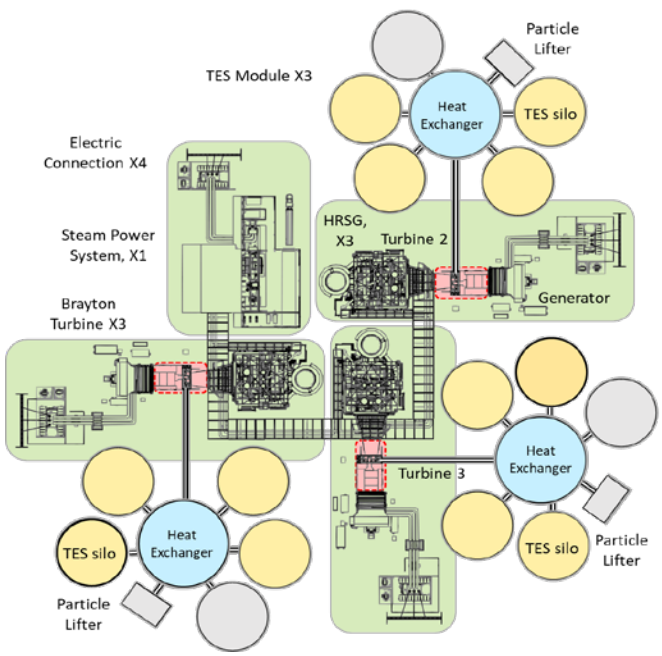

FIGURE 8: A PLANT LAYOUT OF A 400MW, 100-HOUR ETES SYSTEM.

As FIGURE 9 indicates, the GTCC overnight capital costs published in different sources fall well into the cost range with accuracy of ±15% provided by GTW [9]. Subsequently, based on all these validated data, the cost breakdown of GTCC plants was performed and presented in FIGURE 10, with the average values as well as the standard deviations of each essential section [8], [18]–[22]. It needs to be mentioned that the effect of plant capacity on the cost breakdown is negligible when considering plant capacities above 400 MW$_e$. In addition, a combined cycle plant capacity is typically larger than 400 MW$_e$. CEPCI conversion factor is used to convert the cost to the present time. The cost conversion can be defined as [23]:

$$C_{i,B} = C_{i,A} \times F_{CEPCI,A\ to\ B} \quad (7)$$

where $C_{i,A}$ - component cost at year A

$C_{i,B}$ - component cost at year B

$F_{CEPCI,A\ to\ B} = CEPCI\ at\ year\ B / CEPCI\ at\ Year\ A$ - chemical engineering plant index factor updating capital cost from one period to present.

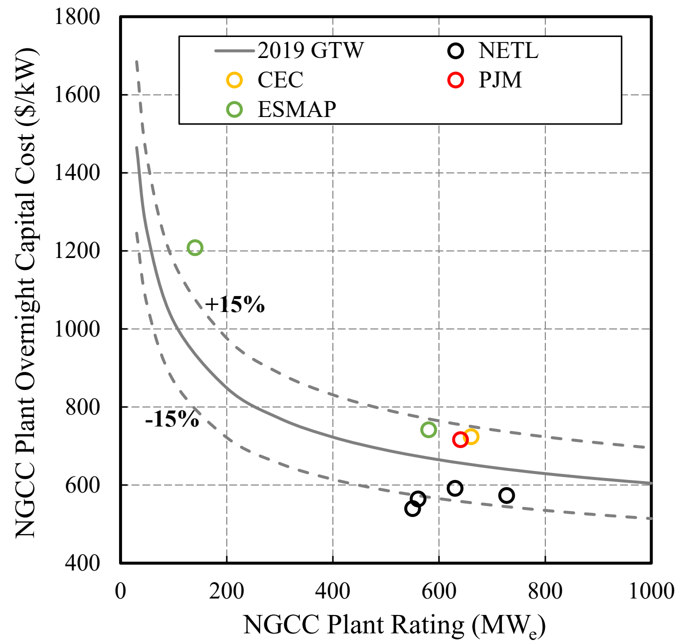

FIGURE 11: PUBLISHED GTCC BARE ERECTED COST DATA.

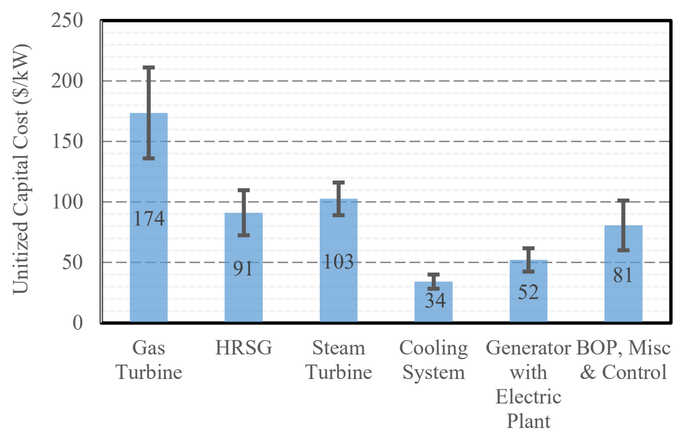

FIGURE 12: COST BREAKDOWN OF ESSENTIAL COMPONENTS OR SECTORS IN CONVENTIONAL GAS TURBINE COMBINED CYCLE PLANT [8], [18]–[22].

The costs of fuel-relevant auxiliary equipment and natural gas pipeline in a GTCC system were deducted in the cost breakdown analysis and the results presented in FIGURE 9. Gas turbine and HRSG costs take up 50% of the total gas turbine combined cycle power generation systems.

Based on the cost breakdown of essential components, the cost estimations of three different ENDURING plant implementation scenarios can be obtained and presented as follows. The power system cost $c_{PowerSys}$ is referred to the six generation components in FGIRUE 9, plus the power specific components including the PFB heat exchanger and charging electric heater. Combined with the power specific component cost $c_{PowerSpecific}$, the overall power system unitized cost c_P is:

$$c_P = c_{PowerSys} + c_{PowerSpecific} \quad (8)$$

The ETES system offers flexibility to achieve a mix of storage durations and power system integrations. The cost estimates of key components including turbine, HRSG, steam turbine, electric generator, and balance of plant (BOP) for combined cycle power systems can range from \$625/kW (GTW 2019 price list) to \$900/kW (CEC 2019 Power Plant Cost). Other plant costs such as land, buildings, and grid-connection substations are not included in the estimates. If an ETES system is built on a retired thermal power plant, the storage plant can leverage the power plant assets to potentially benefit economics, permit, grid resilience, and community. This may be realized by repurposing the site and grid connection or modifying a gas plant by reusing the HRSG and steam turbine.

4. SYSTEM COST SENSITIVITY ANALYSIS AND TECHNOLOGY COMPARISONS

Determining where ETES fits in the storage mix will require a comparison of daily power supply/demand versus weather-related grid energy storage needs, in addition to consideration of the characteristics and flexibility of the ETES technology. In short duration storage of a few hours, frequent diurnal storage cycles allow the storage device to earn revenue frequently for capital returns. The installed storage infrastructure is therefore highly utilized. To substitute baseload power with significant renewable penetration to the grid, longer duration energy storage between 10 hours and 100 hours may be needed to overcome the electricity supply/demand deficits due to weather events. However, long duration energy storage may have fewer storage cycles, thus it favors storage technologies that have lower capital costs. The ETES system based on particle TES can serve both market sectors (e.g., short duration and long duration storage) for near-term and long-term deployment based on a storage cost analysis.

The ARPA-e DAYS formula (Equation 9) was revisited to assess LCOS sensitivity to the electricity purchase price (P_c), round-trip efficiency (η_{RTE}), cost of power (C_P) and energy storage (C_E) systems, service life (t), and annual cycles ($n_c(t)$).

$$LCOS\left(\frac{\$}{kWh}\right) = \left[\left(\frac{1}{\eta_{RTE}} - 1\right) P_c \sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t} + \sum_{t=1}^{T} \frac{O\&M(t)}{(1+r)^t} + \left(\frac{C_E}{\eta_D} + \frac{C_P}{d}\right)\right] \cdot \left[\sum_{t=1}^{T} \frac{n_c(t)}{(1+r)^t}\right]^{-1} \quad (9)$$

Equation 9 separates the storage cost from the cost of power system, reflecting that the ETES system has storage components split from the power generation, which is different from battery storage. The separation of storage from power generation may help longer duration storage by allowing the storage capacity to increase without an increase in power system capacity and cost.

An initial analysis used default operational parameters defined by the ARPA-E DAYS program including storage duration, capacity, and storage cycles. Sensitivity analysis was performed on variations of storage characteristics relative to the base values including capital cost per MW, capital cost per MWh, variable operating cost, roundtrip efficiency, and lifetime.

Table 6 lists the baseline numbers, favorable, and unfavorable assumptions that are justified further below.

Table 6: SENSITIVITY ANALYSIS INPUT VALUES.

	Favorable Value	Baseline Value	Unfavorable Value	Unit	Parameters
P_c	1.0	2.5	4.0	¢/kWh	Input electricity price during charging
η_{RTE}	60	50	40	%	AC system round-trip efficiency
C_P	400	650	1,100	\$/kW	Capital cost for power-specific components with 22% contingency
t	30	20	10	years	System service lifetime
C_E	1.5	2.0	4.0	\$/kWh	Capital cost for energy-specific components and BOP
$n_c(t)$	162	59	45	cycles	Number of equiv. full charge-discharge cycles per year
d	25	75	100	hours	Storage duration

Additional Assumptions:
- $\eta_D = \eta_{RTE} + 1.5\%$ (to account for thermal energy loss from storage)
- $O\&M(t)$ = 0.00171 \$/kWh for fixed/var. operations/maintenance costs and periodic replacements
- r = 0.1 discount rate over project lifetime

Various system integrations are being considered that may affect the techno-economic outcomes. Electricity Purchase Price could be 1 ¢/kWh because of curtailment, amounting to a low average charging price. 4 ¢/kWh represents implementing renewable electricity without discounts. The storage roundtrip efficiency of 60% represents a future PTES implementation [5]. On the low end, a roundtrip efficiency of 40% can be expected from modifying coal or single-cycle gas plants. Cost of the power block ranges from 400 \$/kW by leveraging a retired fossil plant to 900 \$/kW for a new-build plant adapted from a GTCC system. Usually, typical service life for a thermal power plant can be more than 30 years, compared to the typical 10 years of service life for chemical batteries. Cost of particle TES varies between 1.5 \$/kWh$_{th}$ by assuming future automated construction and 4.0 \$/kWh$_{th}$ for an initial, small capacity unit. The annual storage cycles are assumed at 162 cycles as a mix of daily arbitrage up to 25 hours duration storage and 45 cycles for 100 hours long duration energy storage.

Results from the preliminary sensitivity analysis are shown in FIGURE 13, revealing a variety of scenarios that could achieve the 5¢/kWh LCOS target. The ENDURING system shows promise in achieving the 5¢/kWh LCOS target under LDES operation assumptions. A design for dynamic operation (e.g., faster-startup, option for gas addition, etc.) is likely to increase revenue by tapping into daily storage operation. Our current component design, modeling and sizing have indicated that the above cost numbers are reasonably achievable.

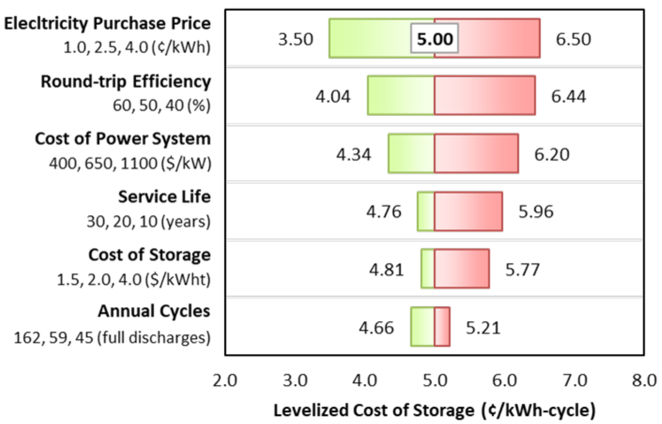

FIGURE 14: TEA SCENARIOS FOR ACHIEVING THE 5¢/KWH LCOS TARGET.

5. CONCLUSION

A novel standalone particle TES system is evaluated for electric energy storage. The system stores low-price, off-peak electricity as thermal energy for later dispatch to produce high-value, peak-demand electricity. The TES system uses particle-storage media at 1200°C to drive a high-efficiency combined cycle to obtain a high roundtrip efficiency. The energy storage system can be integrated with CSP or a standalone TES system consisting of four subsystems: (1) a novel particle heater; (2) insulated particle storage silos; (3) a fluidized bed heat exchanger (FB-HX); and (4) a power system. Preliminary component designs were performed. The TES system is effectively "charged" by heating stable, inexpensive solid particles (e.g., silica sand) using CSP or off-peak, low-price electricity. The hot particles are stored in highly effective insulated silos. During peak electricity hours, energy in hot particles is "discharged" through a particle-to-gas FB-HX that transfers the particle heat to a working gas to drive a thermal power system (e.g., steam-Rankine, air-Brayton combined-cycle, sCO_2 Brayton power, or emerging pumped thermal energy storage).

The current development incorporates low-cost, high-performance TES with high efficiency combined power cycles. The ETES system as introduced in this paper can support large-scale energy storage to address the variability issue and firm up renewable generation in facilitating a baseload generation capacity. The low-cost and high-efficiency ETES is an economically viable way and provides scalability and siting flexibility for grid-scale electric energy storage applications.

ACKNOWLEDGEMENTS

This work was authored by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The work was funded in part by the DOE Advanced Research Projects Agency–Energy (ARPA-E) DAYS Program. We thank for Dr. Scott Litzelman and Mr. Max Tuttman for their direction and support.

REFERENCES

[1] Z. Ma, G. Glatzmaier, and M. Mehos, "Fluidized Bed Technology for Concentrating Solar Power With Thermal Energy Storage," *J. Sol. Energy Eng.*, vol. 136, no. 3, p. 031014, 2014.

[2] M. Mehos *et al.*, "Concentrating Solar Power Gen3 Demonstration Roadmap," *Nrel/Tp-5500-67464*, pp. 1–140, 2017.

[3] C. S. Turchi, Z. Ma, T. W. Neises, and M. J. Wagner, "Thermodynamic study of advanced supercritical carbon dioxide power cycles for concentrating solar power systems," *J. Sol. Energy Eng. Trans. ASME*, vol. 135, no. 4, 2013.

[4] A. J. Farres-Antunez, Pau; McTigue, Joshua Dominic P; White, "A Pumped Thermal Energy Storage Cycle with Ccapacity for Concentrated Solar Power Integration," 2019.

[5] R. B. Laughlin, "Pumped thermal grid storage with heat exchange," *J. Renew. Sustain. Energy*, vol. 9, no. 4, 2017.

[6] K. Gerdes, W. M. Summers, and J. Wimer, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," no. September, p. 26, 2019.

[7] S. Moskowitz, R. Cole, and A. Defeo, "Engineer, design, construct, test and evaluate a pressurized fluidized bed pilot plant using high sulfur coal for production of electric power. Phase I. Preliminary engineering. Topical report, 1 March 1976-1 June 1977," Curtiss-Wright Corp., Wood-Ridge, NJ (USA). Power Systems Div., 1977.

[8] T. Fout, T. Shultz, M. Woods, M. J. Turner, A. J. Zoelle, and R. E. James III, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4," NETL, 2018.

[9] A. G. T. Handbook, "Gas turbine world." Pequot Publishing Inc, CT, USA, 2019.

[10] P. Davenport, Z. Ma, W. Nation, J. Schirck, and M. Lambert, "Thermal Stability of Silica for Application in Thermal Energy Storage, 26th International

SolarPACES Conference, September 28 - October 2, 2020," 2020, no. 1.
[11] Z. Ma, P. Davenport, and R. Zhang, "Design analysis of a particle-based thermal energy storage system for concentrating solar power or grid energy storage," *J. Energy Storage*, vol. 29, no. June, p. 101382, 2020.
[12] J. Gifford, Z. Ma, and P. Davenport, "Thermal Analysis of Insulation Design for a Thermal Energy Storage Silo Containment for Long-Duration Electricity Storage," *Front. Energy Res.*, vol. 8, no. June, pp. 1–12, 2020.
[13] K. K. D. Repole and S. M. Jeter, "Design and Analysis of a High Temperature Particulate Hoist for Proposed Particle Heating Concentrator Solar Power Systems," in *Proceedings of the ASME 2016 10th International Conference on Energy Sustainability*, 2016.
[14] K. K. Repole, "The Development and Application of Design and Optimization Methods for Energy Intensive Mechanical Systems for Challenging Environments as Applied to a Concentrated Solar Power Particle Lift System." Georgia Institute of Technology, 2019.
[15] A. Boiler and P. V. Code, "Section viii division 1," *Rules Constr. Press. Vessel. Append.*, vol. 1, p. 1, 2010.
[16] R. Schaefer, "Cost estimate of fluidized bed combustor air heater for gas turbines. Final report," Curtiss-Wright Corp., Wood-Ridge, NJ (USA), 1979.
[17] M. A. Tribe and R. L. W. Alpine, "Scale economies and the '0.6 rule,'" *Eng. Costs Prod. Econ.*, vol. 10, no. 4, pp. 271–278, 1986.
[18] D. O. E. NETL, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity Rev. 2," *Pittsburgh, PA, US*, 2010.
[19] J. Haslback *et al.*, "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2a," National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV …, 2013.
[20] A. Zoelle *et al.*, "Cost and performance baseline for fossil energy plants volume 1a: Bituminous coal (PC) and natural gas to electricity revision 3," NETL, 2015.
[21] S. A. Newell *et al.*, "Cost of new entry estimates for combustion turbine and combined cycle plants in PJM," *Cambridge Brattle Gr.*, 2014.
[22] G. Newsom, "Estimated Cost of New Utility-Scale Generation in California: 2018 Update California Energy Commission," no. May, 2019.
[23] H. Silla, *Chemical process engineering: design and economics*. CRC Press, 2003.