Project No. 5: Evaluating Dredged Materials for Energy Storage Applications with Economic and Carbon Benefits

Cooperative Research and Development Final Report

CRADA Number: CRD-21-18244

NREL Technical Contacts: Zhiwen Ma and Jonathan Morgenstein

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5700-91468
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NOTICE

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Cooperative Research and Development Final Report

Report Date: September 20, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: New York Power Authority (NYPA)

CRADA Number: CRD-21-18244 (Modification 5)

CRADA Title: Project No. 5: Evaluating Dredged Materials for Energy Storage Applications with Economic and Carbon Benefits

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources.

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Years 1-3 (Modifications #0-8)	$ 0.00
TOTALS	$ 0.00

Executive Summary of CRADA Work:

The New York Power Authority (NYPA) is committed to supporting the Climate Leadership and Community Protection Act (CLCPA) through its VISION2030 strategic plan. As a clean energy provider, NYPA is seeking to demonstrate leadership in every aspect of its business by taking a comprehensive approach to sustainability management and integrating sustainability principles into day-to-day decision-making. This effort includes planning for climate resilience through projects that mitigate climate risk in our operations and prioritize climate opportunities in our investments.

Canal Corporation, a subsidiary of NYPA, is charged with maintaining minimum water depths for navigation in the Cayuga-Seneca, Champlain, Erie and Oswego Canals. In order to do so, an average volume of 280,000 cubic yards of sediment is dredged annually and held in Upland Disposal Sites (UDS) permitted by the New York Department of Environmental Conservation (NYSDEC). The required on-land storage at UDSes are nearing capacity, and disposal opportunities are costly, both economically and environmentally.

Novel energy storage technology developed by NREL provides an opportunity for meeting NYPA's need to find reuse options for dredged materials and commitment to providing clean reliable energy. This would also support NYPA's goal of developing 300 MW of utility scale storage and enabling 150 MW of distributed storage by 2030. NREL will consult NYPA on the environmental and economic impact of reusing dredged materials as useful commodities such as energy storage media, construction sand or industrial uses. Test and material characterization methods will be based on current NREL storage material characterization approaches.

NREL worked with NYPA on sample preparation, material testing, test results analysis. Test and material characterization methods were based on current NREL storage material characterization approaches. The team analyzed the environmental and economic impact of reusing dredged materials as useful commodities such as energy storage media, construction sand or industrial uses. The test and analysis works have achieved the project goal in characterizing NYPA dredging materials and verifying their various uses including construction sand and thermal energy storage media. Uses of dredging materials as useful materials will bring economic and environmental benefits and avoid disposal costs.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope,
- Enhances the laboratory's core competencies on particle-based thermal energy storage,
- Uses the laboratory's core competencies, and
- Enhances U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities

Summary of Research Activities:

The current scope encompasses Phase 1 of a project with 3 potential phases, depending on results of each prior phase.

- Phase 1 includes assessment of promising dredged materials for thermal and reuse properties including economic and environmental cost benefit analyses.
- Phase 2 would include site feasibility analysis for locating and configuring the energy storage technology.
- Phase 3 would include the design and specification of a prototype/demonstration.

Prior to completion of Phase 1, the Parties may agree upon an optional Phase 2 and Phase 3, which may include site analyses of the plant plan and layout and the component sizing and capital cost estimation and the design and specification of a prototype. Upon agreement to proceed with the optional Phase 2, the Parties will modify this Agreement in accordance with Article XIII.B prior to its completion for the addition of work and funding or execute a separate agreement for follow on work.

Phase 1 Scope of Work:

NYPA will send dredged materials from Canal waterways for testing by NREL. NREL will test dredged materials to determine composition and suitability for use in energy storage, construction or other applications. NREL will then further test certain dredged materials that are promising for energy storage media. NREL and NYPA will analyze the economic benefits of using dredged material for energy storage, including energy arbitrage from energy storage and grid service, processing dredged materials by using low-cost electricity in energy storage, saving the cost of disposing of dredged materials, and generating potential income from processed materials after use for energy storage (e.g., construction sand or high-purity silica sand for industry uses). The potential environmental impacts and carbon emission reductions achieved from processing the dredged materials and integrating renewable energy with energy storage to supply heat and power will also be assessed.

TASK DESCRIPTION:

Task 1: Dredged material assessment

This task will involve assessment of two UDS for suitability for energy storage and post-storage construction and industrial application. This may include but is not limited to:

1.1. NREL will develop a test plan that will include testing procedures to investigate the material properties of interest. NREL will collaborate with NYPA to prepare test objectives, procedure, and successful criteria.

1.2. NYPA will provide material samples with two types of dredged material (Sylvan Beach UDS 4-60 sand and UDS 4-56 gravelly/silty sand).

1.3. NYPA will prepare and deliver material samples for testing.

1.4. NREL will test the samples for at minimum:

  a. Usability: size, thermal stability, etc.

b. Material characterization: properties (density, specific heat, etc.), and contamination as applicable

c. X-Ray Powder Diffraction (XRD) analysis on material compositions before and after heating test to identify energy storage lifecycle, and processes of converting dredged materials to potentially useful commodities

1.5. NREL will provide raw data and summary of results, including suitability for use in energy storage as well as other applications such as construction or manufacturing.

Task 2: Preliminary cost benefit analysis

Based on the suitability outcome in Task 1, this task will analyze preliminary economic potentials of using suitable dredged materials for energy storage and after-storage uses. This may include:

2.1. NREL will conduct a cost-benefit analysis incorporating the following at minimum:

a. Energy storage revenue estimation excluding capital and operating and maintenance (O&M) costs of future studies.

b. Material income estimates.

c. Estimating material handling costs and savings.

d. Estimating material disposal costs and savings.

2.2. NREL will provide raw data and summary of results.

Task 3: Carbon footprint and environmental analysis

This task will explore environment and public benefits of reuse of the dredged materials based on Task 1 results. This may include:

3.1. NREL with collaboration from NYPA will conduct a carbon footprint and environmental analysis incorporating the following at minimum:

a. Renewable electricity uses

b. Lifecycle impacts (comparison of raw material extraction, material processing, manufacturing, assembly, product use, and disposal) of using dredged material versus other options (other energy storage technologies, business as usual, disposal of dredged material in other ways, etc.)

c. Public benefits of energy storage using dredged materials and converting them into useful commodities

3.2. NREL will provide raw data and summary of results

Phase 1 Deliverables

- Set up regular conference calls to report task progresses
- Deliver data in processed and raw form
- Deliver reports as requested, at minimum including:
  - Task 1 summary (7 months from the effective date)
  - Task 2 summary (7 months from the effective date)
  - Task 3 summary (7 months from the effective date)
  - Final recommendations and next steps (in collaboration with NYPA) (8 months from the effective date)
- CRADA Final Report: Preparation and submission in accordance with Article X (prior to the expiration of the Agreement).

RESULTS AND EXPLANATION:

Task 1: Dredged material assessment

This task involved assessment of dredged materials from two UDS for suitability for energy storage and post-storage construction and industrial application.

1.1. **NREL will develop a test plan that will include testing procedures to investigate the material properties of interest.**

NREL collaborated with NYPA to prepare test objectives, procedure, and successful criteria.

Test Plan

The finalized material test plan was outlined by the flowchart in Figure 1. The test plan includes material characterization and thermal performance and stability tests by using NREL's test facility and equipment.

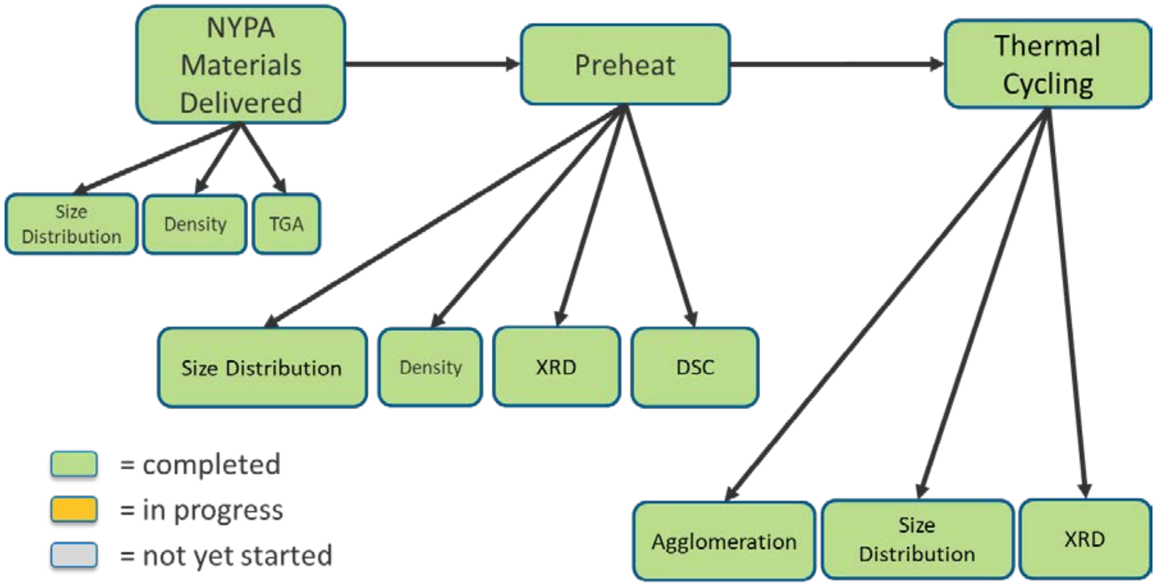


Figure 1. Test plan flowchart.

The initial materials received were tested for particle size distribution, density, and with thermogravimetric analysis (TGA). Material preheat was intended to deliver thermal behavior of materials over heating range, while also drying and removing organic content prior to differential scanning calorimetry (DSC). DSC, powder X-ray diffraction (XRD), and size distribution measurements were performed before and after thermal cycling to demonstrate material behavior in response to elevated temperatures. Instruments used for the material characterization and measurements are listed below with test details described.

Thermogravimetric Analysis (TGA) Test

Equipment Type:	TGA (Q500), TA Instruments. 
Specifications:	Maximum operation at 1000 C Heating rates of 0.01-100ºC/min Sample capacity up to 1 g, sample pans up to 500 µL, forced cooling option (1000 C to 50 C < 12 min)
Test Details:	Place 20 - 50 mg sample placed in alumina crucible. Pictures of sample taken before and after TGA. TGA programmed for the following 1-cycle operation. Program: Ambient to equilibrate at 50º C Ramp up 50ºC to 950 ºC, 10 ºC/min Ramp down 950 ºC to Ambient ºC, 10 C/min 2 separate runs of each material, once under inert gas flow and once under dry, compressed air flow. Do not reuse samples. Successful runs will result in graphs with low noise and smooth signal. The purpose of this test was to investigate the existence of any polymorphic phase transitions, glass transition phenomena, as well as oxidation stability and decomposition onsets. This test may also help to identify presence of minor phases and mass loss on heating and will help determine if preheating is necessary to prepare materials for further study.

Differential Scanning Calorimetry (DSC) Test

Equipment Type:	DSC (404 F3 Pegasus®), Netzsch. 
Specifications:	Maximum operation at 1500 ºC Max heating rate of 0.001-50ºC/min DTA sensitivity 0.001ºC, caloric precision +/-2%
Test Details:	Place ~27 mg sample in alumina crucible. Program DSC for the following operation, to be repeated twice for each sample. Samples will be purged and protected by inert gas during testing. Program: 1. Isothermal at ambient for 10 minutes 2. Ramp up 10 C/min to 1000 C 3. Isothermal for 10 min 4. Ramp down 10 C/min 1000 ºC to ambient 5. Repeat steps 2-4 The purpose of this test was to determine the specific heat capacity of particles of interest. The test will also investigate further the existence of any polymorphic phase transitions, glass transition phenomena, as well as oxidation stability and decomposition onsets, and may help identify presence of minor phases.

Particle Size Distribution Analysis

Equipment Type:	Mastersizer 2000, Malvern Instruments 
Specifications:	Red light beam wavelength: 633 nm Blue light beam wavelength: 466 nm Max. Output power: 4 mW Type: LED
Proposed Test:	If sample displays agglomerating behavior, disperse according to Mastersizer manual. If free flowing, a dry measurement is preferred. Prepare ~20 mL sample and deliver to optical bench. If free flowing, use perforated copper tubing to obtain representative sample. Take measurement, ensuring obscuration range between 10-20%. The purpose of this test was to understand particle size distribution of extracted samples.

Powder X-ray Diffraction (XRD) Test

Equipment Type:	Rigaku Ultima IV 
Specifications:	Powder Diffraction Multipurpose theta-theta X-ray diffractometer Independent theta-theta geometry Bragg-Brentano geometry
Test Details:	Procedure 1. Grind powder using mortar & pestle to diminish particle size and fit powder slide (maximum 200 um particle diameter). 2. Pour powder to 200 um inset powder XRD slide, remove excess. 3. Run powder XRD from 0 – 100 (2-theta), 5 degrees/min, fixed monochromator. The purpose of this test is to identify major and minor crystalline phases in each sample.

1.2. NYPA will provide material samples with two types of dredged material (Sylvan Beach UDS 4-60 sand and UDS 4-56 gravelly/silty sand).

1.3. NYPA will prepare and deliver material samples for testing.

Two types of dredged material (Sylvan Beach UDS 4-60 sand and UDS 4-56 gravelly/silty sand were delivered by NYPA. Their locations and conditions are summarized in Table 1. NYPA sent samples in mid-November 2022, and NREL developed test plan accordingly, which was reviewed by NYPA to prepare sample tests at NREL.

Table 1. Material samples with two types of dredged material (Sylvan Beach UDS 4-60 sand and UDS 4-06 gravel/silt)

UDS Site	Confluence and Location (township)	Type of Material	UDS Size (acres)	How Often Utilized	Access Conditions	Rank within the Utica Section
4-56	Wood Creek- Town of Verona	Gravelly/Sandy silt	45	approx. every third yr.	Gravel/dirt field drive through canal Corp. prop.- Very difficult access	13
4-60	Fish creek- Town of Verona	Silty sand	31	approx. every other yr.	Gravel entrance road from county hwy to site- easy access	4

Figure 2 shows pictures of the delivered samples before testing. Five samples were taken from each site with 1 foot depth apart and up to 6 feet in depth, marked from 1 through 5. Different layers may contain various sediments. Samples were contained inside glass bottles that conserved water content and organic materials. All samples were tested except for sample 4-60-4, which contained significant organic residues of leaves or branches that prohibit particle size analysis.

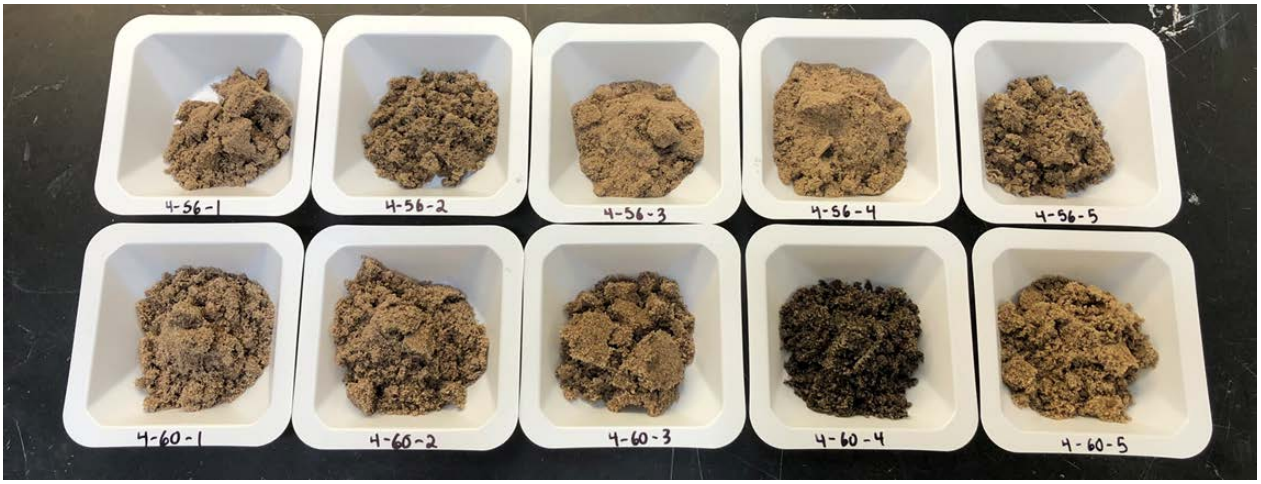


Figure 2. NYPA prepared and delivered material samples for testing.

1.4. Material sample testing at NREL

a. Usability: size, thermal stability, etc.

Dredged materials were first tested in the as-delivered state for particle size distribution. Figure 3 shows particle size distributions obtained from samples in the as-delivered state. 4-56 materials contain particles with narrower distributions and smaller diameters than all 4-60 materials, mostly between 50 – 400 µm. 4-60 materials contain larger particles with wider distributions, mostly between 100 – 700 µm. 4-56 materials exhibited a volume-weighted mean diameter of 154.81 um, while 4-60 materials exhibited a volume-weighted mean diameter of 295.28 um. These size ranges are typical of medium-fine sands.

As-delivered materials were also subjected to a thermogravimetric analysis to observe loss-on-ignition behavior up to 950 C. Temperature was ramped at 10 °C/minute in a dry air environment to simulate atmosphere likely to be present in thermal energy storage applications, and to observe possible oxide formation at elevated temperatures. Observed mass loss from heating was correlated to candidate mineral and organic species based on known temperature ranges of decomposition. Results of TGA for 4-56 and 4-60 materials are displayed below in Figure 4a, and Figure 4b, respectively.

For 4-56 materials, there is negligible mass loss up to 300°C, indicating low amounts of moisture. Precipitous mass loss occurs for all samples between 600 – 750°C, which indicate the decomposition of chlorites, vermiculites, and serpentines:

Chlorites:

$$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$$

$$(Mg,Fe)_3(OH)_6$$

Vermiculite:

$$M_{0.7}^{+}Al_2(Si_{0.7}Al_{3.3})O_{10}(OH)_2$$

$$M^+ = Ca^{2+},\ Mg^{2+},\ K^+,\ etc.$$

Serpentines:

$$Mg_3Si_2O_5(OH)_4$$

Additionally, negligible mass loss occurs for all 4-56 materials above 750 °C, which indicates a lack of carbonate minerals. Total average mass loss was 5.27%.

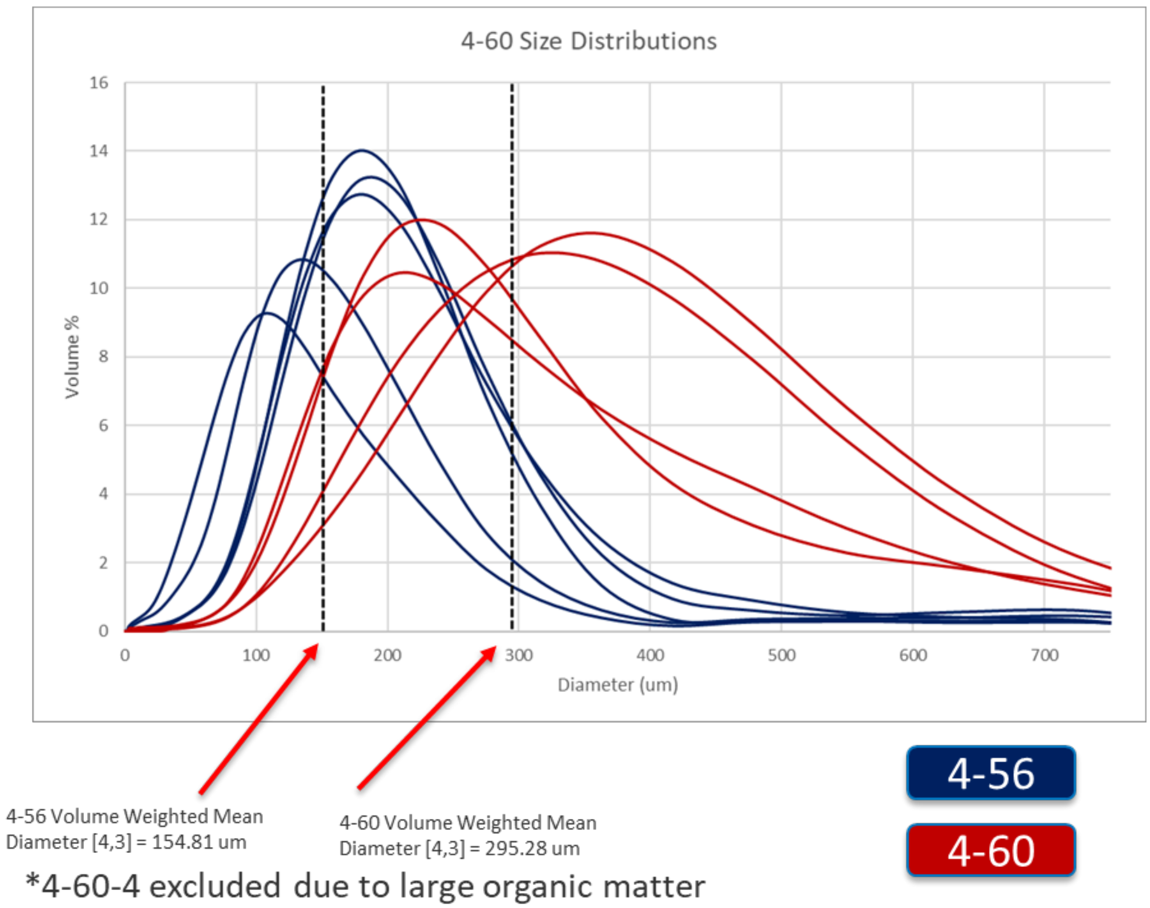
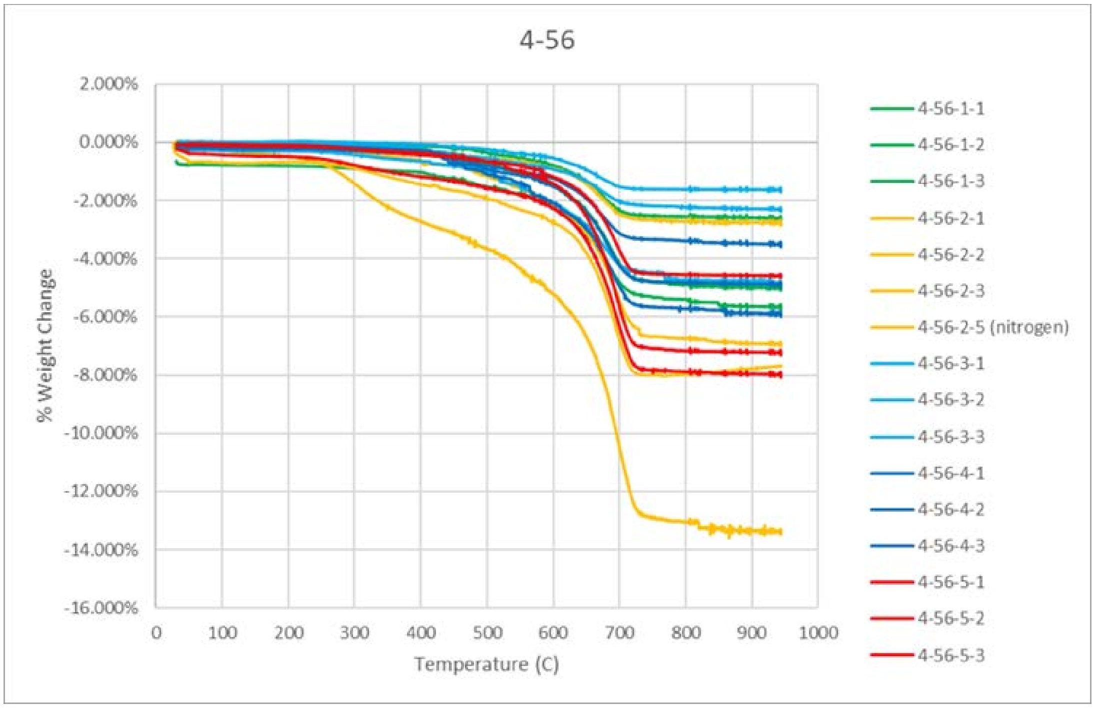
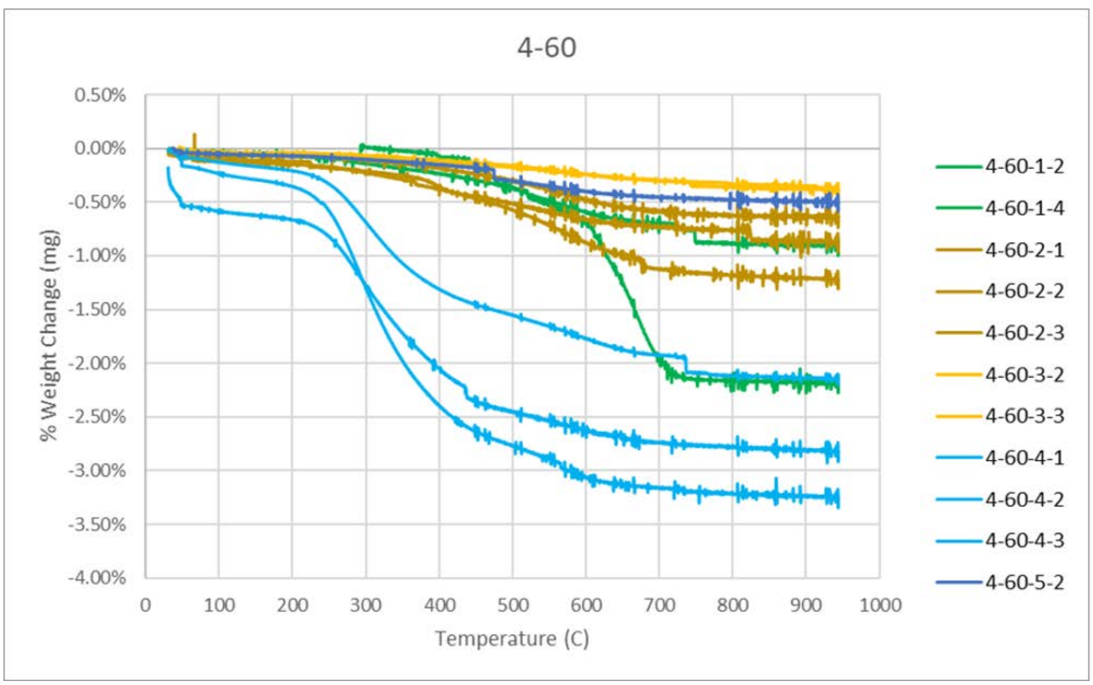


Figure 3. As-Received Particle Size Distributions (µm).



a) 4-56 Thermogravimetric Analysis



b) 4-60 Thermogravimetric Analysis

Figure 4. TGA results for 4-56 and 4-60 dredging materials.

4-60 materials showed very little mass loss in general, so decomposition species were difficult to identify. However, sample 4-60-4 showed precipitous mass loss between 250 – 500 °C, indicative of decomposition of organic species.

Prior to heating, all materials appear like a wet, heavy sand, and are not free flowing. Some agglomeration is present, and material can be gathered in clumps. Following heating, materials appear dry and free-flowing, like a medium-fine sand, and have undergone a slightly red color change. TGA also revealed that at no point during heating in the range of interest was a mass increase measured, suggesting that oxides were not formed. All as-delivered materials therefore undergo only decomposition and off gassing during heating, a good indication of thermal stability of the mineral and inorganic fraction of the material.

Following initial size distribution measurements and thermogravimetry, thermal stability was investigated by subjecting materials to preheating and thermal cycling. Mass loss on ignition, color change, agglomeration, and particle size distribution after thermal cycling were all measured to help determine behavior of materials through a range of typical thermal storage media temperatures.

Preheating was performed to prepare materials for DSC and XRD, but also gave initial insight into thermal behavior outside of TGA. A 5 C/min ramp rate was performed up to 1000 C with a 24-hour dwell. Mass loss-on-ignition values are shown in Figure 5 and Table 2.

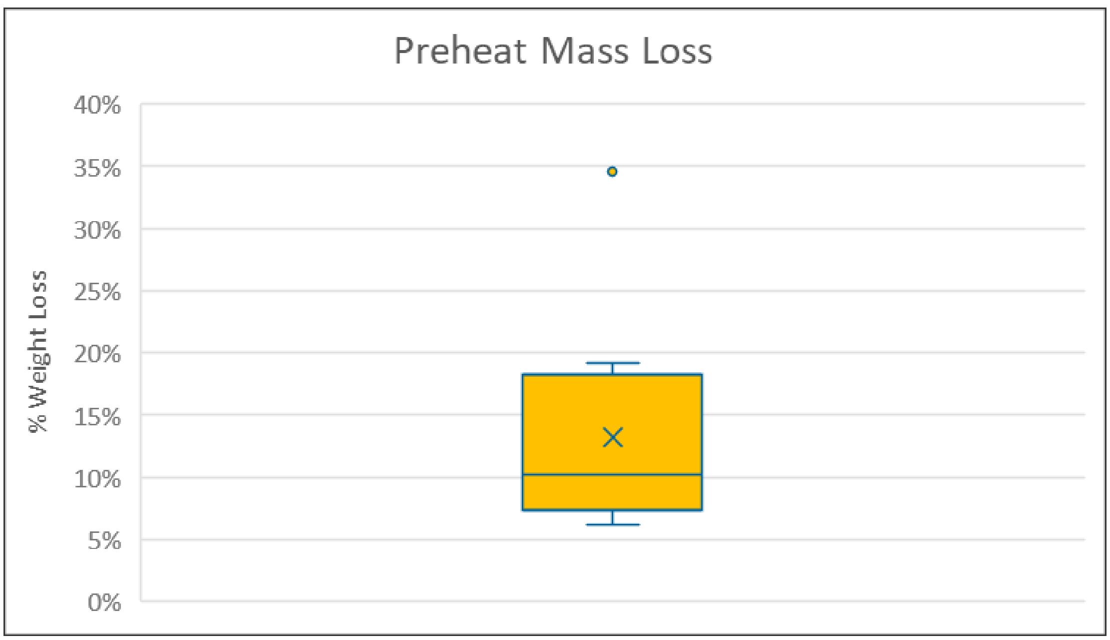


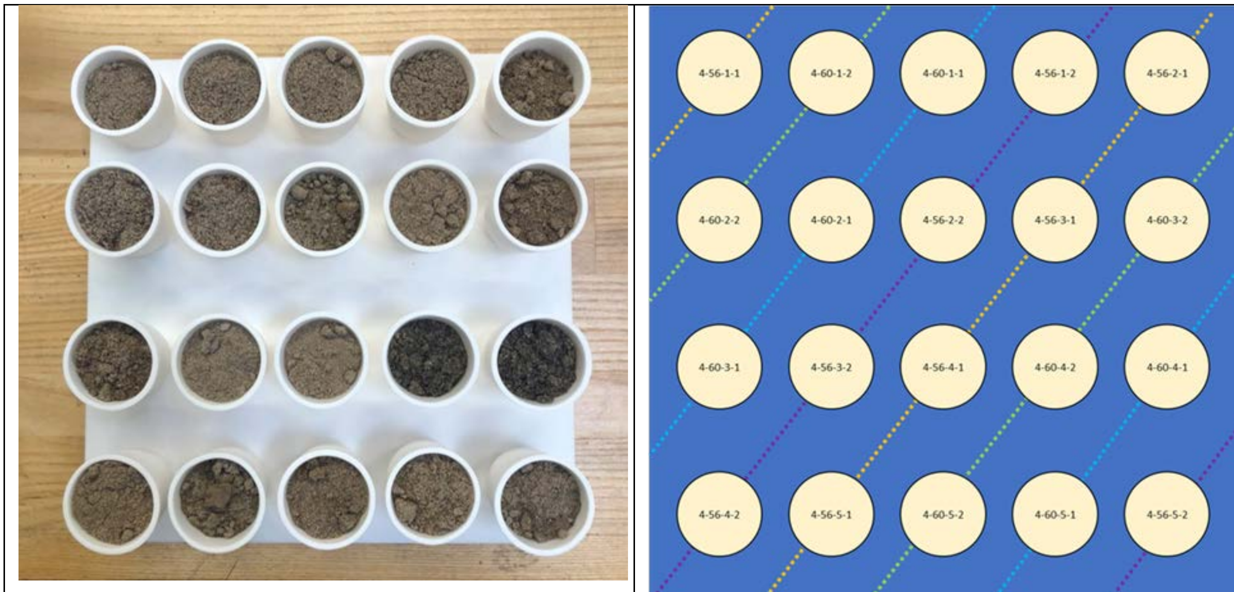
Figure 5. Preheat Mass Loss (all materials lumped together).

Average mass loss of 13% was observed from the preheat. This is high relative to thermogravimetry results, suggesting that dwelling at elevated temperatures results in additional mass loss not seen in TGA, in which a simple ramp up and ramp down is performed. It is believed this mass loss can be attributed to additional decomposition of hydrated minerals during dwell time.

Table 2. Preheat Mass Loss

	4-56-1	4-56-2	4-56-3	4-56-4	4-56-5	4-60-1	4-60-2	4-60-3	4-60-4	4-60-5
Start Mass [g]	151.67	138.81	138.13	138.91	142.78	130.57	147.9	151.27	114.09	140.4
End Mass [g]	136.28	112.24	124.06	126.06	117.22	122.45	136.95	135.77	74.63	130.29
Difference [g]	15.39	26.57	14.07	12.85	25.56	8.12	10.95	15.5	39.46	10.11
% Mass Loss	10%	19%	10%	9%	18%	6%	7%	10%	35%	7%

Thermal cycling was performed to subject materials to several elevated temperatures, and to subject some samples to several cycles of elevated temperatures. This was planned to give insight into material behavior at different temperatures and thermal lifetimes. Two sets of materials, ***Set 1*** and ***Set 2,*** were prepared and positioned for heating as shown in Figure 6.



a) Sample holders

b) Sample labeling to track samples

Figure 6. Sample holders with detailed labels to track samples.

Both sets were exposed to a 10-hour dwell at 800 °C. Set 1 then had a small amount of material removed and stored from each crucible before placing back in the furnace. Both sets then were exposed to a 10-hour dwell at 1000 °C, after which the remaining material in Set 1 was removed and stored. Finally, a third 10-hour dwell was performed at 1200°C which only Set 2 was exposed to. In this way, some material was obtained which saw only 800 °C, some which saw 800 °C and 1000 °C, and some material was obtained which experienced a dwell at all three temperatures.

Color change was expected for materials during thermal cycling and was recorded using an iPhone camera under consistent lighting, as shown in Figure 7. Initial color changes from the as-received state up to 1000 °C are likely due to formation of iron oxides within the samples, resulting in the red color often associated with iron oxides formed in rusting phenomena. Additional color changes above 1000 °C are possibly due to the formation of additional oxides.

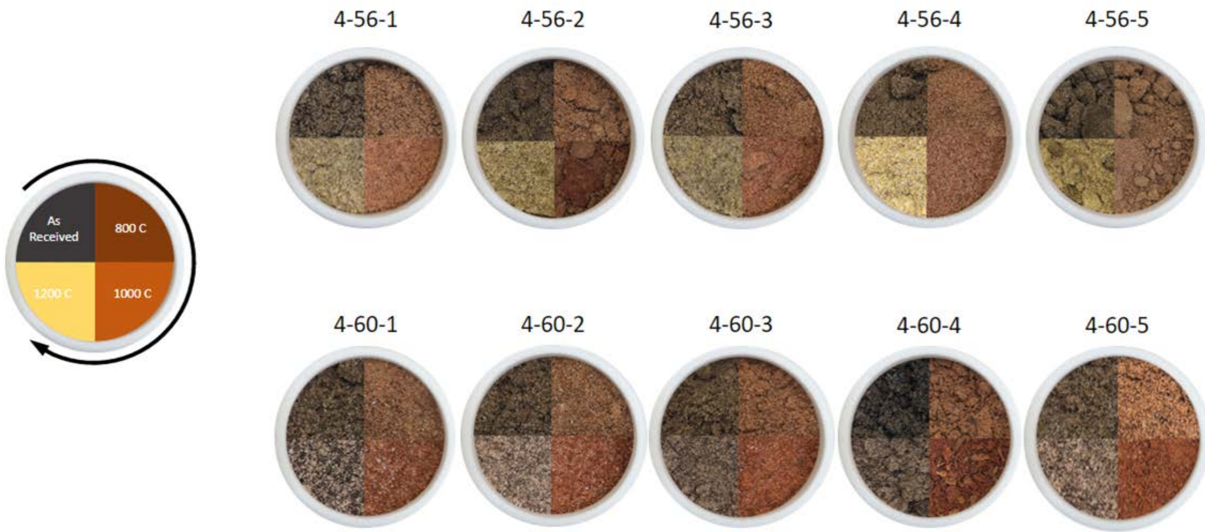


Figure 7. Color changes of as-received dredging materials and heating to temperatures of 800°C, 1,000°C, and 1,200°C, respectfully.

Upon removal from the furnace, materials were also tested quantitatively for agglomeration behavior. At 800 °C, materials experienced essentially no agglomeration and were free flowing. At 1000 °C, materials were free flowing, but showed some tendency for soft agglomeration which was easily broken with mechanical force, as shown in Figure 8. Materials subjected to the 1200 °C dwell experienced severe agglomeration. 4-60 materials subjected to 1200 °C were difficult to remove from the crucibles, while 4-56 materials subjected to 1200 °C were near-impossible to remove from the crucibles.

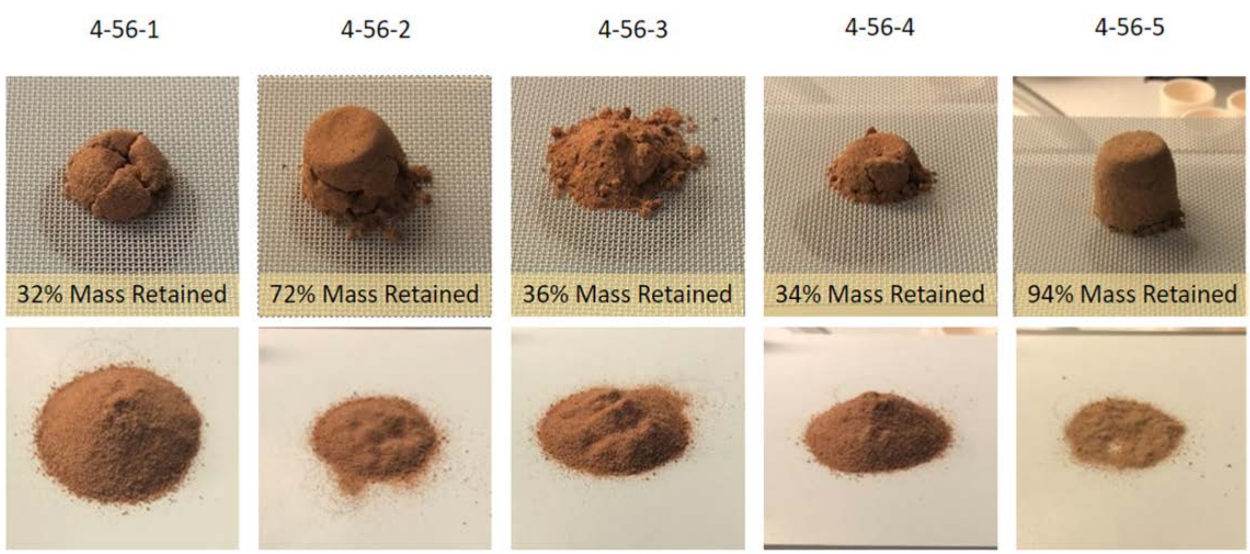
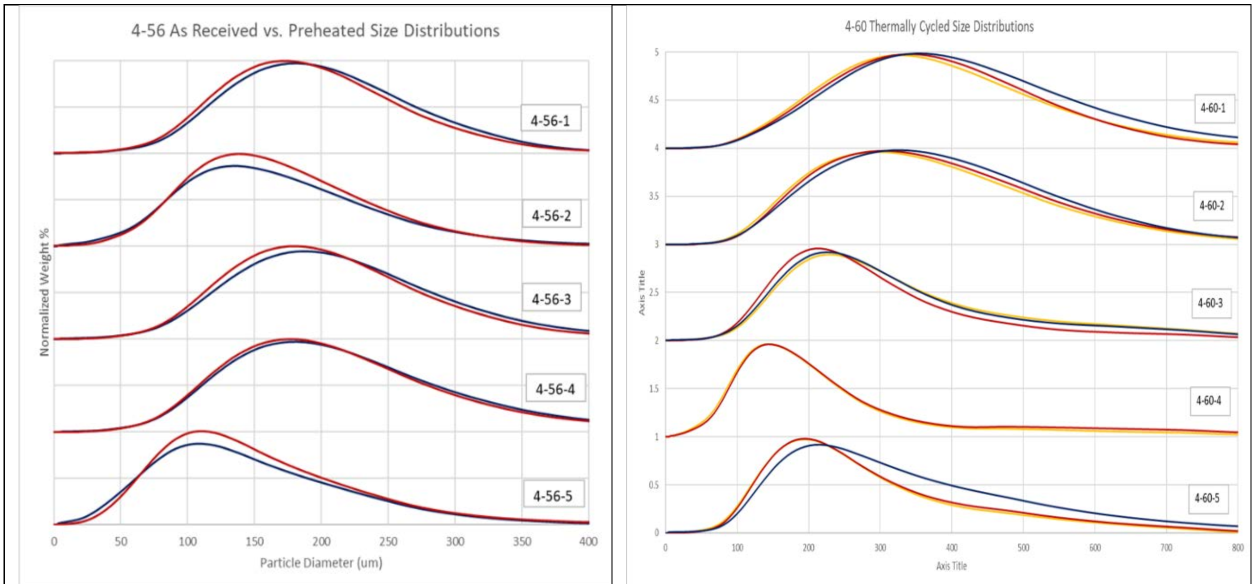


Figure 8. Particle clustering and agglomeration test of 4-56 materials after heating up to 1000 °C.

Agglomeration behavior observed suggests excellent flowability of NYPA materials up to 800 °C, and good flowability up to 1000 °C. Above 1000 °C, more severe agglomeration forms likely due to minor phases within the particle mixture, whose components have a lower melting point than main phase quartz. When these minor phases melt, upon cooling, they may adhere to neighboring quartz grains, resulting in agglomerates.

Following thermal cycling, materials were again tested for particle size distributions. Figure 9 shows the comparison of particle size distributions for materials before and after heating. The sand size distribution change is negligible for 4-56 materials, while 4-60 materials slow a very slight trend toward smaller particle sizes after heating. Both results suggest excellent stability of particles, even after several heating cycles.

The size stability favors processed sand to be used for construction after thermal energy storage uses.



a) 4-56	b) 4-60

Figure 9. As-received/preheated particle size distribution (µm).

b. *Material characterization: properties (density, specific heat, etc.), and contamination as applicable*

Material property characterization included investigation of density, specific heat, and crystalline composition by XRD. To start, materials were investigated for both bulk density and true (skeletal) density. Bulk density was measured using a graduated cylinder and mass balance, while true density was measured with a gas pycnometer. Figure 10 shows as-received and preheated particle densities in bulk and real weights. The particle bulk density of 1,375 kg/m^3 is typical sand pile density and used to determine the storage volume. Real density of 2,605 kg/m^3 reflects that the major composition is silica sand. Comparison of as-received versus preheated densities shows little change through heating processes and indicates that material composition is thermally stable.

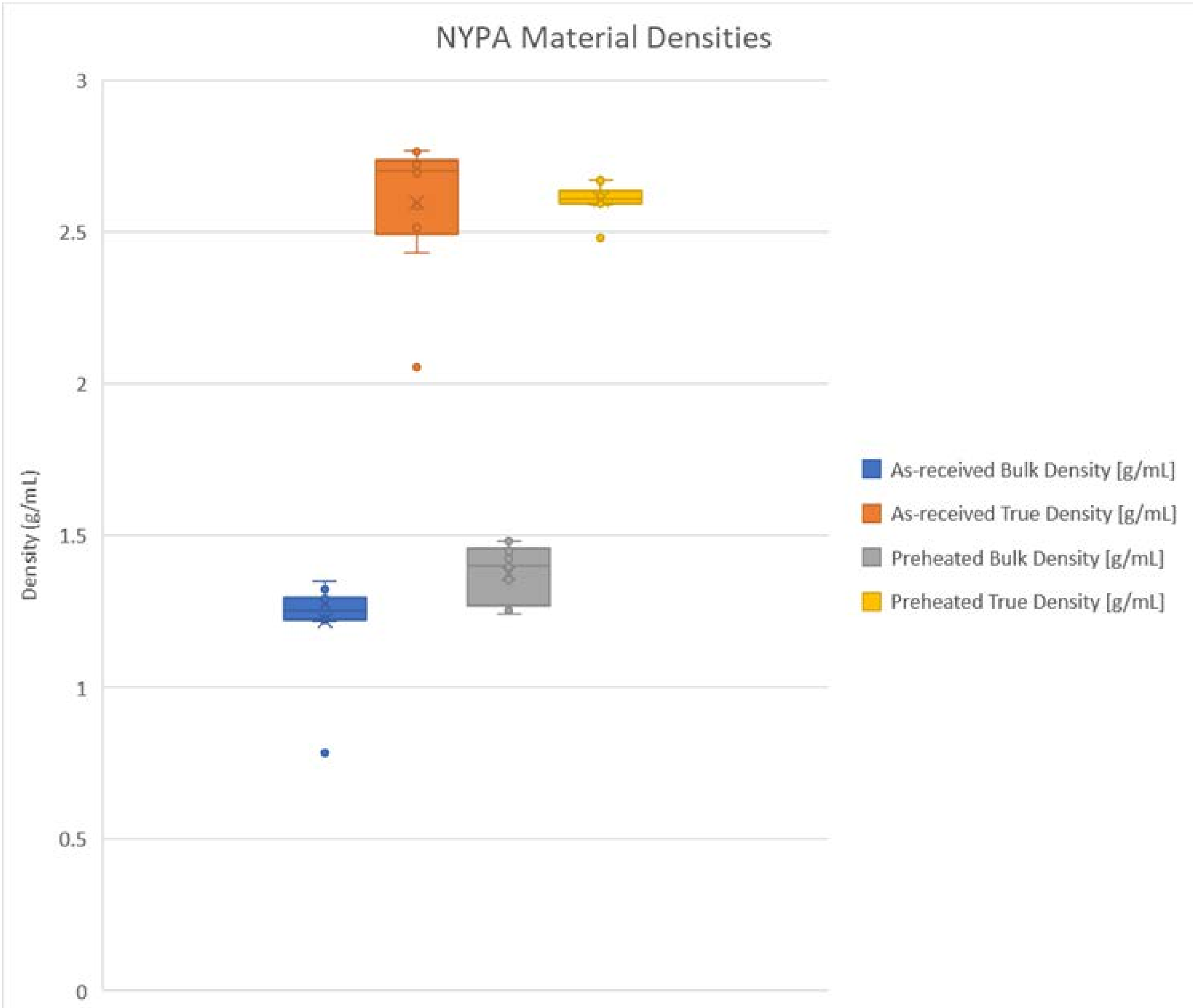


Figure 10. Average bulk density: 1.375 g/mL (1,375 kg/m3). Average true density: 2.605 g/mL (2,605 kg/m3). Little change caused by preheating, Indication of good thermal stability.

Figure 11 shows Differential Scanning Calorimetry (DSC) measurements and Specific Heat calculation.

The heating curve indicates clear alpha to beta phase quartz transition at 573 °C. The curve deviates below ideal quartz behavior but is consistent with a majority quartz composition. Curve deviation at low end temperature could be due to instrument reaching equilibrium and removing moisture at the beginning of the test, while the wavy curve shape at high temperature could be due to radiative heat loss. Calculation of average specific heat, C_p from 150 °C to 700 °C, is 0.85 J/g-K.

The Netzsch DSC instrument was also used to investigate heat flow in or out of the sample during preheating, as in TGA. Endotherms and exotherms observed during heating could indicate phase transition phenomena or decomposition reactions observed in TGA and calculate enthalpy required to drive these reactions.

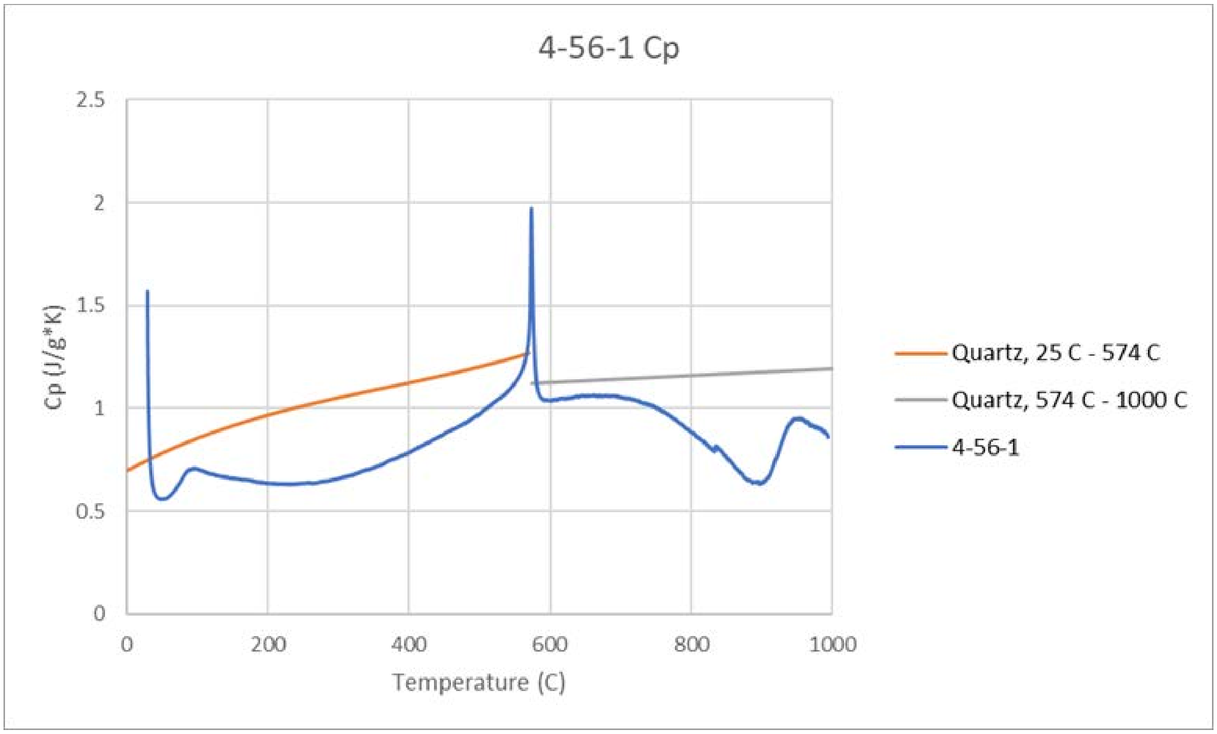


Figure 11. Differential Scanning Calorimetry and Specific Heat Calculation

Figure 12 shows a calibrated DSC signal (mW/mg) with respect to temperature, the integral of which gives area under the curve. This value is equal to total heat flow into or out of the sample during heating (enthalpy). 4-56-1 measured enthalpy was 258.58 kJ/kg. In other words, it took 258.58 kJ to preheat 1 kg of material. This energy goes toward removing moisture and organics and decomposing hydrated minerals.

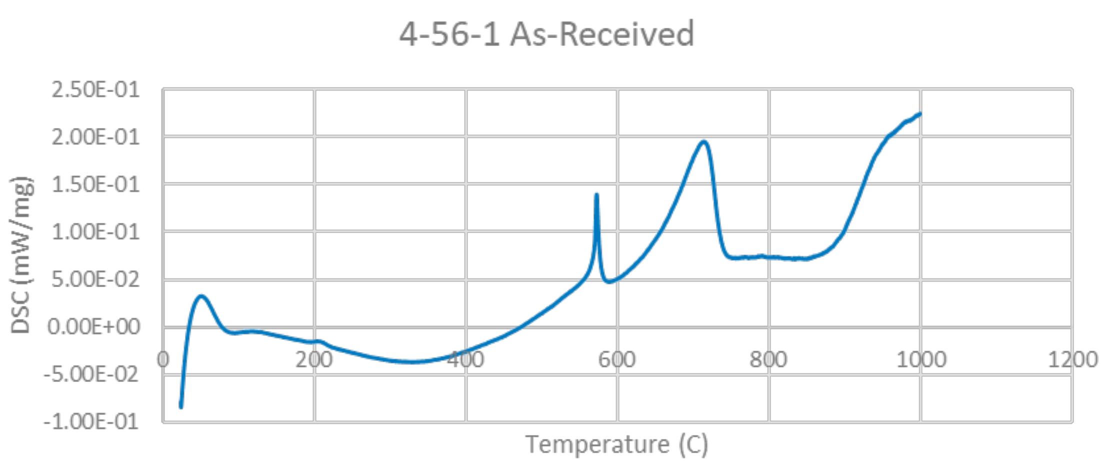


Figure 12. DSC Measurement for Enthalpy of Preheating

The value calculated for average specific heat suggests a majority quartz composition and a material suitable for thermal energy storage with a high potential for sensible heat acquisition.

Powder X-ray diffraction was performed on samples before and after thermal cycling to confirm material compositions and identify minor phases, as well as observe crystalline material stability. Figure 13 shows a comparison of each preheated material in a powder diffraction spectrum from 20 – 70 2-theta. The observed spectrum was analyzed using MDI JADE, and all materials were found to have a major crystalline quartz phase. Minor phases could not be identified with confidence due to the strong quartz signal.

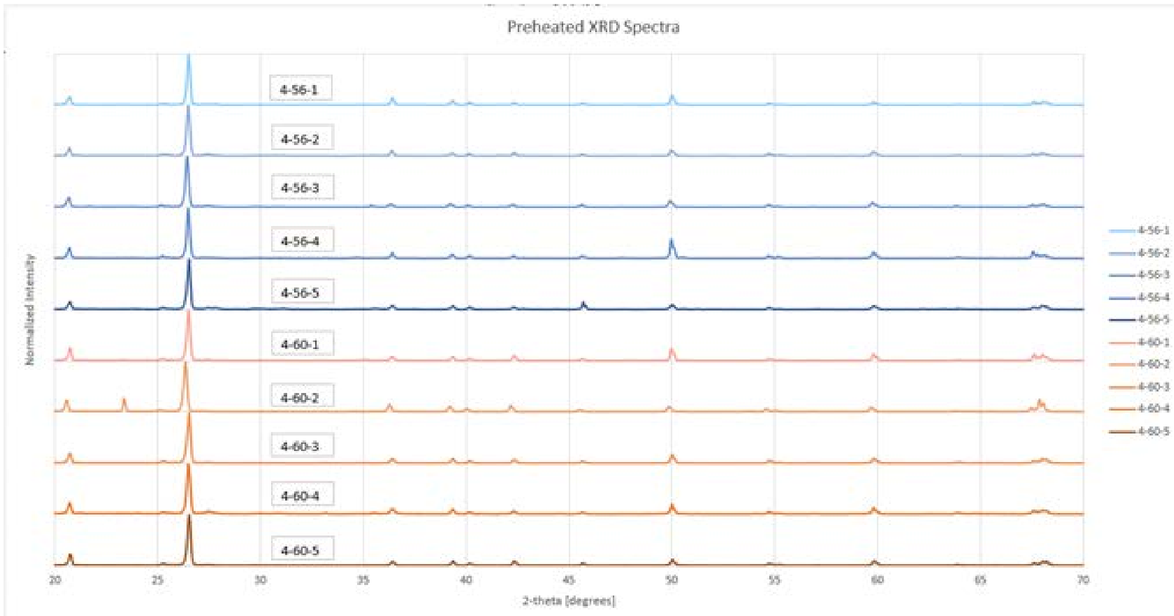


Figure 13. X-Ray Diffractometry of the material phase diagram

Future XRD should use ball-milling and careful preparation to help bring about stronger signal from minor and trace phases. Such analysis may also confirm the presence of iron minerals, which would explain the red color change up to 1000 °C. For all materials, quartz signal remained strong after thermal cycling, suggesting a thermally stable quartz phase at all temperatures. Such a material is suitable for thermal energy storage at high temperatures.

1.5. NREL provides raw data and summary of results, including suitability for use in energy storage as well as other applications such as construction or manufacturing.

NREL has stored raw data in a OneDrive folder that is shared with NYPA for free access. The shared data folder includes all dredged material characterization study. This includes data for TGA, Size Distribution Analysis, DSC, Powder XRD, SEM/EDS, Density, and mass loss on ignition. In addition, images of tests and resulting color changes of samples are provided for qualitative support of conclusions.

The materials provided by NYPA for the dredged material characterization study show potential for use in particle thermal energy storage up to 1000 °C. Among the suitable characteristics of these materials are a free-flowing nature upon drying and removal of organics, thermal stability, and high specific heat capacity similar to quartz.

Summary Conclusion of Task 1

NREL has accomplished all activities that were planned under Task 1. Major technical summaries are:

- Particles of dredging materials are irregularly shaped with 100-700 µm size distribution. Particles have free flowing, fine sand-like behavior that can be used as construction sand or storage media.
- Particles exhibit mass loss on order of 15% b/w RT and 1000 °C.
- Oxides not formed on heating up to 1000 °C.
- Limited soft agglomeration occurs up to 1000 °C. Severe agglomeration occurs between 1000 °C and 1200 °C. Increased soft agglomeration for finer particle sizes after heating above 1000 °C.
- Excellent thermal stability shown after preheating up to 1000 °C.
- Material characterization: properties (density, specific heat, etc.), and contamination as applicable:
    - Bulk Density: 1.22g/ml
    - True Density: 2.60g/ml
    - Average Specific Heat from 0 - 1000°C: 0.85 kJ/kg-K
- X-Ray Powder Diffraction (XRD) analysis on material compositions before and after heating test to identify energy storage lifecycle, and processes of converting dredged materials to potentially useful commodities:
    - Quartz phase dominant, stable through all thermal cycles.
    - Minor phases difficult to identify through XRD.
    - Likely large amount of minor amorphous phases.
    - In-depth study may help understand minor and trace phases present in samples.

In conclusion, dredging materials can be used for construction sand or thermal storage below 1000 °C that drives a steam power cycle or heat supply. Task 1 facilitates further work on alternative disposal of dredging materials better than upland disposal sites (UDS).

Task 2: Preliminary cost benefit analysis

Here, we present the development of preliminary techno-economic analysis to assess the feasibility and cost benefits of using dredged material as media for particle thermal energy storage (TES) systems. Since limited resources were available for the benefit analysis, many assumptions were employed and studies are preliminary by focusing on establishing an analysis framework for NYPA to further evaluate the economic and environmental benefits with NYPA-verified parameter inputs and development scenarios.

During low electric tariff periods, grid electricity can be used to run the electric particle heater and charge TES. The heated particles will be stored in the TES and used later to heat steam in a heat exchanger that can be utilized either for industrial process heat, power generation, or both heat and power in cogeneration. Here, we investigated the feasibility of using this steam to run a simple Rankine cycle for electricity generation with an assumed power cycle efficiency of 40% during high tariff periods which is then sold to the grid. Such a strategy would maximize the benefits from energy storage and processing dredge material where we present economic and environmental comparison to other alternative applications for this dredge material.

2.1. Techno-economic Analysis (TEA) Method

NYPA estimates the annual dredged material from the canal to be around 280,000 cubic yards (~214,000 m^3). Removing this material is expensive, needs disposal sites, and has adverse environmental effects. Hence, NYPA is interested in investigating the techno-economic and environmental benefits from utilizing this dredged material as a TES media and compare that to benefits gained if used for other applications.

Here we present a techno-economic and environmental assessment of the use of dredged material as TES media and benchmark it against two scenarios:

- Disposal of dredged material to landfills.
- Use dredged material in concrete mixing.

As aforementioned, the material sent by NYPA was tested to evaluate their properties. Here, we use the following properties in the TEA model:

- Dry Dredged Material Bulk Density of 1,259 kg/m^3
- Wet Dredged Material Bulk Density of 1,375 kg/m^3
- Dry to Wet Sediment Mass Ratio of 0.87
- Specific Heat of 850 J/kg K

Additionally, we assume the maximum material temperature in the TES were assumed to be 750ºC to prevent material agglomeration as discussed previously whereas the cold material temperature was assumed to be around 200 ºC with the ability to recover 50% of the waste heat and sell it for district heating.

The economic parameters related to the TES system and the power cycle were adopted from the work previously presented in the TCF project which are summarized in Table 3. Moreover, it is assumed that the system will have a lifespan of 30 years. Furthermore, we assume that the particle heater has an efficiency of 97% and the TES has a daily efficiency of 99%.

Table 3. TES economic parameters adopted in this study.

Parameter	Value	Unit
Discount Rate	10	%
Annual O&M	5	%
TES Capital Cost without Media	4.69	$\$/kWh_{th}$
Power Cycle Cost	500	$\$/kW_e$
Heater Cost	21.82	$\$/kW_{th}$
Skip Hoist	8.17	$\$/kW_{th}$
Steam Boiler	300	$\$/kW_e$

As afore discussed, the TES will be charged during low tariff periods, 0.01 \$/kWh is used as the charging threshold in this analysis, where the hourly grid tariff near the location of the dredging site is obtained from the NY ISO utility website for the year of 2022. Figure 14 shows the relative frequency of different tariffs throughout the year. Additionally, it is assumed to have a power purchase agreement (PPA) with the local power authority to sell the back the electricity at a fixed rate (GT_{PPA}) of 0.04 \$/kWh, whereas waste heat will be sold for district heating at constant rate of 0.01 $\$/kWh_{th}$.

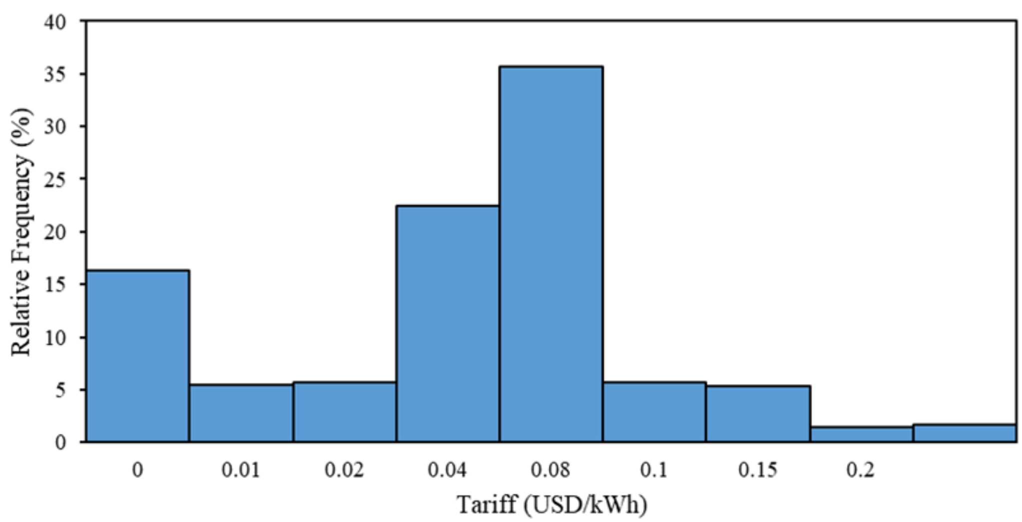


Figure 14. Relative frequency of utility tariffs in 2022 obtained from NY ISO.

2.2. Economic Assessment of the System

Here, we employ several economic indicators to assess the economic feasibility of the proposed system, which is summarized below:

- Levelized Cost of Electricity (LCOE),

$$LCOE = \frac{C_{tot} + \sum_{y=1}^{LS} \frac{O\&M}{(1+d)^y}}{\sum_{y=1}^{LS} \frac{\sum_{h=1}^{8760} E_{TES}^h \times \eta_{rank}}{(1+d)^y}}$$

where C_{tot} is the total capital cost, LS is the system's lifespan, $O\&M$ is a total operation and maintenance cost, d is the annual discount rate, E_{TES}^h is thermal energy stored in the TES at hour h , and η_{rank} is the Rankine power cycle efficiency. Other economic terms are defined as:

- Simple Payback Period (PBP),

$$PBP = \frac{C_{tot}}{P_{ann}}$$

with

$$P_{ann} = \left(\sum_{h=1}^{8760} E_{TES}^h \times \eta_{rank} \right) \times GT_{PPA} - Exp + M_{selica}$$

where P_{ann} is the annual profit, Exp is the total expenses including cost of electricity purchased form the grid, cost of material dredging and processing and $O\&M$ cost. Whereas M_{selica} refers to the annual revenues from selling the silica after using it in the TES.

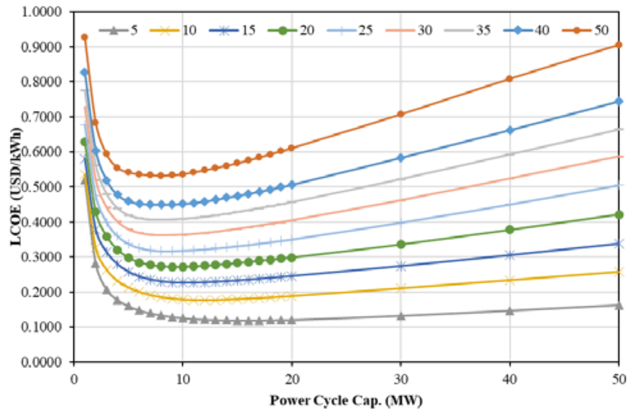
- Net Present Value (NPV),

$$NPV = \sum_{y=1}^{LS} \frac{P_{ann}}{(1+d)^y} - C_{tot}$$

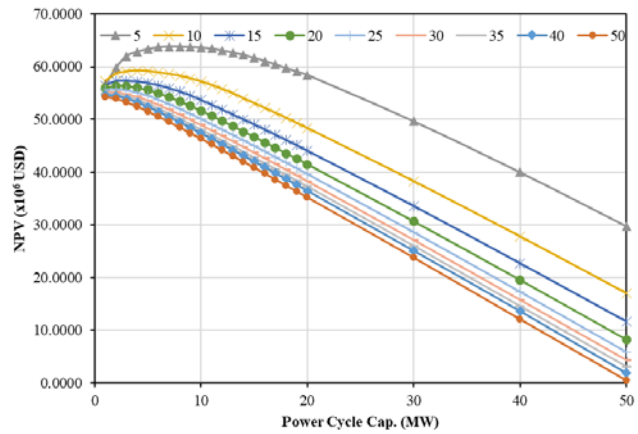
2.3. Preliminary Benefits Assessment

The results show that the disposal of the dredged material costs almost $25,474,925 yearly which results in a negative NPV of $-240,149,939 over 30 years. These numbers emphasis the need to utilize the dredged material to reduce the economic burdens caused by the disposal of these materials. For instance, the literature proposes the use of such material in the concrete industry; such application will generate an annual cash flow of $5,968,652 which results in a NPV of $56,265,974 over 30 years.

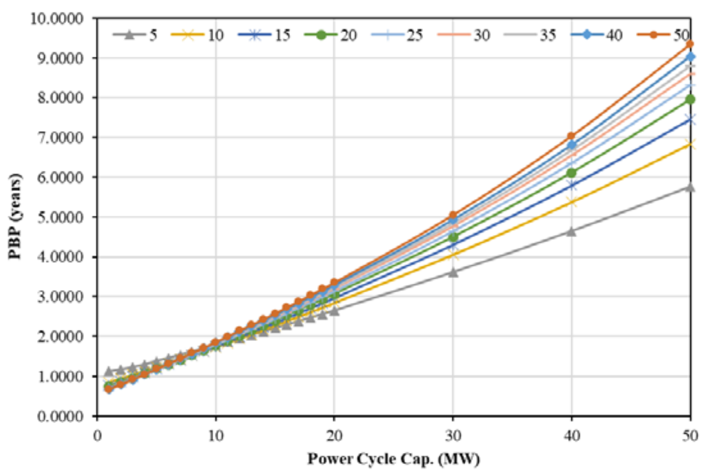
On the other hand, we proposed the use of this material as media for solid particle TES where the TES will be used to harvest low-cost electricity and sell it back at high tariff periods. First, we investigate the effect of the power cycle capacity and the TES storage duration on the economics of the system, as shown in Figure 15.



(a)



(b)



(c)

Figure 15. The effect of the variation of the power cycle capacity and the TES storage duration on the: (a) Levelized cost of electricity, (b) Net present values, and (c) Payback period.

After obtaining TES capacity and operation, we used Excel Solver to find the optimum power cycle capacity and the TES storage duration that maximizes the NPV. The analysis shows high potential for the utilization of dredged material in TES where Excel solver finds that 12.98 MW power cycle capacity and 4.84 hours of duration are optimum capacities as shown in Table 4. The simulated case includes ~$9 million annual profit gained from the use of this material in concrete production. Some key economic outcomes are listed in Table 4. Results show that using dredging materials for thermal storage could be economically attractive considering the short PBP and larger positive NPV if the assumed capital cost and development expenses are in the range.

Table 4. Evaluation of the potential economic benefits gained from the use of dredged material as TES media.

Parameter	Value	Unit
Annual Electricity Income	1,403,364.43	$
Annual after use material Revenues	8,963,052.66	$
Annual Waste Heat Income	461,633.04	$
Annual Combined Profit from Material, Electricity and Heat	8,526,261.00	$
Net present values, and (NPV)	63,025,157.52	$
Payback period (PBP)	2.04	Years

Note that the current TES capital cost only consists of key storage components with bare erected cost. Site, engineering, procurement, construction, and system integration will add substantial investment cost and are not in the scope of current benefit study. Thus, PBP can be significantly longer than this basic estimation. It should be noted that these benefits estimation are preliminary due to the uncertainties that lie within the assumptions used in the model, which can be summarized as shown in Table 5.

Table 5. Source of uncertainties in the TEA model.

Source	Explanation
TES Capital Cost	Costs were adopted from ENDURING project which does not account for the recent price inflation
O&M Cost	Assumed to be 5% of the total capital cost, literature suggest that O&M could reach 10% of the total capital cost
Grid Tariff	Adopted from NY ISO for the region near the canal

Task 3: Initial carbon footprint and environmental analysis

The disposal of the dredged material is not only costly but also has several environmental concerns such as the CO_2 emissions produced during the fermentation of this material in landfills, which was approximated to be 0.05-ton CO_2 per ton of wet sediments (Kox, Klimkowska, Kauffman, Tonneijck, & Jansen, n.d.). Hence direct use of this material in concrete blending may help mitigate emissions, where the organic materials are locked in concrete from emitting to the environment.

Additionally, the use of this dredged material in the concrete industry as an alternative for recycled concrete reduces the CO_2 emissions associated with cement recycling which is an energy intensive process. The following assumptions have been made in this comparison with regarding to retain sand from recycling concrete:

- Electricity consumption rate required for cement grinding of 100 kWh/ton concrete
- Carbon footprint of electricity of 0.857 kg CO_2/kWh

We picked a case for sand production by recycling concrete by grinding the concrete into sand and blending into concrete. Table 6 shows the environmental impact of dredged material utilization in concrete/ TES compared with the assumed case of recycling concrete to produce sand. CO2 emission is estimated by total electricity required for concrete recycling. The power used to recycle concrete can generate significant amounts of CO_2 that can be reduced substantially by using dredging materials to construction sand. This comparison would be changed if the sand is produced from other sources that have different energy usage and transportation needs, which are more specific cases beyond the capacity of this study.

Table 6. Carbon benefits of comparing dredged materials with recycling concrete.

Quantity	Value	Unit
Total CO_2 emissions avoided from material fermentation	283	ton
Total electricity required for concrete recycling	25,608,722	kWh
Total CO_2 emissions avoided by the use of dredged material in concrete	21954	ton

All the above analysis on Tasks 2 and 3 were performed in an Excel analysis tool that may be useful for further scenario studies. Information on the Excel tool is introduced below for potential uses of this tool.

Introduction to TEA Excel Tool

The outputs of the TEA model highly depend on the input parameters and hence the input parameters should be reviewed carefully in order to generate correspondent results. For instance, the grid tariff profile in column B as shown in Figure 16 is one of the critical inputs.

A	B	C	D	E	F	G	H	I	J	K	L
Time Stamp	Tariff	Stored Energy in TES	TES losses	Available in TES	Stored in TES after selling to grid	Bought from grid	Cost	Sold to Grid	Electricity Revenues	Waste Heat Recovery	Waste Heat Revenues
(MM/DD/YY hh:mm)	(USD/kWh)	(kWh_{th})	(kWh_{th})	(kWh_{th})	(kWh_{th})	(kWh)	(USD)	(kWh)	(USD)	(kWh_{th})	(USD)
1/1/2022 0:05	0.02922	0	0	0	0	0.00	0	0.00	0.00	0.00	0.00
1/1/2022 0:10	0.02931	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:15	0.02905	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:20	0.0282	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:25	0.02797	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:30	0.02618	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:35	0.02483	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:40	0.02478	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:45	0.02478	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:50	0.02463	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 0:55	0.02051	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 1:00	0.0108	0	0	0	0	0	0	0.00	0.00	0.00	0.00
1/1/2022 1:05	-0.00809	11018.52109	9.182100911	11009.33899	11009.33899	11349.83401	-91.82015716	0.00	0.00	0.00	0.00
1/1/2022 1:10	0.00054	22027.86009	18.35655007	22009.50354	22009.50354	11340.37582	6.123802942	0.00	0.00	0.00	0.00
1/1/2022 1:15	0.00054	33028.02463	27.52335386	33000.50128	33000.50128	11330.9255	6.118699773	0.00	0.00	0.00	0.00
1/1/2022 1:20	0.0006	44019.02237	36.68251864	43982.33985	43982.33985	11321.48307	6.79288984	0.00	0.00	0.00	0.00
1/1/2022 1:25	0.0006	55000.86094	45.83405079	54955.02689	54955.02689	11312.0485	6.787229098	0.00	0.00	0.00	0.00
1/1/2022 1:30	0.01099	54955.02689	45.79585574	54909.23104	54909.23104	0	0	0.00	0.00	0.00	0.00

Figure 16. Snapshot of the TEA tool showing the utility tariff profile column and other columns used to model the energy dispatch strategy.

Additionally, the threshold at which the system should charge and discharge the TES, cells marked in yellow in Figure 17, should be carefully reviewed and maybe optimized to maximize the economic profits. Additionally, the selling price of the electricity of the grid (PPA tariff) should be revised to reflect real values, which could be obtained from market prices between electricity supply and demand.

Technical Input Paramters	
TES Eff (% stored energy per hour)	0.99
Heater Eff	0.97
T_h (°C)	750
T_c (°C)	200
TES Stored at t=0	0.00
PPA Tariff	0.04
Charging Tariff Limit	0.01
Discharging Limit	0.02
Waste Heat Selling Price (USD/kWh_{th})	0.010
Lifespan	30
Power Cycle Eff	0.4
Generator Eff.	0.95
Efficiency of Heat Recovery Process	0.5

Figure 17. Snapshot of the main technical input in the TEA model.

Additional costs need to be revised such as the dredging and processing cost showing in Figure 18. After updating these parameters, the best power cycle capacity and the TES storage duration that maximizes the NPV can be found using Excel Solver as shown in Figure 19 or manually inputted in the designated cells shown in Figure 20. After inputting proper parameters, the model will generate economic and environmental results for the material disposal, material use in cement and material use in TES as shown in Figure 21.

Material Dredging Assumptions	
Total Annual Dredged Material (m^3)	214075
Frequency of TES media change (days)	7
Number of Media Replacements	52
Annual Wet Sediments Volume (m^3)	4117
Annual Wet Sediments Mass (ton)	5661
Silca sand selling cost (USD/ton_{dry})	35
Processing Cost (USD/m^3_{dry})	7.2
Dredging Cost (USD/m^3_{dry})	10

Figure 18. Snapshot of material dredging assumptions.

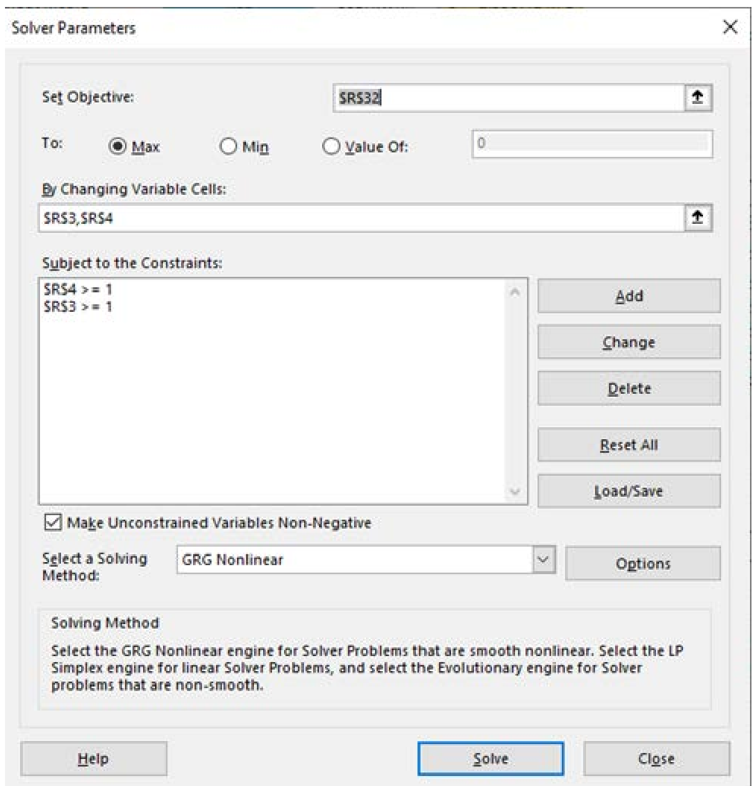


Figure 19. Snapshot of Excel solver with the objective, constraints and variables defied.

Optimized Input Paramters	
Storage Duration (hours)	4.84
Rated Cap. Of Power Cycle (MW)	12.98

Figure 20. Snapshot of the cells where the storage duration and the power cycle capacity can be entered manually if the solver is not used.

TES Economic Parameters	
Capital recovery factor (CRF)	9.427
LCOE (USD/kWh$_e$)	0.1181
LCOS (USD/kWh$_{th}$)	0.0403
LCOH (USD/kWh$_{th}$)	0.0384

TES Economic Benefits	
Annual Electricity Income (USD)	$ 1,403,364.43
Annual after use material Revenues (USD)	$ 8,963,052.66
Annual Waste Heat Income	$ 461,633.04
Annual Combined Profit from Material, Electricity and Heat (USD)	$ 8,526,261.00
NPV (USD)	$ 63,025,157.52
PBP (years)	2.04

Concrete Economic Benefits		
Total profit if used for concrete production (USD/m^3)	35	(Y
Total Annual Profit (USD)	$ 5,968,652.32	
NPV (USD)	$ 56,265,974.91	

Cost of Directly Disposing Dredging Material to Sites		
Sediment Disposal Cost (USD/m^3)	119	(Y
Annual Disposal cost (USD)	$ 25,474,925.00	
NPV (USD)	$ (240,149,939.03)	

	Enviromental Impact (Based on Electricity needed for Recycle Concrete Grinding)		
	Electrcity consumption rate required for grinding (kWh/ton concrete)	100	ht
Annual	Average kg CO2 produced per kWh	0.85728888	ht
	Total Electrcity Required (kWh)	25,608,722	
	Total CO2 emissions (ton)	21954	

	Enviromental Impact (from material fermentation)	
Annual	CO2 produced from material fermentation (ton CO2 per ton of wet sediments)	0.05
	Total CO2 emissions (ton)	283

Figure 21. Snapshot of the economic and environmental benefits of the dredged material.

Summary Conclusion of Tasks 2 and 3

NREL has completed Tasks 2 and 3 with the following outcomes:

- Developed evaluation tools with assumptions of operating conditions
- Both energy storage and material processing benefits were analyzed.
- Benefits are obvious with various investment levels:
    - Economic returns including electricity storage for arbitrage to generate energy storage revenues.
    - Dredging material can be sold as construction sand, upgraded sand after thermal storage uses, or refined silica sand if further purification processes were applied.
    - Use for construction sand could have environmental benefits due to less CO_2 emissions from organic decomposition.

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Final Task. CRADA Final Report

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X.

Subject Inventions Listing:

None.

ROI #:

None.