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Repurposing Fossil-Fueled Assets for Energy Storage

Final Report

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List of Abbreviations:

- Bureau Of Economic Analysis: BEA
- Capital Expenditure: CAPEX
- Coal-Fired Electricity Generation Units: CF-EGU
- Coefficient Of Performance: COP
- Combined Heat and Power: CHP
- Concentrating Solar Power: CSP
- Direct Current: DC
- Duke Energy Progress: DEP
- Energy Intelligent Partners: EIP
- Fossil Energy: FE
- Heat and Mass Balance: HMB
- Heat Exchanger: HX
- Heat Rejection Heat Exchanger: HRHX
- Integrated Systems and Operations Planning: ISOP
- Interagency Working Group: IWG
- Jobs And Economic Development Impact: JEDI
- Long Duration Energy Storage: LDES
- Molten Salt Steam Generator: MSSG
- Motor Control Centers: MCC

- National Renewable Energy Laboratory: NREL
- Pumped Heat Energy Storage: PHES
- Pumped Storage Hydropower: PSH
- Operational Expenditure: OPEX
- Operations and Maintenance: O&M
- Overall System Efficiency: OSE
- Present Value Revenue Requirement: PVRR
- Process Flow Diagrams: PFD
- Regional Input-Output Modeling System: RIMS
- Round-Trip Efficiency: RTE
- Single Line Diagram: SLD
- Technology Readiness Level: TRL
- Thermal Power Library: TPL
- Technology Maturation Plan: TMP
- Uninterruptible Power System: UPS
- Variable Renewable Energy: VRE
- Voltage Source Inverter: VSI

1. Executive Summary

The annual retirement of U.S. coal-fired electricity generation units (CF-EGU) is at an all-time high and is expected to continue[1]. This loss of reliable baseload generation, combined with predicted growth of variable renewable energy (VRE) generation, is expected to stress grid reliability as the number of load-following resources drops below the experienced load variability. Many regions are already experiencing challenges, and fossil retirement-related warnings by the North American Electric Reliability Corp. are becoming more dire[2]. All CF-EGU retirements pose significant challenges to asset owners, local workforces, and their communities. Repurposing a retiring CF-EGU as a long-duration energy storage plant can address these challenges and offer a suite of additional benefits to asset owners, the grid, and society.

This project performed a techno-economic evaluation and assessment of repurposing a Duke Energy fossil-fueled asset (in particular, a coal plant) into an energy storage system by integrating the retiring asset with a Malta long duration Pumped Heat Energy Storage (PHES) system. The project validated the technoeconomic benefits of repurposing retiring coal plants into long-duration energy storage using Malta's PHES. Key findings for this project are summarized in the table below.

Table 1: Key Findings

Technical	• Retiring coal plants (and other steam turbine fossil generation) can be repurposed to enable the clean energy transition using Malta's technology. • For older retiring coal plants, repurposing the site and electrical interconnection for a standalone PHES plant is the most economically favorable option. • For newer coal plants where there is also a local peaking capacity need, repowering the steam cycle into a hybrid integration with PHES is attractive. • A process was developed to assist fossil generation owners in choosing the best path for each plant's circumstances.
Economic	• Communities facing economic challenges caused by the retirement of fossil generation would benefit from repurposing the plant as long-duration energy storage using Malta's PHES. • On a $/MW basis, repowering retiring coal units into Malta PHES plants can maintain the same number and types of jobs and economic activity. • For a 70% carbon reduction scenario, a 10-hour Malta PHES plant is more economic for the asset owner than similar-power 4-hour batteries.

Malta PHES is a long duration energy storage (LDES) system based on the thermodynamic principles of a closed-loop air Brayton cycle heat engine in discharge mode and a reversed closed-loop air Brayton cycle heat pump in charge mode. The Malta PHES stores its thermal energy in molten nitrate "solar salt" at the standard 565°C. Malta PHES utilizes compressors, turbines, and other power equipment like that currently in thermal generation power plants and familiar to fossil-economy workforces and asset owners.

[1] Sweeney, D., Kuykendall, T. and Duquiatan, A. 2022 February 10. More than 23 GW of coal capacity to retire in 2028 as plant closures accelerate. S&P Global Market Intelligence. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/more-than-23-gw-of-coal-capacity-to-retire-in-2028-as-plant-closures-accelerate-68709205

[2] Malik, N. and Baker, D. 2022 May 19. Vast Swath of US at Risk of Summer Blackouts, Regulator Warns. Claims Journal. https://www.claimsjournal.com/news/national/2022/05/19/310552.htm

The project work was done following a systematic approach and was divided into two phases. Phase 1 focused on the selection of a host site, determination of the integration options to explore, and evaluation and down-selection of the most optimal integration option (for the chosen site) to advance in the next phase. Phase 2 focused on the preliminary conceptual design of the down-selected integration option and on the evaluation of the economic benefits to Duke Energy and to the local community. Translatable insights from this project to other fossil-fueled assets were identified as well.

Phase 1 started with collection of stakeholders' needs and wants, which were then translated into requirements and criteria for host site and integration option down-selection. Multiple sites with retiring coal plants were evaluated and compared based on their rated power, tentative retirement dates, availability of land, and Duke Energy's preferences. Of the multiple sites evaluated, Cliffside and Mayo were the two final candidate sites. When comparing the two sites using importance scoring, the two sites' scores were close, with the Cliffside site being chosen as the host site for the first phase of the study. The project team had easier access to the technical data for the Cliffside Unit 5 coal plant, which was important for the first phase of the study, including integration option concept generation and down selection. Because of their similarity, the technical assessment for Cliffside 5, especially with respect to site-specific conditions, is translatable and applicable to Mayo.

A total of four different integration concepts were created and compared in terms of technical feasibility, capability, and economics. All four options use solar molten salt as energy storage but have different mechanisms for charge and/or discharge. These four integration options are as follow:

- Option 0: Resistance heating - Traditional resistance heaters are used to heat up molten salt (charging) and the coal plant's steam Rankine cycle is reused for discharge. A molten salt steam generator (MSSG) is used to create steam from the hot salt. This option served as baseline as it has been previously proposed in Europe [1] and sometimes called Store2Power.
- Option 1: Electrical Integration of a Standalone Malta system – Malta heat pump is used to charge; Malta heat engine is used for discharge. Grid interconnection of Cliffside 5 is repurposed.
- Option 2: Thermal Integration – Malta heat pump is used to charge; Cliffside Unit 5's steam Rankine cycle is used for discharge. A molten salt steam generator (MSSG) is used to create steam from hot molten salt.
- Option 3: Hybrid Integration – Malta heat pump is used to charge; Cliffside Unit 5's steam Rankine cycle and Malta heat engine can both be used for discharge. A molten salt steam generator (MSSG) is used to create steam from hot molten salt.

The four options were compared based on their estimated site-specific CAPEX, OPEX, and benefits to the grid. The benefits to the grid were done based on a dispatching use-case like that of a pumped hydro storage facility in the Duke Energy portfolio. For the repurpose of Cliffside Unit 5, Integration Option 1 was found to be the most optimal. Contributing factors were the age of the Cliffside Unit 5, the cost to keep Unit 5 in service for another 30 years and retrofit for salt, and the lack of need for low-utilization capacity assets in the area.

It should be noted that Option 3 would be more appropriate for other coal plants where the following conditions exist: there is a strong need to maintain the rated capacity of the coal unit; the overhaul cost of the Steam-Rankine Cycle is relatively low; and there is a need for daily load shifting. Option 3 provides the flexibility to use the Malta Heat Pump and Heat Engine to get the best efficiency for daily load shifting while also allowing the option to occasionally use coal's plant steam cycle to get the highest power output.

Phase 2 of the study focused on the preliminary conceptual design and economic benefits of Integration Option 1. The work included creation of more detailed Process Flow Diagrams (PFDs), further evaluation of any potential reuse of Cliffside 5 equipment, and transient simulations of main system operability (charge, discharge, and trips). It was found that the grid-interconnection of Cliffside Unit 5 can be reused for the Malta PHES system and would save around $20MM in cost (compared to a greenfield application that requires a new substation). However, it is not worthwhile to try to reuse Cliffside Unit 5 existing generator, main step-up transformer, or the Cliffside 5 cooling tower given the age of the equipment. The cost of refurbishing these components was determined to be about the same as that of new equipment for the Malta option, while the complexity and risk increase with trying to re-use much older equipment. Industry-standard transient simulations confirmed the basic operability of the overall system. Future work on the design includes more refined control algorithms so that system operations can be fine-tuned and optimized. Unit and integration tests of the control system's algorithms would be critical in ensuring the system to work as expected.

Economic benefits were determined at the grid level and local community level. At the grid level, the Duke Energy Integrated Systems and Operations Planning (ISOP) modeling team analyzed the performance of the Malta system (Integration Option 1) in the Duke Energy Progress (DEP) region for a 70% CO_2 reduction by 2030 scenario. This scenario assumed a substantial buildout of solar and batteries to meet the 70% CO_2 reduction. The modeling team found that, the 10-hour 100 MW Malta system had a substantial savings compared to a 10-hour 100 MW battery system. The team also found that, for this resource mix, replacing 100 MW of shorter duration (4-hour) batteries for the longer duration (10-hour) 100 MW Malta PHES plant also resulted in compelling savings. The analysis considered both CAPEX and OPEX of all systems involved. These results validate the need for long-duration energy storage in a grid that requires low CO_2 emissions.

At the local community level, Energy Intelligent Partners (EIP) evaluated the economic benefit to the local community of repurposing the Mayo coal plant as a Malta PHES plant (Integration Option 1) rather than retiring the site when the coal unit retires. The local community would benefit from one-time construction activities of the Malta system and from on-going operation and maintenance of the system. A 100 MW, 10-hour Malta PHES at the Mayo site would bring about a one-time local economic benefit of ~$39MM from construction (more than 200 jobs) and an on-going yearly benefit of ~$3MM (for at least 30 years). Like any other standalone coal plant, once Mayo, a 727 MWe coal plant, retires, it will have large negative economic impact to the local region unless the plant is repurposed into something like the Malta PHES system. The analysis showed that on a $/MW basis, the Malta PHES system can maintain a similar number of jobs as the retiring coal units—and hence maintain positive local economic activity for the entire life of the system (30+ years).

In addition to the techno-economic analysis tasks, outreach activities were also done under this project. There was a lot of interest from other utilities who want to know more about how the work done here can be applied to their retiring coal plants. The project team spoke with these utilities and provided insights to what can be done with their coal plants based on their individual scenarios. Most importantly, the work done under this project has received attention from the highest level of government. Malta and Duke Energy were invited to the White House to participate in a roundtable discussion hosted by Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization (IWG). Malta's CEO presented to the IWG, the Director of the National Economic Council, the White House National Climate Advisor, and the Secretaries of Commerce and Energy on the progress of this study and how it could help with what the IWG is trying to carry out.

In summary, this project showed that repurposing a retiring coal unit into thermal energy storage, by integrating it with a Malta PHES system, makes techno-economic sense. At least two integration options are available, with the optimal solution depending on the coal plant and its location. Repurposing retiring coal plant into energy storage results in economic benefits for the plant owner and local communities.

2. Project Overview

2.1. Background and Objective

The annual retirement of U.S. CF-EGU is at an all-time high and expected to continue. This loss of reliable baseload generation, combined with predicted growth of variable renewable energy (VRE) generation, is expected to stress grid reliability; many regions are already experiencing challenges and retirement-related warnings from the North American Electric Reliability Corp. becoming more dire. All retirements pose significant challenges to asset owners, CF-EGU workforces, and their communities. Repurposing a retiring CF-EGU as long-duration energy storage can address these challenges and offer a suite of additional benefits to asset owners, the grid, and society.

The objective of the project (Project) is to develop the concept of repurposing retiring CF-EGUs as long-duration energy storage (LDES) systems. Here, this Project looked at how to integrate a Malta Pumped Heat Energy Storage (PHES) system with one or more CF-EGUs in Project partner Duke Energy Corporation's (Duke Energy) portfolio that are being considered for retirement. The CF-EGU(s) could comprise an entire generation plant or could be one or more units of a plant, the balance of which will continue to operate. Malta PHES is a long-duration, molten-salt-energy storage technology that uses components (e.g., heat exchangers, turbomachinery, pumps, etc.), workforces (e.g., thermal plant operators, power plant engineers, maintenance technicians, etc.), and skill sets substantially like those used by fossil energy (FE)-fueled EGUs (i.e., construction, operation, and maintenance). The Project would model reusing existing CF-EGU equipment to construct an integrated MPHES to store VRE, nuclear, or other electricity generation from Duke Energy's portfolio. It would identify benefits to operational, environmental, and economic performance of Duke Energy's operating assets, retention of incumbent workforces, and replacement of local economic impact of retiring CF-EGU(s).

2.2. Scope of the Study

This one-year long Project included six major tasks, as shown in Figure 1. The project team included Malta Inc., Duke Energy, and Energy Intelligence Partners (EIP). Malta Inc. led most of the tasks, while EIP led the "Local Impacts Benefit Analysis and Economic Benefits Study" as part of Task 4. Duke Energy provided data, consultation and agreement on site selection, data, and site access, as well as other tasks. Most of the work for this project was for task 2 to 5. Task 2 and Task 3 were done during the first half of the project while Task 4 and Task 5 took place in the second half. Task 1 and Task 6 took place throughout the entire Project.

For Task 2, the focus was on identification of potential host sites, developing site selection criteria to compare them, and down selection of one host site. Cliffside Unit 5 was selected as the host site for the next step. For Task 3, the major focus was on developing different integration options between the Malta PHES and Cliffside Unit 5. Four different integration options were identified (more details below). Their technical feasibility was evaluated, and the four options were compared based on their technoeconomic performances. Task 4 focused on the preliminary conceptual design of the down selected integration option and evaluation of the economic benefits that system brings to Duke Energy and the local community. Task 5 looked at the typical transients the system may experience such as startup, shut-down, load change and trip. This included transient model development for the system and running these transients in the model to look at how the system would behave. Part of Task 4 and Task 5 also included identifying technology gap and what can be done in the future to close these gaps.

Task	MALTA Benjamin Bollinger VP of Engineering	eip energy intelligence partners Edward May, Partner Ron DiFelice, Partner	DUKE ENERGY Jared Troyer Senior Engineer
1.0 Project Management & Planning	**Lead**		Provide data, site access, and consultation
2.0 Determine potential host sites and Customer Requirements	**Lead**	Assist in site selection process	Provide consultation, agreement on site selection, data, and site access
3.0 Evaluate and Down-select Integration Options	**Lead**	Participate in down-selection	Participate in down-selection
4.0 Perform Conceptual Design & Economic Benefits Study and Technology Gap Assessment on Down-selected Integration Option	**Lead** for Conceptual Design and Technology Gap Assessment	**Lead** for Local Impacts Benefit Analysis and Economic Benefits Study	Provide data, consultation
5.0 Perform Additional Transient Simulation Studies	**Lead**		Provide consultation on R&D
6.0 Network with Potential End - Users and Technology Developers	**Lead**	Participate in networking	Participate in networking

Figure 1: Project Organization Chart

Task 6 involved many discussions with different utilities who are facing coal-retirement issues. For example, the project was discussed with New Brunswick Power related to its Belledune coal power plant, which is scheduled to stop burning coal by 2030. The most important networking activities for this project was that Malta Inc. was invited to the White House to participate in the Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization (IWG) roundtable, where Malta discussed specifically how the work of this Project can offer solutions to the problem the IWG is trying to solve.

3. Site Selection Summary

The site selection was done using the following steps:

i. Identify criteria for selection that have an impact on the potential integrated system, including any must-have criteria.
ii. Screen out potential sites that do not meet at least one of the must-have criteria.
iii. Provide relative importance ranking for the different criteria with score of 5 being most important and 1 being least important.
iv. Score remaining sites for each of the criteria and calculate overall scores for each site.
v. Choose the site based on the scores and provide any additional notes.

Between 2020 and 2030, Duke has multiple coal-fired energy generation units (CF-EGU) being evaluated for potential retirement. To quickly narrow down the sites for more detailed comparison, the following screening out criteria were used: Retirement year, CF-EGU rated power and CF-EGU minimum power. This helped to narrow down to two top candidate sites: Cliffside and Mayo. These two sites were then further evaluated using importance ranking of different criteria, as shown in Table 2. Site available footprint, timeline for project execution, and minimizing grid interconnection load issues were considered most important.

Table 2: Importance Ranking for Site Selection Criteria

Criterion	**Explanation for Determining Importance Ranking**	**Importance Ranking**
Coal Unit Equipment Reusability	How important is it to reuse as much equipment from the to be retired coal plant as possible?	3
Timeline	How important is it for the new integrated system to be in operation as soon as the coal plant retires?	4
OPEX Saving	How important is it that the new integrated system can share OPEX (operators, utilities, maintenance crews, etc.) with remaining coal plants on site (if there is any)?	3
Maintain Coal Unit Capacity	How important is it to maintain the capacity of the to-be-retired coal unit with the integrated system?	1
Job maintenance/creation	How important is it to maintain as many jobs from the to be retired coal plant as possible?	3
Reconfiguration Capability	How important is it for the integrated system to have the provision to be reconfigured to an alternate option (for example: from thermal integration to only electrical integration) in the future?	4
Discharge duration	The standalone Malta system is configured to be discharged at 100 MW for 10 hours. How important is it for the integrated system to have the same discharge duration?	2
Site Footprint Availability	The ability of the current site to host the integrated system.	5
Grid Interconnection Load Issue	How important is it to ensure there is no issue with the additional load from charging the system on the grid?	4

Table 3 shows the individual score and the total score for the two sites. The scores were done by collaboration between all partners in the project. Cliffside has a total score of 75 while Mayo has a total score of 71. Overall, Cliffside was slightly more favorable as a site on which to base the project studies, with Mayo serving as close second alternative. The project team also has easier access to Cliffside 5 technical data for next steps of the study as well.

Table 3: Final Site Selection Results

Criteria	**Importance Ranking**	**Cliffside**	**Mayo**	**Note**
Coal Plant Equipment Reusability	3	3	3	For both sites, equipment could be reused
Timeline	4	3	3	Both sites have potential retirement date far enough in the future for project execution
OPEX Saving	3	3	1	Cliffside has unit 6 still operating and has the potential to share some OPEX
Maintain Coal Plant Capacity	1	2	1	Lower rated power is better for an integrated project. Mayo has rated power of more than 700 MW while Cliffside 5 has rated power of a little bit more than 500 MW.
Job maintenance/creation	3	3	3	Both sites have equal chances of creating/maintaining jobs.
Reconfiguration capability	4	2	2	Both sites have equal chance for reconfiguration
Discharge Duration	2	2	3	Lower minimum power is better to achieve longer duration
Footprint Availability (see Figure 1 and 2)	5	2	3	Mayo has better footprint for accommodating each of the integration options (see Figure 1). Cliffside 5 presents more challenge with respect to layout with higher integration option (see Figure 2)
Potential load issue with grid	4	3	2	Scoring numbers were generated in consultation with Duke.
	Total Score	**75**	**71**	

4. Integration Options Description and Down-Selection Result

4.1. Integration Metrics

The identification of the metrics for comparing the different integration concepts/options started during the site selection process. A list of questions was provided to Duke Energy to determine the ranking importance for each metric as part of site selection. Some of these questions overlapped with the importance ranking for integration options, particularly:

- **Maintain Coal Plant Capacity**: How important is it to maintain the capacity of the to be retired coal plant with the integrated system? This was ranked as a 3 out of 5, with 5 being most important.
- **Discharge duration**: The standalone Malta system is configured to be discharged at 100 MW for 10 hours. How important is it for the integrated system to have the same 10-hour discharge duration? This was ranked as a 2 out of 5.
- **Reconfiguration Capability**: How important is it for the integrated system to have the provision to be reconfigured to an alternate option (for example: from thermal integration to only electrical integration) in the future? This was ranked as a 4 out of 5.

The above questions/answers indicated that a concept that provides some flexibility is important. This helped identify additional concepts that could provide some additional flexibility

During the July 13 – 14th, 2021 site visit and meeting at Duke Energy's Cliffside Power Plant, further discussions between Duke Energy and Malta Inc. led to the conclusion that the concept that would be the most attractive for further study would be the one that provides the best benefit-to-cost ratio. Therefore, the parameters shown in Table 4 were identified both to be important for any concept and as providing a good comprehensive picture of each option. For example, overall system efficiency (OSE) drives how much electricity is required to charge the system and affects the benefit the system can provide. Similarly, all the capital expenditure (CAPEX) and operational expenditure (OPEX) metrics are included in the lifecycle cost calculation.

Table 4: Metrics for Comparison of Different Integration Options

Parameter	Definition	Note
CAPEX ($)	Total capital spending to get the integrated system ready for commercial operation.	This mainly focuses on cost of new equipment and does not include any existing equipment from steam cycle of unit 5
Levelized cost of power ($/kW)	Ratio of CAPEX over maximum rated power output	This is calculated based on the maximum power output that the option can provide.
Cost of Storage ($/kWh$_e$)	Ratio of CAPEX over total amount of stored energy (amount that can be generated)	All options are assumed to store the same amount of 1000 MWh$_e$
Overall System Efficiency	The ratio of discharge energy over charge energy over a standard storage cycle	This includes parasitic/auxiliary loads. A standard storage cycle includes fully charging the system and fully discharging the system.
Fixed OPEX ($/year)	Yearly fixed operation cost	This includes cost of staffing as well as planned maintenance/overhaul of major equipment.
Variable OPEX ($/year)	Yearly anticipated variable OPEX	This does not include charging cost. Charging cost is included in calculation of benefits.
Lifecycle Cost ($)	The total cost to run the system over 30 years	Assuming a 30-year life. The life cycle cost includes CAPEX and OPEX
Benefits ($)	Benefits the system can provide to the grid. This assumes dispatch profiles like pumped hydro storage system in the future and marginal cost of production (as provided by Duke Energy Modeling Team)	The benefit here mainly focuses on energy shifting benefit assuming different charging costs. It does not include any ancillary services that the different options can provide.

4.2. Integration Options Description

4.2.1. Overall Summary for the Four Integration Options

A total of four integration options were identified, including the originally proposed higher-level and lower-level integration options as well as a hybrid integration third option. An “Option 0” comparison was also made to the European Store2Power resistance heater option [1]. For all four options, the thermal energy is stored in molten salt tank(s). Table 5 provides an overview of the four different integration options. For each option, the charging mechanism is either the resistance heaters or the Malta heat pump. The discharging mechanism can be either the Malta heat engine, the Unit 5 steam cycle, or both. For the options that repurpose the unit 5 steam cycle, a molten salt steam generator (MSSG) is required.

Table 5: Overview of the Different Integration Options

Parameter	Option 0	Option 1	Option 2	Option 3
Option Name	European Store2Power Concept	Lower-level Integration (Electrical Only)	Higher-level Integration (Heat Pump + Rankine)	Hybrid Integration
Charging Mechanism	Resistance heaters	Malta Heat Pump	Malta Heat Pump	Malta Heat Pump
Discharging Mechanism	Unit 5 steam cycle	Malta Heat Engine	Unit 5 steam cycle	Malta Heat Engine + Unit 5 steam cycle
Major New Equipment required	Molten salt steam generator, resistance heaters	None	Molten salt steam generator	Molten salt steam generator
Equipment reused from Coal Plant	Unit 5 steam cycle + electrical system	Some equipment from electrical system; grid interconnection	Unit 5 steam cycle	Unit 5 steam cycle
Notes	Most simple but very low round trip efficiency.	Malta stand-alone system with Unit 5 system electrical system repurposed	Does not need Malta system discharge power train	Most complex but provides the most flexibility

Preliminary sizing of major equipment, such as resistance heater, MSSG, and Malta system was done. The size of the different equipment was used to determine the cost. The cost of resistance heater and MSSG were determined based on a $/MWth basis from budgetary quotes from vendors. For options that reuse Unit 5 steam Rankine cycle, the cost of refurbishment of the different equipment was provided by Duke Energy Unit 5 engineering personnel. This included cost of cooling tower overhaul, steam turbine overhaul, generator overhaul, etc. All these refurbishment costs were included in the overall cost of the option 0, 2 and 3. For each option, the round-trip efficiency (RTE), which is defined as charge coefficient of performance (COP) * discharge efficiency, was also estimated. This does not account for standby load or loads during cold start from ambient.

For each of the option above, estimation for CAPEX and OPEX was done. This includes estimation of what from unit 5 could be reused. Table 6 lists the normalized CAPEX, the OPEX over 30 years (not including fixed staff), and the total life cycle cost (over 30 years) for each option. Option 0 and Option 1 have similar life cycle cost while Options 2 and 3 have a life cycle cost that is 50% higher than that of Option 0 or Option 1.

Table 6: Total Life Cycle Cost for Different Integration Options

Option Number	Normalized CAPEX	Normalized OPEX (over 30 Years)	Normalized Total Life Cycle Cost
Option 0	1.14	1.18	1.15
Option 1	1.00	1.00	1.00
Option 2	1.53	2.45	1.69
Option 3	1.76	2.85	1.95

The next four subsections provide more details about each of the integration options.

4.2.2. Option 0 – Resistance Heater – Repurposing Unit 5 Steam

This option was included because this was the original idea/concept[3] of how to repurpose coal plant in Germany. It is also technically the simplest solution, in that the utilized resistance heater for charging is simple to install and operate. A simplified schematic of this option is shown in Figure 2.

During the charging process, molten salt pumps are used to pump salt from the warm salt tank to a series of inline electric resistance heaters, which heat up the salt to the desired temperature. The hot salt is then directed toward the hot salt tank for storage. During the discharge process, hot salt from the hot salt tank is pumped through a molten salt steam generator (MSSG), which replaces the current coal boiler of Unit 5. Feedwater is fed into the MSSG using existing feedwater pump(s) from unit 5. The hot salt transfers heat to the feedwater and converts water into steam, which then drives the turbine and sends discharge electricity back to the grid. For this option, the following major equipment is required: resistance heaters, hot salt tank, warm salt tank, salt pumps, MSSG, and associated controls.

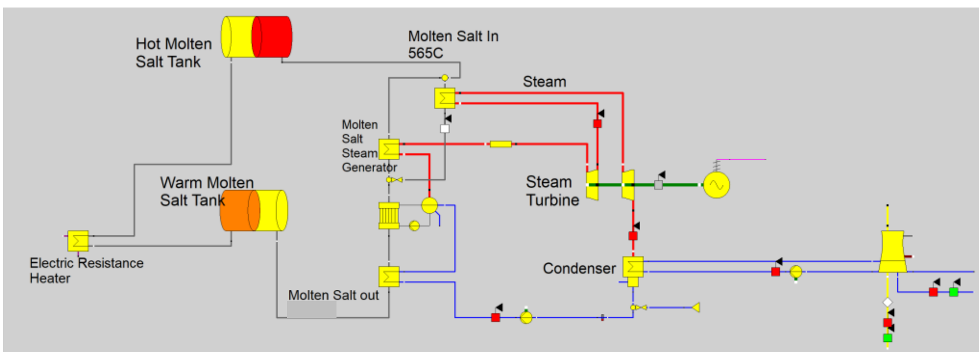

Figure 2: Schematic of Option—Resistance Heaters

For any option that requires a MSSG, the MSSG is first sized such that it requires minimal changes to the Unit 5 steam cycle operating conditions. Currently, the Unit 5 steam cycle is operated under fixed pressure regime, which means that the steam pressure is essentially constant (with variation of about 10%) between minimum and maximum power. The power output is controlled by adjusting the feedwater flowrate into the boiler.

Figure 3 shows the heat and mass balance (HMB) for the MSSG that would allow the Unit 5 steam cycle to operate very close to it current conditions. The main of objective of this model is to size the MSSG so that a cost estimate can be done. The entire steam cycle of Unit 5 has been modelled (though not shown in Figure 3 for clarity) and the modeling confirms that it is indeed feasible to operate the Unit 5 steam cycle at rated condition using MSSGs. Based on the HMB, the MSSG has rated heat transfer of about 1308 MW_{th}, with hot salt temperature at 565°C and warm salt temperature of 310°C. The power output of the cycle is about 562 MW_e (approximately the present rated power of Unit 5), which gives the discharge cycle efficiency at rated power of about 42.8%.

The major OPEX cost for this Option 0 is for the steam cycle. Minimal OPEX is expected for the resistance heaters or for the molten salt. The staff required for operation and maintenance of the Unit 5 steam cycle should be able cover both the resistance heaters and the molten salt system.

[3] https://atainsights.com/wp-content/uploads/2019/05/190508-_MGeyer_DLR_Decarbonization_Coal_Plants-5minutes.pdf

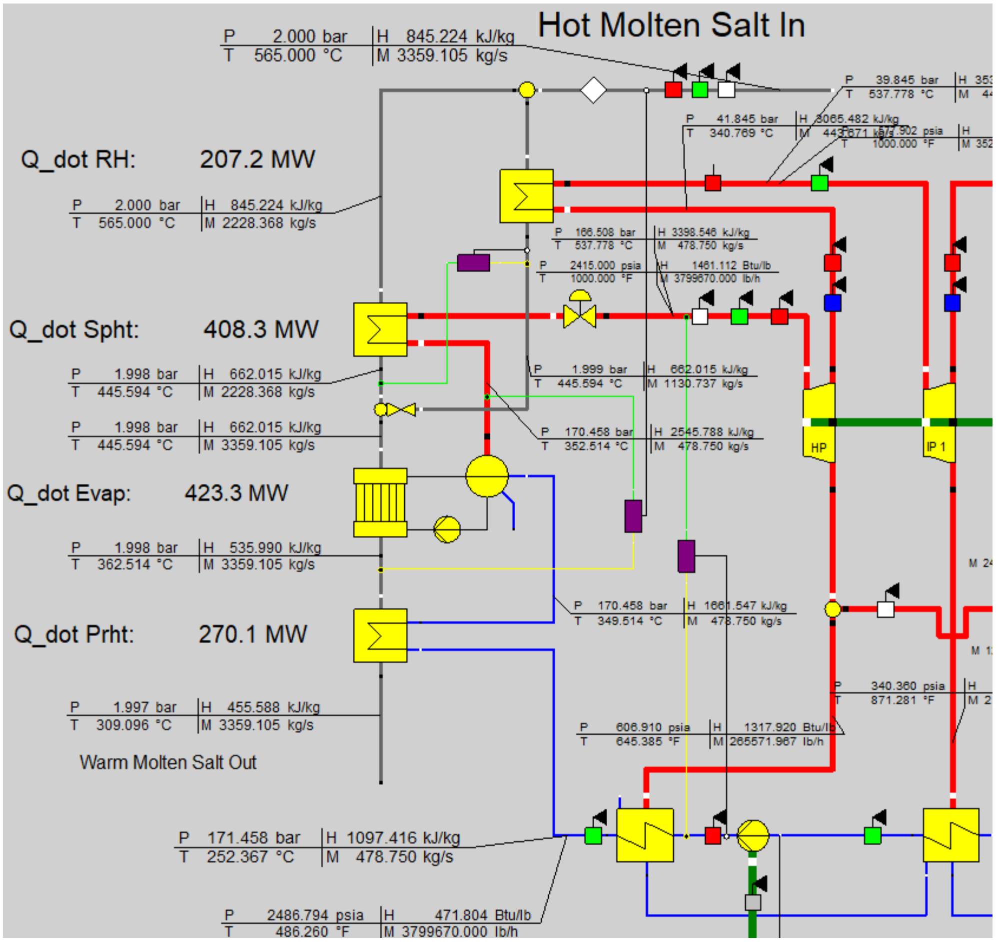

Figure 3: Heat and Mass Balance for Molten Salt Steam Generator

4.2.3. Option 1 – Malta System Stand-Alone – Repurposing Unit 5 Grid Interconnection

This integration utilizes both the charge and discharge cycles from the Malta PHES system. Figure 4 and Figure 5 show the temperature and flow rate for the charge and discharge cycle of the Malta PHES, respectively. The charge cycle compressor has pressure ratio of about 4.6 while the discharge cycle has pressure ratio of about 5.9. The warm salt is at approximately 270°C while the hot salt is nominally 565°C. The system is designed to take 10 hours to charge and 10 hours to discharge (symmetric on duration). For a 100 MW rated discharge system, the charging power is approximately 182MW. Both charge and discharge cycles have a minimum load of 25% and the power ramp rate options ranging from 10% to 25% per minute.

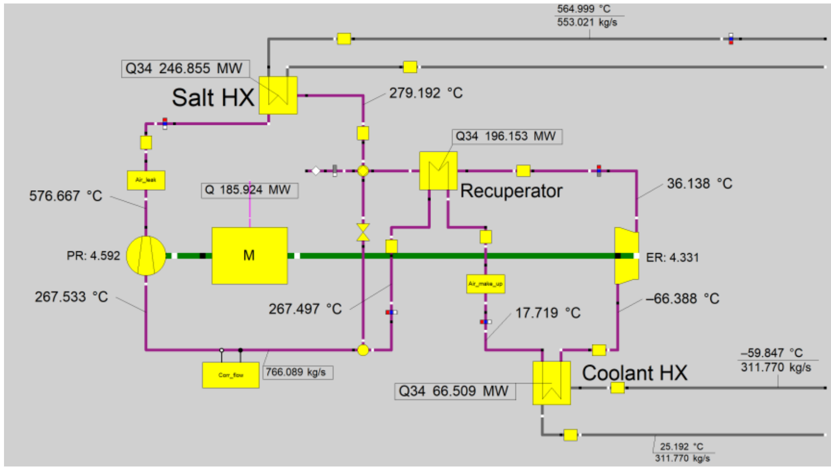

Figure 4: Malta PHES Charge Cycle – COP of 1.33

The salt Heat Exchanger (HX), the recuperator, and the coolant HX are used in both cycles. In the discharge cycle, an additional discharge heat subsystem is required to remove the inefficiency heat that accumulates in the system during both charge and discharge, and which is removed during the discharge cycle as discharge heat. The discharge heat subsystem includes a heat rejection HX (HRHX) that transfers heat from the air loop to a hydronic fluid. The ~115°C hydronic fluid is then cooled down using a set of air coolers or can be supplied to combined heat and power (CHP) or other low-grade industrial heat applications. The charge cycle has a coefficient of performance (COP) of ~1.3 while the discharge cycle has a thermal efficiency of about 43.3%. This gives round trip efficiency of about 57% (not counting parasitic load).

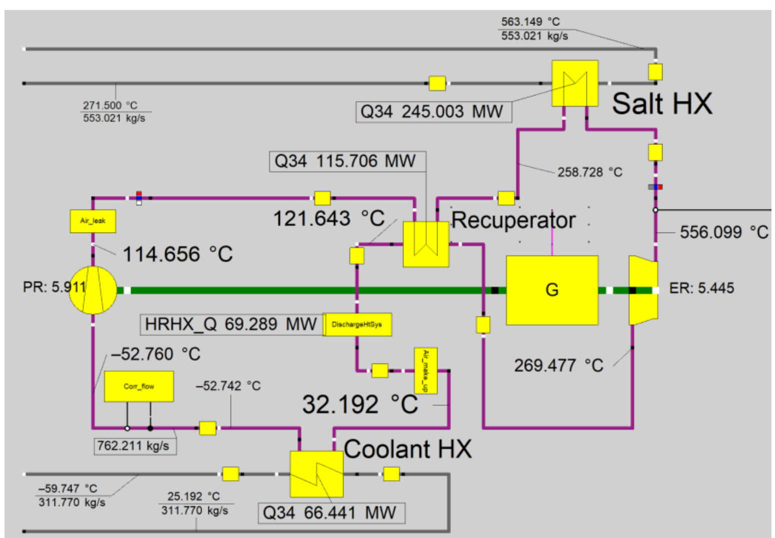

Figure 5: Malta PHES Discharge Cycle – Cycle Efficiency of 43.3%

For this integration option, the main equipment from Cliffside Unit 5 that could be repurposed include those from the electrical system (such as the generator, transformer, breakers, switch yard equipment, etc.). The cooling tower from Unit 5 could potentially be used in place of the Malta PHES air cooler to remove the discharge heat during the discharge process. Figure 6 shows a schematic of what equipment from the coal plant could be reused.

Whether a piece of equipment from the coal plant can be repurposed or not requires a more detailed analysis on the potential saving vs. the cost to re-engineer. In addition, the remaining lifetime of each piece of equipment is also a factor that impacts whether effort should be spent to try to re-use the equipment. At this stage of study, rapid evaluations based on engineering experience and judgement were used to identify how easily it might be to repurpose any given piece of equipment. The potential savings were calculated by multiplying the probability of repurposing and the cost of the equipment. If this Option 1 is chosen for further study in the second phase of this project, then a more detailed CAPEX saving will be determined based on further analysis of whether each piece of equipment should be reused or not. Table 7 shows the results of the evaluation and the potential savings. The total potential savings in Table 7 is used to adjust the CAPEX for the Malta system for Option 1.

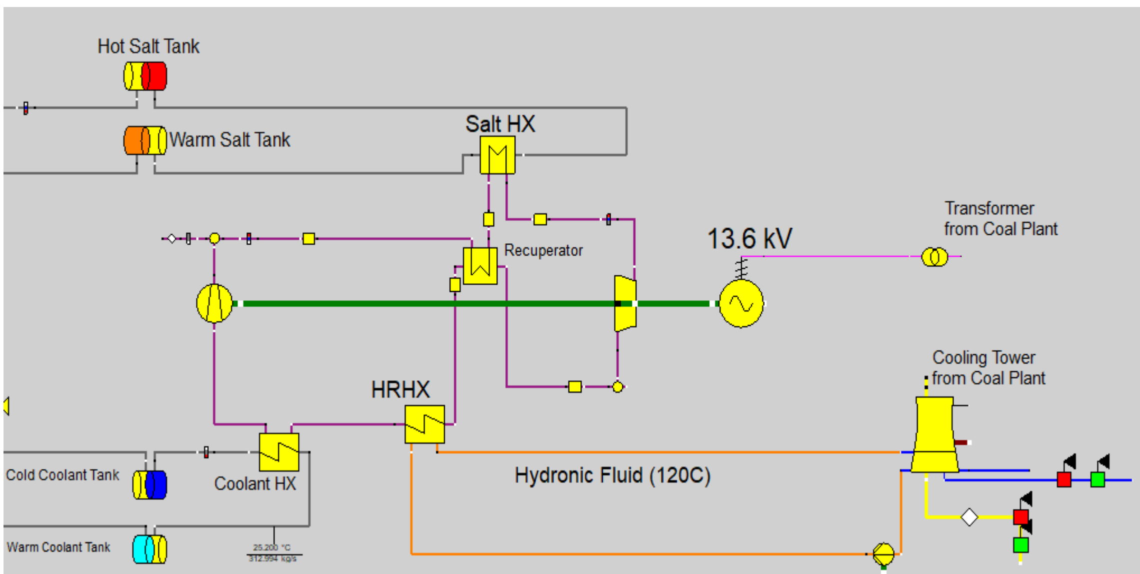

Figure 6: Schematic Showing Potential Coal Plant's Equipment Repurposing (Charge Cycle Not Shown)

Table 7: Evaluation of Potential Equipment Reuse and Associated Saving for Option 1

Potential Equipment for Repurposing	**Reusability**	**Rationale/Note**
Unit 5 generator	Unlikely (5%)	The Unit 5 generator has much larger MVA rating and inertia as compared to Malta discharge cycle generator. Using the Unit 5 generator is likely to require redesign of the Malta system turbomachinery, including detailed rotodynamic analyses.
Main & Auxiliary Transformer	Possible (50%)	A slightly greater loss may be expected since the Unit 5 transformer is rated for a higher voltage. Some rewinding may be required.
Main breaker	Likely (90%)	A slightly greater loss may be expected

Cooling Tower	Possible (50%)	Unit 5 cooling tower is an "open cooling tower" (water from condenser interacts directly with air) that has more than 5 times the heat removal capability as compared to Malta PHES air cooler. To use the Unit 5 cooling tower to remove heat from the Malta hydronic loop, cooling coils would need to be added. In addition, the cost of operating the existing cooling tower is more expensive than that for an air cooler.

4.2.4. Option 2 – Malta Heat Pump – Repurposing Unit 5 Steam Cycle

This integration option uses the Malta Heat Pump to charge the system by heating up the molten salt. In the discharge mode, the molten salt is used to create steam in the MSSG, which then drives the Unit 5 steam turbine to make electricity. A schematic of this option is shown in Figure 7.

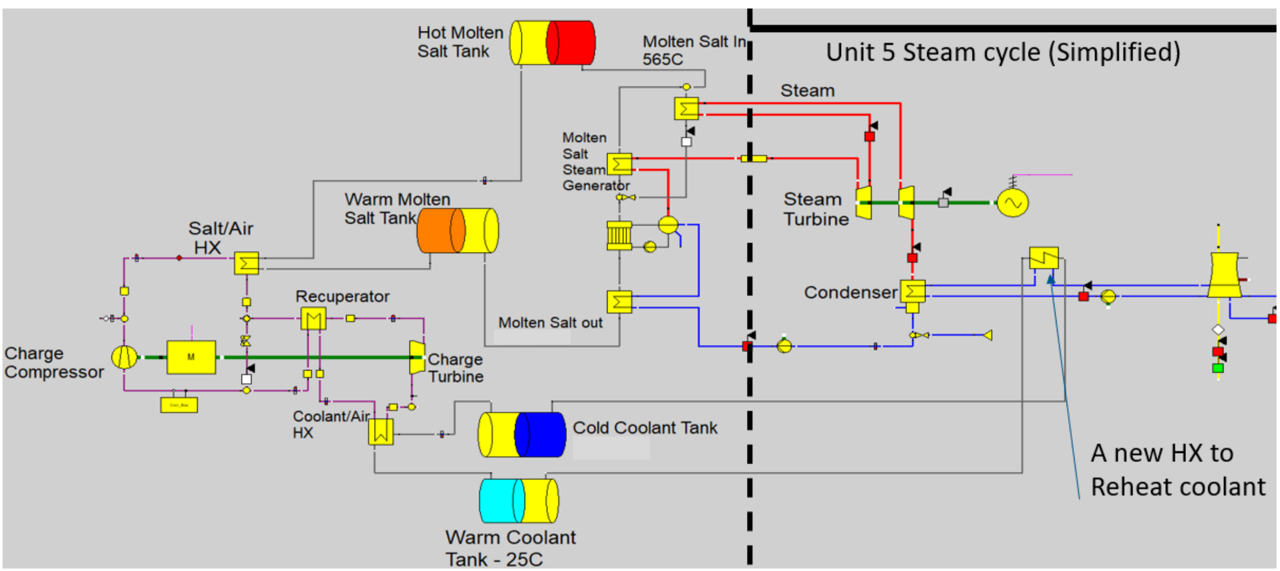

Figure 7: Schematic for Option 2—Malta Heat Pump—Steam Cycle

The Malta Heat Pump (charge cycle) normally operates by taking heat out of the coolant and depositing that heat into the salt. The coolant goes from ambient temperature to around -60°C as a result. During the discharge process, the cold coolant needs to be reheated back to ambient temperature to balance the cycle. Therefore, when the Malta heat pump is coupled with the Unit 5 steam cycle, the heat from the condenser can be used to reheat the coolant during discharge. (Viewed from another perspective, the heat-absorbing capability of the cold coolant can be used to partially replace the function of the steam cycle condenser.) This new condensing HX is located between the existing condenser and the cooling tower. It effectively reduces the load on the cooling tower as some of the heat from the condenser is used to reheat the coolant. This condensing HX is expected to be relatively inexpensive because it is a water-to-coolant counterflow HX.

Like Option 0, an MSSG is necessary. As already shown in Figure 3, for the Unit 5 steam cycle to operate in the current fixed pressure regime, the outlet temperature of the MSSG needs to be approximately

310°C, which is different from the Malta PHES standard design temperature of 270°C. Therefore, the Malta heat pump cycle needs to be adjusted to be able to heat the warm salt over a smaller range, from 310°C to 565°C.

The objective here is to keep the turbomachinery pressure ratio relatively close to the standard Malta charge cycle so that no new turbomachinery is required. Additionally, the charge compressor outlet temperature cannot exceed a design limit of approximately 585°C. To achieve this, a recuperator with higher approach temperature is used, (around 55°C, as compared to ~10°C in the standard cycle). This does mean that a much lower recuperator area is required, which lowers cost. This charge cycle is shown in Figure 8.

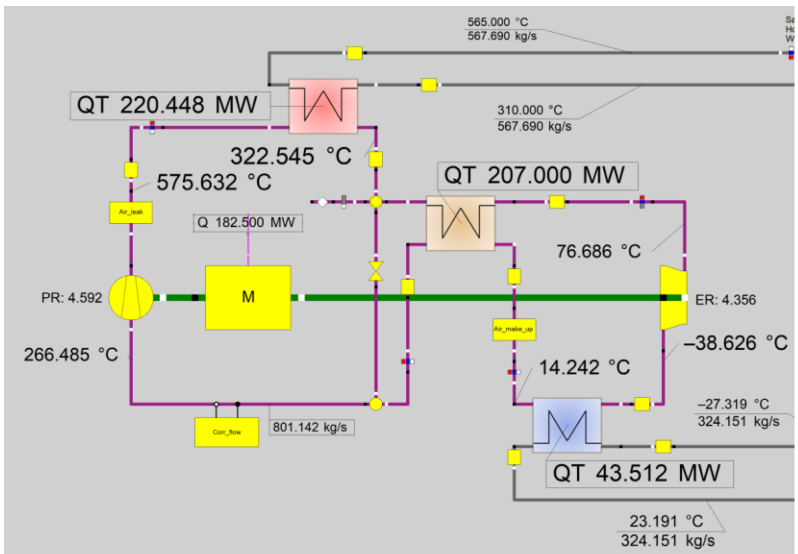

Figure 8: Malta Heat Pump Cycle for 310°C Warm Salt and 565°C Hot Salt

Two things to note for this cycle:

- The COP of this cycle is only 1.2 as compared to the COP of 1.3 for the standard cycle.
- The coolant cold temperature is higher, at around -27°C instead of -60°C. This could help reduce cost on cold coolant tank and piping materials. Coolant HX is also about 50% smaller than standalone design.

Molten salt HX has a heat transfer rate of around 220 MW_{th}. This means that it would take about 10.6 hours to supply 2330 MWh_{th} to the salt tank, the required amount to get 1000 MWh_e at steam cycle efficiency of 43%.

4.2.5. Option 3 – Malta Heat Pump with Malta Heat Engine and Unit 5 Steam Cycle

This integration option uses the standard Malta heat pump to heat up the molten salt and store thermal energy. The hot molten salt is then used to drive the standard Malta heat engine, or the unit 5 steam cycle, or both. A simplified schematic for this option is shown in Figure 9.

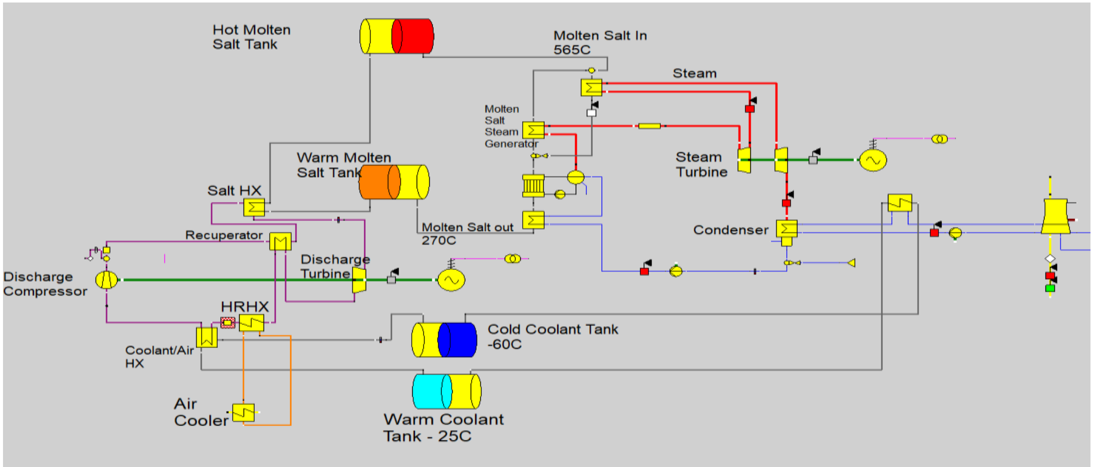

Figure 9: Simplified Schematic for Option 3 (Charge Cycle not Shown)

While this option is the most complex and has the highest CAPEX in overall dollar amount, it also provides the greatest flexibility and has the highest power output (100 MW_e from Malta heat engine + 567 MW_e from the steam turbine). With an integrated system in this configuration, it is expected that the Malta heat pump and heat engine would be used on a regular basis (for example daily cycling), and that the steam cycle would only be run when there is an anticipated need for excess peaking capacity. The attractiveness of this option is that, even though it is anticipated that the steam cycle only run occasionally, there are technical options for pulling heat from the frequently cycling Malta powertrains and using that heat to keep the steam cycle equipment warm. This means that high-power steam generation train can start with the responsiveness of a hot-start rather than a cold-start even though it may be used for infrequent peaking.

There are three things that need to be considered for this Option 3.

- Warm Salt Tank Temperature. Like option 0 and option 2, if the steam cycle operates under fixed pressure mode, the salt outlet temperature of the MSSG salt will be around 310°C. Because of the Malta heat engine operation, the option of raising warm salt temperature to 310°C, like in option 2, is not possible. (A higher 310°C warm tank operation would have very large impact on the Malt heat engine efficiency and, more importantly, its operating conditions.) This means that, for Option 3 to run with both the Malta and the steam cycle generation powertrains, whenever the Unit 5 steam cycle is run, this 310°C warm salt output from the MSSGs will need to be further cooled down to 270°C before it can be returned to the warm tank. In a worst-case design scenario, this heat could just be dumped to ambient, which means about 15% of the salt's heat energy would be wasted whenever the steam cycle is run. Since the steam cycle is not expected to operate very often for Option 3, this heat energy loss should not have a large impact on the overall system benefits.
- Steam Cycle Sliding Pressure. The major parameter driving the salt outlet temperature of the MSSG is the pressure of the steam. If this steam pressure is lowered, the salt outlet temperature will be lowered. Preliminary calculations show that the steam pressure may need to drop to as low as 1500 psia (see Figure 10) for the salt outlet temperature to return at around 270°C. This means that the steam cycle needs to be operated under a sliding pressure mode. While the Cliffside Unit 5 steam cycle has never been operated under a sliding pressure mode, similar

steam cycles in other coal plants operated by Duke Energy have done this before. It is expected that a sliding pressure is possible with the Cliffside Unit 5 steam cycle. The lowest steam pressure level at which Unit 5 can operate needs to be further investigated if this integration Option 3 is further pursued in phase 2 of this grant project. Also, the impact on maximum power output and efficiency would need to be further quantified, as a lower steam pressure means a lower power output and, potentially, a lower steam cycle thermal efficiency. Compared to the first bullet point above, this will be a trade-off analysis between operational complexity vs. efficiency gain (less energy wasted).

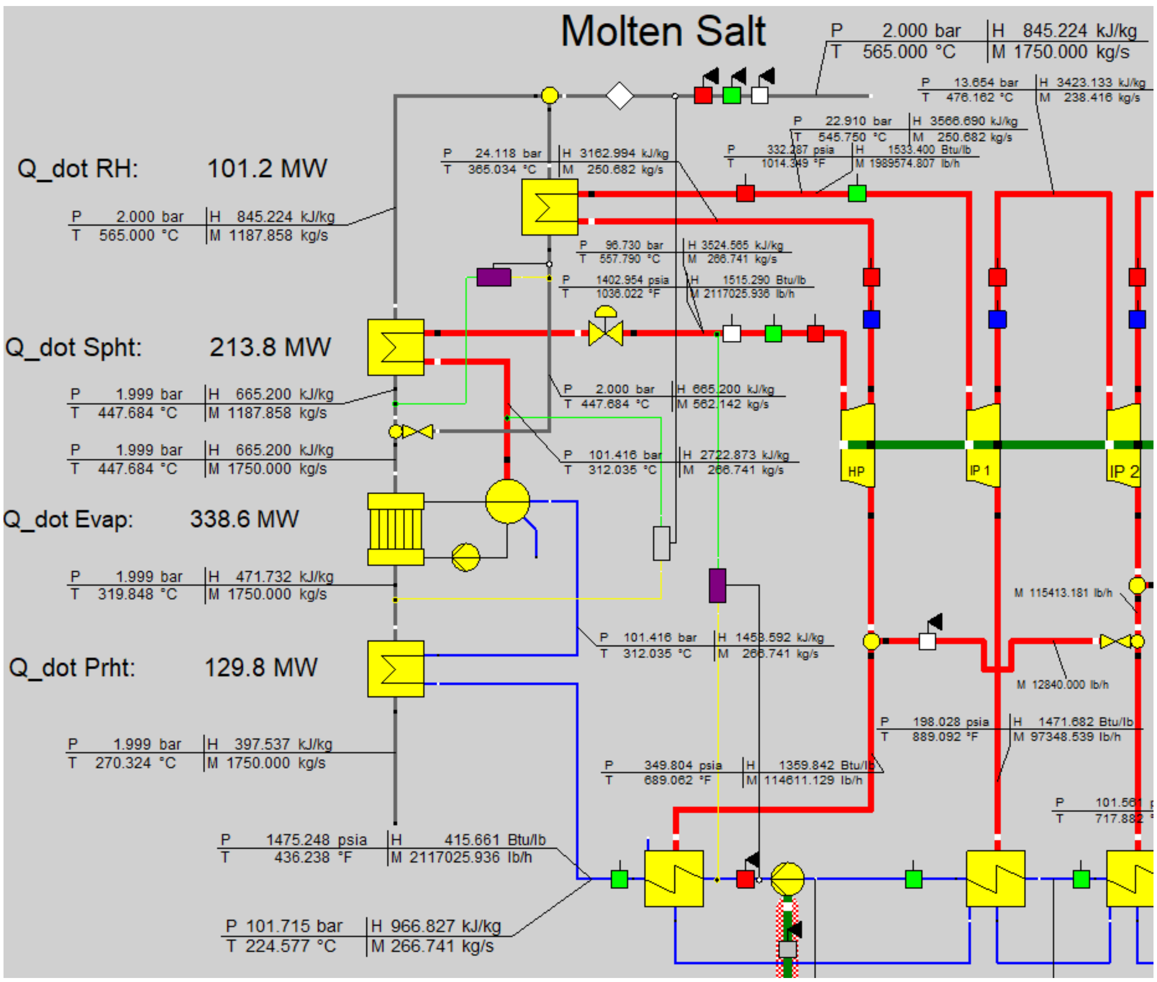

Figure 10: Sample HMB for MSSG with Steam Pressure at ~ 1500 psia Option 3

- Options for Heat Use. If a sliding pressure is not possible or is deemed too risky, there are still several ways to utilize the heat from the 310°C. This heat could be used to fully return the cold coolant to ambient temperature on discharge, which is necessary when the steam cycle is used. The heat could also be used to keep the steam cycle equipment and MSSG warm, shortening the time for the next startup. These options ultimately might help reduce any waste energy, although as stated before, operating steam cycle with this integration option is expected to be rare, so the saving is small.

4.3. Integration Option System Benefit Calculation

To compare the different options, the main benefit (metric) calculated is the reduction in production cost of electricity. This is done assuming that the storage system is used to store energy when production cost is low and then is discharged the next day when the production cost of electricity is high. In actual operation, each these integrated options can provide other ancillary services as well, such as demand response, load following, regulation, reactive power, and frequency support (rotational inertia). However, the ancillary services are not expected to be differentiating between the options.

To calculate a reduction in the marginal cost of production that would result from operating the energy storage system, a dispatch profile and marginal cost of production data are required. For this, the Duke Energy modeling team provided the dispatch profile data (8760 hours per year) of a Duke-territory pumped storage hydropower (PSH) system for three future milestone years (2025, 2030, 2040) assuming a future generation asset portfolio scenario that achieves a 70% CO_2 reduction by 2030 (compared to 2005 levels). The associated anticipated marginal costs of production for those years were also provided.

The following assumptions were also made in the benefit calculation:

a) The charge COP and discharge thermal efficiency are assumed to be constant at all power levels. In reality, the steam cycle thermal efficiency would change slightly at different loads. The Malta system discharge cycle thermal efficiency and charge cycle COP are essentially the same at all loads. This impact is expected to be small.
b) The startup and shutdown times are ignored in the calculation as these would only take 10-15 minutes for hot start. It is expected that the system would turn on and charge or discharge for several hours at a time; this run-time is large compared to the start times, so they can be reasonably ignored at first order. In addition, the impact of start times is not a differentiating factor between the different options. Cold starts are not considered here as they would take hours for any of the options.
c) The impact of ambient temperature is assumed to be negligible (the impact is small for each system), and it also has a similar impact on each of the four integration options.
d) The charge or discharge of the system does not have significant impact on the price of electricity on the grid. (I.e., a system of this size is a price taker, not a price maker.)

Table 8 shows the power ranges for charge and discharge for each of the different integrated options that was used for the benefit calculations. The roundtrip efficiency (COP*discharge efficiency) which does not include standby load, is also included for each option. Option 2 has a lower RTE than option 1 because the COP of the charge cycle in Option 2 is lower (at 1.2 COP) due to the higher warm salt temperature for that option. For Option 3, when the steam cycle is used for discharge, the effective RTE is only 49% because approximately 15% of the stored heat needs is dumped in the worst-case scenario where the salt is cooled from 310°C to 270°C because the heat cannot be used for anything else. When the Malta heat engine is used in Option 3 for discharge, RTE is 55% because the salt is returned to warm tank at the design temperature of 270°C. Since the steam cycle is not expected to be used very often, an assumed time weighted average RTE of 53.75% is used for Option 3.

Table 8: Power Characteristics of Integrated Systems for Dispatch

Option #	Min Discharge Power (MW_e)	Rated Discharged Power (MW_e)	Rated Charged Power (MW_e)	Min Charge Power (MW_e)	Charge Cycle COP	Discharge Cycle Thermal Efficiency	Round Trip Efficiency*
0	127.6	567.0	259	50	0.90	43%	39%
1	25.0	100.0	182	46	1.3	43%	55%
2	127.6	567.0	182	46	1.2	43%	52%
3	25	667.0	182	46	1.25	43%	54%

*Defined as $COP * \eta_{discharge}$. Does not include standby load or cold start-up loads.

Table 9 shows a comparison of the net yearly benefit for 2025, 2030 and 2040 for the different options. Of the 4 options, Option 1 provides the highest benefit. It should be noted that the benefit here only accounts for energy shifting following the PSH system's dispatch profile. Potential ancillary services benefits are not captured here. Furthermore, the energy shifting benefit could be still higher than what is captured here once dispatch optimization for the actual thermal systems' parameters is included.

Table 9: Comparison of Energy Shifting Benefit Between the Four Options

Option	Year 2025 Benefit ($MM)	Year 2030 Benefit ($MM)	Year 2040 Benefit ($MM)
Option 0	-1.58	-1.23	2.89
Option 1	-0.30	0.10	5.26
Option 2	-0.32	0.03	4.37
Option 3	-0.47	-0.07	4.8

4.4. Comparison Summary and Option Down Selection Decision

Table 10 provides a comparison of the four integration options across the multiple metrics: CAPEX, RTE, life cycle cost, and benefits. Of the four options, Option 1 has the lowest CAPEX and life cycle cost while also providing the highest net benefit (following a PSH system dispatch profiles).

Option 0, with its very low OSE, does not offer much benefit in the scenario where the system is used many hours daily, which is the case for the PSH dispatch profile on which thermal system dispatch is modelled. Its main advantage is that it can generate up to 576 MW of capacity. Option 2 improves upon the RTE of Option 0 by adding the higher performance charging heat pump, but at the expense of additional cost. While Option 3 is most expensive, it does provide the most flexibility in that it can use the Malta heat engine for daily energy shifting operation and reserve the kept-warm steam cycle equipment for rare occasions when additional peaking capacity is needed.

Table 10: Comparison of the Four Options (all at 1000 MWh_e) Across Multiple Metrics

Parameter	Option 0	Option 1	Option 2	Option 3
Option Name	European Store2Power Concept	Lower-level Integration (Electrical Only)	Higher-level Integration (Heat Pump + Rankine)	Hybrid Integration
Maximum Discharged Power (MW_e)	576	100	576	676
Normalized Specific Storage ($/$kWh_e$)	1.14	1.00	1.52	1.75
Normalized Lifecycle Cost	1.15	1.00	1.70	1.95
Energy Shifting Benefit, Duke 2025 to 2040 resource mix ($MM/year)	-1.58 to 2.89	-0.3 to 5.26	-0.32 to 4.37	-0.47 to 4.8

*Does not consider standby loads, cold startup loads.

Malta Inc, the prime on this grant project, consulted with the project utility partner, Duke Energy, on the integration options studied in phase 1 of this project and listed in Table 10. Based on the specifics of each option and its net benefits—which are derived from grid scenarios supplied by Duke Energy and particular to Duke's anticipated future needs—Malta and Duke recommended the further pursuit of Option 1 for second phase of the project, which will advance the engineering design and the evaluate in detail how repowering a retiring CF-EGU as a thermal energy storage can benefit the economics and operation of Duke's grids in the Carolinas.

4.5. Transferrable Results

Although the results presented in this study are in some ways specific to the data and scenarios provided by Duke Energy, there are learnings from the study's efforts that are translatable to other coal-fired energy generation unit (CF-EGU) retirement scenarios and to other regions as well. Key variations that impact which retrofit scenario will be best suited for a particular application include the age of the retiring CF-EGU and the generation asset mix in the region of interest and over the timeframe of interest, particularly as it relates to the need for bulk energy shifting vs. the need for high-power peaking.

There are a few key rule-of-thumb takeaways that impact the various scenarios for the repowering of retiring CF-EGUs as thermal energy storage plants. These takeaways are as follows.

i. Although resistance heaters themselves are relatively inexpensive, the Molten Salt Steam Generators (MSSG) needed to power a steam Rankine cycle with hot molten salt storage are not inexpensive and are a much larger cost driver than the electric resistance heaters. This reduces the number of scenarios for which electric resistance heaters for charging makes economic sense.
ii. The energy equipment (molten salt tanks and systems) is less expensive than the power equipment (e.g., MSSGs, PHES charge and discharge powertrains), which makes a CF-EGU

retrofit as a thermal storage plant better suited to longer-duration energy shifting applications (e.g., 10 – 20 hours) than to peaking applications (e.g., 1 – 2 hours).

iii. The age of the retiring CF-EGU impacts which integration option is most desirable. This is influenced in part by the overhaul costs associated with life extension, but to a greater extent by whether the original CAPEX of the existing steam-cycle equipment has been fully depreciated or not.
iv. The ability for a molten-salt powered generation cycle to serve in a peaking capacity largely depends on the ability to keep the equipment hot-start ready vs. cold-start ready.
v. The residual lifetime of the steam Rankine-cycle equipment impacts the ability to repower the equipment into a daily-cycling energy shifting application vs. into an infrequent peaking-only application.
vi. The capacity factor of the retiring CF-EGU (e.g., above 70% or below 15%) can impact which integration option is best suited
vii. The grid resource mix (e.g., penetration of VREs) greatly impacts the energy shifting benefit of repowering scenarios
viii. The energy shifting benefit will change over time as the resource mix changes
ix. Repower decisions will likely be based not just on the net energy shifting benefit but also on the ancillary services, grid stability (frequency support/inertia, voltage support), and reliability benefits of the repowered projects.

Ultimately, there are several driving factors that will impact which integration option is appropriate for a particular plant—including age, depreciation, capacity factor, local resource mix, ancillary services value, and others—and each retirement should take these factors into consideration when considering how best to repower CF-EGUs as thermal energy storage plants.

5. Down-Selected Integration Option Conceptual Design Study

5.1. Overall Integrated System Description

As previously described, the Integration Option 1 consists of the Malta heat pump for charging and the Malta heat engine for discharge (more details will be described shortly). Both the heat pump and heat engine will be connected to the current switch yard of Cliffside Unit 5. For this option, it is ideal to have the Malta system to be as close to the existing switch yard as possible. Figure 11 shows where one may locate the Malta system at the current Cliffside site. The area on the left hand of the current Unit 5 switch yard has enough land to accommodate the Malta heat pump and heat engine. This minimizes the length of electrical cable between the Malta system and the existing switch yard. This also allows the integrated system construction before Unit 5 completely retires so that it will be a seamless transition. The new integrated system could be in operation as soon as the coal unit is retired.

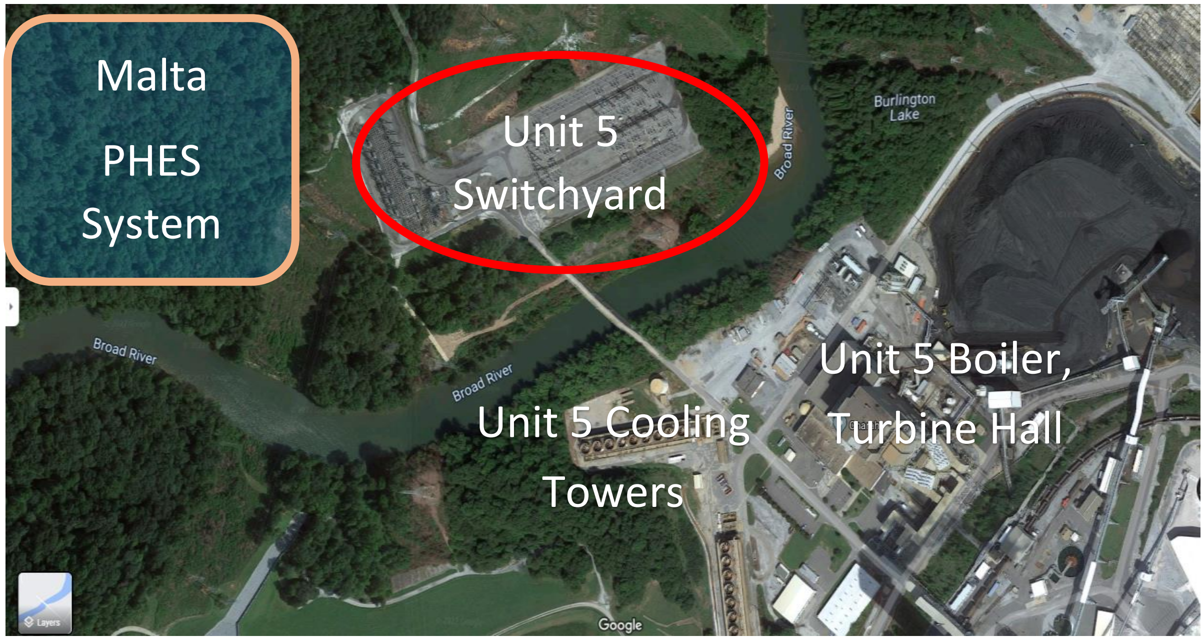

Figure 11: Proposed Location of Malta System for Integration Option 1

In the next few subsections, more detailed descriptions of the major subsystems of the Malta Pumped Heat Energy Storage (PTES) system are described. Evaluation of any potential reuse of existing equipment of unit 5 are also discussed.

5.2. Malta PHES System Description

The Malta PHES is a long duration energy storage system. At a high level, the Malta process can be broken down into 6 steps, as illustrated in Figure *12*.

1. **Collects**. Renewable energy is collected from co-located or grid-connected wind or solar farms—or any other generation source—and is sent to Malta's energy storage system.
2. **Converts**. The electrical energy that is collected drives a heat pump, which is a machine that uses electricity to move heat from a colder location to a hotter location, effectively "converting" electricity to stored thermal energy.
3. **Stores**. The heat is stored in hot molten salt and the cold is stored in a cold coolant.
4. **Reconverts**. The heat stored at the large temperature difference between the hot and cold tanks is used to drive the heat engine and reconvert the stored thermal energy back into electrical energy when it is needed.
5. **Distributes**. Electricity is sent back to the grid or end use.
6. **Heats**. Useful process heat for industry and/or district heating/cooling is released by the heat engine during discharge and can be buffered for continual heat output.

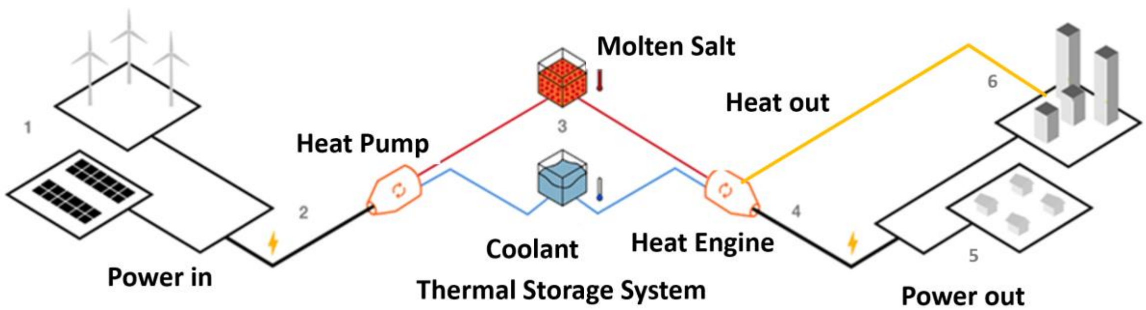

Figure 12: Conceptual Diagram of the Malta charge and discharge sequence

The Malta PHES system uses two separate powertrains (one for charge and one for discharge) and a common set of heat exchangers and thermal storage tanks to create an electricity-in-electricity-out long-duration energy storage system.

The charge cycle uses a reverse Brayton cycle heat pump—with clean dry air as the working fluid—operating in a closed loop with three heat exchangers (a salt heat exchanger, a coolant heat exchanger, and a recuperator), as shown in Figure *13*. During the process, electricity from the grid drives an electric motor which in turn drives the compressor. The compressor takes air that has absorbed heat from the coolant and compresses it, making the air hot enough to heat molten salt up to 1050°F (565°C) and to store energy as heat. Following this heat transfer from the working fluid to the molten salt, the now cooler air is first passed through the recuperator to transfer additional heat to the air inbound to the compressor and then expanded through a turbine, producing power to help drive the compressor. This expansion reduces the working fluid temperature to approximately -76°F (-60°C). The working fluid passes through the coolant heat exchanger, gaining heat from the coolant and thereby "storing cold" in the now cold coolant. The now warmer air passes through the recuperator to receive heat and then returns to the compressor to complete the cycle.

The Malta hot storage medium is "solar salt," a blend of nominally 60% sodium nitrate and 40% potassium nitrate, which has been shown to be stable up to 1050°F (565°C) and is the storage medium that has been proven in commercially operating "power tower" concentrating solar plants—such as Gemasolar CSP plant in Seville, Spain—for over 10 years. Although the initial cost of the salt is not immaterial, it suffers no degradation and does not need replacement over the life of the facility, which is designed to exceed 30 years and many thousands of charge-discharge cycles.

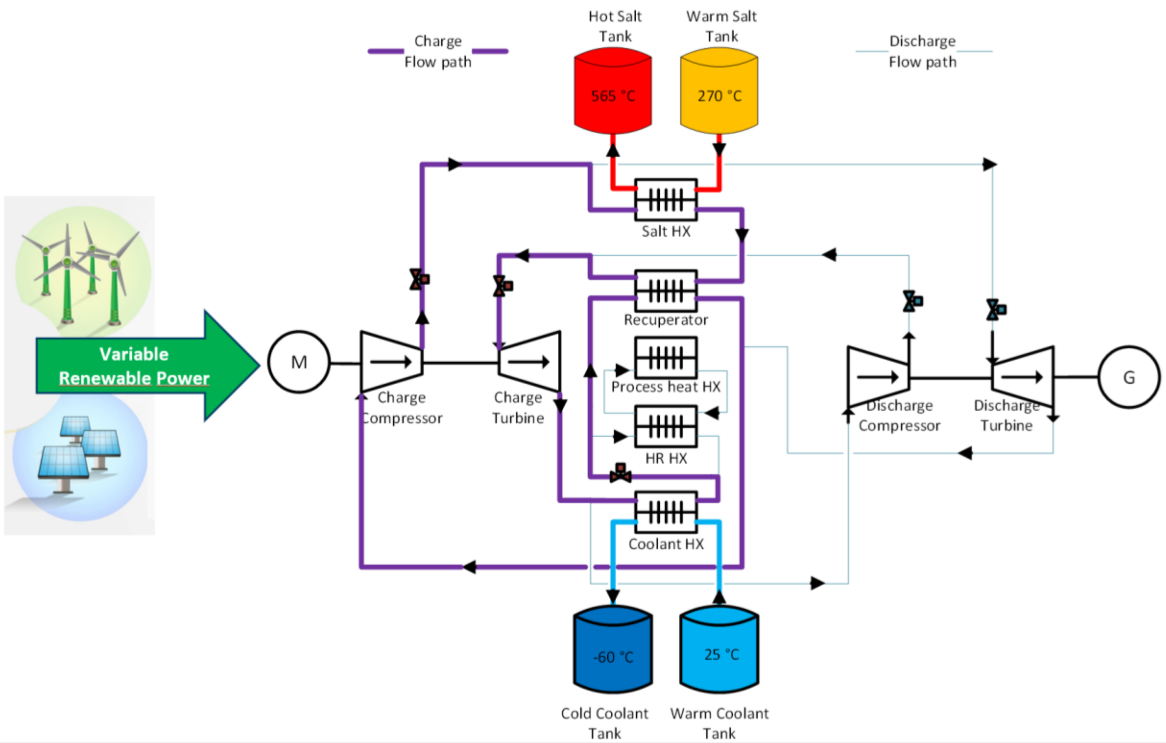

Figure 13: Malta PHES Charge Cycle

The Malta cold storage medium is a coolant with a minimum working temperature of approximately -76°F (-60°C). This temperature is higher than the LNG applications from which the components are derived, subsequently reducing the challenge of materials selection. Like the molten solar salt, the coolant is stable across its usage temperature range and is not anticipated to need replacement over the plant life.

The discharge cycle uses a standard forward Brayton cycle heat engine operating in a closed loop with the same three heat exchangers but with a separate powertrain (compressor, turbine, generator), as shown in Figure *14*. Like any thermal power plant, heat from a hot source (in this case the hot salt rather than a fuel) is allowed to flow through the engine to a colder location (in this case the cold coolant tanks rather than a cooling tower) to produce mechanical shaft power that drives a generator. During this process, heat from the hot salt tank serves the same function as fuel in a gas turbine—the salt heats the air in the closed loop to the high 1050°F (565°C) temperature, allowing the hot, high pressure to air expand through the turbine providing power to drive the generator, supplying electricity to the grid, as well as the compressor. In the closed loop, the now-warm expanded air is further cooled through the recuperator and finally again by transferring heat to the cold coolant, with the air reaching a temperature of -76°F (-60°C), making it easier to compress as it enters the compressor. After compression, the now pressurized air returns, via the recuperator, to the salt heat exchanger to be heated up, completing the closed cycle.

Electricity generation and off-take of the system is flexible between 25% and 100% of nominal power output rating with a slight increase in efficiency at lower power levels. Similarly, the charge cycle load can be flexed from 25% to 100% of nominal, providing reg-up/reg-down ability during charge as well. During discharge process, the Malta PHES produces useable discharge heat in addition to output electricity. The output heat is provided at up to 248°F (120°C) and at thermal power up to 70% of rated electrical power, making it useful for district heating or low-grade industrial heat processes. The Malta system has a "hot" startup time, associated with frequent usage of the system, of less than 10 minutes, and a fast-ramping capability like modern combined cycle gas turbine facilities. The storage duration depends on the volumes of salt and coolant (i.e., tank capacities) and is expected to be in the range of 10 hours to 200 hours based on use cases within customer and market needs.

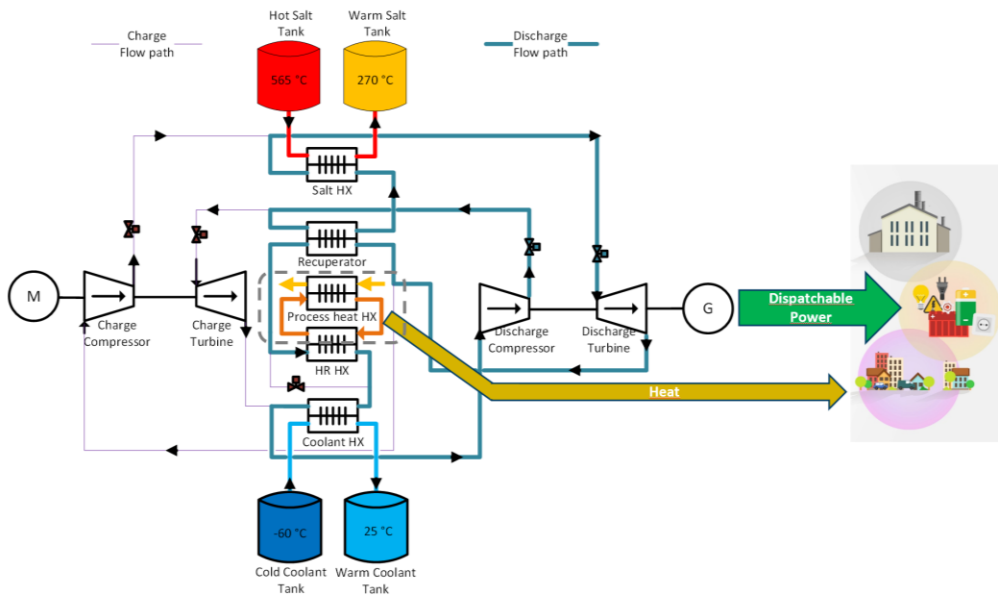

Figure 14: Malta PHES Discharge Cycle

The Malta Standard Product is a duration-symmetric 100 MW_e discharge, 10-hour PHES system. The product is an integrated power plant system that comprises underlying technology elements, each of which is in development by Malta and its partners. A block diagram of the system architecture is shown in Figure 15.

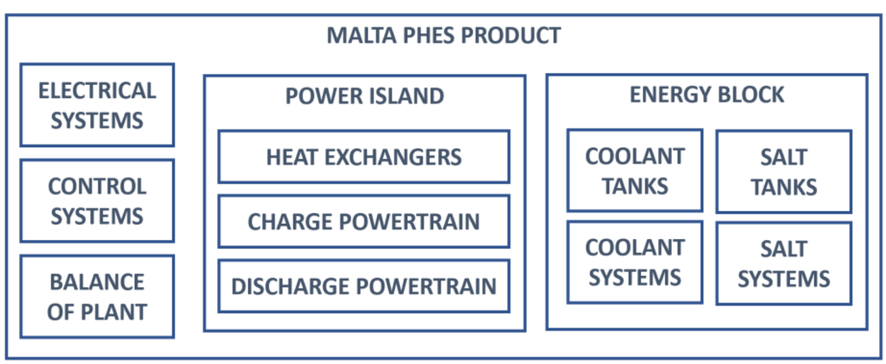

Figure 15: Malta PHES Product Architecture Block Diagram

Figure *16* (PFD) shows the flow paths of the primary fluids through the turbomachinery trains, the heat exchangers, and the storage tanks. The air flow is marked in green, molten salt in red, coolant in blue and the hydronic fluid, which is used in the heat extraction cycle in brown. The air, salt and coolant flows through the heat exchangers are bidirectional.

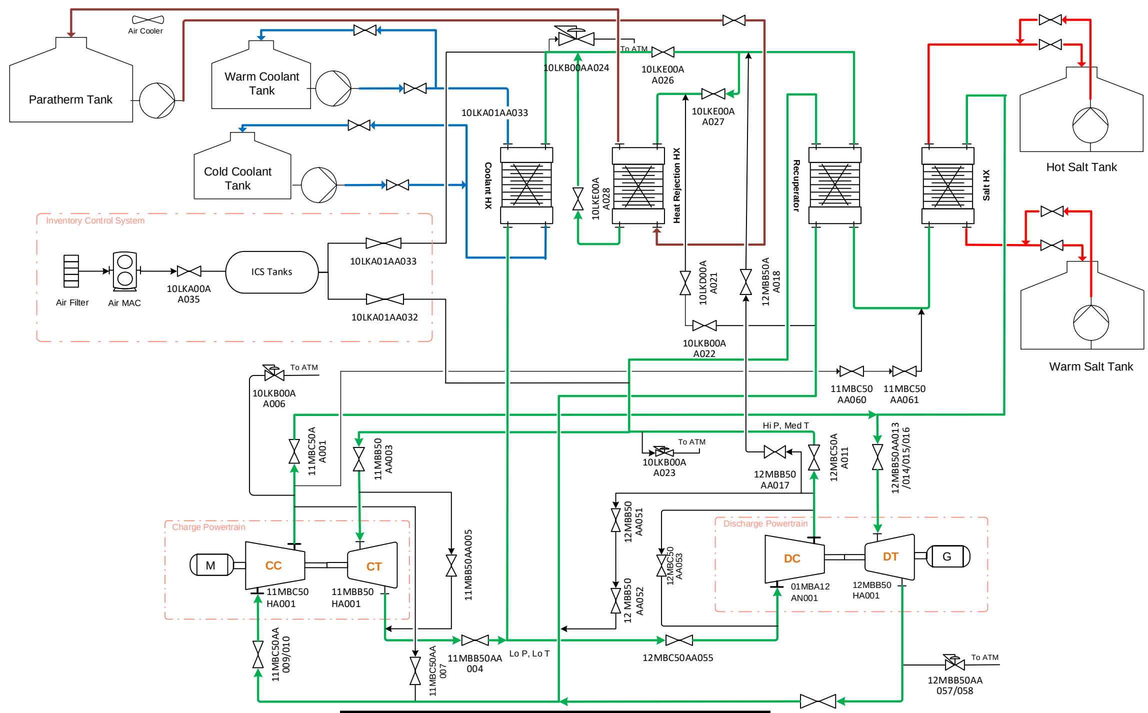

Figure 16: Preliminary PFD - Main Flow Paths and Components Malta PHES System

5.2.1. Power Island System Description

The Power Island includes the charge power train, discharge power train, the set of four heat exchangers, associate air piping and valves. The main functions of the power island include:

1. Operate as a heat pump during charge mode to take heat from the coolant system at the coolant heat exchanger and deposit this heat into the molten salt system at the salt HX.
2. Operate as a heat engine during discharge mode where it takes heat from salt system at the salt HX to run the discharge turbine, making electricity.

The charge power train consists of the charge motor, the charge compressor, the charge turbine and associated auxiliary equipment (such as lube oil). The discharge power train consists of discharge turbine, discharge compressor and the generator. The two powertrains share the same set of heat exchangers (salt, coolant, recuperator and HRHX). The main air loop piping provides flow paths for the main charge and discharge processes. In general, when one powertrain is running, the other one is isolated by closing inlet and outlet isolation valves. There are valves throughout the power cycle to help manage pressure and temperature throughout the loop.

5.2.2. Salt System Description

The salt system's main function is to store heat in the molten salt during the charging process. In the discharging process, the salt system releases the heat from the molten salt to heat up the air, which then drives the discharge turbine, making electricity.

The molten salt system consists of the molten salt itself, a hot salt tank and a warm salt tank. Each salt tank is equipped with two vertical submersible pumps with roof-mounted motors and piping connections. The two salt pumps for each tank help increase the availability of the system. The hot tank operates at approximately 565°C and the warm tank at approximately 270°C. The molten salt side system is connected to the process through the molten salt-air heat exchanger station, which transfers heat to and from the hot side of the air loop. Each salt tank is also equipped with immersion heaters, located radially at the bottom of the tank, to help maintain the salt temperature above freezing point.

Figure *17* shows the preliminary PFD of the molten salt subsystem during discharge process. Salt is flown from warm tank to hot tank where it is heat up at the salt HX. The flow of the molten salt is controlled using pump speed and the control valves. Each salt tank has a sparger ring that helps distribute the incoming salt uniformly throughout the tank.

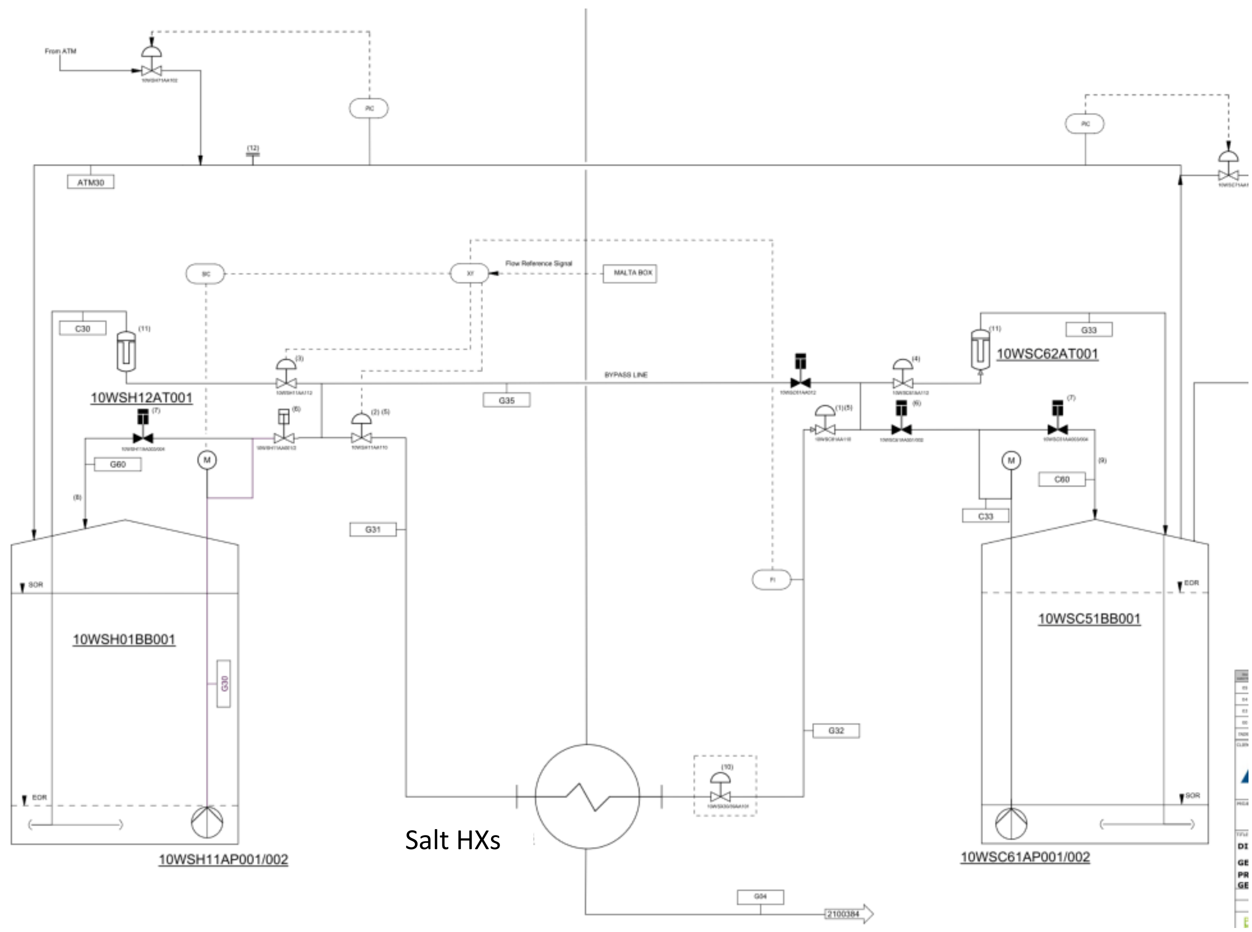

Figure 17: Preliminary PFD – Molten Salt System in Discharge Mode

The Molten Salt System design is fully contained, and exposures to ambient air from venting and vacuum relief purposes are minimized. This helps minimize salt leaks, the exposure of salt to relatively colder air, and ingress of moisture from ambient air. The molten salt system is also equipped with an appropriate method for monitoring, sampling, and controlling the salt quality in the loop (e.g., impurities, salt degradation, and corrosiveness).

The system design allows for it to be properly drained, flushed, and cleaned during the installation process and before and after any maintenance activities. The operating pressure of the Molten Salt System is less than that of the Air Loop System for all operating modes, including partial load and transients. This ensures that salt does not leak into the Air Loop and safeguards against catastrophic failure of the turbomachinery and the Air Loop piping system.

The design of the system ensures that the molten salt can drain back into a drain tank and pumped into either main storage tank, such that salt does not freeze at any point in the system because of an extended period of power loss and/or heat losses to ambient. This is a critical consideration for salt piping layout, insulation design, and heat tracing specification. Safety relief valves will be installed, as required by code, for equipment and piping systems that can be over-pressurized by a high-pressure source or a fire case.

5.2.3. Coolant System Description

Like the salt system, the coolant system's main function is to transport heat between the power cycle (air loop) and the cold storage. The coolant system also consists of two tanks, a warm tank storing coolant at ambient and cold tank storing coolant at approximately -60°C. Each tank is also equipped with two coolant pumps operating in parallel to improve overall availability. However, unlike the salt pumps, the coolant pumps are inline centrifugal pumps. In addition to pumps and tanks, the coolant system has appropriate piping and valves to create flow paths for the charge and discharge process. Figure *18* shows the preliminary PFD for the coolant system during discharge mode where the cold coolant is pumped from the cold tank to the warm tank. The cold coolant helps cooling down the air at the coolant HX before it goes into the discharge compressor. The process is reversed in charging mode where the coolant is pumped from warm tank to cold tank. Here, the warm coolant is used to heat up the air coming out of the charge turbine from ~-70°C back to ambient. The coolant flow rate is controlled using pump speed and/or control valves.

The coolant tank vapor spaces are blanketed with nitrogen. The vapor spaces of the coolant tanks are connected by a balancing line, which eliminates the need for a large breather valve and minimizes coolant losses as coolant is transferred between the tanks during normal operations

Like the salt system, the Coolant System is equipped with methods for monitoring, sampling, and controlling the coolant composition and quality in the loop (e.g., total dissolved solids, chloride content, pH). The system will be properly drained, flushed, and cleaned during the installation process and before and after any maintenance activities.

The operating pressure of the Coolant System is less than that of the air loop system for all operating modes, including partial load and transients. This ensures that coolant does not leak into the air loop and safeguards against failure of the turbomachinery and the air loop piping system.

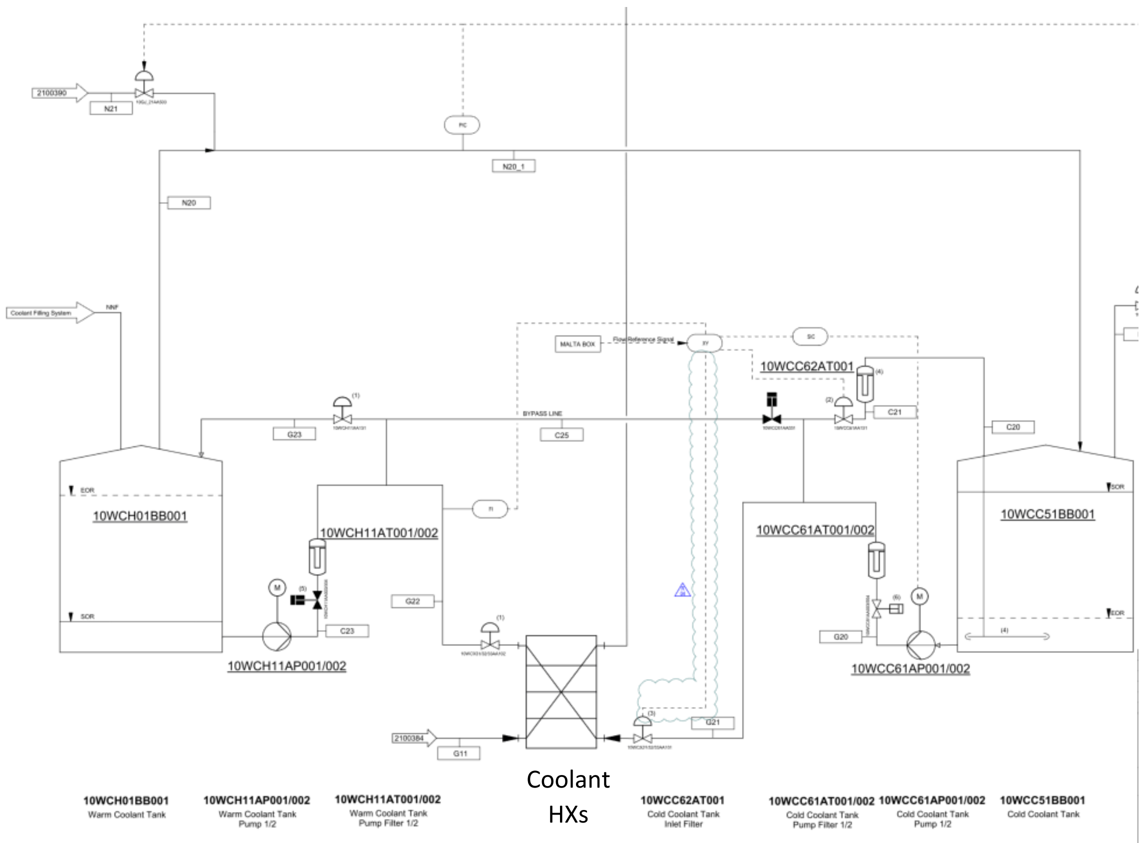

Figure 18: Preliminary PFD – Coolant System in Discharge Mode

5.2.4. Discharge Heat System Description

The Discharge Heat System removes excess heat from the cycle during the discharge process. This excess heat (~120°C) could be used for district heating and/or other industrial processes. The Discharge Heat system consists of a tank of Paratherm, two centrifugal pumps (in parallel), the air cooler, an optional "Paratherm Trim Cooler," associate piping and valves. These are shown in the preliminary PFD for the Discharge Heat system, Figure *19*.

During the discharge process, Paratherm is circulated from the tank to the heat rejection heat exchanger (HRHX), where it removes the heat from the air. In the process, the Paratherm is heated up from ambient to around 120°C. The hot Paratherm is cooled down using the dry air coolers before it is circulated back to the Paratherm tank. The Paratherm tank is blanketed with nitrogen and its pressure is controlled with appropriate feed and bleed valves. Flow rate of the Paratherm is controlled by using pump speed and/or control valves.

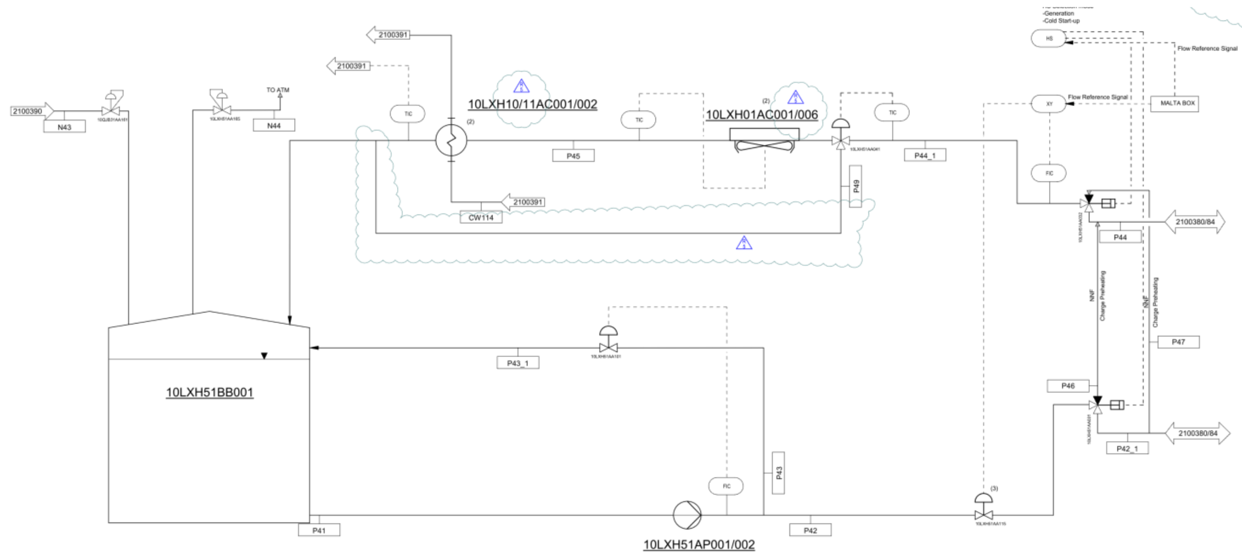

Figure 19: Preliminary PFD – Discharge Heat System Discharge Mode

The operating pressure of the Discharge Heat System is less than that of the air loop system for all operating modes, including partial load and transients. This ensures that hydronic fluid does not leak into the air loop and safeguards against failure of the turbomachinery and the air loop piping system.

5.2.4.1. Evaluation of Reusability of Unit 5 Cooling Tower

Cliffside Unit 5 has a cooling tower that is used to remove the heat from the steam cycle. An evaluation was done to see if it is worthwhile to reuse this cooling tower in the Malta PHES system in place of the air cooler.

The Unit 5 cooling towers consists of 18 bays, divided into two groups. Based on their capacity, about 2-3 of these bays would be needed to remove all the discharge heat from the Malta PHES system during the discharge process. However, the cooling tower cannot be directly integrated into the discharge heat system because of two main reasons:

- Cooling tower is designed for wet bulb temperature of around 76F (~25°C), which is much lower than Paratherm temperature of 120°C
- Paratherm cannot be sprayed directly on the cooling tower.

For the cooling tower to be reused, a Paratherm to water HX (called Paratherm Trim Cooler) needs to be added to the downstream of the air cooler (as shown in Figure *19*). In this process, the Paratherm is first cooled by the air cooler from 120°C to about 85°C. Then, the Paratherm Trim Cooler cools it further down to about ambient temperature. The secondary side of the Paratherm Trim Cooler is water. This water would go the existing cooling tower and get cooled down before returning to the Paratherm Trim Cooler. A schematic of this configuration is shown in Figure 20. It should be noted here that the existing cooling tower needs a large refurbishment for it to be used for another 30 years. In addition, the water piping from the Paratherm Trim Cooler needs to go across the river from the proposed location for Malta system to the existing Unit 5 Cooling Tower (see Figure *11*). This further adds additional cost and complexity.

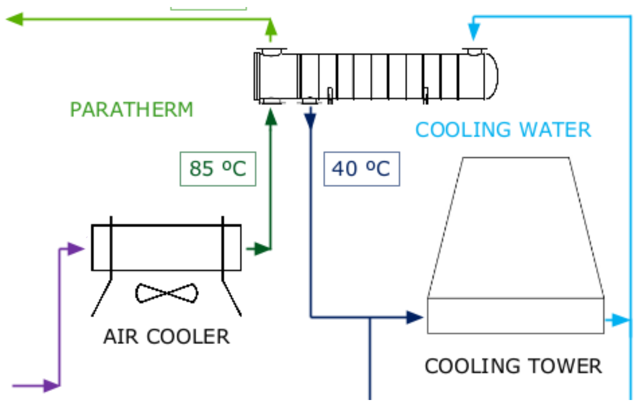

Figure 20: Schematic of Integration of Air Cooler, Paratherm Trim Cooler and Cooling Tower

Table *11* compares between the standard option of dry air cooler design vs. reusing the cooling tower. Overall, the standalone air cooler option is preferred. While it is a little more expensive (~10%) in terms of initial CAPEX, it is much simpler and has lower OPEX as compared to the Cooling Tower Reuse option. Also, the stand-alone air cooler option does not need water/water treatment, which is required for cooling tower. The cost of water + water treatment over time can add up.

Table 11: Comparison between Standalone Air Cooler and Reuse of Cooling Tower

Parameter	Standalone Air Cooler	Re-Use Coal Plant Cooling Tower
Major equipment and normalized CAPEX	Full set of air cooler fans: 1.0	Half of the Air Cooler: 0.5 Paratherm Trim Cooler: 0.1 Retrofit of two cooling tower bays: 0.3 Total: 0.9
OPEX	Lower, only needs electricity	Higher, need electricity, water, and water treatment.
Complexity	Simple	High

5.2.5. Electrical System Description

The main function of the Electrical System is to ensure reliable connection between the Electrical Grid to the Malta PHES plant's Charge Motor, Discharge Generator, and the Electrical Auxiliaries. The electrical system is a collection of systems and components that enable electricity flow between the grid interconnection point and plant electrical machines with an appropriate protection system. It also provides electrical power to all the components in the plant at an appropriate rating. The electrical system includes the plant switchyard, step-up transformer, auxiliary power transformer, MV switchgear, MV/LV Power transformers, Power Centers, Motor Control Centers (MCC), LV/LV Power transformers, lighting and miscellaneous services distribution boards, lighting system, lightning protection, grounding system, emergency generator, Direct Current (DC) system, and back-up Uninterruptible power system (UPS). The electrical system interfaces externally with the interconnection point and internally with all the power components and systems including the power island and energy island.

Figure 21 shows the preliminary Single Line Diagram (SLD) that indicates connections between the major equipment of the Malta PHES plant and the substation. As currently envisioned, there is only one main connection between the plant and the substation. There is one main utility meter measuring energy transferred between the plant and the grid. However, separate circuit breakers and utility meters are used for each of the major loads. Trip logic is implemented at each circuit breaker to ensure protection of the grid and the plant equipment. The discharge generator and the charge motor are driven by a shared VFD. The load used by VFD is measured with the auxiliary utility meter. The charge motor and discharge generator have voltage around 16.5kV and 13.8kV, respectively. The grid line voltage is assumed to be 345 kV line; therefore, the main step-up transformer is rated for 345kV/16.5-13.8kV. The voltage for auxiliary load is currently designed for 600V.

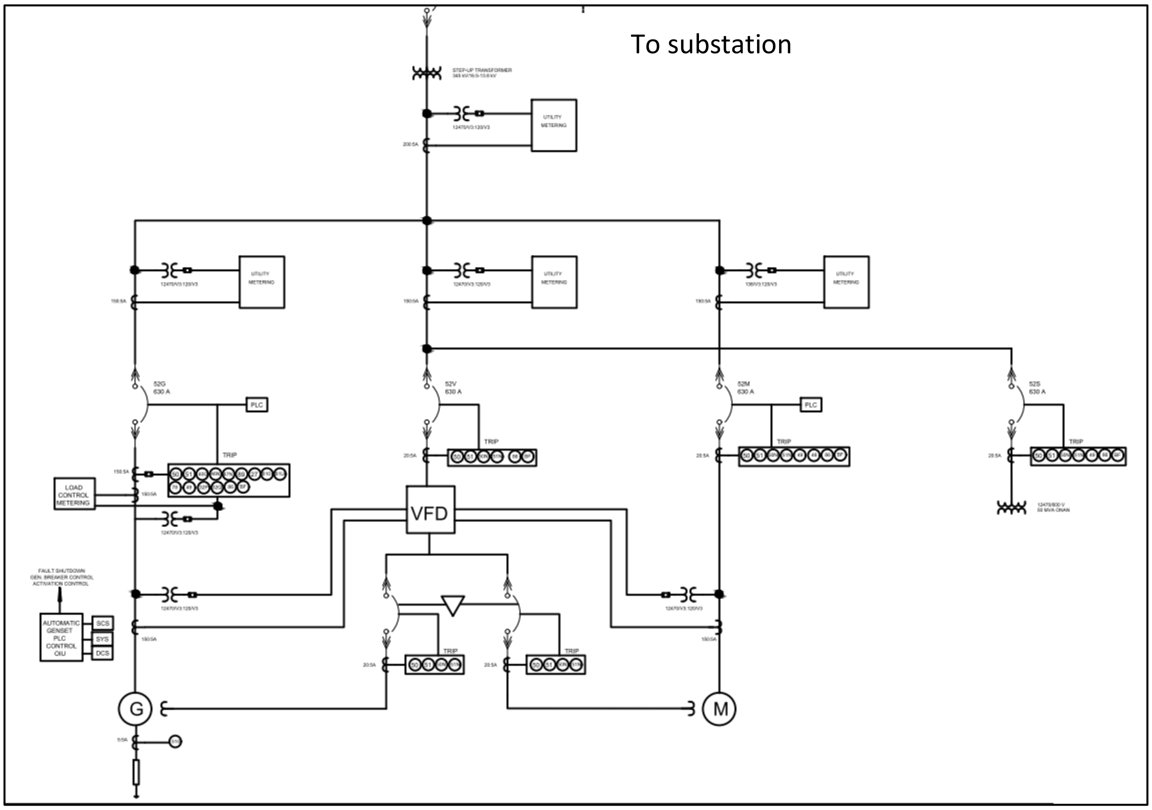

Figure 21: Preliminary Single Line Diagram Showing Connection between Substation and Major Equipment in the Malta Plant

5.2.5.1. Evaluation of Reusability of Coal Plant Electrical System Equipment.

An evaluation was done to see if any major electrical equipment from Cliffside Unit 5 electrical system could be reused. In general, discussion with Unit 5 electrical engineer indicated that most of the electrical equipment for Unit 5, except for a couple of small switch gears, is near the end of life. To reuse them again either requires major overhaul (if possible) and/or full replacement. Therefore, we only evaluated three main big items that could have potential cost saving. These included Unit 5 generator, Unit 5 main step-up transformer and Unit 5 Switchyard/substation.

Unit 5 Generator: This generator is rated for approximately 570MWe with voltage output of 24kV. This generator is cooled with hydrogen. This is quite different from the Malta PHES discharge generator which is rated for 100 MWe at 13.8KV and is air cooled. Discussion with the generator vendor indicated that while there is no obvious showstopper in downgrading the generator from 570MWe to 100MWe, detailed study needs to be done to make sure there is no limitations on things like short circuit behavior and cooling. In addition, the generator vendor themselves do not have much experience performing such a large downgrade. Their main assessment was that this may not be the most optimal path.

With respect to potential cost saving, according to Duke Energy, for this generator to be used again for another 30 years, a major overhaul is needed. The cost of this overhaul is almost as much as a brand-new Malta PHES 100 MWe generator. Between the cost of the detailed study and potential modification required for reusing Unit 5 generator, and the additional cost of hydrogen cooling (Malta system currently does not have), very minimal cost saving may be realized. Therefore, it was determined that it is not worthwhile to reuse Unit 5 generator.

Unit 5 Main Step-up Transformer: Current Unit 5 step up transformer is rated for 133-230KV/22.8KV and 690/750MVA while the main step-up transformer for the Malta PHES is rated for 345KV/16.5-13.8 KV and 200/250MVA. This means that Unit 5 transformer is oversized for what the Malta system needs and would cause some more loss and reduce system efficiency. In addition, for the Unit 5 transformer to be used for the Malta system voltage, rewinding of the transformer would be required. According to Duke Energy, the Unit 5 main step-up transformer is also at the end of its life and would need major overhaul if it is to be used again for another 30 years. Between the cost of major overhaul and complexity of redesigning and redoing the winding coils, it was determined that it is not worthwhile to try to re-use Unit 5 Step-up Transformer.

Unit 5 Main Switchyard/Substation: For Integration Option 1, this is the main cost and potential schedule saving. According to Duke Energy, building a new switchyard/substation with 230KV lines on a greenfield would cost at least $20MM. Figure 22 shows the representative SLD for Unit 5 Substation. This substation is one-and-a-half configuration, which is a reliable solution. There are two connections from the substation to the Unit 5 Electrical System. One connection is for the main transformer and generator and the other connection is for the auxiliary transformers load.

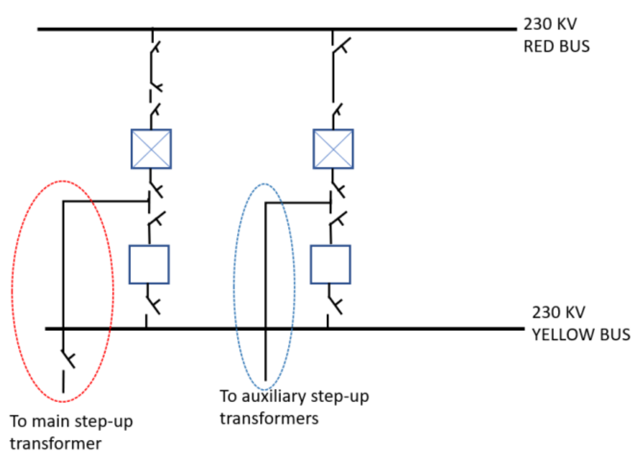

Figure 22: Representative Single Line Diagram (SLD) for Unit 5 Substation

The substation equipment detailed information was not available (due to the nature of Critical Infrastructure), therefore, no specific detailed calculation was done. However, it was determined that the connection from the substation to the existing step-up transformer (red circle), should be reusable for the Malta system. Calculation will need to be done in the future to determine the exact protection relays. The second connection point to the existing auxiliary transformer is not necessary for the Malta PHES electrical system because the Malta PHES only needs one connection point.

5.3. Transient Simulations

5.3.1. Transient Model Description

A transient model was developed to evaluate basic operations of the Malta PHES system for charge and discharge processes. This is a detailed physics-based model of the Malta PHES system in the Modelica modeling language, using the commercial Dymola platform with validated Thermal Power Library (TPL) components by the systems modeling and simulation software company Modelon AB. Dimensional and performance parameters for each piece of standard equipment are input by the Malta team based on OEM equipment data sheets and specifications. Particular attention has been paid to the non-standard equipment within the power loop under development by vendors.

The heat exchanger models utilize Modelon's standard heat exchanger component models with physical dimensions. The resulting subsystem-level heat exchanger models were then validated against HX data-validated models.

TM performance maps for each of the turbomachinery elements (charge compressor, charge generator, discharge compressor, discharge generator) that relate the inlet and exhaust conditions of each element were modeled. The air leakage through the turbomachinery seals is also captured through characteristics specified for each TM. The performance of the two electrical machines (the charge motor and the discharge generator) are captured through mechanical and electrical efficiencies and a combined drivetrain inertia.

The performance maps were generated with TM high fidelity multi-physics modeling tools that have been validated through decades of development and operations experience. These analytical toolsets are validated against test stand operation and against fleet data of fielded designs. The tools used to model drivetrain characteristics have also been validated against test stand operation and field data of equipment from the same family.

The turbomachinery dynamics model utilizes these performance maps, which have been validated with both test facility data and fleet experience data, and that the equipment for Malta is within the data-validated experience range of these models.

Air loop components such as pipes and valves are modeled using standard model components without modifications and using component specifications. Fluid loop components are similarly based on unmodified library components and physical characteristics of the equipment.

The steady-state performance of the transient, system-level model is checked against the steady-state model by simulating the transient model under steady-state-like conditions—by holding inputs steady for long durations of time.

For this study, this transient system model is utilized for evaluation of basic operations of the Malta PHES system. Typical simulation conditions of the transient model include startup, shutdown, load charge and trip for charge and discharge processes. Critically, these simulations enable us to ensure that the anticipated operation of the plant during both normal operation and emergency scenarios is well below the transient capabilities and limitations of the underlying equipment, further ensuring that the underlying equipment will not be unduly stressed by transient operation, which will be important for future equipment lifetime calculation.

5.3.2. Charge Cycle Transient Results

The Preliminary Full Charge Cycle simulation results are shown in this section. To establish the initial conditions of the simulation, a Full Charge cycle was simulated and the resulting state of the system at the end of the cycle were used. At the start of the simulation, the pressure in the air loop is equalized and is at the system's settle-out pressure.

The experiment is set up as follows:

- Charge Drivetrain is accelerated to full speed and synchronized to the grid – Breaker is closed at 275 seconds.
- When the Malta PHES Plant is connected to the grid, the plant power is commanded to ramp up to 100% load.
- Steady-state operation until 3500 seconds (this is an arbitrary duration, can be much shorter or longer)
- Turndown to minimum plant power of 25% is initiated at 3500 seconds
- Charge drivetrain shutdown initiated at 4000 seconds when the system is at minimum power.

The plot below shows the rotor speed and power consumed during the full charge cycle simulation. The rotor is accelerated to full speed using a Voltage Source Inverter (VSI) and connected to the grid once synchronized. During shutdown, the VSI is assumed to be used to bring the power down to 0 MW before disconnecting from the grid in the real plant. However, in this simulation, the drivetrain is allowed to coast down during shutdown after disconnecting from the grid. The oscillations seen during steady-state operation of the plant at full speed in the plots will be improved by optimizing the plant controllers. The spike in power at breaker closure is a simulation artifact (will be removed in future simulations) and not representative of the real system behavior.

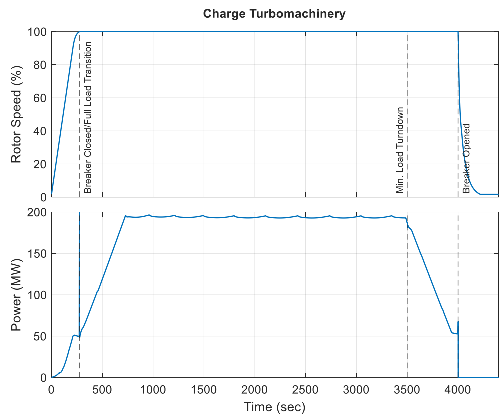

Figure 23: Preliminary *Charge cycle rotor speed and power curves*

The plots below show the pressures and temperatures at the boundaries of the turbomachinery during this cycle. Temperature profiles during transients may be improved by using better controllers.

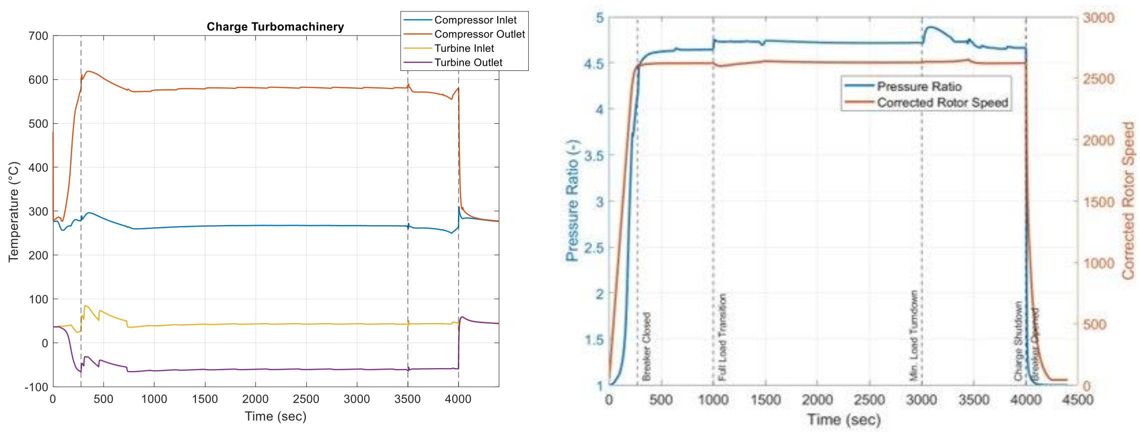

Figure 24: Preliminary *Charge Cycle Turbomachinery Temperature and Pressure Ratio*

5.3.3. Discharge Cycle Transient Results

The Preliminary Full Discharge cycle simulation results are shown in this section. To establish the initial conditions of the simulation, a Full Discharge cycle was simulated and the resulting state of the system at the end of the cycle were used. At the start of the simulation, the pressure in the air loop is equalized and is at the system's settle-out pressure.

The experiment is set up as follows:

- Discharge Drivetrain is accelerated to full speed and synchronized to the grid – Breaker is closed at 275 seconds.
- When the Malta PHES Plant is connected to the grid, the plant power is commanded to ramp up to 100% load.
- Steady-state operation until 3000 seconds (this can be much shorter or longer)

- Turndown to minimum plant power of 25% is initiated at 3000 seconds
- Discharge drivetrain shutdown initiated at 3480 seconds when the system is at minimum power.

The plot below shows the rotor speed and power consumed during the full discharge cycle simulation. The rotor is accelerated to full speed using a load commutated inverter and connected to the grid once synchronized. During this period, the drivetrain is kept net power absorbing. During shutdown, load in the system is reduced to close to 0 MW in a controlled manner at which point, the plant is disconnected from the grid. The drivetrain is allowed to coast down during shutdown after disconnecting from the grid. The oscillations seen during steady-state operation of the plant at full speed in the plots will be improved by optimizing the plant controllers. The spike in power at breaker closure is a simulation artifact and not representative of the real system behavior.

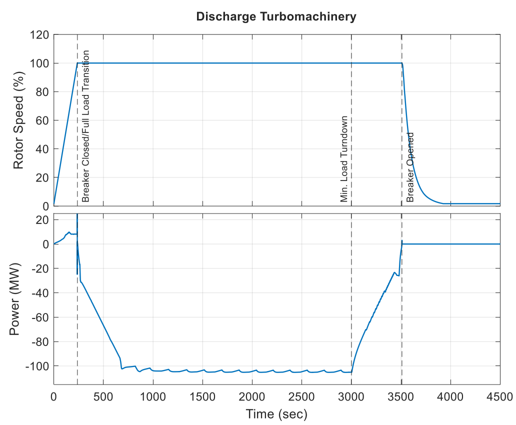

Figure 25: Preliminary Discharge cycle rotor speed and power curves

The plots below show the pressures and temperatures at the boundaries of the turbomachinery during this cycle. Temperature profiles during transients may be improved by improving the controllers.

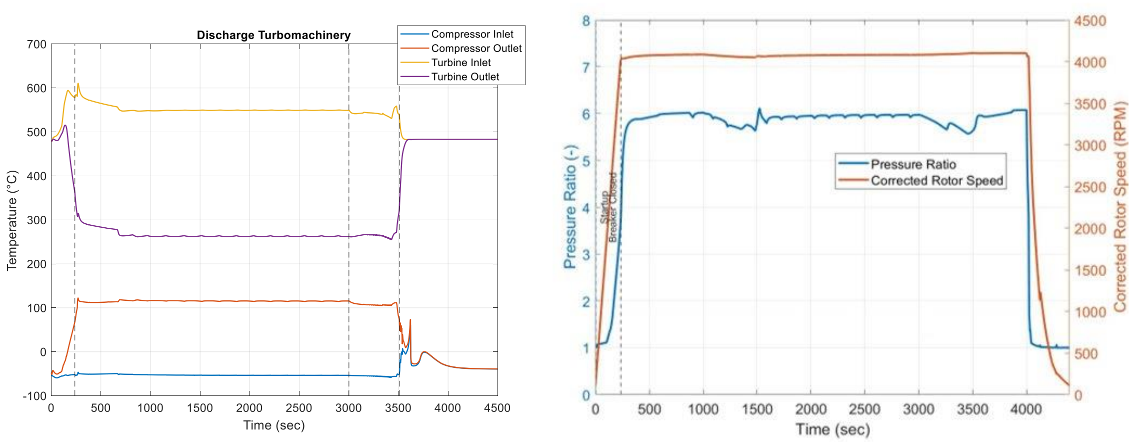

Figure 26: Preliminary Discharge Cycle TM Temperature and Pressure Ratio

5.3.4. Charge Trip Transient Result

The preliminary charge trip simulation results are shown in this section. The system is initialized at full load charge steady-state condition.

The experiment is set up as follows:

- The system is at steady state full load from 0 to 100.1 seconds
- At 100.1 second: trip is initiated by opening the breaker
- At 100.6 second: trip is detected
- 100.6 to end of transient: trip protection algorithm takes place to put the system in a safe state.

The next three figures show the preliminary rotor speed, power, temperatures, and pressure ratio of the TM during this transient. As shown, the power dropped quickly once the trip is initiated. The pressure ratio of the TM always stays below the surge line, ensuring the TM is always protected. The temperatures at the inlet and outlet of the TM stayed within their limits.

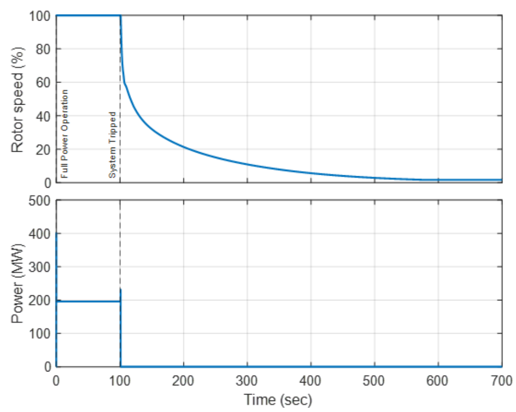

Figure 27: Preliminary *Charge Trip Turbomachinery Rotor Speed and Power*

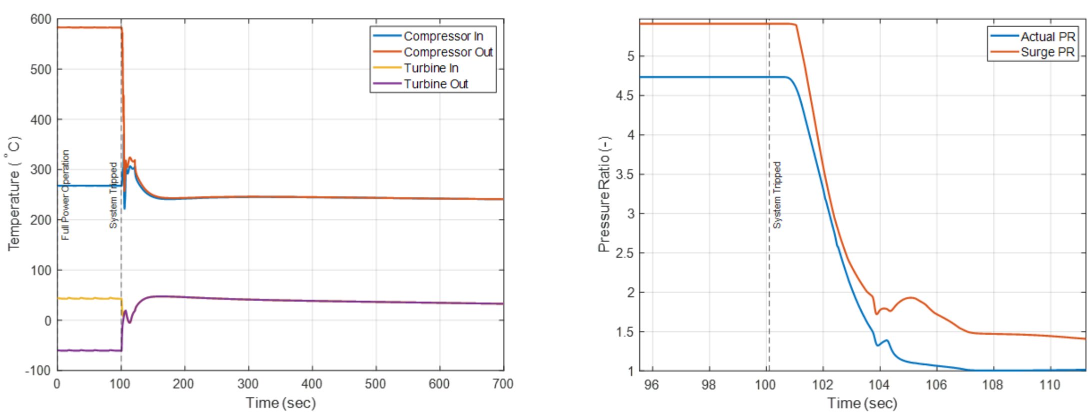

Figure 28: Preliminary Charge Trip Turbomachinery Temperature and Pressure Ratio

5.3.5. Discharge Trip (Overspeed Event) Transient Result

The preliminary discharge overspeed event simulation results is shown in this section. The system is initialized at full load discharge steady-state condition.

The experiment is set up as follows:

- The system is at steady state full load from 0 to 200.1 seconds
- Rotor overspeed from 200.1 to 202.7 seconds
- At 202.7 second, overspeed is detected
- From 202.7 to 600 seconds: Overspeed protection algorithm takes place to trip and put the system in a safe state

The next three figures show the preliminary rotor speed, power, temperatures, and pressure ratio of the TM during this transient. As shown, the rotor speed initially increased to ~110% before trip is initiated. Once that happened, the speed of the rotor dropped. The temperatures at the inlet and outlet of the TMs stayed within their limits.

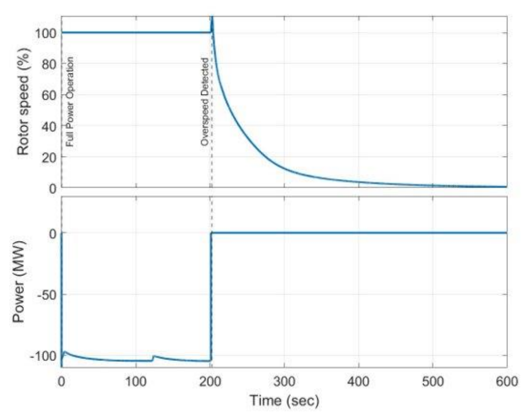

Figure 29: Preliminary Discharge Trip Turbomachinery Rotor Speed and Power

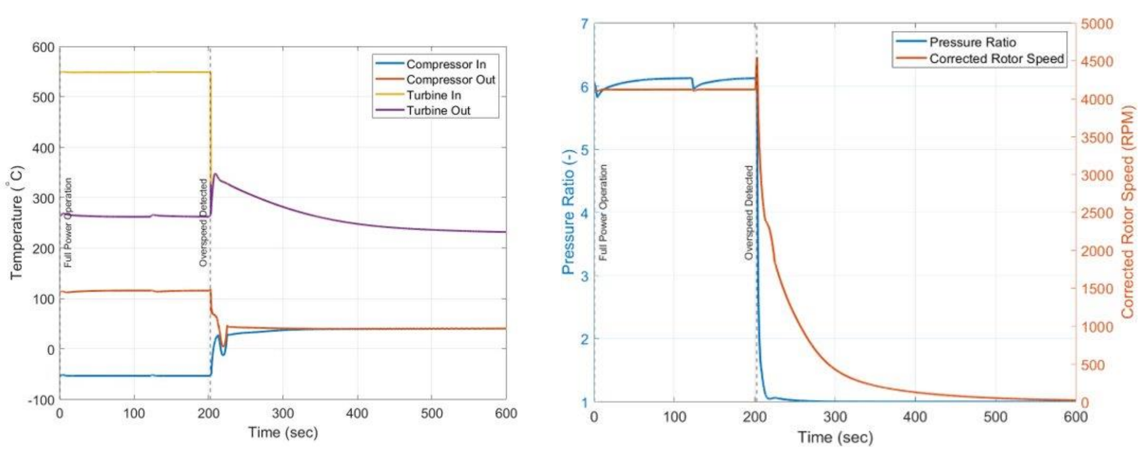

Figure 30: Preliminary Discharge Trip Turbomachinery Temperature and Pressure Ratio

5.3.6. Transient Results Summary

The previous four subsections showed the preliminary results of the typical transients the Malta PHES are expected to experience. Overall, it was shown that the system behaved as expected. The results showed that the system is operable. In case of an emergency trip (such as overspeed during discharge), the system could be brought to a safe state without any major complications. Since the results are preliminary, there are areas of improvement that can be done in the future. In particular, the followings have been identified:

- The current simulations still used lot of open loop controls. More closed loop controls would help to smooth out some of the profiles during these transients.
- Removing of any simulation artifacts that are not physical.
- Continue to integrate new data from equipment vendor to ensure the model is up-to-date and meet the different limits.
- Further optimization to minimize any large pressure and/or temperature ramp.

6. Economic Impact Analysis

6.1.1. Overview of Economic Impact Analysis

In this section, results from economic impact analysis are presented. The economic impact was evaluated at both the electric grid level and at the local community level. The economic impact analysis was done for Integration Option 1 assuming that it will be located at Mayo, the 2nd alternative site (during site selection process) instead of Cliffside 5. While this is counter-intuitive because all the technical work was done based on Cliffside 5, there were good reasons to do economic analysis with Mayo 5, which are described below.

- **Equality during site selection**: during the site selection process, Cliffside 5 and Mayo were the two final candidate host sites. Their overall score was essentially the same (within uncertainty). One driving factor for choosing Cliffside 5 during Phase 1 of the study was that it would be much easier to obtain detailed technical information at Cliffside 5 than at Mayo. The detailed heat and mass balance for the Steam-Ranking cycle was essential for evaluation of the different integration options during Phase 1. It was unlikely that the project team could obtain the same information from Mayo plant in a timely manner for the study.

- **Translatability of technical work from Cliffside 5 to Mayo site**: For Integration Option 1, where one only mainly reuses the grid interconnection of a coal plant for a stand-alone Malta PHES, all the conceptual design work in this report should be appliable to both sites. Because Mayo site is rated for 727MW interconnection, which is larger than the 560MW rated power of Cliffside, there should be no reason that Mayo site interconnection cannot be reused for the Malta system. In fact, Mayo site has better readily available land as compared to Cliffside 5, where some trees need to be cleared out for the Malta system.

- **Economic Analysis Results at Mayo are more translatable beyond Duke**: For Cliffside site, once unit 5 is retired, there is still Unit 6 onsite (that can burn gas). Unit 6 is not in the schedule to retire any time soon so even if Unit 5 is retired and decommissioning, there is still lot of activities at the site with Unit 6 still operating. For Mayo site, there is only one unit. Once the plant is retired and decommissioned, there would be no more economic activities at the site. This would have a large impact on the local community. For many coal plants, the situation is more like Mayo than Cliffside. Therefore, the economic impact, especially on the local community, at Mayo would be more translatable to other coal plants across the countries. Most of other coal plant sites, once the plants retire, there would be nothing left unless it is repurposed into something such as long duration energy storage systems described in this study.

6.1.2. Grid Benefit Impact Analysis by Duke Modeling Team

The economic benefit for the grid was calculated entirely by the Duke Energy ISOP team using EnCompass modeling suite. The Malta system cost (CAPEX, OPEX) and technical performance were provided to the Duke Energy ISOP team. As previously stated, the model was done with the assumption that the Malta PHES system would be located at Mayo in DEP territory. The benefit was calculated using the following major steps:

a. **Pick a base case scenario**: here DEP IRP 2020 [2] Portfolio D scenario was chosen as the base case. This scenario "outlines a pathway for the Carolinas combined system to achieve 70% CO_2 reductions, from a 2005 baseline". The IRP scenarios assumed high amount of offshore wind but for the analysis, the offshore wind was removed.
b. **Calculate Base Case Net Present Value Revenue Requirement (PVRR):** calculate how much it would cost to have a system that meets base case scenario from 2025 to 2045.
c. **Run the Base Case again with each of the following modifications:**
    - Remove 100 MW of 4hr Li-on battery and add 100MW-10hour Malta PHES system – This is to compare the value of the 100MW-10-hour Malta PHES to a 4-hour battery.
    - Remove 100 MW of 10hr Li-on battery and add 100MW-10hour Malta PHES system – This is to compare the value of the 100MW-10-hour Malta PHES to a 10-hour Lion battery.

The models provided output data such as the hourly dispatch profile of the Malta PHES system, as shown in the Figure 31 for 2035. The results of the grid benefits to Duke Energy are as follows:

- 100MW of Malta PHES with 10hr storage had a substantial savings through 2045 compared to 10hr Li-ion. The CAPEX and OPEX of both systems were included. CO_2 cost is excluded.
- 100MW of Malta PHES with 10hr storage had compelling savings through 2045 compared to 100MW of 4hr Li-ion storage. The CAPEX and OPEX of both systems were included. CO_2 cost is excluded.

Overall, the Malta PHES system had compelling savings for Duke Energy compared to Li-on battery (same power) for the scenario considered.

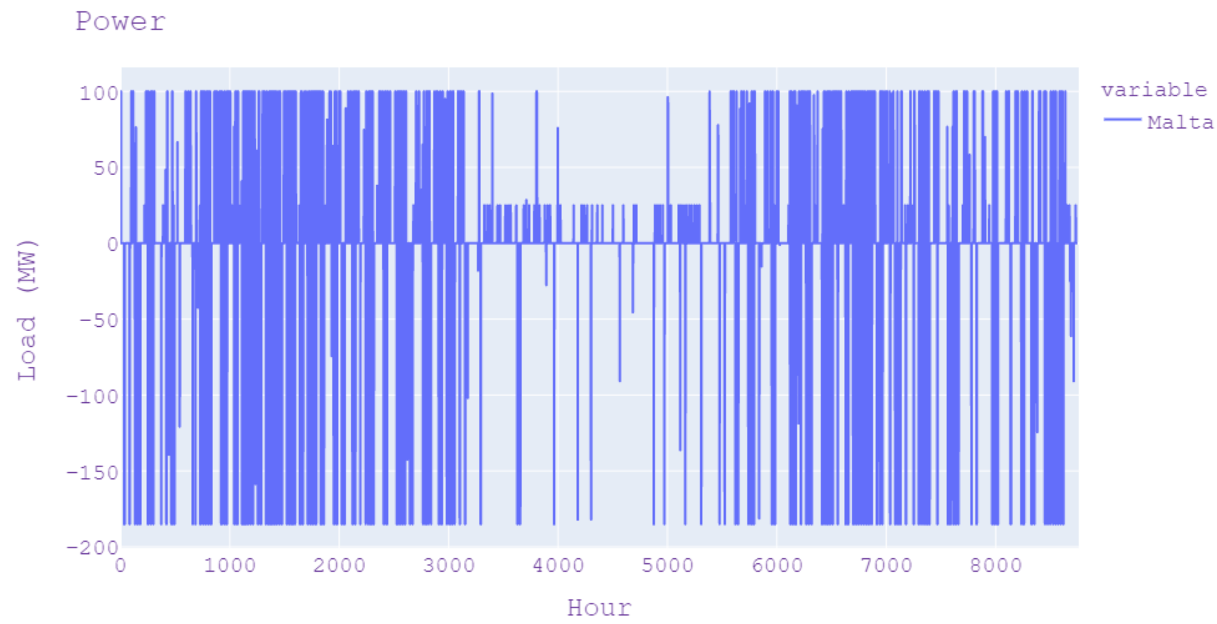

Figure 31: Hourly Dispatch Profile of a Malta System in 2035

6.1.3. Local Economic Impact Analysis

The local economic impact analysis was performed by EIP, one of the participants in this study. EIP performed the analysis with the assumption of the Malta PHES system repurposing Mayo coal plant.

This analysis focused on the region highlighted below. This represents the county the project is in (Person County, NC) as well as the adjacent counties in NC and VA. These are generally rural counties with a total population estimate of 156,448 as of 7/1/2021[4] .

Economic impact would be felt in four different ways: 1) the one-time positive economic impact of the decommissioning of the Mayo plant; 2) the negative economic impact of ceasing of operations of the Mayo plant, including local spending, jobs and taxes; 3) the one-time positive local economic impact of the construction of the Malta plant; and 4) the positive economic impact of the operations of the Malta plant on local spending, jobs and taxes (together, the "Activities"). This analysis did not attempt to quantify any benefits outside of the Selected Region, or beyond economic impact, nor any environmental impacts.

Selected Region

Given the focus on local economic impact, the analysis was limited to the following counties, which are used as the proxy for the local area surrounding the plant:

Caswell County, NC
Granville County, NC
Person County, NC
Halifax County, VA

<u>Multipliers</u>

These impacts are felt not only from demand by the Activities, but from the subsequent spending in the local community by companies and individuals being paid for

[4] Data.census.gov accesses February 2nd, 2022.

goods at services by the Mayo plant and/or the Malta facility. In addition, spending by these Activities would not all occur in the Selected Region. The follow-on impact of the Activities was assessed through economic multipliers, which are used to reflect the total impact of a project or activity on a region. Specifically, the multipliers were applied to projected local spending related to the Activities. This local spending must be assessed and quantified at the beginning of the analysis to avoid over-counting the impact of a project. Given the Selected Region is rural and relatively sparsely populated, local spending is expected to come largely from wages and locally procured commodities and services.

Input-output models measure the flow of goods and services within a local economy. The model shows how a change in one area of the economy affects other parts of the economy. This analysis utilized the U.S. Department of Commerce's Bureau of Economic Analysis's ("BEA") Regional Input-Output Modeling System ("RIMS II") county level multipliers for the Selected Region for the Electric Power Generation, Transmission and Distribution and Construction industries as defined by the BEA. This included both Type I and Type II multipliers. Type II multipliers consider interindustry and household spending of the change in Final-Demand, while Type I do not account for changes in household spending. Type I are more appropriate when the location of the spending by labor is uncertain, as with construction. For this reason, Type I was used for the impact of the construction of the Malta facility and the decommissioning of the Mayo plant, and Type II for the rest of the analysis. BEA's Industry Detailed Multipliers for the Electric Power Generation, Transmission and Distribution and Construction industries were used for calculating the industry level detailed impact.

In addition to the inputs from BEA, the study relied upon inputs from Duke and Malta for the construction and decommissioning costs and O&M of the facilities. Because the bulk of the decommissioning costs will not be incurred until several years in the future and the actual decommissioning will take place over many years, Duke Energy was only able to provide a high-level budget. The budget was compared with an October 2017 report by Resources for The Future entitled *Decommissioning US Power Plants: Decisions, Costs and Key Issues*, which provided high-level guidelines for typical costs in decommissioning a US coal fired power plant. The percentage break down of these costs was applied to the Duke Energy budget (except for asbestos abatement, given the Mayo plant was constructed in 1983).

<u>Local Allocation</u>

As mentioned above, the local component of spending must be determined to accurately apply the multipliers. In addition to the challenges presented with the early-stage nature of the construction projects, Duke relies on several companywide services and generally does not classify facility budgets or spending based on location of spending. Consequently, in addition to conferring with the management of the Mayo plant and the team at Malta, the analysis utilized the National Renewable Energy Laboratory's ("NREL") Jobs and Economic Development Impact ("JEDI") models for concentrating solar power ("CSP") and coal generation for determining the local share of construction and O&M for the Malta Facility and the Mayo Plant. NREL specifically designed the model to allow for quick and detailed analysis of the economic benefit of certain renewable energy projects. CSP has several of the same operating needs as the Malta facility, and coal generation is clearly in line with the Mayo plant. While CSP equipment has some significant differences from Malta, JEDI's local share of O&M should be a reasonably good proxy for Malta. It should be noted that while the JEDI model is a state level model, it can be modified to look at smaller population regions. For this reason, the JEDI model is a reasonable proxy for the local share of spending for the Activities.

Finally, the Consumer Price Index and a 2% rate of inflation were used for calculating future costs. Costs were discounted to the 2019 multiplier year, and the local sales tax and property tax rates were used for calculating taxes (assuming all taxes are paid in NC with no abatements granted).

Economic Factors

The report focused on the following economic impacts, as defined by BEA, calculated by their respective multipliers:

Final-Demand Output – The impact on total output for the selected region based on the Final-Demand.

Final-Demand Earnings – The total change in household earnings per dollar of Final-Demand change, for the selected region. This includes wages, salaries, and business owner incomes, sometimes referred to as proprietors' income.

Final-Demand Employment – The impact on the total change in employment, per one million dollars of final demand, for the selected region. This is in addition to the jobs generated by the two plants. It should be noted that generally partial jobs are not reflected in local economic impact analysis and thus this number is usually rounded down to the nearest whole job.

Final-Demand Value-Added – The total change in value added, per dollar of final demand, for the selected region. This is comparable to the region's GDP.

Local Economic Impact Result Summary:

The economic impact of the Mayo plant in the Selected Region is significant, especially considering the rural nature and low population density of the area. It is expected that Mayo's shut down will have a significant negative economic impact on the Selected Region (defined below). Construction of a Malta facility can offset this somewhat, by providing a significant one-time positive impact during construction and a long-term positive impact through the retention of jobs for the operations and maintenance ("O&M") of the Malta facility. Table *12* summarizes the economic impact in the Selected Region of the shutdown and decommissioning of the Mayo plant and the construction and operations of the Malta facility.

Table 12: Summary of Local Economic Impact – plant basis.

Summary					
Activity	**Final-Demand Output**	**Final-Demand Earnings**	**Final-Demand Jobs**	**Final-Demand Value Added**	**Comments**
Loss of Mayo Plant O&M	$(12,855,829)	$(1,823,731)	(21)	$(7,446,903)	Ongoing
Decommissioning of Mayo Plant	$7,405,152	$2,327,385	44	$3,776,051	One-time
Construction of Malta Facility	$39,040,482	$12,270,134	236	$19,907,603	One-time
O&M of Malta Facility	$3,226,311	$457,685	5	$1,868,882	Ongoing

It should be noted that the Malta facility has not been sized to replace the Mayo plant on a one-to-one basis. The proposed Malta facility size is based on the current design and engineering parameters for Malta. For this reason, it is worth looking at the local economic impact of the above categories on a per MW basis. This gives some idea as to the overall impact of a full replacement of the Mayo plant by a Malta facility. Table 13 provides the output on a per MW basis. It shows a net positive impact on an ongoing as well as one-time basis per MW of capacity.

Table 13: Summary Economic Impact – per MW basis.

Per MW of Facility Output					
Activity	**Final-Demand Output**	**Final-Demand Earnings**	**Final-Demand Jobs**	**Final-Demand Value Added**	**Comments**
Loss of Mayo Plant O&M	$(17,683)	$(2,509)	(0.03)	$(10,243)	Ongoing
Decommissioning of Mayo Plant	$10,186	$3,201	0.06	$5,194	One-time
Construction of Malta Facility	$390,405	$122,701	2.36	$199,076	One-time
O&M of Malta Facility	$32,263	$4,577	0.05	$18,689	Ongoing

The economic impact will not be felt evenly across the Selected Region. Some industries will see a significant positive impact while others will feel a loss of economic activity.

Table 14 illustrates the top five most positively impacted sectors,[5] as well as the top 5 most negatively impacted sectors.

[5] Data.census.gov accessed February 2nd, 2022.

Table 14: Summary Economic Impact – Industry Detail (plant basis).

Top 5 Highest Impacted Industry Sectors - Gain				
	Final-Demand Output	Final-Demand Earnings	Final-Demand Jobs	Final-Demand Value Added
Construction	$37,197,787	$12,700,510	233	$19,171,263
Durable goods manufacturing	$2,782,130	$340,133	6	$1,039,057
Retail trade	$1,819,667	$575,154	22	$1,153,819
Nondurable goods manufacturing	$1,002,123	$89,334	1	$278,976
Transportation and warehousing*	$607,414	$163,333	3	$261,522

Top 5 Highest Impacted Industry Sectors – Loss				
	Final-Demand Output	Final-Demand Earnings	Final-Demand Jobs	Final-Demand Value Added
Utilities*	$(8,004,989)	$(974,129)	(7)	$(4,647,713)
Health care and social assistance	$(136,636)	$(42,910)	(0)	$(83,449)
Food services and drinking places	$(29,787)	$(6,545)	(0)	$(15,684)
Educational services	$(5,755)	$(3,953)	(0)	$(3,383)
Accommodation	$(1,802)	$(791)	(0)	$569

*As defined by the Bureau of Economic Analysis

It should be noted that these sector level economic impacts include the onetime impacts of the Mayo plant decommissioning and the Malta facility construction. These one-time vs ongoing impacts are broken out below.

Overall, the analysis shows that while the loss of the Mayo plant will have a significant impact on the local economy, the construction of the Malta facility will add a significant one-time Final-Demand Output impact of over $39 million and 236 jobs (excluding direct plant employment) and will offset the ongoing negative economic impact of the closure of the Mayo plant by contributing approximately $3.2 million annually to Final-Demand Output and at least 5 jobs to the local economy.

7. Technology Gap Assessment Summary

For Integration Option 1, at the beginning of the project, the Technology Readiness Level (TRL) was determined to be at level 2. This corresponds to high level concepts and some initial intended applications of this options being formulated. At the end of this project, TRL of the Integration Option 1 is at least at level 3, which corresponds to Proof-of-Concept validation has been achieved. The work described in Section 5 and Section 6 demonstrated that Integration Option 1 is more cost effective than a standalone Malta system (the main cost saving is in grid interconnection and substation). This options also provides economic benefits to Duke Energy and local community where it will be located.

With respect to the main electrical integration, technically, there is no obvious showstoppers for the Malta PHES to use existing grid interconnection of a retiring coal plant. Detailed calculations will need to be done and some minor modifications may be required to get optimal configuration between the Malta electrical system design and the available grid interconnection point. However, there is no new technology required.

With respect to the rest of this Integration Option 1, evaluation was done on which components/systems would need further development to advance to TRL 6 (or higher). Only one major critical technology element, the Integrated System Technology, was identified as one that would need further work to advance to TRL 6. For this project, very rudimentary control logics were used in the simulation of the different transients (start up, shutdown, trips, etc.). For example, some of the fluid flow rate controls were done using tables of pump speed vs. time. Certain valves opening and closing time were done using tables as well. Very few closed-loop control was implemented. Nevertheless, the work completed here showed that the integrated system technology is feasible. For the control and integration to advance to TRL level 6 (or beyond), the following development work needs to be done:

- Further development of control and integration system by implementing more sophisticated closed loop controls to ensure the system not to exceed its design conditions in different transients.
- Perform verification and validation of control and integration methodology and approach. This needs to happen at both individual component and integrated system level.
    i. Verification and validation of individual components can be completed in a relatively straightforward manner by comparing the model's output against hardware performance data (to be provided by vendor).
    ii. Verification of the integrated system model can be done with either independent evaluation (such as running software unit and system tests) and/or code-to-code comparison.

iii. Validation of the integrated system model with a physical integrated system (pilot) where relevant control sequences are translatable between the pilot scale and the eventual commercial system.

8. Network with Potential End-Users and Technology Developers Activities Summary

Throughout this project, Malta team was frequently in contact with technology developers and potential end-users.

For technology developers they provided inputs on budgetary cost and evaluation of technical feasibility for the different equipment considered throughout the project. For example, a resistance heater vendor provided budgetary quote for the resistance considered in Option 0. A MSSG vendor evaluated for us whether they could provide a solution that could meet the heat and mass balance based on what they have in their portfolio. Once that is feasible, they provided us a budgetary quote for the MSSG considered in option 2 and 3 in the study.

For potential end-users, we have been approached by many utilities facing the coal retirement issues to see how they can work with us to figure out how to repurpose these retiring coal plants into long duration energy storage system. For example, we had discussion with NB Power on the potential options they can do with the Belledune coal plant, which is required to move away from coal by 2030. In general, we have found that either Integration Option 1 or Integration Option 3 can work for potential end-users.

Finally, the most important networking activity resulted from this work is that Malta and Duke Energy was invited to the White House to participate in the roundtable discussion hosted by Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization (IWG). Malta CEO presented to the IWG the progress of this study and how it could help with what the IWG is trying to accomplish.

9. Summary

This project performed a techno-economic evaluation and assessment of repurposing a Duke Energy fossil-fueled asset (in particular, a coal plant) into an energy storage system by integrating the retiring asset with a Malta long duration PHES. The project validated the technoeconomic benefits of repurposing retiring coal plants into long-duration energy storage using Malta's PHES.

Technical	• Retiring coal plants (and other steam turbine fossil generation) can be repurposed to enable the clean energy transition using Malta's technology. • For older retiring coal plants, repurposing the site and electrical interconnection for a standalone PHES plant is the most economically favorable option. • For newer coal plants where there is also a local peaking capacity need, repowering the steam cycle into a hybrid integration with PHES is attractive. • A process was developed to assist fossil generation owners in choosing the best path for each plant's circumstances.
Economic	• Communities facing economic challenges caused by the retirement of fossil generation would benefit from repurposing the plant as long-duration energy storage using Malta's PHES. • On a $/MW basis, repowering retiring coal units into Malta PHES plants can maintain the same number and types of jobs and economic activity. • For a 70% carbon reduction scenario, a 10-hour Malta PHES plant is more economic for the asset owner than similar-power 4-hour batteries.

The project work was done following a systematic approach and was divided into two phases. Phase 1 focused on the selection of a host site, determination of the integration options to explore, and evaluation and down-selection of the most optimal integration option (for the chosen site) to advance in the next phase. Phase 2 focused on the preliminary conceptual design of the down-selected integration option and on the evaluation of the economic benefits to Duke Energy and to the local community. Translatable insights from this project to other fossil-fueled assets were identified as well.

Phase 1 started with collection of stakeholders' needs and wants, which were then translated into requirements and criteria for host site selection and integration option down-selection. Multiple sites with retiring coal plants were evaluated and compared based on their rated power, tentative retirement dates, availability of land, and Duke Energy's preferences. Of the multiple sites evaluated, Cliffside and Mayo were the two final candidate sites. When comparing the two sites using importance scoring, the two sites' scores were very close, with the Cliffside site being chosen as the host site for the first phase of the study. The project team had much easier access to the technical data for the Cliffside Unit 5 coal plant, which was important for the first phase of the study, including integration option concept generation and down selection. Because of their similarity, the technical assessment for Cliffside 5, especially with respect to site-specific conditions, is translatable and applicable to Mayo.

A total of four different integration concepts were created and compared in terms of technical feasibility, capability, and economics. All four options utilize molten salt as energy storage but have different mechanisms for charge and/or discharge. These four integration options are as follow:

- Option 0: Resistance heating - Traditional resistance heaters are used to heat up molten salt (charging) and the coal plant's steam Rankine cycle is reused for discharge. A MSSG is used to create steam from the hot salt. This option served as baseline as it has been previously proposed in Europe [1] and sometimes called Store2Power.
- Option 1: Electrical Integration of Standalone Malta system – Malta heat pump is used to charge; Malta heat engine is used for discharge. Grid interconnection of Cliffside 5 is repurposed.
- Option 2: Thermal Integration – Malta heat pump is used to charge; Cliffside Unit 5's steam Rankine cycle is used for discharge. A MSSG is used to create steam from hot molten salt.
- Option 3: Hybrid Integration – Malta heat pump is used to charge; Cliffside Unit 5's steam Rankine cycle *and* Malta heat engine can both be used for discharge. A MSSG is used to create steam from hot molten salt.

The four options were compared based on their estimated site-specific CAPEX, OPEX, and benefits to the grid. The benefits to the grid were done based on a dispatching use-case like that of a pumped hydro storage facility in the Duke Energy portfolio. For the repurpose of Cliffside Unit 5, Integration Option 1 was found to be the most optimal. Contributing factors were the age of the Cliffside Unit 5, the cost to keep Unit 5 in service for another 30 years and retrofit for salt, and the lack of need for low-utilization capacity assets in the area.

It should be noted that Option 3 would be more appropriate for many other coal plants where the following conditions exists: there is a strong need to maintain the rated capacity of the coal unit; the overhaul cost of the Steam-Rankine Cycle is relatively low; and there is also a need for daily load shifting. Option 3 provides the flexibility to use the Malta Heat Pump and Heat Engine to get the best efficiency for daily load shifting while also allowing the option to occasionally use coal's plant steam cycle to get the highest power output.

Phase 2 of the study focused on the preliminary conceptual design and economic benefits of Integration Option 1. The work included creation of more detailed PFDs, further evaluation of any potential reuse of Cliffside 5 equipment, and transient simulations of main system operability (charge, discharge, and trips). It was found that the grid-interconnection of Cliffside Unit 5 can be reused for the Malta PHES system and would save around $20MM in cost (compared to a greenfield application that requires a new substation). However, it is not worthwhile to try to reuse Cliffside Unit 5 existing generator, main step-up transformer, or the Cliffside 5 cooling tower given the age of the equipment. The cost of refurbishing these components was determined to be about the same as that of new equipment for the Malta option, while the complexity and risk increase with trying to re-use much older equipment. Transient simulations confirmed the basic operability of the overall system. Future work on the design includes more refined control algorithms so that system operations can be fine-tuned and optimized. Unit and integration tests of control system's algorithms would be critical in ensuring the system to work as expected.

Economic benefits of were determined at the grid level and local community level. At the grid level, the Duke Energy ISOP modeling team analyzed the performance of the Malta system (Integration Option 1) in the Duke Energy Progress (DEP) region for a 70% CO_2 reduction by 2030 scenario. This scenario assumed a substantial buildout of solar and batteries to meet the 70% CO_2 reduction. The modeling team found that, the 10-hour 100 MW Malta system had a substantial savings compared to a 10-hour

100 MW battery system. The team also found that, for this resource mix, replacing 100 MW of shorter duration (4-hour) batteries for the longer duration (10-hour) 100 MW Malta PHES plant also resulted in a compelling savings. The analysis considered of both CAPEX and OPEX of all systems involved. These results validate the need for Long Duration Energy Storage in a grid that requires low CO_2 emissions.

At the local community level, EIP evaluated the economic benefit to the local community of repurposing the Mayo coal plant as a Malta PHES plant (Integration Option 1) rather than retiring the site when the coal unit retires. The local community would benefit from one-time construction activities of the Malta system and benefit from on-going operation and maintenance of the system. A 100 MW, 10-hour Malta PHES at the Mayo site would bring about a one-time local economic benefit of ~$39MM from construction (more than 200 jobs) and an on-going yearly benefit of ~$3MM (for at least 30 years). Like any other standalone coal plant, once Mayo, a 727 MWe coal plant, retires, it will have large negative economic impact to the local region unless the plant is repurposed into something like the Malta PHES system. The analysis showed that on a $/MW basis, the Malta PHES system can maintain a similar number of jobs as the retiring coal units—and hence maintain positive local economic activity for the entire life of the system (30+ years).

In addition to the techno-economic analysis tasks, outreach activities were also done under this project. There was a lot of interest from other utilities who want to know more about how the work done here can be applied to their retiring coal plants. The project team spoke with these utilities and provided insights to what can be done with their coal plants based on their individual scenarios. Most importantly, the work done under this project has received attention from the highest level of government. Malta and Duke Energy were invited to the White House to participate in a roundtable discussion hosted by Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization (IWG). Malta CEO presented to the IWG and the Secretaries of Commerce and Energy the progress of this study and how it could help with what the IWG is trying to accomplish.

In summary, this project showed that repurposing a retiring coal unit into thermal energy storage, by integrating it with a Malta PHES system, makes techno-economic sense. At least two integration options are available, with the optimal solution depending on the coal plant and its location. Repurposing retiring coal plant into energy storage results in economic benefits for the plant owner and local communities.

10. References

[1] V. Novotny, V. Basta, P. Smola and J. and Spale, "Review of Carnot Battery Technology Commericial Development," *Energies,* vol. 15, p. 647, 2022.

[2] Duke Energy, "Duke Energy Progress Integrated Resource Plan 2020," Duke Energy, Charlotte, NC, 2020.

11. Appendix A – Technology Maturation Plan (TMP)

11.1. Introduction

11.1.1. Purpose of the Project

This purpose of this project is to study the integration of a 100 MW, 10-hour (1,000 MWh) Malta Pumped Heat Energy Storage system (Malta PHES) with one or more coal-fired electricity generation units (CF-EGUs) in Duke Energy Corporation's (Duke Energy) portfolio that are being considered for retirement. The CF-EGU(s) could comprise an entire generation plant or could be one or more units of a plant, the balance of which will continue to operate. Malta PHES is a long-duration, molten-salt energy storage technology that uses components (e.g., heat exchangers, turbomachinery, pumps, etc.), workforces (e.g., thermal plant operators, power plant engineers, maintenance technicians, etc.), and skill sets substantially like those used by fossil energy (FE)-fueled EGUs (i.e., construction, operation, and maintenance). The Project will model the possible reuse of existing CF-EGU equipment to construct an integrated Malta PHES to store variable renewable energy (VRE), nuclear, or FE electricity generation from Duke Energy's portfolio. It will identify benefits to operational, environmental, and economic performance of Duke Energy's operating assets, retention of incumbent workforces, and replacement of local economic impact of retiring CF-EGU(s).

11.1.2. Purpose of the TMP

This is the final TMP for this project and its objective is to provide the status of the TRL assessment for the involved technology at the end of this project. The first TMP was done in June 2021.
The TMP follows the processes outlined in the DOE G 413.3-4A Technology Readiness Assessment Guide (2015 Release).

11.2. Technology Assessment for the Project

11.2.1. Summary of Previous TIPRs

At this stage of the project, no formal Technical Independent Project Review (TIPR) has been conducted as part of this project. However, the work/activities done for this project to improve the TRL of the involved technology has been reviewed by Duke Energy as well as DOE NETL (via quarterly report and monthly updates).

11.2.2. Summary of Previous TRA(s)

For the integration of Malta PHES with a CF-EGU, a previous assessment had put the project at TRL 2 (Technology concept and/or applications formulated). At that point, only very high-level concepts have been formulated for how the Malta PHES could be integrated with a retiring CF-EGU to repurpose it into long-duration energy storage. The higher integration level concept includes repurposing existing steam turbine and generation equipment along with the Malta PHES charging heat pump to convert the unit to PHES (Higher-Level integration), while the lower integration level concept includes repurposing only electrical equipment such as transformers and grid interconnection to achieve savings beyond a standalone Malta PHES. No detailed analysis had yet been done to validate the main assumption that these would be cost-effective applications. The work done to date has been to verify this assumption.

11.2.3. Technology Heritage

The proposed integrated system concepts consist of one or more subsystems of the Malta PHES system and one or more subsystems of a retired CF-EGU. While the steam cycle of a coal plant is well known and the Malta PHES is based on largely known technology, the integration of the two systems have never been done. Therefore, this put the technology at TRL 2 at the beginning of the project.

11.2.4. Current Project Activities and Technology Maturation

Since the last TMP (June 2021), there following activities have been completed as of the end of this project:

1. Selection of a host site with a retiring coal plant (withing Duke Energy's portfolio) where the different integration options between Malta PHES and the coal plant were evaluated in further detail. Cliffside Unit 5 was chosen as the host-site.
2. Development of 4 different integration options between the Malta PHES system and Cliffside Unit 5 coal plant. For each option, schematic diagram, process flow, major equipment sizing, and cost estimate were completed. Duke Energy engineering staff performed sanity check for options that involve substantial integration with the steam cycle of coal plant unit 5.
3. Comparison of the four integrated options based on cost-benefit analyses (ratio of lifetime cost over benefits the system provides to the grid) and down selection to the most preferred concept. Integration Option 1, where the Malta PHES is electrically integrated with the retiring coal plant, was chosen as the concept for further development.
4. Duke Energy modeling team performed more detailed economic benefits the Integration Option 1 could provide to an anticipated future grid (reducing CO_2 emission by 70% by 2030, a scenario in Duke 2020 Integrated Resource Plan) as compared to a Li-on battery systems with 4 hours and 10 hours of storage. The result showed that the Integrated Option 1 (100MW-10hour) provides substantial benefits
5. For equipment reusability, which will help reduce the overall cost of the Integration Option 1, the following have been done:
   a. Confirmation that Cliffside Unit 5's 230kV grid interconnection can be repurposed for the Integration Option 1. However, main transformer should not be reused due to different low-side voltages between the Malta PHES and the coal plant. The existing main transformer of the coal plant is also near the end of its life, making it not economical to be refurbished and modified to be usable with the Malta PHES electrical system.
   b. Reusing the cooling tower of Cliffside 5 is not economical because the total CAPEX to retrofit the cooling tower and the ongoing OPEX together is about the same cost as the standard air cooler of the Malta PHES.
6. Local economic impact analysis has been performed for Integrated Option 1 at Mayo site.

11.2.5. Management of Technology Maturity

Malta Inc. has been the main organization responsible for doing and managing the activities describing in this TMP. Duke Energy has provided inputs and reviews throughout the project. DOE has reviewed quarterly report and monthly updates.

11.3. Technology Maturation Plan

11.3.1. Development of Technology Maturation Requirements

This updated TMP's objective is to assess whether the involved technology has reached TRL 3 based on the work that has been performed for this project. As previously described, the completed and on-going work helps answer one or more of the following questions:

- Do these activities help to evaluate one or more criteria in the TRA calculator?
- Do these activities reduce the risks of the development and deployment of the proposed technology?
- Do these activities help to narrow down and/or confirm applications of the proposed technology?

11.3.2. Life-Cycle Benefit

Successful completion of the activities in this TMP helped down select the integration option/technology based on technoeconomic comparisons. The Integration Option 1 has been further analyzed to better understand cost, performance and needs for further technology development activities. Overall, this provides the following life-cycle benefits if the technology is to be deployed:

- Reduced overall life-cycle cost since risks and mitigation strategies are identified.
- Better targeted performances as the down selection process helps to identify the right requirements for the overall system.

11.3.3. TMP for the Critical Technology Element

Based on the work that has been done for this project, one Critical Technology Element (CTE) has been identified. This CTE is preferred here as the integrated system technology (IST).

CTE: Integrated System Technology (IST)

Key Technology Addressed: The main function of the IST is to electrically integrate a Malta PHES system with the existing electrical system infrastructure of Cliffside Unit 5 coal plant.

Objective: The objective of this CTE to repurpose a retiring CF-EGU by integrating it with a Malta PHES system to allow it to be used as a long duration energy system.

Current State of Art: At the beginning of this project, there was no integration technology for combining a CF-EGU with a Malta PHES. Only very high-level concepts have been generated for what an integrated system may look like, and some initial intended applications of the integrated system have been identified. Therefore, the IST was deemed at maximum TRL 2.

Currently, based on the work that has been done as part of this project, as described in section 11.2.4 and their statuses as provided in Table 15, the TRL for the IST is 3. The Integrated Option 1 preliminary concept design is completed with process flow diagram, heat and mass balance and characteristic transient simulations. Techno-economic analysis was done to show that the system can provide more benefits to Duke Energy as compared to known technology.

Table 15: Summary of Work Done for This Project

Activity	**Timeline (Months)**	**Status/Note**	**TRL**
Identify host site and customer requirements	M1-M2	Completed	
Milestone 1: Identify integration options and metrics	M1-M3	Completed	2
Evaluate and down select integration options	M3-M6	Completed	
Milestone 2: Integration concept down selected	M6	Completed	2
Perform initial conceptual design of down select option at host site and calculated the economic benefits the integrated system can provide.	M6-M12	Completed (System process flow diagram, steady state and operability transients were simulated. Evaluation of economic benefit to the grid and local community were completed).	3
Milestone 3: Preliminary Conceptual design completed	M12	Completed	3

Technology Development Approach: The IST development has been following systematic systems engineering processes to make sure the IST configuration is chosen, and then its TRL advanced, in a logical manner. First, the needs and wants of the different stakeholders (such as Duke Energy, U.S. DOE, Malta Inc., local communities) were identified and translated into requirements for the integrated system. These requirements were then used to evaluate different options, each of which would have different requirements for the IST itself. As previously mentioned, the Integration Option 1, to electrically integrate the Malta PHES with the retiring Cliffside 5, was chosen for further analysis development. As described, the TRL of the IST has been advanced from TRL 2 to TRL 3 based on the work done in this project.

Within this IST, evaluation of which components/systems would need further development to advance TRL 6 (or higher) was done. Only one major component, the IST, was identified as the one that would need further work to advance to TRL 6. For this project, very rudimentary control logics were used in the simulation of the different transients (start up, shutdown, etc.). For example, some of the fluid flow rate controls were done using tables of pump speed vs. time. Certain valves opening and closing time were done using tables as well. Very few closed-loop control was implemented. Nevertheless, the work completed here showed that the integrated system technology is feasible. For the control and integration to advance to TRL level 6 (or beyond), the following development work need to be done:

- Further development of control and integration system by implementing more sophisticated closed loop controls to ensure the system not to exceed its design conditions in different transients.
- Perform verification and validation of control and integration methodology and approach. This needs to happen at both individual component and integrated system level.

iv. Verification and validation of individual components can be completed relatively straight forward by comparing the model's output against hardware performance data (to be provided by vendor)
v. Verification of the integrated system model can be done with either independent evaluation (such as running software unit and system tests) and/or code-to-code comparison.
vi. Validation of the integrated system model with a physical integrated system (pilot scale) where relevant control sequences are translatable between the pilot scale and the eventual commercial system.

Scope
This project's scope is limited to bring the IST from TRL 2 to TRL 3 within one year study at a cost of approximately $312K. This has been completed within the budget.

11.4. Technology Maturity Schedule

The activities in identified in the original TMP have been completed as planned. The work for the concept design activities for the chosen Integrated Option 1 including process flow diagram, transient simulation, equipment reusability evaluation, has been completed. Local and grid economic analyses have been done to quantify the benefits the system would bring to the plant owner and the local community. One component of the IST, the control and integration system, was identified as an area that needs to be further developed to advance it to TRL 6 or higher.

11.5. Summary Technology Maturity Budget

The estimated cost for this project was approximately $312K to bring TRL 2 to TRL 3 for the integrated system. This has been accomplished within allocated the budget.