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Techno-economic Analysis of Energy Storage System Utilizing the STEP Facility

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ABSTRACT

Over the last few years, many studies have attempted to quantify the impact of renewable energy and energy storage systems on various energy grids. This paper presents an analysis of the techno-economics of combining three different thermal energy storage technologies with an sCO2 power cycle at the SwRI campus in a larger micro-grid. The analysis was completed using an in-house toolset for analyzing microgrids and included photovoltaics, wind turbines, and external energy imports to the grid in combination. The three different storage technologies were molten salt, sand and concrete. Each technology was evaluated using a combination of CAPEX, payback period, decarbonization, and LCOE. It was determined that the cheapest solution was either a sand or concrete system that resulted in 51% of the grid being decarbonized at SwRI without increasing the cost of electricity or reducing the reliability of the grid. The paper then went further and explored the option of utilizing the STEP facility to test the system on the SwRI campus. It was estimated that a 100 MWh_{th} storage system would cost $30M for the storage system, including integrating the STEP facility with the storage system. The storage technology would be coupled by replacing the existing natural gas heater with an energy storage technology to provide the high temperature heat required to operate STEP. Coupling the system with a 40MW PV was estimated to reduce SwRI's external electrical load by 37% over a 30-year period and had a simple payback period between 10-14 years. The carbon intensity of the grid was reduced to 0.234 kg/kWh, approximately half the U.S. average in 2024.

INTRODUCTION

Around the world, countries have pledged to reduce emissions by 50% compared to 2023 levels in the pursuit of Net Zero Goals [1]. Southwest Research Institute investigated how to build out a micro-grid for a load of 20-25 MW to meet the decarbonization goals and reduce reliance on the external grid [2]. It was determined that such a grid would primarily require large amounts of variable renewable energy in conjunction with energy storage technologies [3].

This paper explores the possibility of converting the STEP sCO2 facility into an energy storage system to demonstrate a large scale sCO2 energy storage project that would be able to provide several MW to the SwRI grid as needed. The STEP facility is a 10MW-net indirect-fired sCO2 Pilot Plant located on the SwRI campus [4]. The paper utilizes PyZ, a python-based toolset, for exploring the size of VREs needed for the grid and the impact of energy storage on the system. A detailed analysis was performed on a 40MW PV field with an energy storage system that included estimates of the capital costs and the emissions reduction over a 30-year lifespan.

PYZ MODEL

PyZ is a toolset developed by SwRI for analyzing behind-the-meter costs and performance of different grid configurations [5]. The tool has been designed as an agile set of functions that allows for rapid iterations in the design space to explore, optimize, and assess the impacts of technologies on localized grids. The system utilizes a multi-layered approach with component level models for each different technology that are combined into a larger network of components known as the Site Model. An example of a site model is shown in Figure 1. This system includes the PV module, an energy storage module, load module, and the grid import module. Each of these modules includes the technical and financial assumptions for each module. Utility and natural gas costs are calculated using the local utility billing structure.

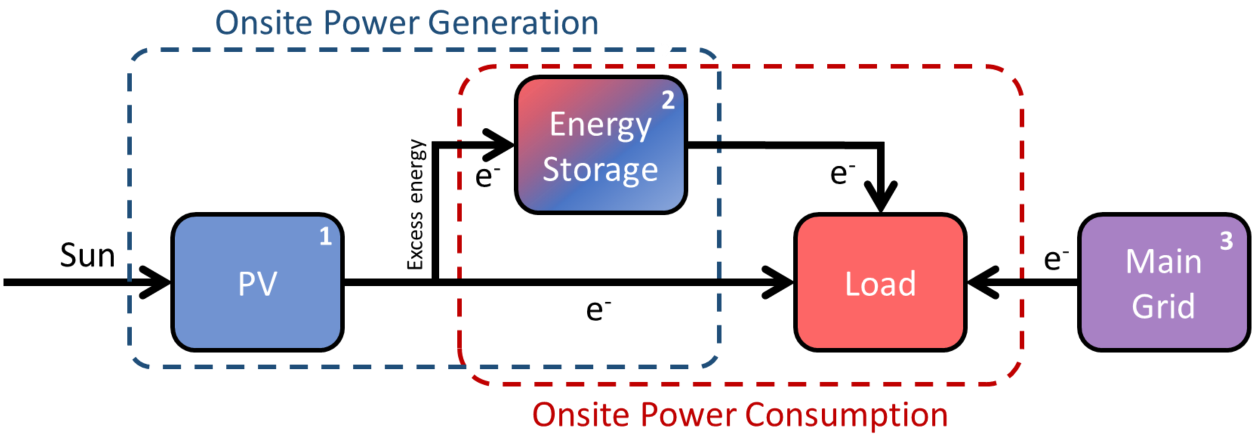

Figure 1. PyZ Site Model Diagram

The PyZ code is then able to output a large variety of economic and technical evaluations including the levelized cost of electricity (LCOE), the capital and operation costs of the grid, natural gas consumption, carbon dioxide emissions, and individual component utilization over time. An example of the outputs from the code can be found in Figure 1. This graph shows a comparison of the normalized LCOE of SwRI compared to the reduction in emissions. The system comprised PV field, wind farm, and molten salt pumped thermal storage system located in San Antonio, TX. The green lines represent the sensitivity of the CAPEX for the optimally sized energy storage system as the renewable systems grow.

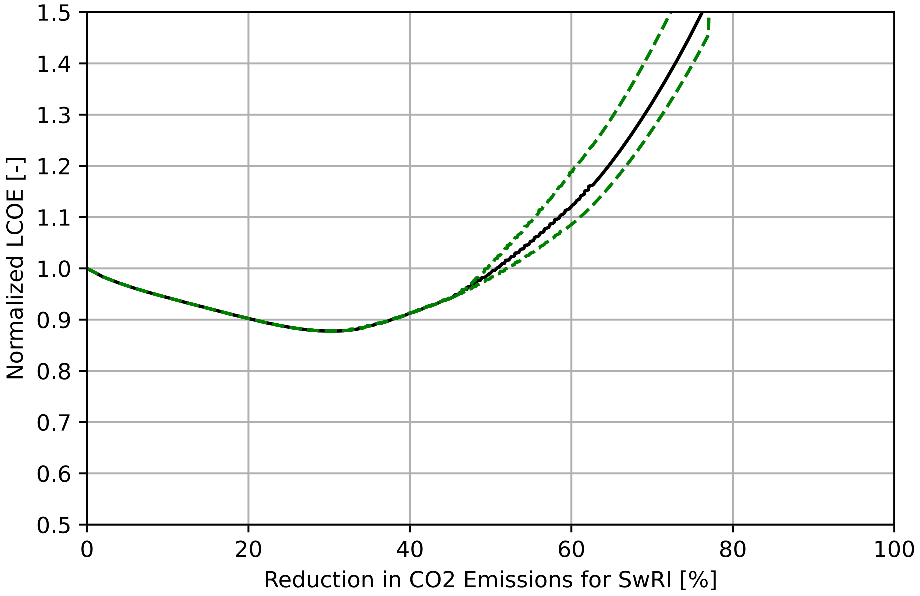

Figure 2. Comparison of the Normalized LCOE vs. the Reduction in CO2 Emissions for a Specific Micro-grid

Previous studies with PyZ have focused on understanding size and cost estimations for a SwRI Net-Zero Microgrid [6], exploring renewable and storage capacity expansion in ERCOT [8] and remote locations [9], a comparison of different storage technologies at SwRI, and a sensitivity analysis of the major cost assumptions for a micro-grid [10].

PRELIMINARY ANALYSIS

A preliminary analysis was performed for the SwRI location to evaluate potential sizes of energy storage systems and the impact on the energy costs at the institute. The model utilized all the components shown in Figure 1. For the preliminary analysis, the PV field size was swept between 0-100 MW, and the storage system was swept from 0-60 MWh. The charge duration was fixed to fully charge the system within 6 hours and to fully discharge the system in 10 hours.

The SwRI electrical load was provided in 15-minute increments from the local utility taken between 2019 and 2022. Previous work has shown that the load is able to be modeled effectively from this data in Pryor et al. [2] and Schmitt et al. [7].

The PV system was modeled from the System Advisory Model Python Interface (PySAM) to calculate the hourly power generation for a given PV field [11]. The solar resources were taken from the NSRDB for the San Antonio area using 4km^2 data in 2023 [12]. Key assumptions for the PV system are shown in Table 1. These values were taken from the Ramasamy et al. [13].

The energy storage system for the preliminary analysis was modeled using the PyZ energy storage module that has been described in Pryor et al. [10]. The system was modeled as a generic sCO2 based system with the charge system having a COP of 1.00 and the discharge system having an efficiency of 32% due to the smaller size than other estimates. The costs for the MSPTES system were modeled from Viswanathan et al. assuming that the capital and operational costs were the same as a MSPTES system [14]. Key assumptions for the energy storage system are shown in Table 2.

Table 1. Key Assumptions for PV System

Parameter	Value
Location for Solar Resource	San Antonio, TX
Ground Coverage Ratio	0.4
Tilt [°]	0
Azimuth Angle [°]	180
Pre-inverter DC Losses [%]	14.1
Inverter Efficiency [%]	96
Inverter Loading Ratio [-]	1.1
Array Type	1-axis-backtracking
Degradation [%/yr]	0.7
PV CAPEX [2024$/kW]	961.40
PV OPEX [2024$/kW]	16

Table 2. Key Assumptions for the Storage System

Parameter	Value
Storage CAPEX [2024$/kW$_{th}$]	126.56
Storage CAPEX [2024$/kW$_{th}$]	126.56
Storage OPEX [2024$/kW]	0
Charge CAPEX [2024$/kW]	934.52
Charge OPEX [2024$/kW]	26.85
Discharge CAPEX [2024$/kW]	597.48
Discharge OPEX [2024$/kW]	26.85

The utility rates were taken from CPS Energy, the local utility in San Antonio, TX. Utility costs were assumed to include an energy charge, seasonal demand charges and a minimum demand charge. The CAPEX for all systems was reduced by 30% at the time of purchase, assuming that SwRI would be able to receive the Investor Tax Credit for the system. The discount rate for the system was assumed to be 4.74%, based on the 10-yr U.S. Treasury Bond. All costs were assumed to escalate at a 2.5% inflation rate, and the load was assumed to increase at approximately 2% per year. Table 3 shows the major financial assumptions for the model.

Table 3. Key Assumptions for the Storage System

Parameter	Value
Utility Energy Charge [$/kWh]	0.066
Utility Demand Charge (Summer Season) [$/kW]	14.37
Utility Demand Charge (non-Summer Season) [$/kW]	9.36
Investment Tax Credit [%]	30
Real Discount Rate [%]	4.74
Inflation Rate [%]	2.5
Load Escalation Rate [%]	2.0

This system was designed to understand the impact that an energy storage system would have on the SwRI grid and to advise about the storage sizes that would impact the grid, determine the amount of PV needed to utilize the storage system and calculate the impacts of cost for SwRI. The first key insight was that a SwRI microgrid would require a minimum of 26 MW of PV installed before the storage system would be utilized and reduce emissions that SwRI currently generates by purchasing power from the local utility as shown in Figure 3. This is because the most economical usage for the PV system is to directly reduce the electricity demand of the grid and the SwRI grid is too large for a system below 26 MW to both fully meet the electrical load and charge an energy storage system. Starting at around 40 MW of PV, the cost of PV becomes increasingly higher for each MW delivered to the grid as the system tries to overbuild capacity to provide electricity during the worst period such as dawn and dusk or cloudy days which reduce the efficiency of the field. The addition of the storage system resulted in an additional reduction of around 7% of the CO_2-equivalent emissions for a PV field of 100 MW and a storage system around 50 MWh_{th} capacity. None of the systems were able to provide more than 50% of the electricity to SwRI due to the small storage system that was modeled.

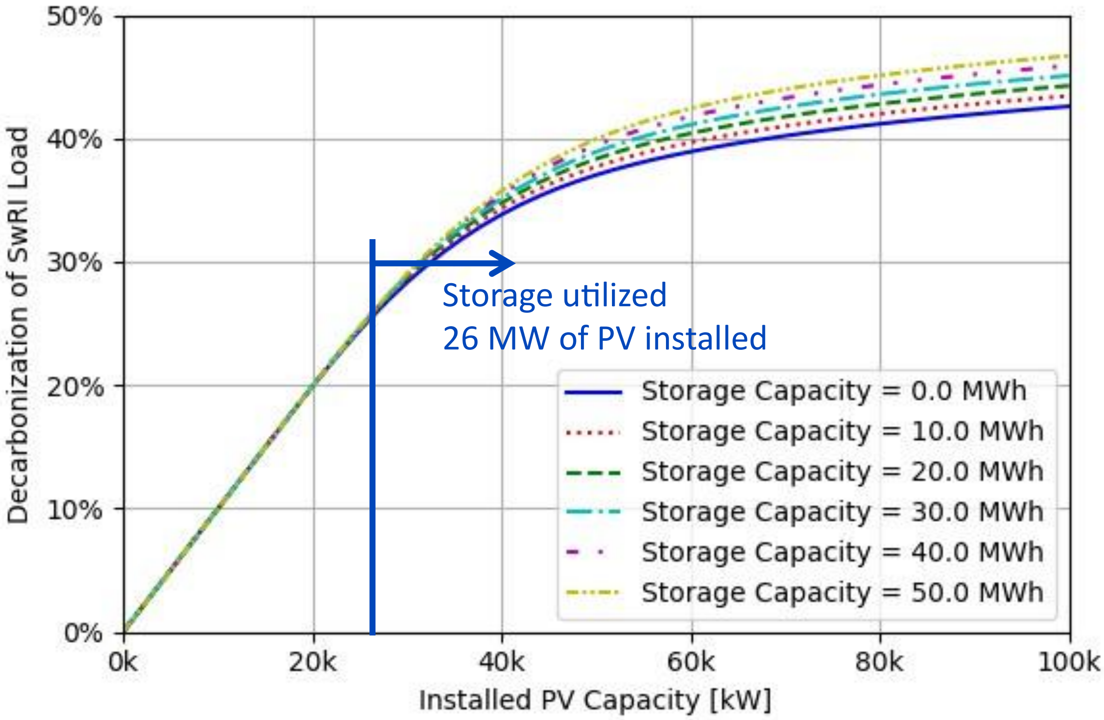

Figure 3. Grid Penetration Compared to the Installed PV Capacity

The preliminary investigation also showed that the storage system would have a negative impact on the costs without an additional revenue stream or regulatory requirement to build the system as shown in Figure 4. The maximum cost savings for SwRI was estimated to be around 14% over a 30-year period by building 32 MW of PV capacity by itself. This allows for the maximum utilization of the PV field. Adding 50 MWh_{th} of storage reduced the lifetime savings by half while pushing out the needed PV to maximize the savings to 40 MW. It also had an impact on the breakeven point for the installed PV capacity. It is estimated that SwRI would be able to build around 85 MW of PV capacity and still breakeven despite the system being massively oversized. The addition of 50 MWh_{th} of storage reduced the breakeven point for the PV to 75 MW. The reason for the reduction in savings and the shift in the breakeven point is that energy storage systems are always a net consumer of energy. The systems require more energy to charge them then they can provide back to the grid. This results in the storage system providing a benefit to the resiliency or reducing the emissions of the system but at the cost of additional capital and operational expenses.

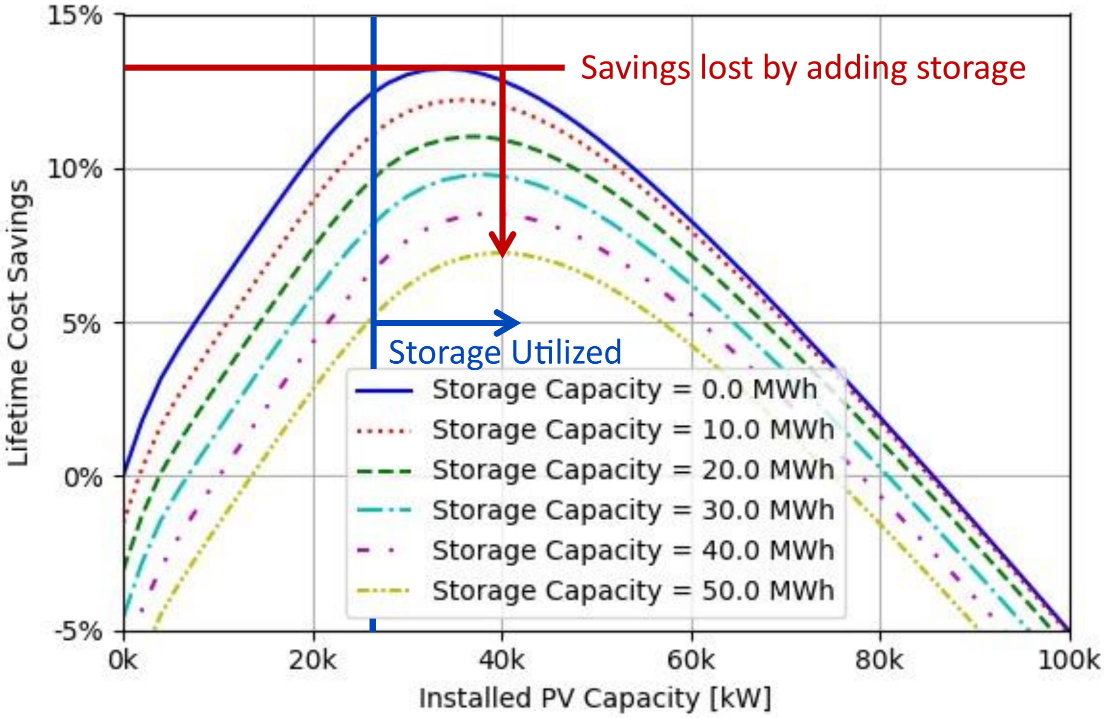

Figure 4. Lifetime Costs Compared to the Installed PV Capacity

COUPLING ENERGY STORAGE WITH THE STEP FACILITY

One option for a possible energy storage system on the SwRI campus was to utilize the STEP facility. The STEP facility is a 10MW indirect sCO2 power plant located on the SwRI campus [4]. This system was demonstrated in the fall of 2024 to be able to produce power up to 4 MW net in the simple cycle configuration and 10 MW net in the recompression Brayton Cycle. One of the drawbacks of the power plant is that it was designed to demonstrate an indirect-fired cycle and therefore uses a 80 MWth natural gas heater to provide the heat input for the cycle which significantly reduces the true cycle efficiency when starting from the fuel source but the STEP facility has the potential to serve as a pre-built discharge cycle for an energy storage system. Using the results from a previous modeling study, the thermal efficiency as a function of power output was estimated between 3-10 MW. The performance estimate was within the range of outputs previously demonstrated by the STEP Facility [15].

The STEP performance was then used to predict the storage duration for a given storage size over the expected power output range as shown in Figure 5. Based on this analysis, a 100 MWh_{th} was chosen as the ideal size for the demonstration system to provide a minimum 10 hour duration of storage and utilize a maximum output around 4 MW which corresponds to the output of the STEP facility in the simple cycle configuration.

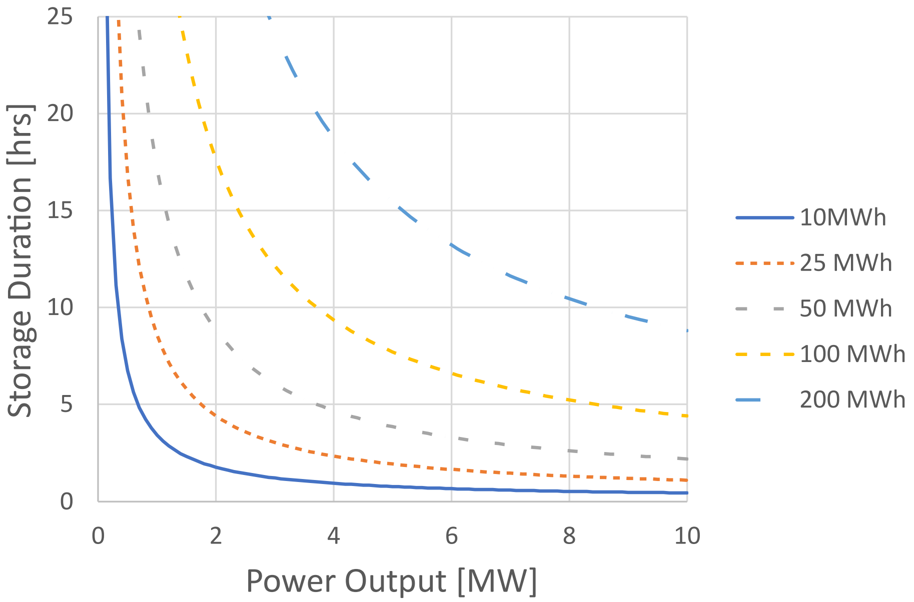

Figure 5. Comparison of the Storage Duration vs. the STEP Power Output

The technology for a potential demonstration system was chosen to be a concrete/sand-based storage system with electric heaters to provide energy for storage. Figure 6 shows the site model for the demonstration system. The system was chosen to have 16.7 MWe of electric heaters that can fully charge the storage system in six hours. It was assumed that the electrical heaters had an efficiency of 98% bringing the RTE to 36.4% like the RTE for the preliminary investigation. The costs of the charge and storage system were estimated to be $\$250/\text{kWh}_{\text{th}}$. This led to a total storage system cost of \$34MM. The model included a two-year test period where the system was required to run daily to validate and commission the system. This forced discharge was estimated to increase the overall emissions by 3% over a 30-year period for the SwRI grid over the two-year period due to the increase in energy imports over the period.

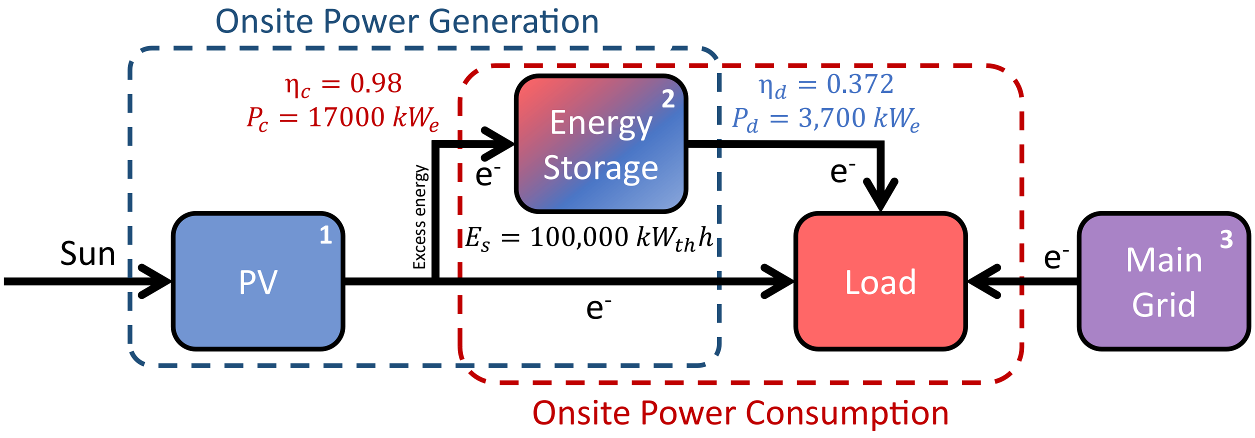

Figure 6. STEP Energy Storage Demo Site Model

The size of the PV field was swept over a range between 0-100 MW with a constant storage system. Results for this system are shown in Figure 7. The results show that a PV field that is built in 2026 and operational in 2027 would result in a reduction in the cost by a maximum of

15% but very quickly increases in costs after the minimum as the PV field is overbuilt to match times that power is needed. The addition of the STEP-ES demo would shift the curve up and to the right, increasing the carbon emission reduction and resiliency at a cost of 12% in the baseline costs. The STEP-ES Demo would be able to extend the breakeven point from 41% to 50%.

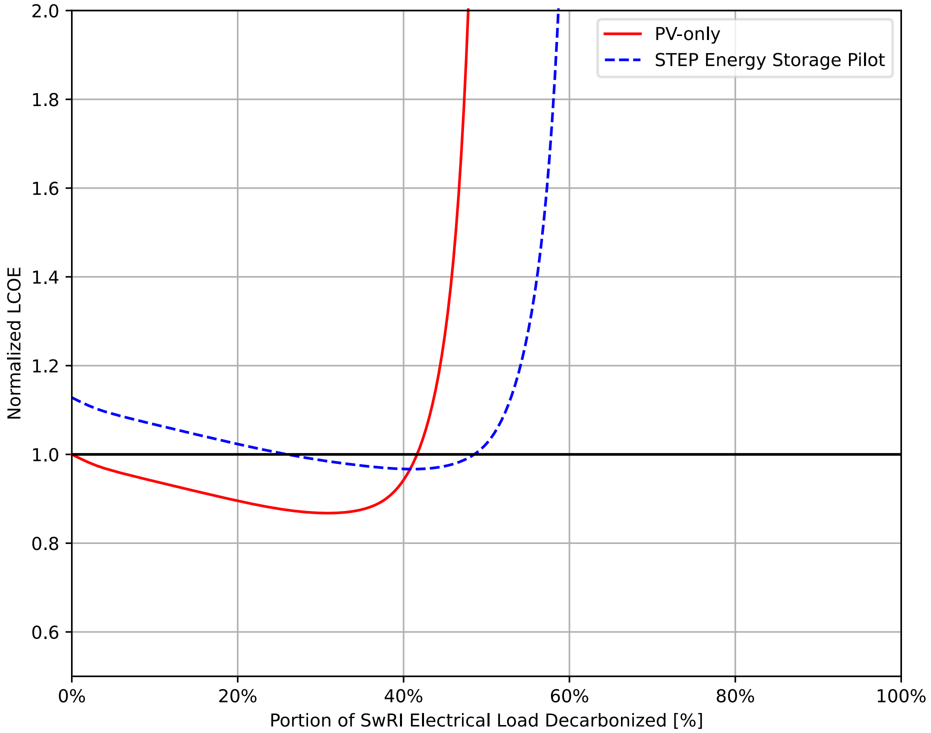

Figure 7. Normalized LCOE vs. Carbon Emission Reduction for PV-only compared to the STEP-ES Demo

Converting the STEP facility into an energy storage demonstration would hurt the emissions without the PV-field installation. Figure 8 shows a comparison of the increased reduction in emissions by adding the energy storage system compared to the PV field by itself as the PV field capacity was swept from 0 to 100 MW. A minimum of 8 MW are needed to counteract the commissioning period built into the model with 55 MW needed to decrease emissions by 5% more than the PV field by itself. Due to the small size of the demonstration system, the energy storage started to level out around a 7.5% improvement compared to the PV field.

SwRI currently imports its electricity with a carbon intensity of 0.367 kg/kWh according to the local utility. The addition of 40 MW has the potential to reduce the carbon intensity to a 0.242 kg/kWh assuming the PV field can be installed in the first year. By increasing the doubling, the PV field to 80 MW a further decrease the carbon intensity to 0.214 kg/kWh but at a cost of increase in the electricity price since SwRI's load is never greater than 25 MW and is not expected to increase beyond 40MW in the next 30 years. The addition of the STEP-ES demo would improve the carbon intensity to 0.234 kg/kWh while still saving the institute money over the period. The system was estimated to have a simple payback period between 10-14 years depending on SwRI collecting the 30% ITC for the project and had a discounted payback period of 13 years with the ITC. This was an increase of 2-3 years compared to the 40 MW PV field. In contrast the 80 MW PV field had a 15-19 year simple payback period and was not economical when discounting the future savings of the project lifespan.

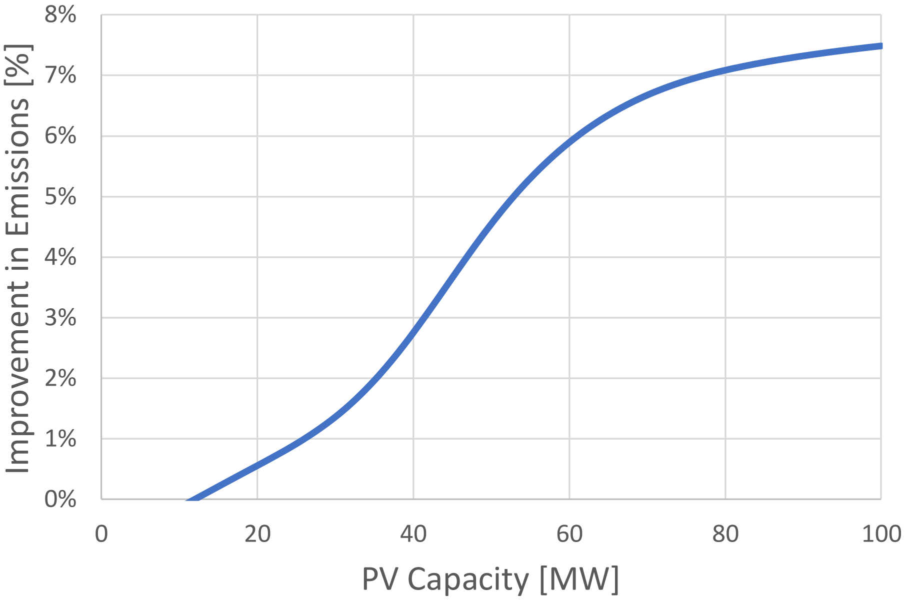

Figure 8. Carbon Emission Improvement vs PV Installed Capacity

CONCLUSIONS

Implementing a storage system at the STEP facility is estimated to require an additional capital expenditure of approximately $30 million. The system would require a large PV field at a minimum of 26MW to utilize the system through the anticipated lifespan of the project. It was estimated that a storage system with 100 MWh of capacity would be able to output 3.7 MW of power over a 10-hour period which is within the proven performance of the STEP facility and improve the resiliency of the SwRI grid by reducing the required grid energy by 8-10% without increasing the costs of the system.

A detailed analysis was performed for the system estimating that a 40 MW PV field would be able to couple with a STEP Energy Storage Demonstration System would further reduce the carbon intensity of SwRI's energy to 0.234 kg/kWh and be able to pay itself back within over a 14-year period while demonstrating how an sCO_2 power cycle could be utilized for energy storage.

The impact of the energy storage system is limited by the size of the STEP facility compared to the SwRI grid. SwRI estimates that it utilizes between 10-25 MW throughout the year which means that a commercial system for SwRI that powers the entire grid would need to cover the full range which is beyond the capabilities of the STEP facility.

REFERENCES

[1] UN Environmental Programme. 2024. “Nations must close huge emissions gap in new climate pledges and deliver immediate action, or 1.5°C lost”. Press Release. https://www.unep.org/news-and-stories/press-release/nations-must-close-huge-emissions-gap-new-climate-pledges-and#:~:text=Cali%2FNairobi%2C%2024%20October%202024,be%20gone%20within%20a%20few

[2] Karg Bulnes, F., Schmitt, J. M., Smith, N. R., Khawly, G. N., Allison, T. C., & McClung, A. (2023, June). Capital and Operational Cost Estimations for a Net-Zero Carbon Emissions Microgrid Application. In Turbo Expo: Power for Land, Sea, and Air (Vol. 86991, p. V006T09A003). American Society of Mechanical Engineers

[3] Denholm, P., Brown, P., Cole, W., Mai, T., Sergi, B., Brown, M., Jadun, P., Ho, J., Mayernik, J., McMillan, C. and Sreenath, R., 2022. *Examining supply-side options to achieve 100% clean electricity by 2035* (No. NREL/TP-6A40-81644). National Renewable Energy Lab.(NREL), Golden, CO (United States).Pryor, Owen, Aaron McClung, George Khawly, Joshua Schmitt, and Timothy Allison. "Development of a Power Generation and Economic Model for Micro-Grid Applications." In Turbo Expo: Power for Land, Sea, and Air, vol. 87981, p. V006T09A020. American Society of Mechanical Engineers, 2024.

[4] Marion, J., Macadam, S., McClung, A. and Mortzheim, J., 2022, June. The STEP 10 MWe sCO2 pilot demonstration status update. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 86083, p. V009T28A034). American Society of Mechanical Engineers.

[5] Pryor, O., McClung, A., Khawly, G., Schmitt, J. and Allison, T., 2024. Development of a power generation and economic model for micro-grid applications. *Proceedings of ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exposition*, GT2024-129362, June 24-28, London, United Kingdom.

[6] Hofer, D., Schmitt, J., McClung, A., Smith, N. and Bulnes, F.K., 2024, January. Economic Modeling of the Application of Battery and Pumped Thermal Energy Storage to Self-contained Microgrid on the Southwest Research Institute Campus. In 2024 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT) (pp. 1-5). IEEE

[7] Schmitt, J., Hofer, D., Pryor, O., Khawly, G., Karg Bulnes, F. and McClung, A., 2024, June. Techno-Economic Analysis of Emerging Energy Storage Technologies for a Microgrid. In Turbo Expo: Power for Land, Sea, and Air (Vol. 87981, p. V006T09A017). American Society of Mechanical Engineers.

[8] Karg Bulnes, F., Hofer, D., Smith, N.R., Schmitt, J., Pryor, O., Khawly, G. and McClung, A., 2024, June. Economic Modeling of Renewable Integration and the Application of Energy Storage to the ERCOT Energy Grid. In Turbo Expo: Power for Land, Sea, and Air (Vol. 87981, p. V006T08A003). American Society of Mechanical Engineers.

[9] Karg Bulnes, F., McCandless, C., Pryor, O., Smith, N.R., Hofer, D., Schmitt, J., "Techno-Economic Analysis for Adoption of Large-Scale Renewable Microgrid Systems in Isolated Communities." In *Energy Sustainability Conference and Exposition*, ES2025-155242. American Society of Mechanical Engineers, 2025.

[10] Pryor, O., Schmitt, J., Karg Bulnes, F., Hofer, D., Smith, N.R., Allison, T. "Techno-Economic Sensitivity of a Renewable Microgrid." In *Turbomachinery Technical Conference and Exposition*, GT2025-153973. American Society of Mechanical Engineers, 2025.

[11] Gilman, Paul, Aron Dobos, Nicholas DiOrio, Janine Freeman, Steven Janzou, and David Ryberg. "SAM photovoltaic model technical reference update." *NREL: Golden, CO, USA* (2018).

[12] Sengupta, Manajit, Yu Xie, Anthony Lopez, Aron Habte, Galen Maclaurin, and James Shelby. "The national solar radiation data base (NSRDB)." *Renewable and sustainable energy reviews* 89 (2018): 51-60.

[13] Ramasamy, Vignesh, Jarett Zuboy, Eric O'Shaughnessy, David Feldman, Jal Desai,

Michael Woodhouse, Paul Basore, and Robert Margolis. US solar photovoltaic system and energy storage cost benchmarks, with minimum sustainable price analysis: Q1 2022. No. NREL/TP-7A40-83586. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2022.

[14] Viswanathan, Vilayanur, Kendall Mongird, Ryan Franks, Xiaolin Li, Vincent Sprenkle, and Richard Baxter. "2022 grid energy storage technology cost and performance assessment." *Energy* 2022 (2022).

[15] Moore, J.J., Klaerner, J.D., Wade, J.L., Mortzheim, J. and Pierre, S., 2025, June. STEP 10 MWe sCO2 Turbine Simple Cycle Testing. In *Turbo Expo* (Vol. 88858, p. V009T28A016). American Society of Mechanical Engineers.

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