

GE Global Research
Final Scientific/Technical Report
Flexible Oxy-Fuel Combustion for High-Penetration Variable Renewables
DE-AR0001304

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Public Executive Summary

GE Research and 8 Rivers developed an ASPEN/HYSYS model of 8 Rivers' oxy-combustion natural gas-fired turbine—the Allam-Fetvedt cycle—for flexible generation on a grid with high-variable renewable energy (VRE) penetration at near-zero carbon emissions. The model has been validated based on 8 Rivers prior modeling experience. The model has been used to calculate the efficiency of the cycle as well as the material balance for the plant at different net power outputs.

The output of the ASPEN/HYSYS model was used to develop an hour-by-hour dispatch strategy based on the price strips supplied by the modeling teams (Princeton and NREL). Using this EXCEL-based dispatch calculator, the (Net Present Value) NPV for each price strip was optimized using a design of experiments approach. Two scenarios were optimized. In the first scenario, the dispatch is not constrained by the CO₂ pipeline capacity. In this scenario the amount of CO₂ going to the pipeline can fluctuate as needed to accommodate the dispatch. In the second scenario, the dispatch is constrained by the CO₂ pipeline. In this scenario the flow rate of CO₂ to the pipeline must be constant for each hour the plant is on. It is assumed that if plant is completely turned off then the pipeline can be turned off as well. In addition to using a CO₂ tank to manage the flow the optimization also adjusts the pipeline size (flow rate) to accommodate the price strips. This approach leads to larger CO₂ tank sizes, more CO₂ venting and lower NPV, but could represent a more realistic approach where the operator wants to avoid a phase change in the pipeline (from sCO₂ to CO₂(g)) which can cause problems with downstream pumps and sequestration.

As the EXCEL based tool was very manual the team explored more advanced optimization routines to ensure that as close as possible to a global maximum was determined. The team formulated this problem as a nonlinear optimization problem represented as a mathematical problem decomposed into two loops. The outer loop maximizes the objective function, that is, the NPV while the inner loop replicates the rule-based formulation in the EXCEL dispatch model to calculate the NPV. The optimization framework takes in as input, the locational marginal price (LMP), optimization variable limits - tank sizes and pipeline flow and initialization values for the optimization variables. The outputs are the optimization variables – air separation unit size, O₂ tank size, CO₂ tank size and CO₂ pipe-line flow.

A positive NPV was obtained for each price strip and for each scenario. This indicates that the oxy-combustion system with oxygen storage would be economically competitive on a future grid with a high degree of variable renewables.

Acknowledgements

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Accomplishments and Objectives

The award allowed GE Research and 8 Rivers Capital to create a thermodynamic model of the Allam-Fetvedt cycle and demonstrate that use of oxygen storage makes this power plant design more valuable on a future grid with a high penetration of variable renewables.

A number of tasks and milestones were laid out in Attachment 3 (the SOPO), the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
M1 – Data Sharing, Methodology Determined	Q1: Data sharing strategy with modeling teams decided, to include plan regarding non-disclosure agreements (if applicable). <i>Actual Performance: Worked with both the Princeton and NREL teams to understand their data requirements and completed an NDA with both parties.</i> Q2: Phase 1 modeling plans presented to ARPA-E, including costing methodology. <i>Actual Performance: presented modeling plans and costing strategy to ARPA-E during the Q1 report out.</i>
M2 – Initial T2M Plan	Q1: Provide a plan, not to exceed two pages, answering the questions in the standard T2M format which will be provided; it describes what product will be "sold" from the technology developed, and how it will be provided (manufacture and sell, licenses). <i>Actual Performance: Developed a T2M plan in the desired format and this plan was reviewed by ARPA-E during 2Q review.</i> Q2: Also describe critical customers and partners. Learn on the electricity market and its characteristics. <i>Actual Performance: During the 2Q review the key partners were discussed as well as two announced projects that 8 Rivers has for this power plant design.</i>

M3 – System Model Validation, Dataset Compatibility, IP analysis	Q1: Preliminary Aspen model shared with ARPA-E, to include full plant model (power generator, CO2 capture and compression, any other relevant processes) which has been validated with experimental data. Proprietary data will be handled as a black box. Actual Performance: A preliminary ASPEN/HYSYS model was shown to ARPA-E during our 3Q review. Key operating parameters were presented for the full power case. Q2: Dataset formatting confirmed with modeling teams, to include transmission of datasets with hypothetical (dummy) values. Actual Performance: Finalized the data format required by the modeling teams. Q3: Present a strategy for developing and protecting your IP and ensuring your freedom to operate. Analysis should include survey of prior art and any issues that it may present. Actual Performance: 8 Rivers has a significant patent portfolio in the oxy-combustion space which secures the freedom to practice. No new IP was generated during this project.
M4 – First iteration of CSS process Review	Q1: Using electricity price signals and carbon prices provided by ARPA-E, provide cost and performance data from the NPV-optimized process to the modeling teams in order to receive feedback on potential for the CCS process to be deployed in future grids. Actual Performance: Data shared with the modeling teams. Q2: Net present value (NPV) reported to ARPA-E, as documented in the quarterly presentations. Actual Performance: The NPV was presented during the 4Q review for the manual optimization using the EXCEL based calculator tool. Q3: Aspen model, to include detailed process flows, provided to ARPA-E. Proprietary data will be handled as a black box Actual Performance: The ASPEN/HYSYS thermodynamic model was shared with ARPA-E. However, they changed this requirement and instead just wanted process diagrams for the high and low power states and these process diagrams were delivered.
M5 – Final Process Review and T2M Update	Q1: Using electricity price signals and carbon prices provided by ARPA-E, provide updated cost and performance data from the NPV-optimized process to the modeling teams in order to analyze the potential for the CCS process to be deployed in future grids. Actual Performance: Data shared with the modeling teams. Q2: NPV reported to ARPA-E, as documented in the final report and quarterly presentations.

	Actual Performance: The NPV was presented during the 5Q review using non-linear automated optimization tools to ensure (as much as possible) a global NPV maximum was found. Q3: Aspen model, to include detailed process flows, provided to ARPA-E. Proprietary data will be handled as a black box. Actual Performance: The ASPEN/HYSYS thermodynamic model was shared with ARPA-E. However, they changed this requirement and instead just wanted process diagrams for the high and low power states and these process diagrams were delivered. Q4: Identify the value chain necessary to deliver your solution to market. Analysis should identify how advancements made in your project fit into this value chain and what partnerships or supply chain relationships will be necessary to deliver your solution. Actual Performance: Multiple vendors were identified to manufacture the various sub-system of the oxy-combustion plant with oxygen storage. Q5: Updated T2M plan and IP analysis presented to ARPA-E Actual Performance: An update T2M plan was delivered to ARPA-E during the 5Q report out.
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Project Activities

Summary:

A thermodynamic model was developed for the oxy-combustion Allam-Fetvedt cycle. This information was then used to develop an optimized dispatch strategy using price strips supplied by the modeling teams. The price strips represent future possible grid configurations that include a high penetration of variable renewables and a carbon tax. Multiple optimization strategies and tools were used to maximize the net present value (NPV) of the plant on these potential future grids. The optimization varied the size of the air separation unit, the size of oxygen storage tanks, the size of carbon dioxide storage tanks and the flow rate of the carbon dioxide pipeline. The team was able to determine a dispatch strategy that resulted in a positive NPV for all price strips. This indicates that an oxy-combustion plant with oxygen storage would be economically viable on a future grid with a high degree of variable renewables.

Thermodynamic Model:

GE Global Research has developed an ASPEN/HYSYS model of 8 Rivers' oxy-combustion natural gas-fired turbine—the Allam-Fetvedt cycle—for flexible generation on a grid with high-variable renewable energy (VRE) penetration at near-zero carbon emissions. The model has been validated based on 8 Rivers prior modeling experience. The model has been used to calculate the efficiency of the cycle as well as the material balance for the plant at different net power outputs. A schematic of the cycle is shown in Figure 1.

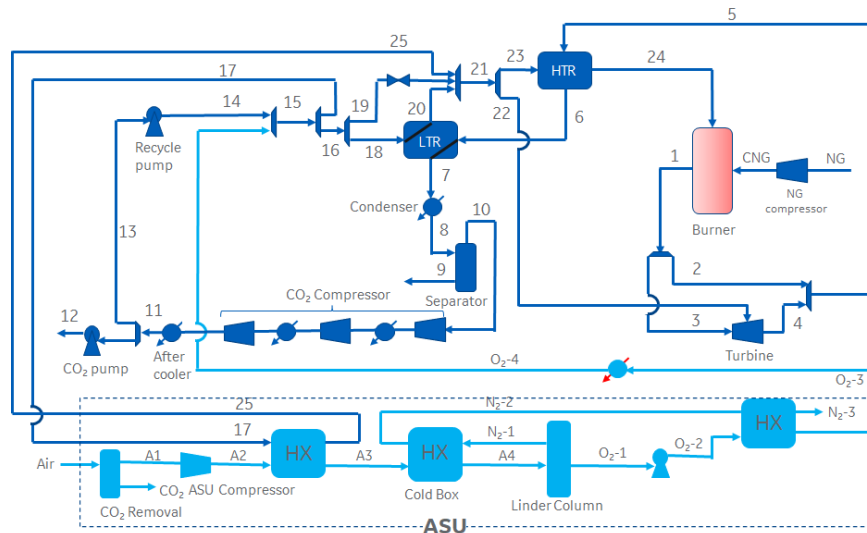


Figure 1. Schematics of 8Rivers oxy-combustion cycle.

Two process flow diagrams were generated from the ASPEN/HYSYS model. One process flow diagram was generated at maximum power output (~270MW, Figure 2) and the other one at near zero net output (6.3 kW, Figure 3). The model had difficulty converging at exactly zero net output.

Net output: 270 MW
Efficiency: 55.54%

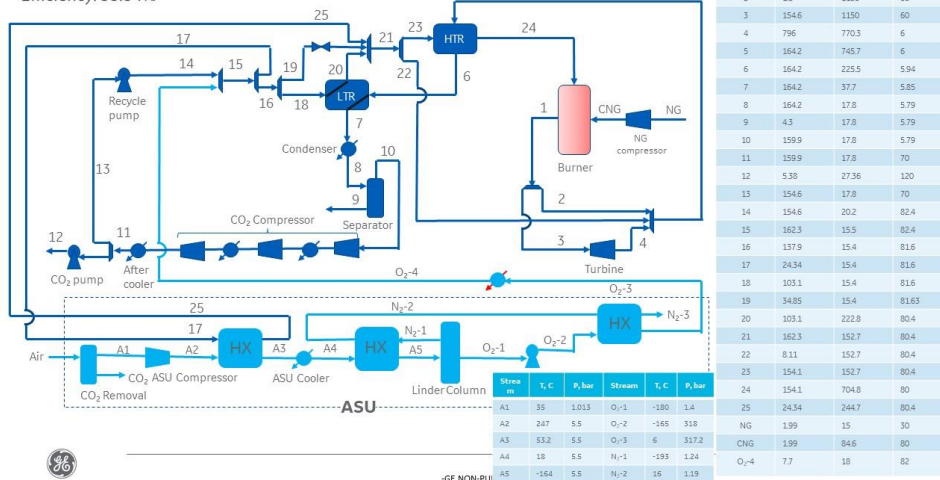


Figure 2. Process Flow Diagram for the full power oxy-combustion plant

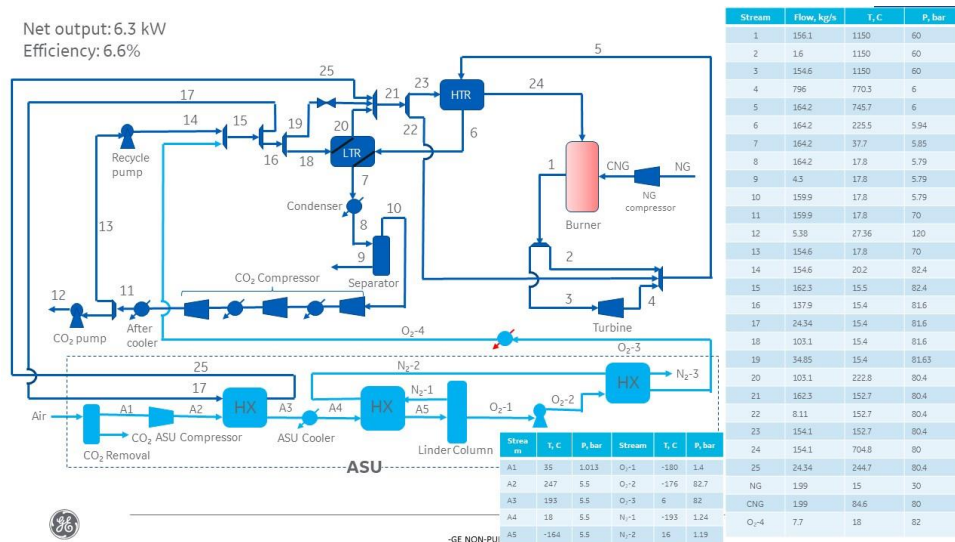


Figure 3. Process Flow Diagram for the minimum power oxy-combustion plant

Optimization:

Using the information derived from the thermodynamic model and the CAPEX and OPEX for an Nth of a kind plant obtain from 8Rivers it was possible to develop multiple optimization strategies to maximize the NPV of the oxy-combustion plant given the price strips from the modeling teams. The optimization started with a simple EXCEL based calculator that would optimize the behavior of the plant every hour of the year based on what would happen to the electricity price in the future. The calculator then manually tried to optimize 4 parameters 1) size of the ASU relative to the O₂ demand at 100% load, 2) the size of the O₂ storage tank (in tonnes), 3) size of the CO₂ storage tank (in tonnes) and 4) the size of the CO₂ pipeline (in tonnes/hr). The EXCEL calculator working it was possible to use multiple optimization techniques to vary the 4 parameters, use the calculator to recalculate the NPV then optimize the 4 parameters.

The optimizations were carried out for two different operational conditions. First, the optimizations were carried out without concern for the flow going to the CO₂ pipeline (unconstrained case), second the flow every hour of the day must match the flow rate of the CO₂ pipeline (constrained case). Requiring every hour to match the flow rate exactly is a very strict requirement. There is variability available in the flow rate but modeling that was beyond the scope of this program.

CAPEX assumptions:

The levelized cost of electricity (LCOE) can be calculated following the methodology in Reference 1 for gas turbines. Estimates of the Capital, Fixed and Variable Costs can be obtained from Reference 2 and scaled up for inflation from \$2011 to \$2020 as shown in Tables 2 and 3. The capital from Reference 2 is for a first of a kind (FOAK) plant, but for this effort, an Nth of a

kind (NOAK) value is needed. 8Rivers has generated an expected learning curve for oxy-combustion system using information from References 3 and 4. The learning curve used here is shown in Table 4 and Figure 4. The cost of the NOAK unit decreases from the FOAK by a compounding 20% at the 2nd, 4th, and 8th build and then by a compounding 10% at the 16th and 32nd build. It is expected that by the 32nd unit the cost will come down by 41.5% for 80% of the capital items. The final NOAK capital cost is shown in Table 3. For comparison the LCOE for a carbon capture plant from Reference 1 (amine) is shown in Table 5. The oxy-combustion system is very competitive to a reference carbon capture plant and captures 98% of the carbon as opposed to 90% for the amine system.

Table 2. Calculation of CAPEX for Oxy-combustion plant

NETL March 2019	\$2011 (\$/kW)	\$2020 (\$/kW)	NOAK SN32 (\$/kW)
Feedwater and BOP	\$62	\$74	
ASU	\$581	\$690	
Gas Cleanup and Piping	\$48	\$57	
sCO ₂ Turbine and Accessory	\$447	\$531	
Cooling Water System	\$46	\$55	
Electric Plant	\$182	\$216	
Instrument & Controls	\$71	\$84	
Improvements to Site	\$22	\$26	
Buildings and Structures	\$12	\$14	
Total CAPEX	\$1471	\$1,746	\$908

Table 3. LCOE of Oxy-combustion system (without storage tanks)

NETL March 2019	2011	2020
Variable O&M (\$/MWh)	\$3	\$3
Fixed O&M (\$/kW-y)	\$48	\$57
Heat Rate (MMBtu/MWh)		6.13
LCOE (\$/MWh) - NOAK		44.43

Table 4. Learning Curve

EIA Standard Learning Curve		
Serial Number	% Reduction	% of FOAK
1		100.00%
2	20%	80.00%
3		80.00%
4	20%	64.00%
5		64.00%
6		64.00%
7		64.00%
8	20%	51.20%
9		51.20%
10		51.20%
11		51.20%
12		51.20%
13		51.20%
14		51.20%
15		51.20%
16	10%	46.08%
17		46.08%
18		46.08%
19		46.08%
20		46.08%
21		46.08%
22		46.08%
23		46.08%
24		46.08%
25		46.08%
26		46.08%
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28		46.08%
29		46.08%
30		46.08%
31		46.08%
32	10%	41.47%

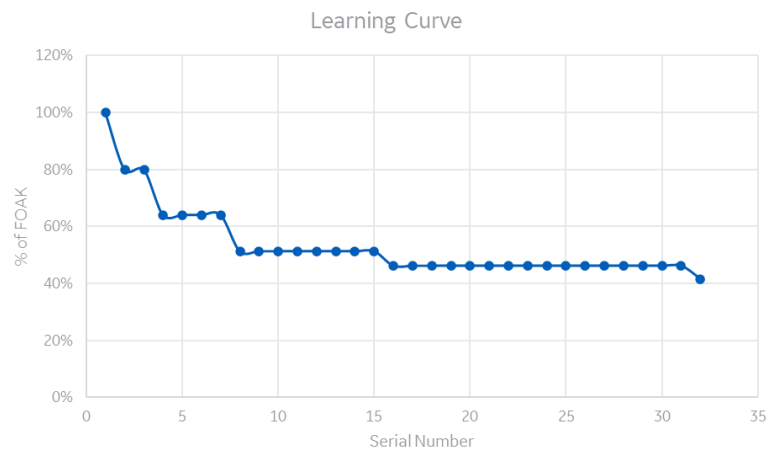


Figure 4. Oxy-combustion learning curve

Table 5. Amine carbon capture reference LCOE

NGCC-CC from ATB	2020
CAPEX (\$/kW)	2549
Variable O&M (\$/MWh)	6
Fixed O&M (\$/kW-y)	27
Heat Rate (MMBtu/MWh)	7.53
LCOE (\$/MWh)	55.1

Results:

The results for the unconstrained cases are shown in Figures 5-9. At a high level the size of the ASU, the size of the CO₂ tank and the flow rate of the CO₂ pipeline did not really affect the NPV. The size of the O₂ tank did make a difference and that difference varied by optimization technique but the overall NPV did not really vary by optimization technique. The manual EXCEL calculator (blue bars) was pretty close to the optimum found by the more complex approaches. The size of the O₂ tank (1-4k tonnes) is not very large and does not add a ton of cost but does generate a fair amount of value.

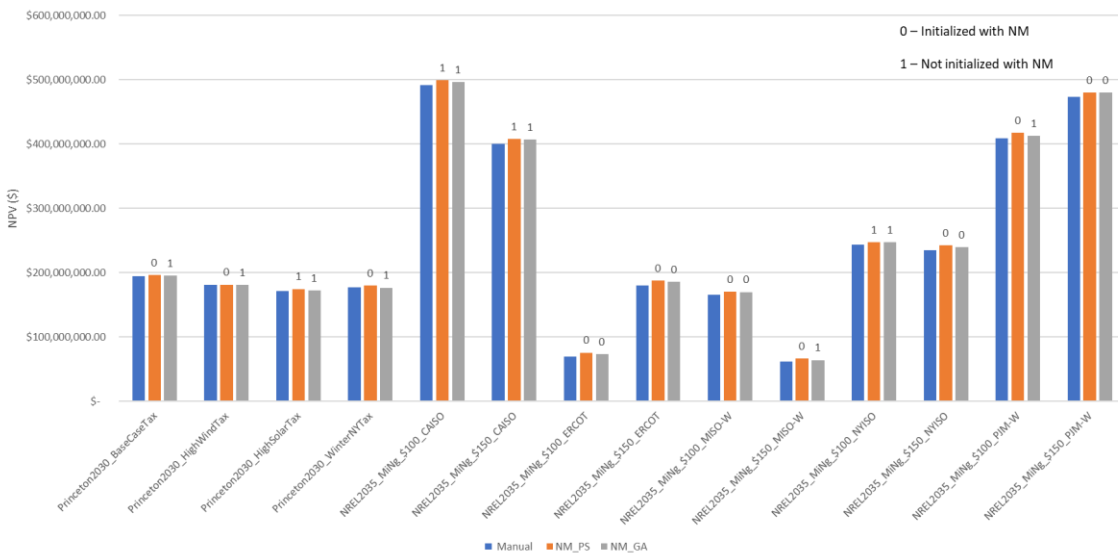


Figure 5: NPV for the Unconstrained Optimization Cases.

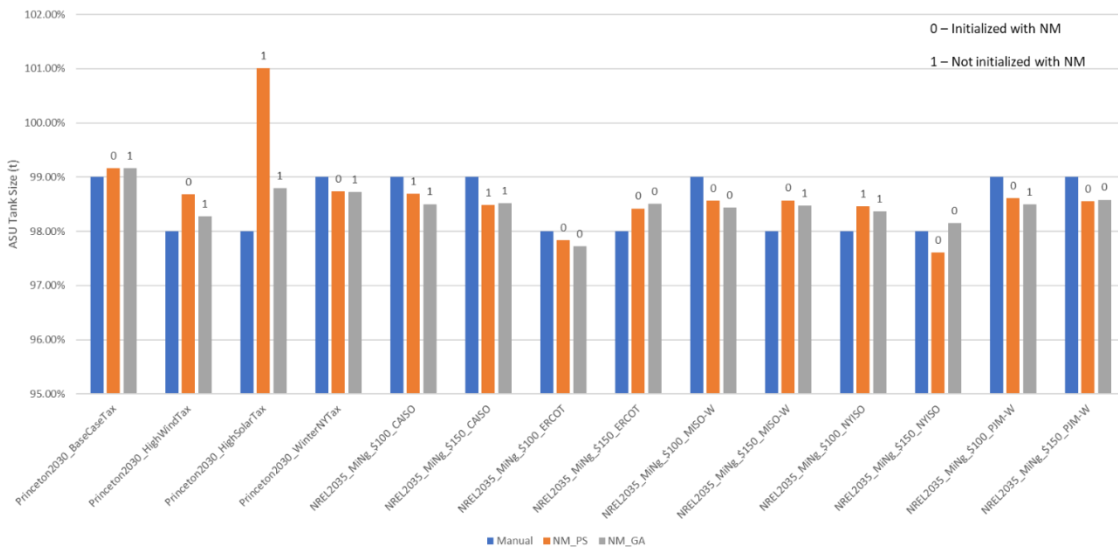


Figure 6: ASU Tank Size for the Unconstrained Optimization Cases.

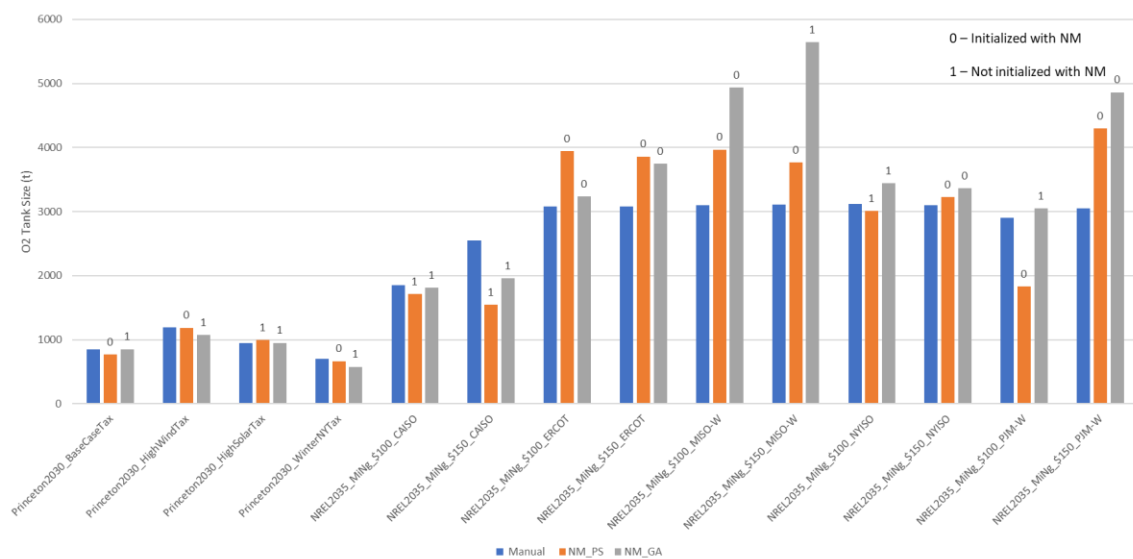


Figure 7: Oxygen Tank Size for the Unconstrained Optimization Cases.

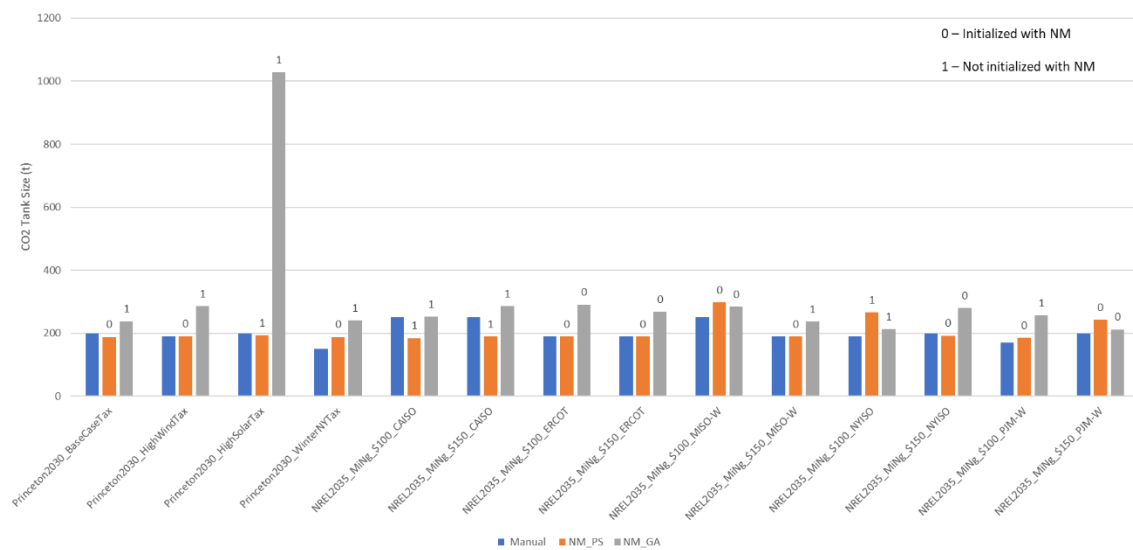


Figure 8: Carbon Dioxide (CO2) Tank Size for the Unconstrained Optimization Cases.

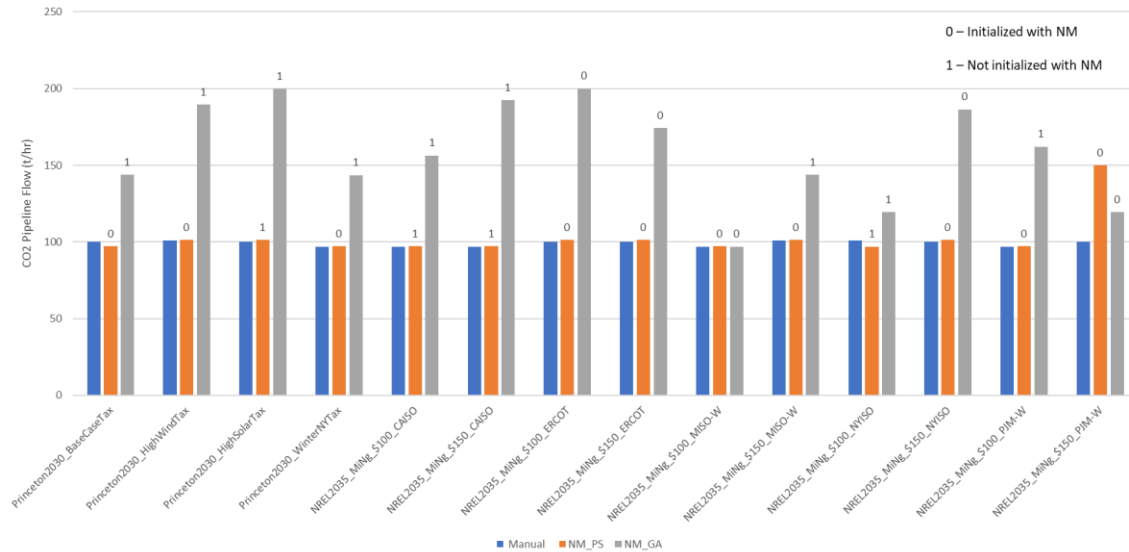


Figure 9: Carbon Dioxide (CO₂) Pipeline Flow for the Unconstrained Optimization Cases.

The results for the constrained case are shown in Figures 10-14. The NPVs for all price strips are lower than for the unconstrained by roughly 25%. That is not a bad result considering the penalty for not supplying a consistent flow to the pipeline is unknown. The size of the ASU was not a significant factor and optimized to near 100% in most cases. The size of the O₂ tank varied a lot by optimization method but that did not translate into a large change in NPV indicating that the response space is very flat in a wide range of O₂ tank sizes. The size of the CO₂ tanks needed to balance the flow were fairly large at 30-50k tonnes. While large these are not unreasonable. Again, the various optimization methods yielded a wide range of values for the same price strip indicating a smooth response surface. Finally, the flow rate of the CO₂ pipeline generally stayed near the 100% flow rate indicating that the CO₂ buffer tanks did most of the work in regulating the flow.

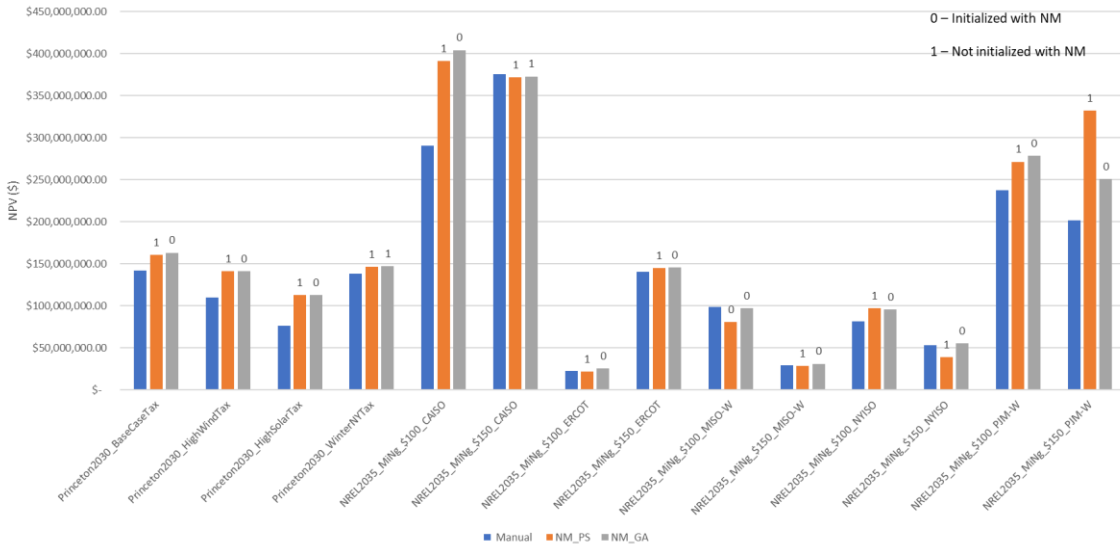


Figure 10: NPV of the Constrained Optimization Cases.

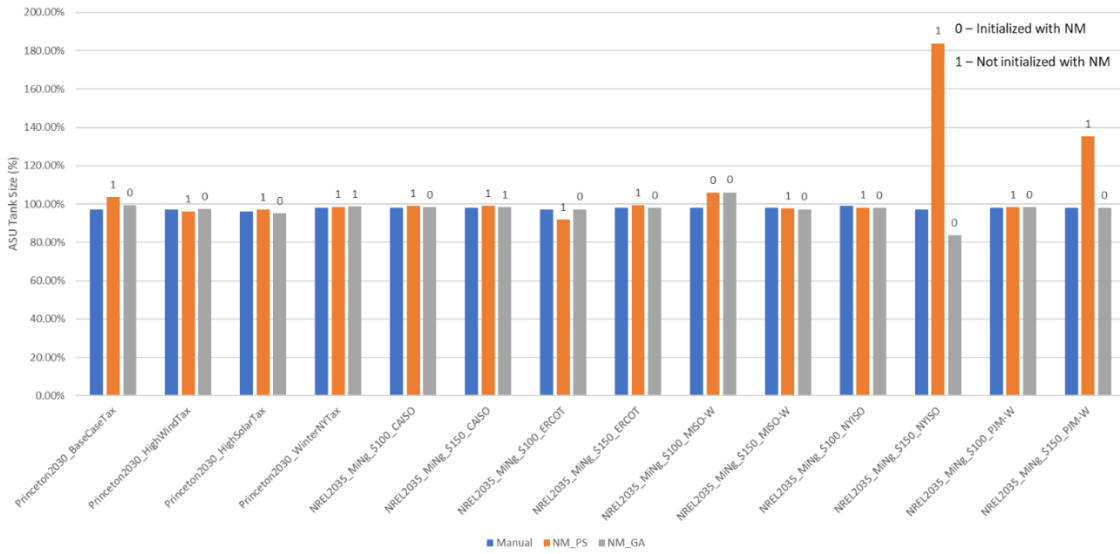


Figure 11: ASU Tank Size for the Constrained Optimization Cases.

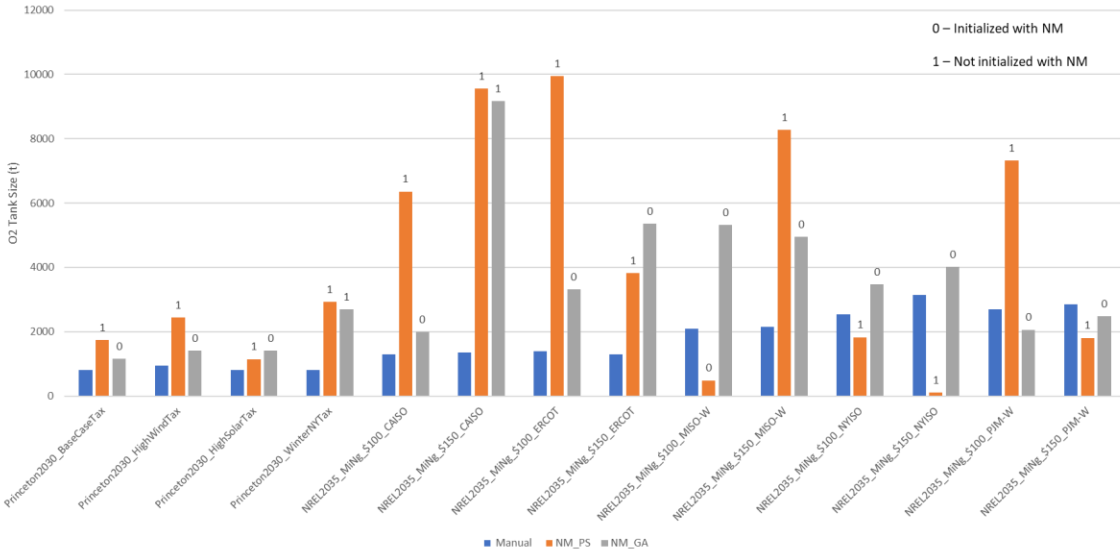


Figure12: Oxygen Tank Size for the Constrained Optimization Cases.

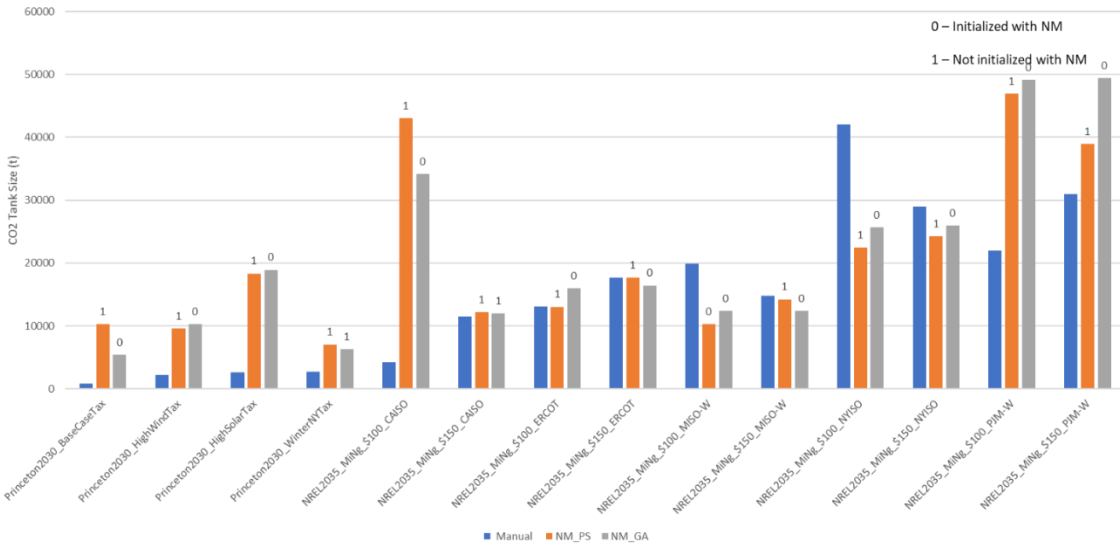


Figure 13: Carbon Dioxide (CO2) Tank Size for the Constrained Optimization Cases.

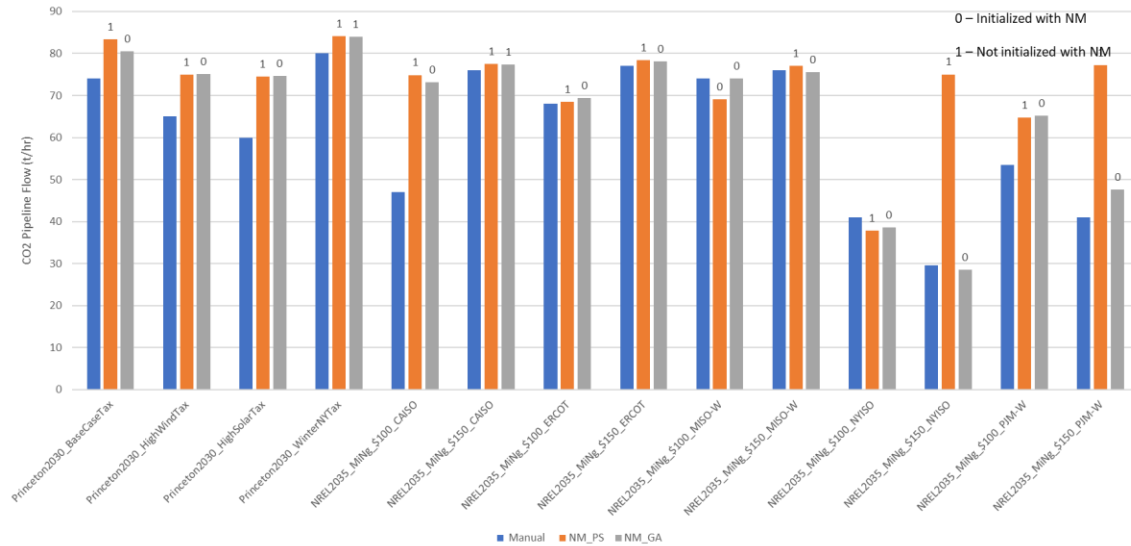


Figure 14: Carbon Dioxide (CO2) Pipeline Flow for the Constrained Optimization Cases.

Project Outputs

No project outputs.

Follow-On Funding

We have put in a proposal for a Phase II of this program, but it was not selected for funding.

References:

1. James III PhD RE, Kearins D, Turner M, Woods M, Kuehn N, Zoelle A. Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. 2019. <https://doi.org/10.2172/1569246>.
2. N. T. Weiland, C. W. White, "Performance and Cost Assessment of a Natural Gas-Fueled Direct sCO2 Power Plant," National Energy Technology Laboratory, Pittsburgh, March 15, 2019.
3. U.S. Energy Information Administration | The National Energy Modeling System: An Overview 2018 (p. 45) [https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581\(2018\).pdf](https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2018).pdf)
4. U.S. Energy Information Administration | Assumptions to the Annual Energy Outlook 2021: Electricity Market Module (Table. 5) <https://www.eia.gov/outlooks/aeo/assumptions/pdf/electricity.pdf>