Planning for Grid Integration of sCO_2 Power Cycles using Capacity Expansion Models

Jeffrey A. Bennett, Claire Trevisan, Andres F. Clarens
Virginia Environmentally Sustainable Technologies Laboratory
University of Virginia
Charlottesville, VA

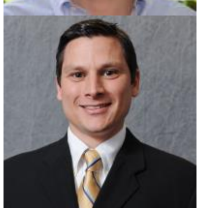
Joseph DeCarolis
Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC

AUTHOR BACKGROUND

Jeffrey Bennett is a PhD student in the Civil and Environmental engineering department at the University of Virginia.

Claire Trevisan is a fourth-year undergraduate student in the Civil and Environmental engineering department at the University of Virginia

Dr. Andres Clarens is an Associate Professor in the Civil and Environmental engineering department at the University of Virginia.



Dr. Joseph DeCarolis is an Associate Professor in the Civil, Construction, and Environmental engineering department at North Carolina State University.

ABSTRACT

Supercritical carbon dioxide power cycles offer high efficiencies and compact footprints making them well suited for smaller-scale distributed power generation applications. Such applications could be very important in power grids with heavy integration of renewable resources resulting in temporally distributed generation. As solar production drops in the late afternoon, the demand for conventional generation will quickly ramp, typically faster than large-scale steam turbines can respond. In this paper, we modeled the power grid of Puerto Rico before and after the deployment of utility-scale renewable energy projects. Like many US states, Puerto Rico has been aggressively pursuing renewable energy standards and will face shortcomings in its diurnal power demand. The goal of our paper was to assess the viability and attractiveness of smaller scale distributed generation to fill this demand, while also improving the resilience of the overall energy grid The TEMOA open-source capacity expansion model was used to develop a set of scenarios related to the deployment of distributed generation using sCO_2 cycles. A cost optimization for the selection of future energy capacity was performed using demand and cost inputs. The results are important for forecasting the ways in which sCO_2-power cycles can move beyond the demonstration phase given that cost and ramp-up times are currently unknown. Sensitivity studies are used to determine which scenarios lead to widespread deployment.

INTRODUCTION

Four months after Hurricane Maria, Puerto Rico is still working to repair its electric grid. The hurricane damaged 80% of the island's electric grid [1] and it is estimated that the repair cost could exceed $5 billion [2]. This event has sparked interest in developing strategies for redesigning the electric grid to reduce its vulnerability in the future [3]. One consideration is to pursue a more localized, distributed network that would have less reliance on long-distance transmission lines. Such an architecture may be a good application for supercritical carbon dioxide power plants, as they offer a compact footprints and high efficiencies [4].

Supercritical carbon dioxide power plants are being developed for a range of plant sizes and fuel types. Because only a few demonstration-scale units have been built to date, a number of plant characteristics, such as installation cost and ramp rate, are not well established. These factors will have a large impact on the successful deployment of a distributed sCO_2 power plant and providing a systems-level estimate of target prices is one motivation for this work. A second motivation is to assess how transmission maintenance costs might factor in to overall cost estimates of designing and operating a distributed grid following a storm like Hurricane Maria. To address these questions, a capacity expansion model was built using the "Tools for Energy Model Optimization and Analysis" TEMOA model, which is an open-source framework with the purpose of evaluating electricity supply and demand markets [5].

MODEL DEVELOPMENT AND VALIDATION

A model was developed in TEMOA to represent Puerto Rico's electricity grid that included current power plants, and potential future power plant options, including a distributed sCO_2 power plant. A diagram of the model is shown in Figure 1. The left-hand-side shows fuel sources which then connect to power plants. Conventional power plants are shown in blue, renewables in green, and the sCO_2 plant in yellow. Each power plant then connects to the electric grid. For the purposes of this model, all power plants with the exception of the sCO_2 plant provide centralized electricity that must be sent through transmission and distribution lines to reach the demand. The sCO_2 plant connects directly into the distribution network.

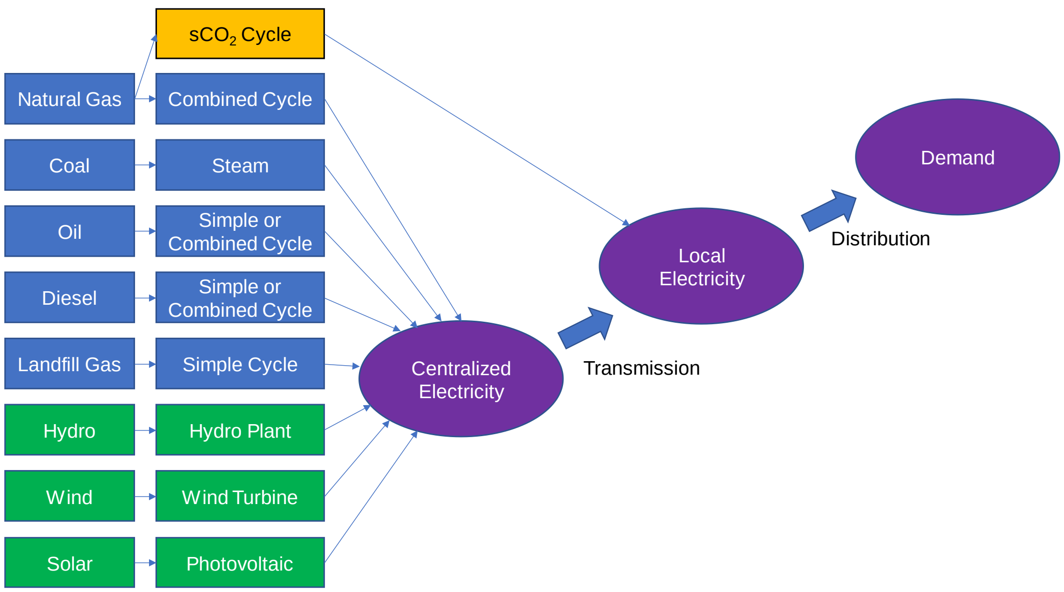


Figure 1. Diagram of TEMOA Electricity Supply and Demand

The model takes into account fuel prices, power plant investment and operational costs, as well as efficiencies. Many of the model inputs come from reports to the Puerto Rico Electric Power Authority (PREPA) [6-7]. The model is run over a 45-year time horizon starting in 2018, and optimizes electricity production to minimize cost in 5 year increments. Each year is broken into two seasons, wet and dry, and a typical day from each season into 24-hour increments. By using 24 hour increments, the model is able to capture the "duck curve" [8]. The potential for the duck curve in Puerto Rico is shown in Figure 2. The blue line (partly covered by the gray line), represents the actual hourly electricity demand in Puerto Rico on March 27, 2016. The expected solar capacity factor throughout the day is shown in orange [7]. According to NREL [9], Puerto Rico has the potential to install up to 1.1 GW of solar power. If this much solar power were installed and operated, then the remaining demand is shown in gray. The gray curve is the so-called "duck", and the primary issue is that all other power plants must quickly ramp-up in production from hours 12 to 20 to meet the evening peak demand.

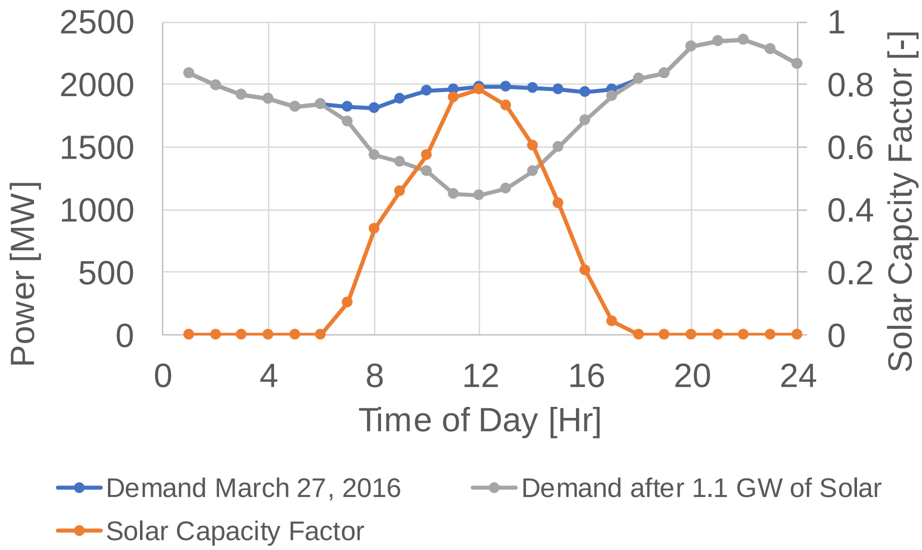


Figure 2. Prediction of "Duck Curve" in Puerto Rico if 1.1 GW of Solar were installed

Three baseline scenarios were developed to answer how well a distributed sCO_2 power plant will fit into the existing grid, as well as a grid with high renewable deployment that exhibits the "duck curve". These are summarized in Table 1.

Table 1. Model Scenarios

Scenario #	Name	Explanation
1	"Business-as-usual"	Puerto Rico continues with existing power plants and power options currently being considered
2	Introduction of distributed sCO_2 power plant	Scenario 1 plus the option to build a distributed sCO2 power plant
3	sCO_2 plant + high renewable deployment	Scenario 2 plus the requirement to have solar capacity of 1.1 GW starting in 2023

Initial parameters for a distributed sCO_2 power plant are based on [4], including an efficiency of 50% and an investment cost of 1000 $/kW. For the purposes of this work, the plant is assumed to be fired by natural gas. Initial simulations assume the plant can start-up and shutdown in 1 hour, similar to modern natural gas open cycle power plants, but this assumption is later evaluated in a sensitivity study.

To validate the model, the mix of energy sources from the first model year, 2018, was compared to the actual energy mix of 2016 [10]. As shown in Table 2, the model shows good agreement, thus it is expected that the model effectively represents the characteristics of Puerto Rico's grid prior to Hurricane Maria.

Table 2. Validation of TEMOA Model against actual electricity production [10]

% of Total Electricity Production		
Energy Source	**2016 Actual [10]**	**2018 Predicted**
Petroleum + Diesel	61.8	56.8
Natural Gas	18.5	20.3
Coal	17.2	17.8
Hydroelectric	0.5	2.7
Wind	1.3	1.9
Solar PV	0.6	0.5
Other Renewable	0.2	0.1

RESULTS

The three scenarios outlined in Table 1 were simulated in TEMOA using baseline values. The results are shown in Figures 3-5. Each figure compares the three scenarios at each time period that TEMOA optimized. Figure 3 shows a comparison of the electricity production by sCO_2 power plants. The percentage shown represents the fraction of Puerto Rico' electricity demand met by an sCO_2 power plant. Scenario 1 does not have sCO_2 plants as an option, thus no deployment. Scenario 3 results in more deployment; this is expected to be in part due to the "duck curve" impact of solar and the quick response assumption of sCO_2 plants.

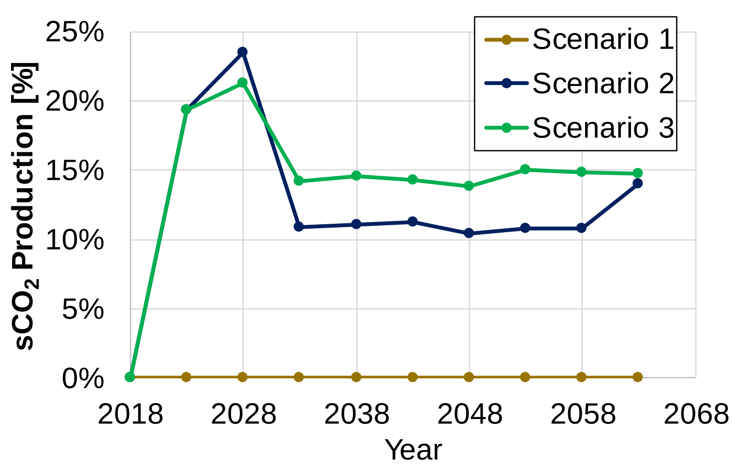


Figure 3. Comparison of baseline scenarios over the model time horizon with respect to sCO_2 deployment

Figure 4 shows the percent of production from renewable sources. It is interesting to see that renewables are expected to increase without any outside incentives. Scenario 3 reaches the maximum available capacity of wind and solar in 2048. Also of interest is that in the later time periods, the scenarios with sCO_2 plants as an option (2 and 3) lead to more renewable deployment than scenario 1, which does not have this option.

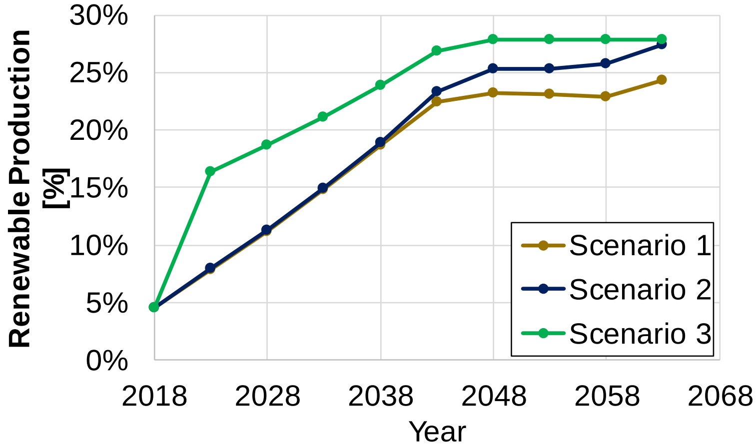


Figure 4. Comparison of baseline scenarios over the model time horizon with respect to renewable deployment

Figure 5 shows greenhouse gas emissions, specifically carbon dioxide, emitted on a yearly basis. Both scenarios with sCO_2 plants have lower emissions than the "business-as-usual" scenario. The quick decrease in emissions across all scenarios in 2023 correlates with moving away from petroleum and diesel fueled power plants.

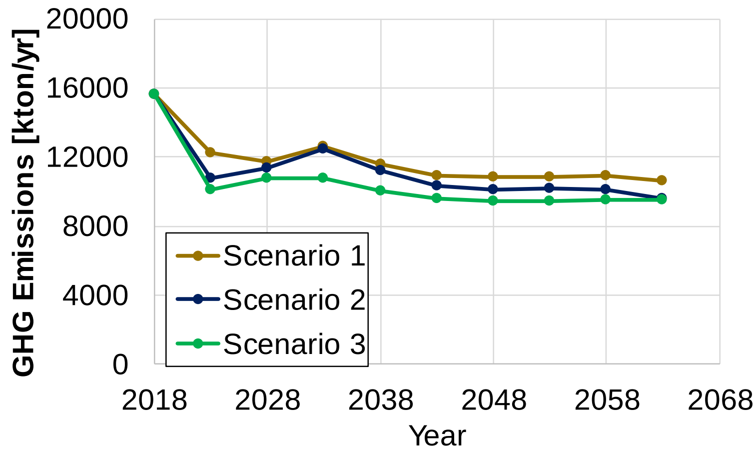


Figure 5. Comparison of baseline scenarios over the model time horizon with respect to: greenhouse gas (GHG) emissions (carbon dioxide)

SENSITIVITY STUDIES

After each scenario was run using initial model inputs, the baseline, the next step was to perform sensitivity studies to understand the importance of several key parameters. When one variable was perturbed, all others remained at their baseline value. The results from this study are shown in Figure 6. The main focus of this study was to quantify how changes would lead to more or less deployment of a distributed sCO_2 plant, thus this is the dependent variables for each plot. No results are shown for scenario 1, as a sCO_2 plant was not an option in that scenario.

The first study, shown in Figure 6a, evaluated the impact of sCO_2 plant efficiency and found a linear relationship with increasing efficiency above 42.5%. For ramp rate, Figure 6b, there is little change between 1 and 8 hours, and a gradual drop-off above 8. This shows that plant flexibility is necessary to stay competitive, but it does not have to match the start-up of simple cycle gas turbines to have a place in the market. With regards to investment cost, Figure 6c, the linear relationship is gradual. Combined with the first subplot, this suggests that moderately priced efficiency improvements will be worthwhile.

Figure 6d investigates the impact of transmission cost per kWh consumed. Distribution costs were kept constant for this study. This was chosen to represent how the electric company will be applying the cost of rebuilding transmission lines to their customers. There is a very sharp rise in sCO_2 deployment above $0.02/kWh. The current model has an sCO_2 plant as the only distributed option, thus it is expected that other forms of distributed production would also increase greatly at this point as well.

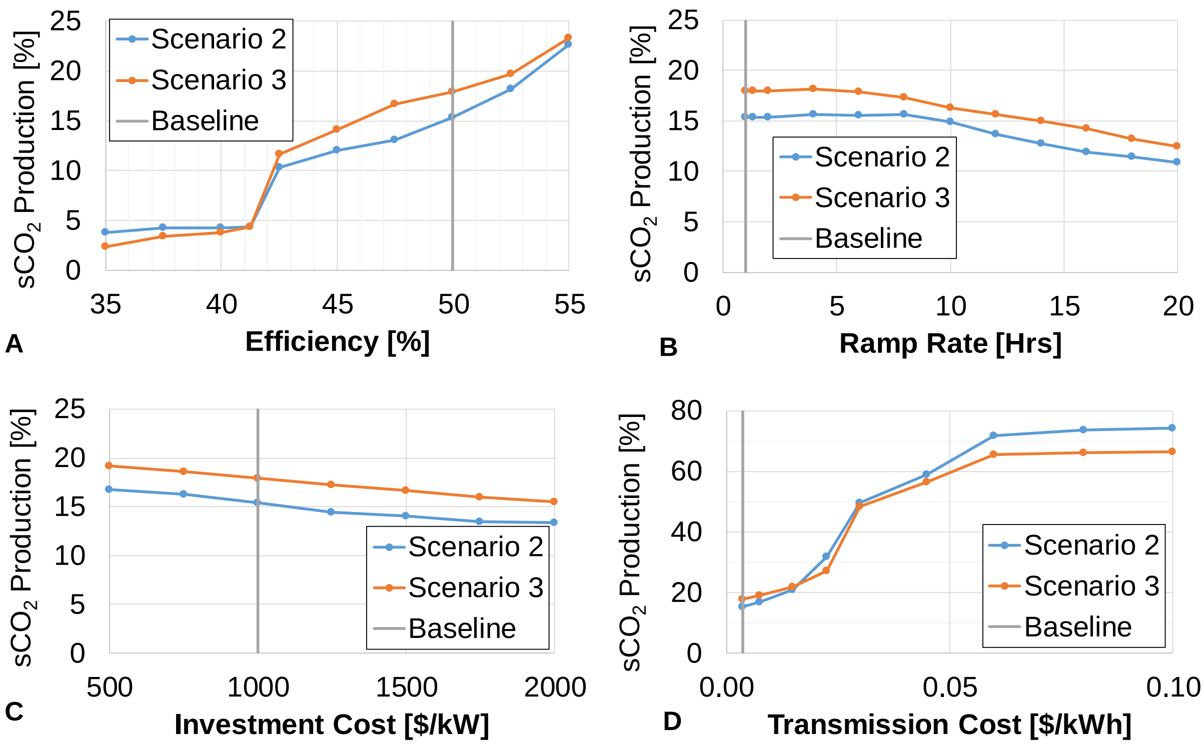


Figure 6. Results of varying the following parameters on the deployment of a distributed sCO_2 power plant: (A) Efficiency, (B) Ramp Rate, (C) Investment Cost, (D) Transmission Cost

CONCLUSIONS

In conclusion, the current estimates of sCO_2 power plant efficiencies and investment costs lead to deployment in Puerto Rico's current electric grid. As more renewable energy sources are deployed, a distributed sCO_2 plant would continue to be a competitive option. Several sensitivity studies found that ramp times faster than 8 hours and plant efficiencies greater than 42.5% will make sCO_2 power plants competitive. While investment cost is important, the plant's other baseline parameters make the deployment not very sensitive to this parameter. Lastly, distributed sCO_2 plants become increasingly attractive as transmission costs increase.

FUTURE WORK

The next steps are to extend the inclusion of sCO_2 plants into other markets to continue improving our understanding of what types of markets and conditions sCO_2 power plants will be best suited.

REFERENCES

[1] Dorell, O., "Five Weeks after Maria most of PR remains an island in the dark", USA Today, published 23 Oct 2017, Updated 25 Oct 2017, Accessed 18 January 2017.https://www.usatoday.com/story/news/nation/2017/10/23/storm-whipped-puerto-rico-power-restoration-plagued-problems-after-maria/792376001/

[2] Kahn, C., "Repairing Puerto Rico's Power Grid Could Top $5 Billion", NPR, published 11 Oct 2017, Accessed 18 January 2017. https://www.npr.org/2017/10/11/557051712/repairing-puerto-ricos-power-grid-could-top-5-billion

[3] Greenemeir, L, “Repair or Renovate? Puerto Rico Faces Stark Power Grid Options”, Scientific American, published 13 November 2017, Accessed 18 January 2017. https://www.scientificamerican.com/article/repair-or-renovate-puerto-rico-faces-stark-power-grid-options/

[4] Dennis, R.A., Musgrove, G., Rochau, G., Fleming, D., Carlson, M., Pasch, J., (2017), “Overview”, In Brun, K., Friedman, P., & Dennis, R., (Eds.), *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO2) Based Power Cycles*, Elsevier Ltd.

[5] K Hunter, S Sreepathi, JF DeCarolis (2013). Modeling for Insight Using Tools for Energy Model Optimization and Analysis (TEMOA), *Energy Economics*, 40, 339-349, ISSN 0140-9883.

[6] Puerto Rico Electric Power Authority (PREPA), “Aguirre Site Economic Analysis”, 25 April, 2017.

[7] URS Corporation, “Fortieth Annual Report on the Electric Property of the Puerto Rico Electric Power Authority”, June 2013.

[8] Lazar, J., 2014. Teaching the “Duck” to Fly. Regulatory Assistance Project, Montpellier, VT.

[9] National Renewable Energy Laboratory, “Energy Snapshot Puerto Rico”, DOE/GO-102015, March 2015.

[10] Puerto Rico Energy Commission, “Distribución Porcentual de la Generación de Energía por Tipo”, http://energia.pr.gov/datos/distribucion-porcentual-de-la-generacion-de-energia-por-tipo/, Accessed 17Jan2018.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the UVA School of Engineering and Applied Science for its support.