Oxy-fuel combustion: A threat or an opportunity for solar?

Mariela Colombo, Sarah Kurtz

University of California, Merced, Merced, California, 95343, United States

***Abstract* — The rapid growth of solar, as well as other variable renewable energies, is key for achieving decarbonization targets. However, their integration to the grid and increased curtailment have become a major challenge for their further development in the most successful markets. In this study, the impacts of introducing an oxy-fuel combustion resource in California's energy grid are evaluated. To do so, we use RESOLVE, a capacity expansion model, to predict the energy grid mix for 2030, 2035, 2040, and 2045. Our results indicate that the model chooses to build the oxy-combustion resource when it is available at relatively low costs. While the introduction of oxy-fuel combustion, even at limited scale, reduces the selected operational capacity of solar PV and Lithium-ion batteries, it substantially reduces the curtailment of the solar that *is* installed. Far from being a threat, this reduction could be an opportunity for solar to continue with robust growth, retaining its economic and environmental value even when the procurement of storage might otherwise limit its adoption rate.**

I. Introduction

To limit global warming to 1.5 °C, as outlined in the Paris Agreement, a comprehensive transformation of the global energy system is necessary. While the deployment of established clean energy technologies like solar and wind power is crucial in initiating a substantial decrease in emissions, additional technologies such as Carbon Capture and Storage (CCS) are recognized as important contributors to achieving net-zero targets [1]-[2].

In California, ambitious targets had been set for decarbonizing its electricity sector. The state's Senate Bill 100 (SB100) sets targets of 60% of electricity generation with renewable energy by 2030, and 100% carbon-free retail electricity sales by 2045.

The case of California is of particular interest, as solar PV is the dominant technology leading the decarbonization. However, its variability and increased curtailment are creating some challenges for its expansion. These challenges not only impact the economic profits for solar projects, but also their potential environmental benefits [3]-[4].

In this context, natural gas with CCS technologies could represent an opportunity for balancing the grid with low-carbon emission alternatives that can be used as dispatchable or baseload resources. However, today, CCS does not have a defined role in California's transition.

In this study, a particular CCS technology, oxy-fuel combustion, is introduced in a capacity expansion model for predicting 2030, 2035, 2040 and 2045 grid mix in California and evaluating the potential effect of this technology on solar PV growth.

II. Methods

A. RESOLVE

For modeling California's grid in 2030, 2035, 2040 and 2045, RESOLVE, a capacity expansion model is used. The model is formulated as a linear optimization problem that co-optimizes investment and dispatch for a selected set of days over a multi-year horizon to identify least-cost portfolios for meeting decarbonization targets and other system goals [5]. Fig. 1 shows a diagram with the main inputs and outputs of the model.

The inputs are described in the PSP scenario [6]. For this analysis, the 38MMT Core Portfolio is considered [6].

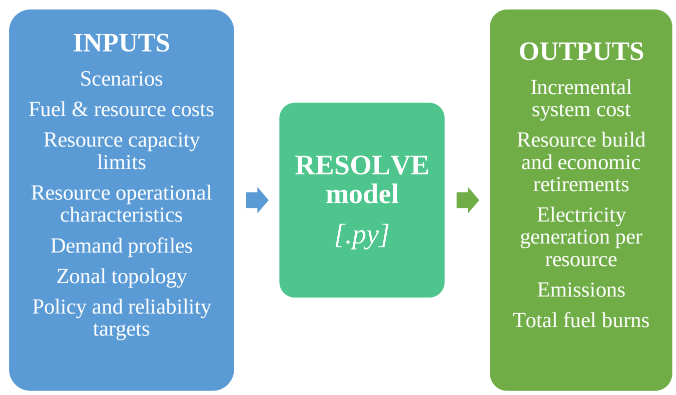

Fig. 1. Schematic of RESOLVE Modeling Components.

For reducing computational resources, instead of running the model with hourly timesteps, a Critical Timesteps (CTS) approach is used. In this approach, two hours of the day are considered: One hour before sunrise and one hour after sunset. [7].

B. Oxy-fuel Combustion Resource Modelling

Oxy-fuel combustion or oxy-combustion involves the combustion of a fuel using nearly pure oxygen (not air); hence the flue gas is composed almost exclusively of CO_2 and water vapor [2]. This process has two main benefits:

•NO_X production is greatly reduced, due to the removal of N_2 from the air,

•H_2O can be removed easily by means of dehydration to obtain a high-purity CO_2 stream which presents an opportunity to simplify carbon dioxide capture in power plant applications.

In general, the inclusion of an air separation unit, CO_2 purification and compression stages increase capital cost and energy use, depending on the purity of the input gases [8]-[9]. However, the Allam Cycle represents a cost-competitive option for oxy-combustion. In this process, a high-pressure supercritical CO_2 working fluid is used in a closed-loop cycle that retains all emissions by design. Apart from producing power, the by-products are liquid water and a stream of high-purity, pipeline-ready CO_2 [9]. The cycle can utilize a variety of carbon-based fuels, including natural gas and gasified solid fuels such as biomass and municipal solid waste. This design would allow a cost competitive oxy-combustion process compared to existing thermal electricity generation technologies, with high efficiency and no greenhouse gas emissions [10]-[11]-[12].

The Allam Cycle powered by natural gas is a licensed process by a private company. The company had a technology validation in a testing facility in Texas and announced the first utility-scale project of 300 MWe planned to be operational in 2026, also in Texas [10]. A simplified diagram of the Allam Cycle with natural gas is shown in Fig. 2:

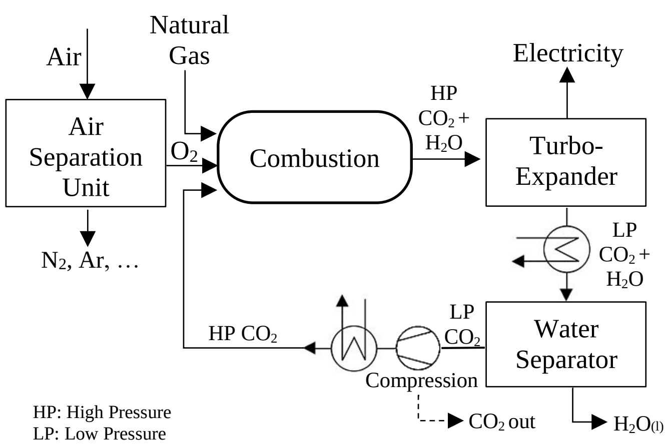

Fig. 2 – Diagram of Allam Cycle with Natural Gas [10].

For evaluating the impact of this technology in California, an estimated projection of the maximum operational capacity was defined (Table I). We anticipate that the growth will be limited both by the implementation of the new Allam cycle technology as well as the infrastructure that will be needed to use or sequester the CO_2 that would be generated in large quantity.

TABLE I
MAXIMUM OPERATIONAL CAPACITY (GW) PER YEAR FOR OXY-COMBUSTION IN CALIFORNIA.

Year	Maximum Operational Capacity (GW)
2030	0.5
2035	1
2040	2
2045	4

Also, a cost sensitivity analysis was performed, considering a cost range from 1 to 2.5 times the cost of existing advanced Combined Cycle Gas Turbines (CCGT).

III. RESULTS AND DISCUSSION

The operational capacity for California's grid in 2030, 2035, 2040 and 2045 has been modelled using RESOLVE.

For the Baseline scenario, no oxy-combustion resource is offered to the model. The Baseline results were compared to the case of having oxy-combustion available at different capital costs.

In Fig. 3, the operational capacity of oxy-fuel combustion selected by the model for the analyzed years is shown. For the lowest cost scenario, the maximum operational capacity is reached for all the years, as established in Table I. However, as the cost increases, the selected operational capacity is reduced reaching zero when the cost is more than 2 times the capital cost of existing CCGT facilities.

Of all the different electricity generation and storage resources, such as wind, geothermal, biomass, pumped-hydro and others, only solar PV and 4-hour Lithium-ion batteries are affected by adoption of the oxy-combustion resource. In Figs. 4 and 5, the operational capacities of these resources, for the different years and cost scenarios are shown.

The oxy-fuel combustion resource, even with limited capacity, reduces the need of 4-hour Lithium-ion batteries as well as solar PV. The major differences are seen for the low-cost scenarios, 100% and 150% of CCGT cost. For example, in 2045, 4 GW of oxy-combustion reduces the need of solar PV by 19 GW and of Lithium batteries by 14 GW. These reductions represent 12% of the overall capacity for both resources, compared to the baseline.

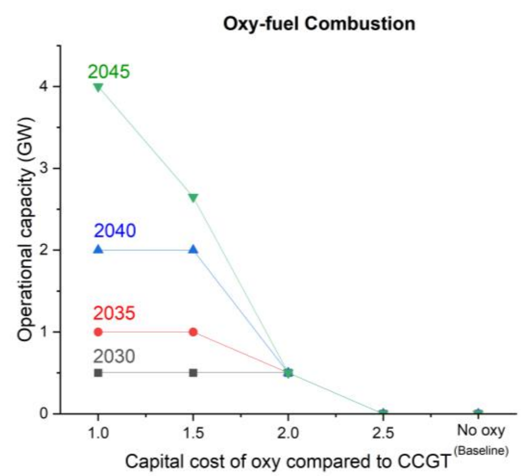

Fig. 3. Oxy-combustion operational capacity selected for 2030, 2035, 2040 and 2045 as a function of its capital cost.

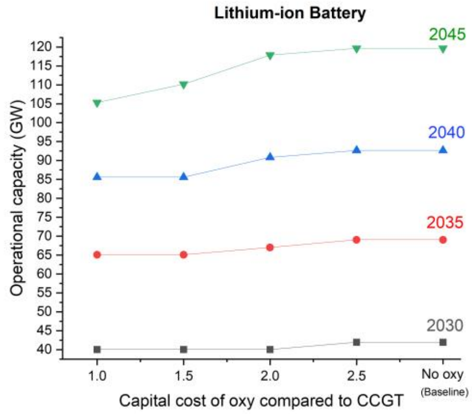

Fig. 4. Lithium-ion batteries operational capacity for 2030, 2035, 2040 and 2045 as a function of oxy-combustion capital cost.

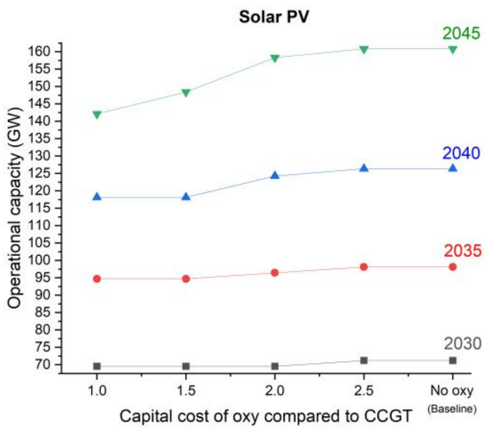

Fig. 5. Solar PV operational capacity for 2030, 2035, 2040 and 2045 as a function of oxy-combustion capital cost.

The capacity factor selected for the oxy-combustion resources for each month and modeled year is shown in Fig. 6.

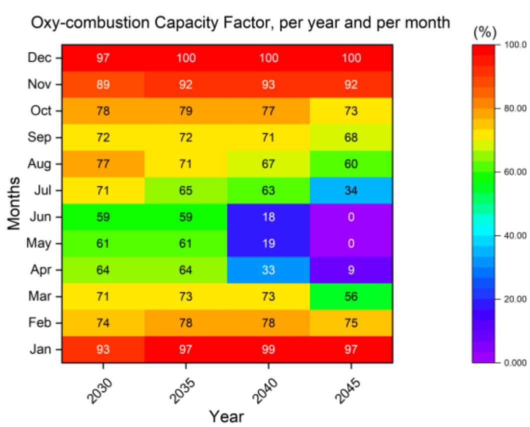

Fig. 6 – Oxy-combustion capacity factor.

As expected in a grid with high solar PV penetration, the higher capacity factors for the oxy resources are found for fall and winter months (November, December, and January). However, for spring and summer the capacity factors are smaller in general and experience a significant reduction from 2030 to 2045. As the deployment of solar PV and Lithium-ion batteries increase, they can supply most of the electricity demand for these months. Moreover, the model chooses to shut down the oxy-combustion resources during these periods, even though there is an associated cost (which solar and batteries don't have).

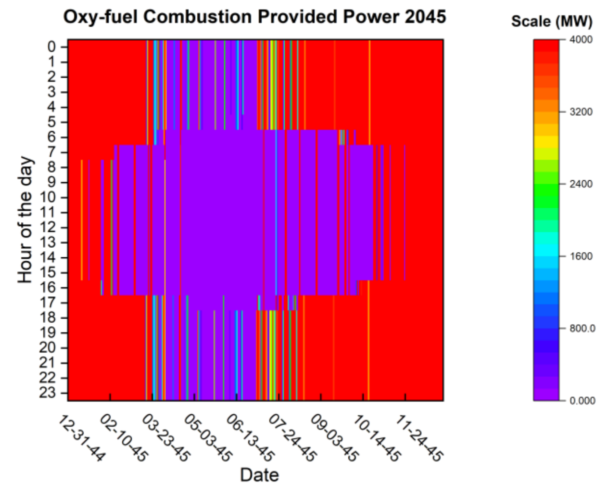

Fig. 7. Hourly dispatch of oxy-fuel combustion resource for 2045.

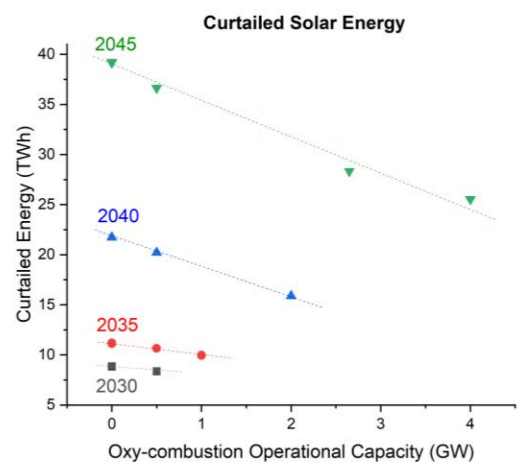

Fig. 8. Curtailed solar energy as a function of oxy-combustion operational capacity for 2030, 2035, 2040 and 2045.

In Fig. 7, the hourly dispatchability of oxy-combustion is shown. Again, the role of this resource is different through the months. During winter, it functions as a baseload type of resource, being ON and at maximum capacity most of the time. However, during spring and summer it is generating only during night-time or completely OFF, functioning more as a dispatchable resource.

As winter is the most challenging season in terms of renewable generation supply in California [12], having this flexible, and with low-emissions resource, reduces the need of surplus capacities of solar and batteries. This helps to decrease the negative economic impact of overproduction during summer, in some cases leading to significant curtailment (Fig. 8). For 2045, 4 GW of oxy-combustion could reduce solar energy curtailment by 35%.

IV. Conclusions

In this study, the impact of oxy-fuel combustion on California's future grid was evaluated.

Even though there is high uncertainty regarding its ability to scale up in the state and in the speed of cost reduction in the short-term, the results indicated that even limited deployment of this technology will reduce selection of solar PV and storage operational capacities.

Even with these reductions, the opportunity for solar growth is huge. However, by 2045 solar curtailment is expected to reach extremely high levels.

The use of oxy-fuel combustion reduces solar energy curtailment, which helps retain the economic and environmental benefits of solar electricity generation. Moreover, reducing the need in the short-term for batteries and solar, helps to ease the current pressure on the supply chain for raw materials allowing for a smoother transition. Effectively, assuming that the oxy-combustion can be used either as a baseload or as a dispatchable resource, reduces the need for storage, providing an excellent complement to solar.

In conclusion, oxy-fuel combustion technology is not in a position to grow to levels that could threaten solar development. In fact, the complement with solar electricity generation could be considered an opportunity for addressing the additional challenges for its increasing penetration.

Acknowledgments

This paper was prepared as a result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this document; nor does any party represent that the use of this information will not infringe upon privately owned rights. This paper has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report.

References

[1] IPCC, "Synthesis report of the IPCC Sixth Assessment Report AR6", IPCC, 2023.

[2] IEA, "About CCUS", IEA, 2021.

[3] D. Millstein, R. Wiser, A. D. Mills, M. Bolinger, J. Seel, S. Jeong, "Solar and wind grid system value in the United States: The effect of transmission congestion, generation profiles, and curtailment," *Joule*, vol. 5, pp. 1749-1775, ISSN. 2542-4351, 2021.

[4] O. Ruhnau, "How flexible electricity demand stabilizes wind and solar market values: The case of hydrogen electrolyzers," Applied Energy, vol. 307, ISSN. 0306-2619, 2022.

[5] Energy and Environmental Economics, "RESOLVE Capacity Expansion Model", Energy and Environmental Economics, 2019.

[6] California Public Utilities Commission, "Decision adopting 2021 Preferred System Plan", 2021.

[7] ZareAfifi F., Mahmud Z., Kurtz S., "Diurnal, physics-based strategy for computationally efficient capacity-expansion optimization for solar-dominated grids", submitted for publication in *Energy*, 2023.

[8] National Energy Technology Laboratory, "Oxy-combustion", National Energy Technology Laboratory.

[9] T. Evans, E. Grynia, "Carbon Capture – Purpose and Technologies", Gas Liquid Engineering, 2020.

[10] R. Allam, S. Martin, B. Forrest, J. Fetvedt, X. Lu, D. Freed, G. William Brown, T. Sasaki, M. Itoh, J. Manning, "Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture," Energy Procedia, vol. 114, pp. 5948-5966, ISSN 1876-6102, 2017.

[11] NET Power, "Projects", NET Power, 2023.

[12] M. Y. Abido, S. R. Kurtz, "Optimal Strategy for Using Biomass to enable California High Penetration Solar," IEEE 49th Photovoltaics Specialists Conference (PVSC), pp. 0212-0212, 2022.