Value of long-duration energy storage and oxy-combustion in renewables-driven grids

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***Abstract*— Decarbonizing the power sector is key for mitigating climate change. However, as the grids integrate higher capacities of variable renewable energy, supply-demand mismatches and increased curtailment are challenging their further adoption. In this paper, two technological alternatives are studied to reduce these challenges: long-duration energy storage (LDES) and oxy-combustion. For modelling high renewable penetration grids, such as California, a capacity expansion model is used. For the modelled years 2030, 2035, 2040 and 2045, the impact of the availability of 100-h LDES and oxy-combustion is studied.**

***Index Terms*— Renewable energies, Long-duration energy storage, Oxy-fuel combustion, Capacity expansion model.**

I. INTRODUCTION

The power sector stands as one of the major contributors to greenhouse gas (GHG) emissions. In 2022 it reached a record high of 14.6 Gt of CO_2 eq., accounting for 40% of the total energy-related emissions for the year [1]. To mitigate climate change, the decarbonization of the electric sector is imperative.

The declining levelized cost of electricity (LCOE) of variable renewable energy (VRE) has led to rapid growth in wind and solar energy adoption. However, integrating large VRE capacities into the power system poses challenges for system operators. The inherent variability of wind and solar power and the fluctuations in electricity demand create short- and long-duration supply-demand imbalances that need to be addressed [2],[3],[4],[5]. Moreover, as VRE penetration increases, excess generation curtailment becomes more prevalent during periods of low net demand [5], while natural gas power plants typically fill the gap during peak net demand and VRE shortage [2]. This dynamic not only affects electricity prices, but also the environment.

Previous studies have highlighted the need for long-duration energy storage (LDES) to achieve cost-effective decarbonization and ensure a reliable electricity supply [3], [4], [6], [7].

In contrast to short-duration energy storage technologies that are expected to be dominated by lithium-ion batteries by 2030 [6], the market for LDES encompasses a wider range of technologies with different readiness levels, including electrochemical, chemical, thermal, and mechanical options [2], [7].

Managing long-duration imbalances in VRE supply and electricity demand also may require the incorporation of firm low-carbon resources, such as fossil fuel power generation with carbon capture and storage (CCS) [8]. Furthermore, Sepulveda et al. (2018) found that additional cost reductions in VRE and batteries, along with surplus installed capacity for meeting peak demand, would be necessary for meeting decarbonization targets without the inclusion of firm low-carbon resources. An example of this type of resource is oxy-fuel combustion, or oxy-combustion. This CCS technology involves burning fuel with nearly pure oxygen (instead of air), resulting in combustion gases primarily composed of CO_2 and water vapor simplifying carbon dioxide capture in power plant applications [9], [10].

The Allam Cycle is a potentially cost-competitive and high efficiency alternative to traditional oxy-combustion processes [11], [12], [13]. This technology involves a closed-loop process, with high-pressure CO_2 used as the working fluid, capturing all emissions by design. The process allows for different types of fuels, such as natural gas, biogas, biomass, or municipal solid waste that has been gasified [11]. Previous research has shown that even limited deployment of this technology can reduce the need for solar and lithium-ion batteries and decrease solar curtailment, with the model selecting it primarily for winter operation [14]. In 2022, the company that licensed this design with natural gas announced the first utility-scale project of 300 MWe, that is planned to be operational in 2026 in Texas [12].

This study investigates how the adoption of long-duration energy storage affects the selection of firm low-carbon resources, such as oxy-combustion. We focus on oxy-combustion because its planned deployment at the 300 MW level is an indication that it could be ready to expand, California because of its high use of renewables already, and 100-h storage to focus on multi-day balancing horizons. We start by describing the publicly available model and inputs. We then show the capacity expansion selected by the model and the resulting curtailment depending on the efficiency assumed for the 100-h storage as well as the year being modeled. Finally, we explore when oxy-combustion is selected to build and when it is selected to be used, highlighting how oxy-combustion in California may include both diurnal and seasonal applications.

II. METHODS

A. California's grid modelling

RESOLVE, a capacity expansion model, is used for modelling California's grid in 2030, 2035, 2040 and 2045. This model uses linear optimization to identify least-cost portfolios for meeting decarbonization targets and other system goals required by grids with high penetration levels of renewable energy [15].

The model has a vast list of inputs, including electricity-generation-resources costs, generation profiles, efficiencies, and operative parameters, as well as demand profiles, and policy targets. For this study, the inputs considered are taken from the "Preferred system portfolio" scenario developed to meet California's targets [16]. With these inputs, a "Baseline" scenario is defined without inclusion of oxy-combustion or long-duration energy storage.

To optimize computational resources, the model employs a critical timesteps (CTS) method instead of hourly timesteps. This method focuses on hours of the day when energy storage is at a relative maximum or minimum, namely one hour after sunrise and one hour prior to sunset [17], significantly reducing the computational complexity while maintaining a high accuracy.

B. Long-duration energy storage

In this study, two options or technologies for 100-h duration LDES are modeled:

- 100-h duration, 50% round-trip efficiency (RTE)
- 100-h duration, 80% RTE

The capital cost for 1 MW of LDES resources is assumed 1.6 times the corresponding cost for 1 MW of 4-h lithium-ion batteries, with 85% RTE. This means that the cost of LDES per energy capacity ($/kWh) is 0.06 times 4h Lithium-ion batteries, which represents an energy capital cost between 8-10 $/kWh for the LDES resource [18]. This cost range might be supplied by different technologies, from more traditional (such as pumped hydro [6]) to more novel options (such as flow batteries, thermal storage [7] or iron-air batteries [18]).

Duration, capital costs and efficiency are the key parameters for modelling the LDES resources. Although it is not part of this study, when selecting specific LDES technologies additional parameters should be considered, such as idle losses, response time, land use, and energy capacity.

C. Oxy-fuel combustion

For California, there are no announced projects with Allam Cycle oxy-combustion technology. For this reason, it was assumed that the scalability of this technology is limited due to the lack of information regarding future projects, but also due to the lack of CO_2 transportation and storage infrastructure.

The following maximum operational capacities per year were considered:

- Maximum operational capacity 2030: 0.5 GW
- Maximum operational capacity 2035: 1 GW
- Maximum operational capacity 2040: 2 GW
- Maximum operational capacity 2045: 4 GW

The selection of this resource is dependent on the capital costs and fuel costs considered. In previous work [14] it was found that when capital costs exceeded two times the cost for combined cycle gas turbine (CCGT) facilities, oxy-combustion was not selected by the model. However, in this study, oxy-combustion is modelled with the same capital cost as CCGT, to represent a competitive cost that would promote the adoption of this technology. The fuel costs for the oxy-combustion were assumed to increase from $6/MMBTU in 2030 to $8/MMBTU in 2045. These costs were estimated from $3.4-3.6/MMBTU outside of California, reflecting the generally higher prices found in California.

In the model, a linearized unit commitment is considered, and a minimum stable level of 20% is established for the operation of each oxy-combustion unit.

III. RESULTS AND DISCUSSION

A. LDES

The Baseline results for the years 2030, 2035, 2040 and 2045 are compared with the LDES-containing scenarios in Fig. 1, including the operational capacities. Only the results for solar PV, 4-h lithium-ion batteries and LDES are presented, as the rest of the resources (such as wind, hydro, biomass or geothermal) do not show any difference compared to the Baseline. This is mainly due to the dominance of solar PV as the primary renewable energy source in California.

At the cost target selected for the LDES resources, the adoption of the 100-h, 50% RTE option is limited. Only for 2040 and 2045, the model selects 2 GW and 4 GW, respectively. However, when the RTE is 80%, the selection of this resource is significant, almost replacing the entire operational capacity of 4-h lithium-ion batteries.

Solar PV operational capacity is not notably impacted by the introduction of LDES resources; however, its curtailment is reduced as shown in Fig. 2. Without LDES resources

(Baseline scenario) solar energy curtailment reaches 9% of the total solar generation by 2045, but with 100-h, 80% RTE LDES curtailment is reduced to 2%. The limited adoption of 100-h, 50% RTE LDES also has an impact on curtailment, reducing it from 9% to 7.5% by 2045. These results indicate that having LDES allows for a higher utilization of the available solar resources.

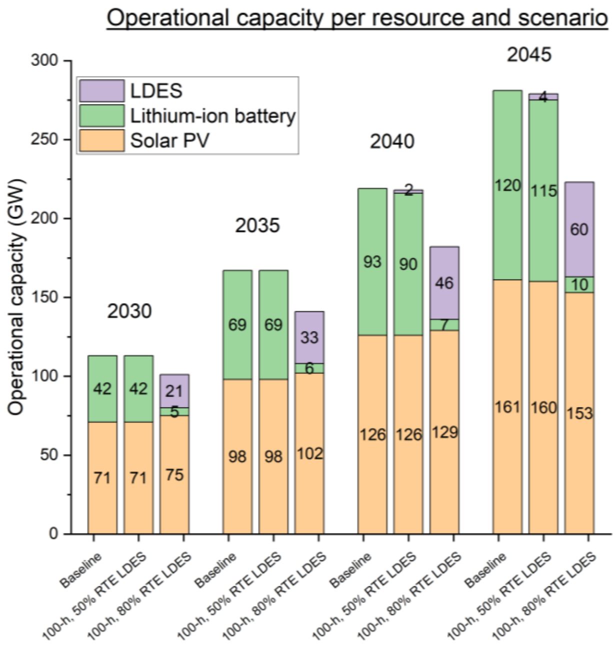

Fig. 1 – 2030, 2035, 2040 and 2045 operational capacity per resource and scenario without oxy-combustion.

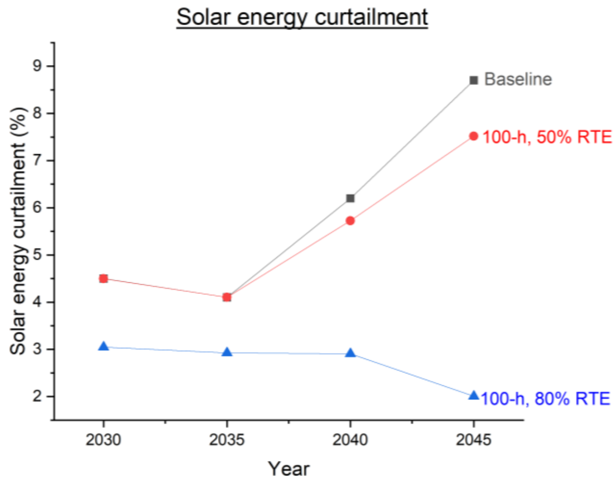

Fig. 2 – Curtailed solar energy per year, and scenario.

B. *Oxy-combustion*

For the two LDES analyzed scenarios (100-h, 50% RTE and 100-h, 80% RTE LDES), the impact of the availability of oxy-fuel combustion was modelled with RESOLVE. The operational capacities obtained are shown in Fig. 3.

For both scenarios, oxy-combustion is built up to the maximum operational capacity offered, while the operational capacities of solar PV and storage are reduced. For 80% RTE in 2045, 4 GW of oxy-combustion reduces solar PV capacity from 153 GW to 144 GW, and 4-h lithium-ion batteries from 60 GW to 54 GW. In fact, the 100-h, 80% RTE with oxy-combustion scenario represents the case with smallest capacity expansion needed for meeting 2045 energy demand.

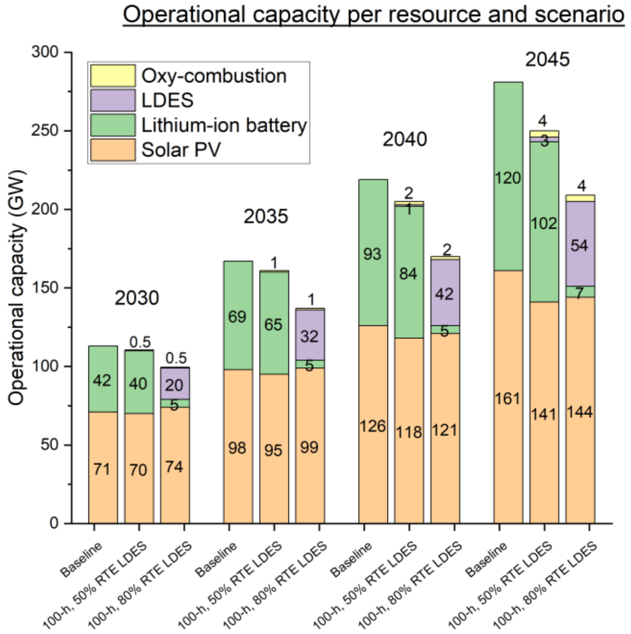

Fig. 3 – 2030, 2035, 2040 and 2045 operational capacity per resource and scenario with oxy-combustion.

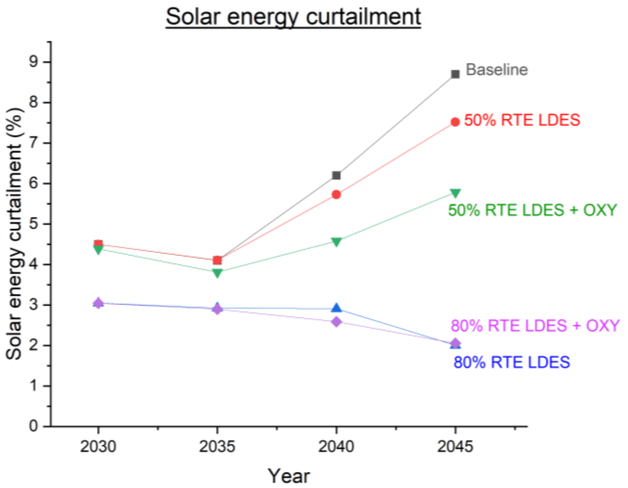

Fig. 4 – Curtailed solar energy with oxy-combustion, per year, and scenario.

Oxy-combustion also impacts curtailment for the 100-h, 50% RTE scenario (Fig. 4). For 2045, solar curtailment is reduced from 7.5% (without oxy-combustion) to 5.8%.

In Fig. 5 and 6, the oxy-combustion dispatchable power is shown for 2045, per day and for the hours of the day analyzed based on the CTS approach.

For both scenarios, the role of the oxy-combustion resource is different throughout the year. During winter, it covers the energy needs not supplied by the solar/LDES available. On the other hand, during spring/summer months, the model does not select this resource for electricity generation. However, the period without generation is longer when the 100-h, 80% RTE LDES resource is offered, mainly due to the higher storage capacity selected by the model. For the rest of the months, it is being utilized as a dispatchable resource, operating at different power levels based on the net load demand fluctuations.

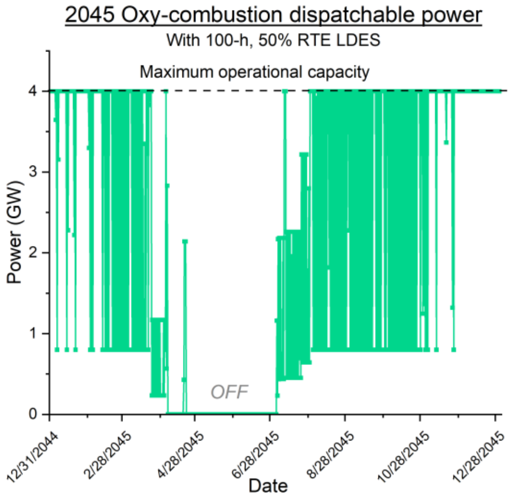

Fig. 5 – 2045 Oxy-combustion dispatchable power, with 100h, 50% RTE LDES.

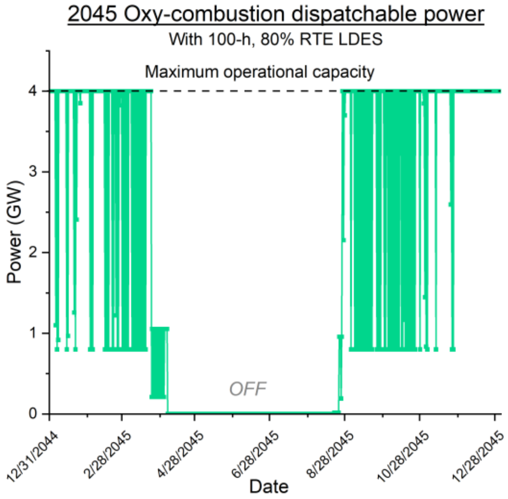

Fig. 6 – 2045 Oxy-combustion dispatchable power, with 100-h, 80% RTE LDES.

IV. CONCLUSIONS

In this study, a capacity expansion model was used for evaluating the potential roles of 100-h LDES with two round-trip efficiencies, and a recently demonstrated oxy-combustion technology.

The cost target considered for the LDES resources is challenging for the adoption of 50% RTE LDES technologies, as the model still prefers 4-h lithium-ion batteries as the main storage reserves. However, for 80% RTE LDES technologies, the cost is competitive enough to allow a significant selection of long-duration storage over lithium-ion batteries. Moreover, for this case, solar energy curtailment is significantly reduced, allowing for a higher utilization of solar resources.

When oxy-combustion is offered, in both scenarios it is selected, and reaches the maximum operational capacity defined based on the status of the technology. When this resource is available, the need for surplus solar and storage capacity for meeting peak demands is reduced. Furthermore, this resource can be utilized as a dispatchable resource during spring, summer or fall months and as a baseload generator during winter months.

In conclusion, the combination of 100-h LDES and oxy-combustion allows for a reduction in the overall capacity expansion needed in grids with high renewable penetration, as they can compensate short- and long-duration supply and demand imbalances, while reducing curtailment and ensuring a reliable supply.

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