NO ALARMS AND NO SURPRISES - DYNAMICS OF RENEWABLE ENERGY CURTAILMENT IN CALIFORNIA

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Overview

As solar and wind become the lowest-cost electricity generation technologies in expanding areas of the World, with costs expected to decline further in the coming decades, their penetration in electricity systems has been consistently increasing. The economics of wind and solar are significantly different from conventional dispatchable technologies, both in terms of costs and value. Solar and wind only produce when the resource is available and the electricity system has to continuously balance demand and supply. For these reasons, renewable generation may have to be curtailed (i.e. reduce generation with respect to what could be produced given available resources) when production exceeds demand, the system is not flexible enough to adapt to intermittency, or the concentration of VRE capacity in a small area causes grid congestion.

We first estimate the relationship between increasing shares of variable renewables and the share of potential renewable electricity curtailed (curtailment rate, Fig. 1), including also the effect of demand and inflexible generation. We compare three different linear regression methods: ordinary least squares (OLS), Prais-Winsten feasible generalized least squares (FGLS) and beta regression. Additionally, we predict wind and solar curtailment depending on each technology's penetration and demand levels with a Generalized Additive Model (GAM) to better understand potential nonlinear effects. Finally, we estimate the effect of curtailment on wind and solar average unit costs (levelized cost of electricity or LCOE). We provide both a wide range of results and potential scenarios for 2030 according to California's goal to reach 60% renewable energy by then.

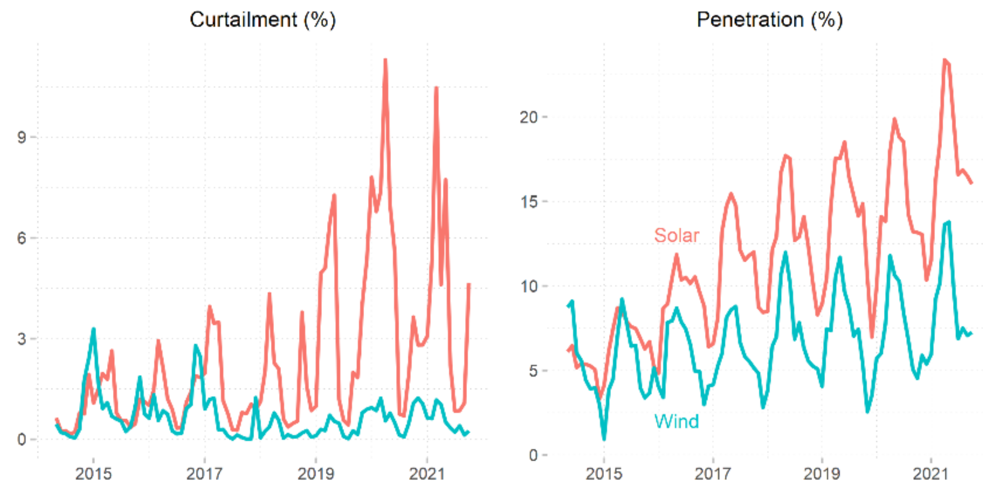

Fig. 1. Wind and solar curtailment rates and penetration in California between 2014 and 2021

Methods

Hourly wind and solar curtailment rates (share of electricity curtailed over potential generation, $y_t^{\{s,w\}}$) are explained as a function of wind, solar and nuclear penetration, demand (expressed as a share of peak load) and time dummies including hours of the day, days of the week, months of the year and year. Battery storage could be used to store excess generation, but its capacity is still negligible in California and mainly used for ramping and spinning reserve, so it is not explicitly modeled. However, the increasing annual battery capacity is captured by the year dummies and any potential seasonal pattern would be captured by the remaining time dummies.

$$y_t^{\{s,w\}} = \alpha + \beta_1 Solar_t + \beta_2 Wind_t + \beta_3 Nuclear_t + \beta_4 Demand_t +$$

$$\gamma_1 Hour_t + \gamma_2 Day_t + \gamma_3 Month_t + \gamma_4 Year_t + \epsilon_t$$

Modeling proportions (curtailment rate) is challenging because the dependent variable is truncated between 0 and 100%. Additionally, the OLS estimations exhibit both heteroskedasticity and autocorrelation. For these reasons, we take three different modeling approaches to tackle these problems and ensure the robustness of the coefficients: (1) Ordinary least squares (OLS) with a logit-transformed dependent variable. Since the residuals present heteroskedasticity and autocorrelation, the standard errors are Newey-West heteroskedasticity and autocorrelation consistent (HAC); (2) Feasible generalized least squares (FGLS) with Prais-Winsten estimator, assuming that the residuals follow a first order autoregressive process; and (3) Beta regression, which is more flexible than the previous as it assumes a beta instead of a normal distribution. To account for non-linearities, we also estimate a generalized additive model (GAM) and predict the effects of wind, solar and nuclear penetration and demand on wind and solar curtailment using as a baseline the year 2019. Finally, we calculate the impact of different levels of solar and wind curtailment on their respective levelized costs, also considering potential declining installation costs.

Results

The results show that increasing both VRE and inflexible generation increases VRE curtailment rates, and that VRE curtailment rates increase exponentially as demand declines below 60% peak load (no surprises). Even at high curtailment rates, VRE levelized costs are likely to stay low, given their expected cost evolution (no alarms). Understanding renewable energy curtailment is important to advance electricity system decarbonization cost-effectively. Knowing its causes may help design mitigation measures and predict future costs and benefits of variable renewables as their penetration increases.

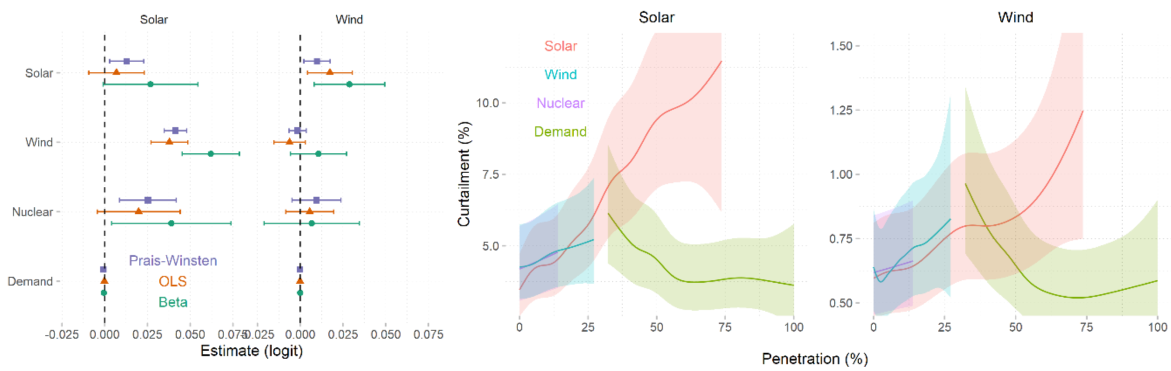

Fig. 2. Results of the linear models (OLS, Prais-Winsten and Beta regression, left) and prediction of solar (middle) and wind (right) curtailment as a function of solar, wind, and nuclear penetration and demand according to the GAM using 2019 as baseline year.

Conclusions

We estimate the effect of wind, solar and nuclear penetration and demand on wind and solar curtailment rates. The results confirm that increasing variable renewables and inflexible generation increase wind and solar curtailment rates. On the opposite, demand is negatively correlated with curtailment. Solar curtailment rates are generally higher than those of wind and likewise all the identified effects are higher for solar. Curtailment rates decline as demand increases up to around 60% of peak load, but then stabilize.

The effect of curtailment is unlikely to hamper the further diffusion of variable renewables, given the expected evolution of installation cost and the moderate effect of increasing penetration on curtailment rates and levelized costs. Further research should expand this analysis to other jurisdictions to verify whether these results are generalizable across countries. Additionally, it would be interesting to assess the effect of different mitigation measures, such as storage, flexibility or interconnections, on variable renewable energy curtailment.