# Executive Summary

## Motivation

Mitigating climate change and improving local air pollution requires an electric grid powered by a significant share of renewable energy. Nevertheless, the intermittent nature of solar and wind power and the nascent utility scale electricity storage make it challenging to assess the emissions offsets of these power sources. Overcoming these methodological difficulties is necessary to estimate the economic value of renewable energy and to evaluate related policies such as feed-in tariffs, renewable portfolio standards and subsides.

## Overview

In this paper I research how the interactions between hydro, wind and solar power affect the economic benefits of the latter two. I use random fluctuations in hourly wind and solar generation in California to estimate how much they reduce emissions of carbon dioxide, sulfur dioxide, and nitrogen oxides. These offsets depend on the direct displacement of high-cost natural gas generators, and on the hydropower reallocation that occurs to the hours with the lowest increase in renewable generation.

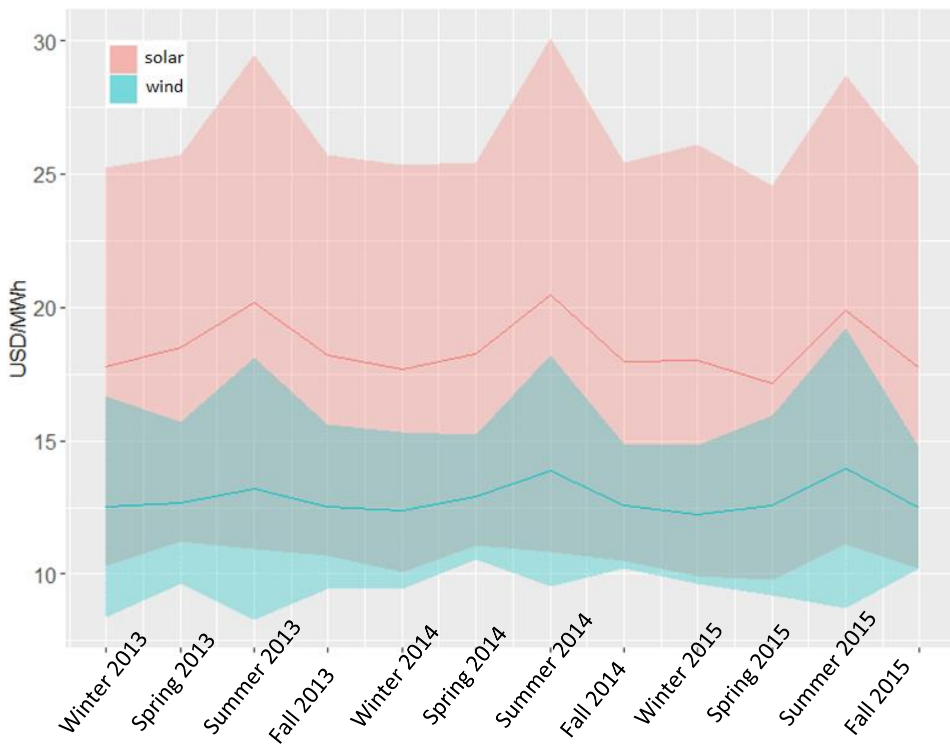
I address the shift in hydro with a dynamic econometric model that accounts for the interactions between the three renewable sources. Using a dynamic model that aggregates hourly into daily data, I estimate the appropriate average marginal carbon dioxide emissions offsets of solar (0.46 tCO2/MWh) to be larger than those of wind (0.319 tCO2/MWh). This occurs since solar power delivers most generation at the midday and decays in the afternoon, which leads to hydro arbitrage that substitutes gas turbines with the cleaner steam turbines. On the other hand, wind power peaks at midnight and decreases during the day which leads to a substitution of generators with similar emissions intensities: combined cycle for steam turbines. Therefore, solar power delivers larger carbon and sulfur offsets than wind.

Furthermore, these offsets vary throughout time: they increase during spring and summer since more polluting fossil generators supply the seasonal larger demand, and they slightly decline as years go by due to new renewable capacity substituting these polluting plants. Accounting for displaced electricity imports, I estimate the bound on solar and wind carbon offsets to be 0.615 and 0.465 $tCO_2$/MWh, respectively.

## Conclusions

These findings highlight that accounting for the dynamic interactions between the three renewable sources is necessary for assessing the proper external benefits and value of intermittent renewables. In California hydropower enhances the emissions offsets of solar power. Using the US social cost of carbon (IAWG, 2015) and marginal damages estimates for $SO_2$ and NOx (Muller and Mendelhson, 2009), solar power external benefits (no imports) range between 9.78 and 30.08 per USD/MWh while for wind the range is 8.31 to 19.2 USD/MWh.

Figure 1. Value of wind and solar power external benefits (no imports) throughout years and seasons




Errors bands are based on 95% CI with 7 lags Newey West std. errors

## Applications and policy implications

Summing up, the external benefits of renewable energy vary per technology and throughout time, and their incentives and subsidies should reflect this (Figure 1). Several emerging economies with electric grids powered by a significant share of hydropower are increasingly adopting wind and solar plants. To the extent that these countries dispatch generators based on the lowest marginal cost (via wholesale market) this paper's methodology is a good approach for assessing the heterogeneous value of their renewable energy emissions offsets and guiding the (re)design of related incentives and policies. Furthermore, the proposed dynamic modelling is key for understanding electricity generation and emissions in grids with increasing adoption of storage technologies since the same insights about hydropower reallocation would also apply to profit maximizing storers.