Power system decarbonization in a world of risk-averse investors and incomplete markets

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Overview

Generation expansion models of power systems typically assume that technology investments are made by firms with perfect foresight in idealized markets (Larson et al., 2020, e.g.). However, in practice, investment decisions are made under irreducible uncertainty, which exposes firms to financial risk. Risk can be decisive because firms are generally believed to be risk-averse (Cote and Salm, 2022, e.g.). Additionally, markets fall short of the theoretical ideal because markets for risk are argued to be incomplete (Newbery 2016, e.g.).

The decarbonization of energy systems necessitates substantial investment in low-carbon technologies such as renewables and storage technologies (Larson et al., 2020; IEA, 2021). This has led authors to call attention to the role of investment risk in the clean energy transition (Larson et al., 2020; IEA, 2021; Pahle et al., 2022). Here, we investigate how risk aversion and market incompleteness influence a power system's capacity mix and its resulting emissions. A growing body of literature addresses the role of risk in generation expansion with incomplete risk trading using equilibrium methods, but has not yet considered how risk impacts renewable investments (Ehrenmann and Smeers, 2011; Hoschle et al., 2018; Pineda, Boomsma, and Wogrin, 2018), storage investments, or resulting carbon emissions (Mays, Morton, O'Neill, 2019).

Methods

We introduce a new method for modeling of risk-averse equilibrium generation expansion. Our method formulates the problem as a Mixed Integer Linear Program. The key advantage of our approach is that it linearizes an otherwise non-linear and non-convex problem. Risk aversion is represented using the Conditional Value at Risk measure (Rockafellar and Uryasev, 2000; Ehrenmann and Smeers, 2011).

We apply our model to investigate generation expansion for a stylized power system with thermal, renewable, and battery storage technologies. The model represents both investment and operational decisions. The system's operation is modeled at an hourly resolution over 4 representative days and includes time-linking storage constraints. We use this numerical case study to explore how risk influences the capacity mix, power system emissions, and the effectiveness of popular climate policies including carbon pricing and investment grants (i.e. tax credits).

Our experimental design models generation expansion under uncertainty about future electricity demand (where stochasticity stems from uncertain electrification trends) and about future fuel prices. We model cases where investors are risk-neutral and where they are risk-averse. We analyze each of these cases using our equilibrium model (which represents incomplete risk trading) and a more traditional optimization approach (which assumes complete risk trading).

Results

Our equilibrium model shows that wind, solar, and battery storage investments decline in the case where investors are risk-averse relative to the risk-neutral case. Conversely, investments in gas plants increase in the risk-averse case relative to the risk-neutral case. This shows that risk aversion advantages gas and disadvantages renewables and storage. These results occur even though risk-averse renewable investors face a lower risk premium compared to risk-averse gas investors (the economics of gas investments depend on rare instances of scarcity pricing). Our paper investigates the underlying mechanisms behind these results.

We further show that power system emissions increase in the risk-averse case relative to the risk-neutral case. This finding can be explained by the impacts of risk on the capacity mix described above. Our analysis also shows how risk aversion impacts the effectiveness of climate policy, and how this impact varies depending on how researchers measure effectiveness.

Finally, we compare our equilibrium model findings to results obtained from a more traditional optimization approach. In the latter case, risk aversion decreases emissions relative to the risk-neutral case. The discrepancy between this result and the findings obtained with the equilibrium model showcases the significance of market completeness (implicitly assumed by the optimization approach) for generation expansion modeling.

Conclusions

This research shows how financial risk can interfere with efforts to decarbonize power systems. When markets for risk are incomplete, investors' risk aversion incentivizes technology choices that result in higher carbon emissions compared to the optimal choices of risk-neutral investors. Estimates of the effectiveness of climate policy are also influenced by modeling assumptions about the level of risk aversion and the completeness of risk trading. These findings lend support to accounting for risk aversion and market incompleteness in policy advice based on generation expansion modeling.

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