EVOLVING RELATIONSHIP BETWEEN NUCLEAR AND RENEWABLES IN A NEAR-ZERO ENERGY SYSTEM

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Overview

The electricity sector worldwide has seen increasing integration of variable renewable energy resources such as wind and solar photovoltaic (PV). This trend may continue in the coming decades, contributing to a transformation towards a near-zero emissions energy system. The high variability of renewable resources poses challenges to system robustness, highlighting the importance of reliable storage and flexible baseload power needed to fill the gap between intermittent generation and variable demand. Nuclear energy represents one prominent form of low-carbon baseload power. Recently, however, nuclear power plants have faced substantial competition from low-cost renewables and natural gas and are exposed to risks of early retirement in countries such as the US and Germany (Froggatt and Schneider 2015, Roth and Jaramillo 2017).

Nuclear energy is traditionally considered a non-dispatchable generation technology, although recent French experience suggests that nuclear power plants can be operated flexibly to assume a more load-following role (Lokhov 2011). Nuclear power plants are also characterized by high fixed costs and low variable costs (Lokhov 2011). High fixed costs motivate high capacity factors, so even if nuclear power plants can be made technically dispatchable, there can be economic incentive to operate them as baseload generation. The high fixed costs have negatively impacted investment in nuclear energy and remain to be a source of uncertainty for the penetration of nuclear. Natural gas power plants, in contrast, have lower fixed costs, making them more suitable for a gap-filling role. In addition, natural gas has lower carbon intensities than its fossil fuel counterparts such as coal. Natural gas thus has been viewed as a bridge fuel for the energy transition. In a longer timeframe, however, the penetration of natural gas is subject to emissions policy such as a carbon tax or cap. It is therefore important to understand the possible development trajectories of nuclear, renewables, and natural gas under cost and policy uncertainties.

In this study, we examine examples of near-zero electricity systems, focusing on the relationship between nuclear energy and renewables. The analysis is motivated by the following questions:

- Does nuclear energy compete with or facilitate renewable energy integration? How would the role of nuclear energy in a low-carbon energy system change if fixed costs of nuclear are substantially lower?
- Would nuclear energy be more economically competitive if it is dispatchable? Under what cost and resource availability scenarios would nuclear dispatchability start to influence the overall system cost?

To answer these questions, we developed a simple energy system model with idealized assumptions and a small number of decision variables. Resource availability, costs of technology, and operational flexibility are considered in the analysis. We aim to provide insights as to how the energy system is shaped by economic and technological characteristics of its technology components.

Methods

The energy system model developed for this analysis is a simple, linear optimization code. The aim is to understand fundamental dynamical relationships that are independent of details of system representation. We assume perfect transmission and a highly efficient market. System components include natural gas, nuclear energy, wind, and solar PV as generation technologies and generic energy storage. The optimization code minimizes the total system cost, or levelized cost of electricity (LCOE), by varying capacity and time-varying generation. The system is energy-balanced at all timesteps. Cost and efficiency assumptions are based on those in US EIA's Annual Energy Outlook (US EIA 2017). Hourly demand data and wind and solar capacity factors are taken from the reanalysis data by Shaner and coworkers (Shaner et al. 2018).

We performed preliminary analyses for a total of six scenarios assuming two dispatchability levels for nuclear energy and three cost and availability levels for natural gas generation. Specifically, we assumed that nuclear generation is fixed at full capacity ("fixed nuclear") or can be load-following with no additional costs to accommodate flexibility ("flexible nuclear"). The three natural gas scenarios are: (a) Natural gas generation has fixed and variable costs representative of current costs. (b) Natural gas generation has twice the current fixed and variable costs, representing cost projections with carbon capture and storage (CCS) installation. (c) Natural gas is completely excluded from the electricity mix unfavorable due to economics or stringent emissions regulations.

Results

Discussion of our full range of scenarios is precluded here due to space considerations. Here, we describe a case simulated by our model considering natural gas, solar, wind, nuclear, and storage, in which natural gas costs are doubled to represent CCS and nuclear is represented as being as technically dispatchable as natural gas, with costs as per EIA estimates, as described above. In this case (Figure 1), nuclear starts to penetrate the market when fixed costs of nuclear become less than about \$0.1/kW/h (i.e., ~\$900/kW/yr). As fixed costs of nuclear decrease, nuclear penetration increases at the expense of wind and solar. In our simulations, as fixed costs of nuclear decrease, wind deployment becomes zero before solar, largely because of the covariation of solar generation with afternoon peaks in demand.

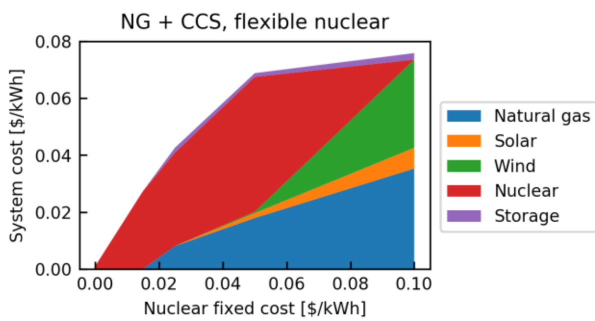

Figure 1. Contributions to system cost from generation and storage technologies, assuming natural gas costs are twice the current costs due to CCS installation, and nuclear is as dispatchable as natural gas.

Conclusions

In no case have we observed a situation in which deeper penetration of nuclear power is associated with deeper penetration of wind or solar power. In contrast, in all cases considered, deeper penetration of nuclear power is associated with reduced deployment of wind and solar. Thus, our fundamental conclusion is that nuclear power may directly compete with, rather than facilitate, the deeper penetration of intermittent renewables such as wind and solar. Using the cost assumptions and resource availability data in our current model, we find that increased dispatchability increases the value of nuclear power, but this has a relatively small impact on overall system costs. The actual value of dispatchability relative to the system cost would likely change with model formulation and input data such as costs and capacity factors. Preliminary optimization results suggest that the total system cost, contributions to system cost from individual technologies, and capacity shares vary greatly with the availability of natural gas generation. Of course, this is a highly idealized model, and it is possible that factors not considered here could alter our conclusion.

References

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