Cutting carbon emissions on the US power grid: Online model enables users to calculate the least-cost strategy

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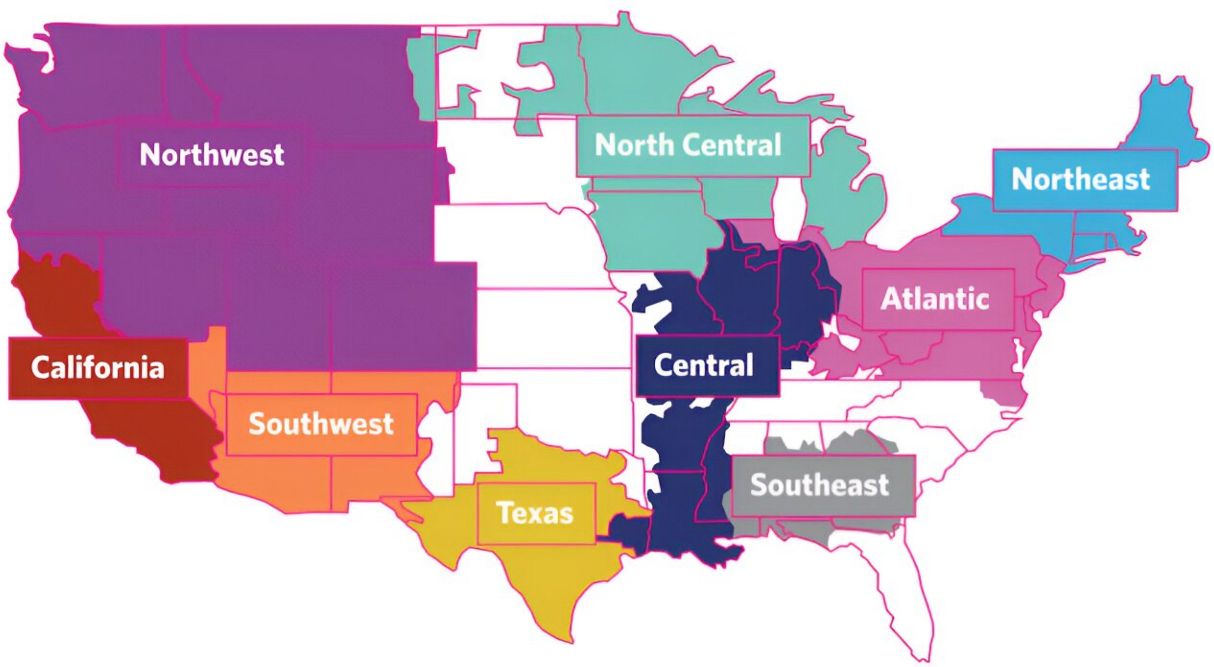

An online model developed by an MIT Energy Initiative team enables other researchers and operators of U.S. regional grids to explore possible pathways to decarbonization. Case studies of the nine regional power grids shown here confirm the importance of designing a strategy based on the resources and electricity demand profiles of specific regions. Credit: Massachusetts Institute of Technology

To help curb climate change, the United States is working to reduce carbon emissions from all sectors of the energy economy. Much of the current effort involves electrification—switching to electric cars for transportation, electric heat pumps for home heating, and so on.

But in the United States, the electric power sector already generates about a quarter of all carbon emissions. "Unless we decarbonize our electric power grids, we'll just be shifting carbon emissions from one source to another," says Amanda Farnsworth, a Ph.D. candidate in chemical engineering and research assistant at the MIT Energy Initiative (MITEI).

But decarbonizing the nation's electric power grids will be challenging. The availability of renewable energy resources such as solar and wind varies in different regions of the country. Likewise, patterns of energy demand differ from region to region. As a result, the least-cost pathway to a decarbonized grid will differ from one region to another.

Over the past two years, Farnsworth and Emre Gençer, a principal research scientist at MITEI, developed a power system model that would allow them to investigate the importance of regional differences—and would enable experts and laypeople alike to explore their own regions and make informed decisions about the best way to decarbonize.

"With this modeling capability you can really understand regional resources and patterns of demand, and use them to do a 'bespoke' analysis of the least-cost approach to decarbonizing the grid in your particular region," says Gençer.

To demonstrate the model's capabilities, Gençer and Farnsworth performed a series of case studies. Their analyses confirmed that strategies must be designed for specific regions and that all the costs and carbon emissions associated with manufacturing and installing solar and wind generators must be included for accurate accounting. But the analyses, published in *Cleaner Energy Systems*, also yielded some unexpected insights, including a correlation between a region's wind energy and the ease of decarbonizing, and the important role of nuclear power in decarbonizing the California grid.

A novel model

For many decades, researchers have been developing "capacity expansion models" to help electric utility planners tackle the problem of designing power grids that are efficient, reliable, and low-cost. More recently, many of those models also factor in the goal of reducing or eliminating carbon emissions. While those models can provide interesting insights relating to decarbonization, Gençer and Farnsworth believe they leave some gaps that need to be addressed.

For example, most focus on conditions and needs in a single U.S. region without highlighting the unique peculiarities of their chosen area of focus. Hardly any consider the carbon emitted in fabricating and installing such "zero-carbon" technologies as wind turbines and solar panels. And finally, most of the models are challenging to use. Even experts in the field must search out and assemble various complex datasets in order to perform a study of interest.

Gençer and Farnsworth's capacity expansion model—called Ideal Grid, or IG—addresses those and other shortcomings. IG is built within the framework of MITEI's Sustainable Energy System Analysis Modeling Environment (SESAME), an energy system modeling platform that Gençer and his colleagues at MITEI have been developing since 2017.

SESAME models the levels of greenhouse gas emissions from multiple, interacting energy sectors in future scenarios.

Importantly, SESAME includes both techno-economic analyses and life-cycle assessments of various electricity generation and storage technologies. It thus considers costs and emissions incurred at each stage of the life cycle (manufacture, installation, operation, and retirement) for all generators. Most capacity expansion models only account for emissions from operation of fossil fuel-powered generators.

As Farnsworth notes, "While this is a good approximation for our current grid, emissions from the full life cycle of all generating technologies become non-negligible as we transition to a highly renewable grid."

Through its connection with SESAME, the IG model has access to data on costs and emissions associated with many technologies critical to power grid operation. To explore regional differences in the cost-optimized decarbonization strategies, the IG model also includes conditions within each region, notably details on demand profiles and resource availability.

In one recent study, Gençer and Farnsworth selected nine of the standard North American Electric Reliability Corporation (NERC) regions. For each region, they incorporated hourly electricity demand into the IG model. Farnsworth also gathered meteorological data for the nine U.S. regions for seven years—2007 to 2013—and calculated hourly power output profiles for the renewable energy sources, including solar and wind, taking into account the geography-limited maximum capacity of each technology.

The availability of wind and solar resources differs widely from region to region. To permit a quick comparison, the researchers use a measure called "annual capacity factor," which is the ratio between the electricity produced by a generating unit in a year and the electricity that could have been produced if that unit operated continuously at full power for that year. Values for the capacity factors in the nine U.S. regions vary between 20 percent and 30 percent for solar power and for between 25 percent and 45 percent for wind.

Calculating optimized grids for different regions

For their first case study, Gençer and Farnsworth used the IG model to calculate cost-optimized regional grids to meet defined caps on carbon dioxide (CO_2) emissions. The analyses were based on cost and emissions data for 10 technologies: nuclear, wind, solar, three types of natural gas, three types of coal, and energy storage using lithium-ion batteries. Hydroelectric was not considered in this study because there was no comprehensive study outlining potential expansion sites with their respective costs and expected power output levels.

To make region-to-region comparisons easy, the researchers used several simplifying assumptions. Their focus was on electricity generation, so the model calculations assume the same transmission and distribution costs and efficiencies for all regions. Also, the calculations did not consider the generator fleet currently in place. The goal was to investigate what happens if each region were to start from scratch and generate an "ideal" grid.

To begin, Gençer and Farnsworth calculated the most economic combination of technologies for each region if it limits its total carbon emissions to 100, 50, and 25 grams of CO_2 per kilowatt-hour (kWh) generated. For context, the current U.S. average emissions intensity is 386 grams of CO_2 emissions per kWh.

Given the wide variation in regional demand, the researchers needed to use a new metric to normalize their results and permit a one-to-one comparison between regions. Accordingly, the model calculates the required generating capacity divided by the average demand for each region. The required capacity accounts for both the variation in demand and the inability of generating systems—particularly solar and wind—to operate at full capacity all of the time.

The analysis was based on regional demand data for 2021—the most recent data available. And for each region, the model calculated the cost-optimized power grid seven times, using weather data from seven years. This discussion focuses on mean values for cost and total capacity installed and also total values for coal and for natural gas, although the analysis considered three separate technologies for each fuel.

The results of the analyses confirm that there's a wide variation in the cost-optimized system from one region to another. Most notable is that some regions require a lot of energy storage while others don't require any at all. The availability of wind resources turns out to play an important role, while the use of nuclear is limited: the carbon intensity of nuclear (including uranium mining and transportation) is lower than that of either solar or wind, but nuclear is the most expensive technology option, so it's added only when necessary. Finally, the change in the CO_2 emissions cap brings some interesting responses.

Under the most lenient limit on emissions—100 grams of CO_2 per kWh—there's no coal in the mix anywhere. It's the first to go, in general being replaced by the lower-carbon-emitting natural gas. Texas, Central, and North Central—the regions with the most wind—don't need energy storage, while the other six regions do. The regions with the least wind—California and the Southwest—have the highest energy storage requirements. Unlike the other regions modeled, California begins installing nuclear, even at the most lenient limit.

As the model plays out, under the moderate cap—50 grams of CO_2 per kWh—most regions bring in nuclear power. California and the Southeast—regions with low wind capacity factors—rely on nuclear the most. In contrast, wind-rich Texas, Central, and North Central don't incorporate nuclear yet but instead add energy storage—a less-expensive option—to their mix. There's still a bit of natural gas everywhere, in spite of its CO_2 emissions.

Under the most restrictive cap—25 grams of CO_2 per kWh—nuclear is in the mix everywhere. The highest use of nuclear is again correlated with low wind capacity factor. Central and North Central depend on nuclear the least. All regions continue to rely on a little natural gas to keep prices from skyrocketing due to the necessary but costly nuclear component. With nuclear in the mix, the need for storage declines in most regions.

Results of the cost analysis are also interesting. Texas, Central, and North Central all have abundant wind resources, and they can delay incorporating the costly nuclear option, so the cost of their optimized system tends to be lower than costs for the other regions. In addition, their total capacity deployment—including all sources—tends to be lower than for the other regions. California and the Southwest both rely heavily on solar, and in both regions, costs and total deployment are relatively high.

Lessons learned

One unexpected result is the benefit of combining solar and wind resources. The problem with relying on solar alone is obvious: "Solar energy is available only five or six hours a day, so you need to build a lot of other generating sources and abundant storage capacity," says Gençer.

But an analysis of unit-by-unit operations at an hourly resolution yielded a less-intuitive trend: While solar installations only produce power in the midday hours, wind turbines generate the most power in the nighttime hours. As a result, solar and wind power are complementary. Having both resources available is far more valuable than having either one or the other. And having both impacts the need for storage, says Gençer. "Storage really plays a role either when you're targeting a very low carbon intensity or where your resources are mostly solar and they're not complemented by wind."

Gençer notes that the target for the U.S. electricity grid is to reach net zero by 2035. But the analysis showed that reaching just 100 grams of CO_2 per kWh would require at least 50 percent of system capacity to be wind and solar. "And we're nowhere near that yet," he says.

Indeed, Gençer and Farnsworth's analysis doesn't even include a zero emissions case. Why not? As Gençer says, "We cannot reach zero." Wind and solar are usually considered to be net zero, but that's not true. Wind, solar, and even storage have embedded carbon emissions due to materials, manufacturing, and so on. "To go to true net zero, you'd need negative emission technologies," explains Gençer, referring to techniques that remove carbon from the air or ocean. That observation confirms the importance of performing life-cycle assessments.

Farnsworth voices another concern: Coal quickly disappears in all regions because natural gas is an easy substitute for coal and has lower carbon emissions. "People say they've decreased their carbon emissions by a lot, but most have done it by transitioning from coal to natural gas power plants," says Farnsworth. "But with that pathway for decarbonization, you hit a wall. Once you've transitioned from coal to natural gas, you've got to do something else. You need a new strategy—a new trajectory to actually reach your decarbonization target, which most likely will involve replacing the newly installed natural gas plants."

Gençer makes one final point: The availability of cheap nuclear—whether fission or fusion—would completely change the picture. When the tighter caps require the use of nuclear, the cost of electricity goes up. "The impact is quite significant," says Gençer. "When we go from 100 grams down to 25 grams of CO_2 per kWh, we see a 20 percent to 30 percent increase in the cost of electricity." If it were available, a less-expensive nuclear option would likely be included in the technology mix under more lenient caps, significantly reducing the cost of decarbonizing power grids in all regions.

The special case of California

In another analysis, Gençer and Farnsworth took a closer look at California. In California, about 10 percent of total demand is now met with nuclear power. Yet current power plants are scheduled for retirement very soon, and a 1976 law forbids the construction of new nuclear plants. (The state recently extended the lifetime of one nuclear plant to prevent the grid from becoming unstable.) "California is very motivated to decarbonize their grid," says Farnsworth. "So how difficult will that be without nuclear power?"

To find out, the researchers performed a series of analyses to investigate the challenge of decarbonizing in California with nuclear power versus without it. At 200 grams of CO_2 per kWh—about a 50 percent reduction—the optimized mix and cost look the same with and without nuclear. Nuclear doesn't appear due to its high cost. At 100 grams of CO_2 per kWh—about a 75 percent reduction—nuclear does appear in the cost-optimized system, reducing the total system capacity while having little impact on the cost.

But at 50 grams of CO_2 per kWh, the ban on nuclear makes a significant difference. "Without nuclear, there's about a 45 percent increase in total system size, which is really quite substantial," says Farnsworth. "It's a vastly different system, and it's more expensive." Indeed, the cost of electricity would increase by 7 percent.

Going one step further, the researchers performed an analysis to determine the most decarbonized system possible in California. Without nuclear, the state could reach 40 grams of CO_2 per kWh. "But when you allow for nuclear, you can get all the way down to 16 grams of CO_2 per kWh," says Farnsworth. "We found that California needs nuclear more than any other region due to its poor wind resources."

Impacts of a carbon tax

One more case study examined a policy approach to incentivizing decarbonization. Instead of imposing a ceiling on carbon emissions, this strategy would tax every ton of carbon that's emitted. Proposed taxes range from zero to $100 per ton.

To investigate the effectiveness of different levels of carbon tax, Farnsworth and Gençer used the IG model to calculate the minimum-cost system for each region, assuming a certain cost for emitting each ton of carbon. The analyses show that a low carbon tax—just $10 per ton—significantly reduces emissions in all regions by phasing out all coal generation. In the Northwest region, for example, a carbon tax of $10 per ton decreases system emissions by 65 percent while increasing system cost by just 2.8 percent (relative to an untaxed system).

After coal has been phased out of all regions, every increase in the carbon tax brings a slow but steady linear decrease in emissions and a linear increase in cost. But the rates of those changes vary from region to region. For example, the rate of decrease in emissions for each added tax dollar is far lower in the Central region than in the Northwest, largely due to the Central region's already low emissions intensity without a carbon tax. Indeed, the Central region without a carbon tax has a lower emissions intensity than the Northwest region with a tax of $100 per ton.

As Farnsworth summarizes, "A low carbon tax—just $10 per ton—is very effective in quickly incentivizing the replacement of coal with natural gas. After that, it really just incentivizes the replacement of natural gas technologies with more renewables and more energy storage." She concludes, "If you're looking to get rid of coal, I would recommend a carbon tax."

Future extensions of IG

The researchers have already added hydroelectric to the generating options in the IG model, and they are now planning further extensions. For example, they will include additional regions for analysis, add other long-term energy storage options, and make changes that allow analyses to take into account the generating infrastructure that already exists. Also, they will use the model to examine the cost and value of interregional transmission to take advantage of the diversity of available renewable resources.

Farnsworth emphasizes that the analyses reported here are just samples of what's possible using the IG model. The model is a web-based tool that includes embedded data covering the whole United States, and the output from an analysis includes an easy-to-understand display of the required installations, hourly operation, and overall techno-economic analysis and life-cycle assessment results.

"The user is able to go in and explore a vast number of scenarios with no data collection or pre-processing," she says. "There's no barrier to begin using the tool. You can just hop on and start exploring your options so you can make an informed decision about the best path forward."

More information: Amanda Farnsworth et al, Highlighting regional decarbonization challenges with novel capacity expansion model, *Cleaner Energy Systems* (2023). DOI: 10.1016/j.cles.2023.100078

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