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Achieving a national-scale, 100% renewable electric grid

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Credit: National Renewable Energy Laboratory

With recently announced federal emissions-reduction targets, a push for national power-sector decarbonization, and plummeting wind and solar costs, the United States is poised to deploy major amounts of renewables, and fast.

At smaller scales, hundreds of U.S. cities, states, and corporations have already taken bold action in setting their own local targets for 100%

renewable energy—and with recent analyses like the Los Angeles 100% Renewable Energy Study (LA100), we have growing confidence that reliable, 100% renewable power grids are feasible.

But expanding this end-goal across the entire United States presents an equally expansive set of challenges—and the plausibility of doing so has been a topic of fervent debate among the energy research community in recent years. Now, a team of 17 power systems experts from the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) and DOE's Office of Energy Efficiency and Renewable Energy (EERE) is chiming in with a fresh take.

Published in the journal *Joule*, "The Challenges of Achieving a 100% Renewable Electricity System in the United States" offers important insights into the technical and economic challenges that would need to be overcome to achieve 100% renewable electric power across the United States. The research was funded by EERE's Office of Strategic Analysis.

"Our paper offers perspective drawn from real-world experience in deploying variable renewables, the literature, and our team's experience studying these issues in detail over the past two decades at a variety of scales—from our 2012 national-scale Renewable Electricity Futures Study to our 2021 work on LA100," said Paul Denholm, NREL principal energy analyst and lead author of the paper. "While our focus here is on the U.S. power system, many of the issues addressed and lessons learned apply more generally to other regions—and these are complex, multidisciplinary challenges that will require a lot of collaboration among the research community to solve."

First things first: Defining what we mean by a 100% renewable grid

In looking at the challenges of achieving a national-scale, 100% renewable-powered grid, it is important to first precisely define what we mean by that phrase. For this paper, the authors explain two key aspects of the definition: technology type and system boundary.

"Technology type essentially establishes the definition of the word renewable—which can vary based on the parameters of a research study or the priorities of a community setting a renewable target or policy," Denholm said. "Here, we distinguish between two general types of technologies: what we call variable technologies that depend on short-term weather conditions and typically use inverters, like wind and solar photovoltaics [PV]; and those that are less—or not at all—variable and typically use traditional synchronous generators, including hydro, biomass, geothermal, and concentrating solar power."

In this paper, 100% renewable systems are not limited to only variable technologies like solar PV and wind. However, because non-variable renewable resources are usually geographically constrained, the authors generally assume variable ones would make up a large fraction of a 100% renewable grid at the national scale.

When it comes to defining the system boundary, the authors require the grid to physically operate with a 100% renewable energy supply at all times. This contrasts with systems, businesses, or corporate entities that achieve 100% renewable targets using renewable energy credits, offsets, or other financial mechanisms.

What we know, what we think we know, and what we do not know

To frame the most critical questions and propose a research agenda toward solutions, the authors explore the increasing contribution of renewables in the U.S. electricity system along three lines: 1) what we know based on real-world experience, 2) what we think we know based on grid planning and operation studies, and 3) what we do not know without additional study or experience.

"Our emphasis is on questions we think can be addressed through technology development and engineering, but we recognize that other topics are critically important—from siting considerations, to energy equity concerns, to policy, regulatory, and market design challenges," Denholm said. "We want to clear a path for resolving the technical and economic issues so that we can better address other complex aspects of the power system transition."

Rather than focusing solely on the end goal of a 100% renewable grid, the team looks at how the challenges of incorporating renewables change with increasing deployment. This is partly due to the lack of detailed engineering analysis of 100% renewable systems at the national scale—but also because practical plans for achieving the target would not be developed from a blank slate. Robust 100% renewable solutions must consider how to optimally use existing power system assets.

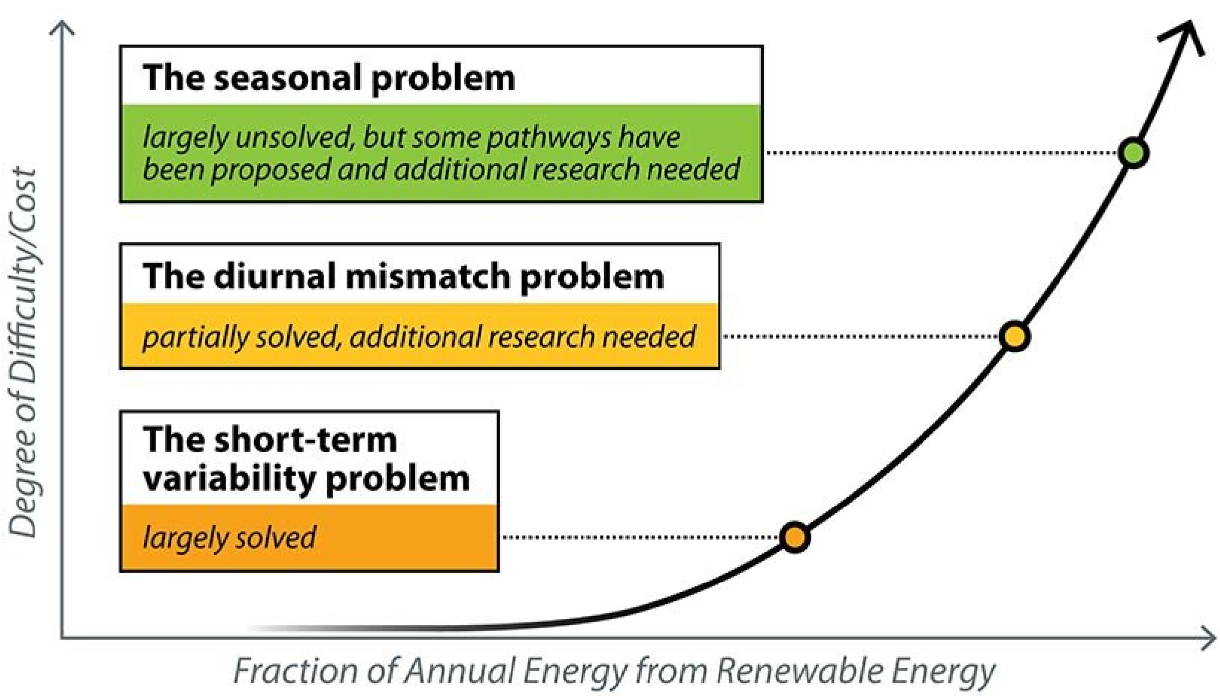
"Ultimately, the engineering challenges, costs, and benefits of renewables vary as a function of their share of the generation mix," Denholm said. "100% is just one point on a continuum, so exploring costs and benefits at all levels of renewable deployment is useful."

Within this framework, the paper organizes the techno-economic challenges of achieving 100% renewables across all timescales into two categories: 1) economically maintaining a balance of supply and demand (referred to as the Balance Challenge) and 2) designing technically reliable and stable grids using largely inverter-based resources like wind and solar (referred to as the Inverter Challenge).

The balance challenge: Economically matching supply with demand

The Balance Challenge boils down to making sure the power system can economically balance supply and demand at a variety of timescales—from the critical seconds-to-minutes scale required to withstand unexpected outages, to the seasonal scale that matches scheduled power plant outages and maintenance with periods of lower demand.

"Variable resources are just that—variable—so they inherently fluctuate across various timescales," Denholm said. "There's what we call a diurnal mismatch between the timing of peak demand and when solar and wind generation are highest during the day, which we see in phenomena like the duck curve. Beyond that, there's a significant seasonal mismatch between wind, solar, and demand patterns that is even more challenging to address."



Credit: National Renewable Energy Laboratory

This chart from the paper conceptually illustrates the Balance Challenge in terms of how expected costs and challenges may change with increasing deployment of renewables. At current levels, renewable energy is cost-competitive with traditional generation sources in many regions of the United States because the utility industry has been able to cost-effectively address the hourly and sub-hourly variability.

Beyond these levels, we reach the second zone, where studies have explored how the diurnal mismatch problem might be cost-effectively addressed to reach annual contributions in the range of 80% renewables. But beyond this point, in the third zone, the seasonal mismatch issue may require technologies that have yet to be deployed at large scale—so their costs and requirements are unclear.

The inverter challenge: Designing reliable, stable grids that rely on inverter-based resources

The Inverter Challenge is similar to the Balance Challenge in that they both involve balancing supply and demand on various timescales. But the Inverter Challenge is different in that concerns are narrowly focused on a set of specific engineering considerations, as opposed to the broader economic issues associated with the Balance Challenge.

The Inverter Challenge is all about issues associated with transitioning to a grid dominated by inverter-based resources (IBRs)—primarily wind and solar PV generation, along with battery storage.

Most electrical energy in the United States is currently derived from turbines coupled to synchronous generators; the generators are electrically coupled and rotating at the same frequency. To provide a reliable and stable grid, system planners and operators have leveraged several inherent characteristics of synchronous generators, including rotational inertia (stored kinetic energy in large rotating masses) and the ability to inject large amounts of current into the grid. These characteristics are the basis of traditional power-system stability and protection.

"Inverter-based resources have very different characteristics compared to synchronous generators, including a lack of physically coupled inertial response and, historically, a limited ability to provide large amounts of current under fault conditions," said Ben Kroposki, director of NREL's Power Systems Engineering Center and co-author of the paper. "So, as we rely more on inverter-based resources, they will need to provide services currently provided by synchronous generators—which may mean changes in the way the power system is controlled and protected."

So what do we not know?

The paper explores both the Balance Challenge and the Inverter Challenge in detail—including the significant unanswered questions that remain when it comes to getting close to or achieving 100% renewables at a national scale for all hours of the year.

"There is no simple answer to how far we can increase renewable deployment before costs rise dramatically or reliability becomes compromised," Denholm said. "As far as the 'last few percent' of the path to 100%, there is no consensus on a clear cost-effective pathway to address both the Balance Challenge and the Inverter Challenge at the national scale.

"Studies have found no specific technical threshold at which the grid 'breaks," and we can't just extrapolate from previous cost analyses because, when it comes to the future, there are many nonlinearities and unknown unknowns—things we don't even know we don't know yet."

The authors say additional research is needed to evaluate the suite of technologies that can help ensure renewable supply matches demand patterns across all time periods—and that we will need significant engineering and design to transition the grid from one that is dependent on synchronous machines to one that is based on inverters.

Where do we go from here? A call for collaboration—and continuous re-evaluation

Realizing a high renewable electricity future for the United States will require more than just addressing the Balance and Inverter Challenges—including addressing resource access, environmental, market, and human behavior issues that themselves can affect the design and pace of getting to 100% renewable electricity. These are complex, multidisciplinary challenges that cannot be solved by any one entity and will require collaboration across technical research communities, academia, labs, and industry.

"The unanswered questions in our paper provide a research agenda for the analysis, technology R&D, and engineering needed to achieve cost-effective 100% renewable systems," said Dan Bilello, director of NREL's Strategic Energy Analysis Center and co-author of the paper. "Not only do we need new tools and data sets to advance future studies, but we need more uniform terminology and facilitated interaction between researchers and research organizations, especially across different fields."

What's more, the authors point to a need to continuously re-examine the most effective pathway toward national emissions reduction and decarbonization goals—whether that is through 100% renewable electricity or through another combination of low-carbon technologies.

"Right now, it's difficult to establish an economic basis for achieving these environmental benefits in a grid powered exclusively by renewables," Denholm said. "Economically reducing overall emissions will likely involve achieving very high—but potentially below 100%—renewable generation while also focusing on decarbonizing other sectors, or keeping non-renewable but low-carbon resources in the mix."

The LA100 study—while not at the national scale—found that electrifying the vehicles and buildings sectors can lead to substantial improvements in air quality—and that realizing these benefits is principally a matter of achieving high energy efficiency and electrification, independent of any particular renewable energy pathway for the power sector. LA100 also found that technology restrictions result in higher costs when it comes to meeting the last 10% of electricity demand with renewable energy—with minimal incremental emissions reductions.

"Looking ahead, continued research, analysis, and an adaptable approach to technology solutions will help guide the electricity industry and increase our odds of achieving the decarbonization goals we're ultimately targeting when we talk about 100% renewables," Denholm said.

More information: Paul Denholm et al, The challenges of achieving a 100% renewable electricity system in the United States, *Joule* (2021). DOI: 10.1016/j.joule.2021.03.028

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