U.S. DEPARTMENT OF ENERGY

On The Path to 100% Clean Electricity

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Introduction to 100% Clean Electricity

Clean electricity is a cornerstone of broader decarbonization

Rapid decarbonization of the power sector is a critical strategy for meeting the nation's climate goals of reducing economy-wide greenhouse gases by 50-52% below 2005 levels in 2030, on the way to net-zero economy-wide greenhouse gas (GHG) emissions by no later than 2050 [1]. Power-sector decarbonization is especially important because efficient electrification, when paired with clean electricity, can decarbonize large parts of the transportation, buildings, and industrial sectors. Recognizing the key role of the power sector in overall decarbonization and other key benefits, the United States has set a goal of 100% carbon pollution-free electricity by 2035 [1,2,3].

The U.S. power sector has made significant progress over the last 15 years in reducing carbon emissions, driven by technological change, state and federal policy, and other factors [4] —with clean electricity already contributing more than 40% of America's power generation. Today, with low-cost clean power supply options broadly available and the country confronting both a climate crisis and energy security concerns, we have the ability and motivation to rapidly accelerate clean power deployment.

This report identifies ten key all-of-society actions needed to move toward 100% clean electricity and realize the benefits of a fully decarbonized power system.

America benefits tremendously from a clean electricity system

Making progress toward power-sector decarbonization will reduce the damages from climate change: extreme weather, heat-related illness and deaths, reduced agricultural productivity, and more. Power-sector decarbonization will also deliver significant health and related economic benefits, enhance energy security by reducing the impact of oil and natural gas price volatility on American households, improve social equity and justice, and support good-paying jobs in new and emerging industries.

A recent analysis concludes that 100% clean electricity[1] by 2035, with accelerated electrification, can:

- Reduce economy-wide energy-related GHG emissions by 2.4 gigatons in 2035—equivalent to a 62% reduction relative to 2005 levels.
- Avoid an estimated $200 billion per year in climate damages by 2035, from reduced power sector emissions.
- Reduce health damages from power-sector pollution by at least $40 billion per year in 2035, and avoid a total of at least 45,000 premature deaths in the United States through 2035.

The combined value of these climate and health benefits significantly exceeds the power-sector costs, with benefit-to-cost ratios from 2.2 to 4.8, with the total value of net benefits from 2023-2035 ranging from $900 billion to $1.3 trillion [5].

[1] In this report, "clean electricity", "clean generation," "clean power," and "clean energy" include wind, solar, geothermal, hydropower, nuclear, biomass with and without carbon capture and sequestration, and fossil energy with carbon capture and sequestration.

The Inflation Reduction Act and Bipartisan Infrastructure Law put 100% clean electricity in closer reach

The Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law (BIL) contain critical programs to support reaching 100% clean electricity. A recent assessment by the National Renewable Energy Laboratory found that these two laws could drive rapidly increasing levels of clean electricity generation, potentially reaching over 80% clean by 2030 [6], consistent with other analyses showing significant increases in clean electricity [7,8,9,10,11,12]. With the long-term extensions and expansions of federal energy tax incentives in the IRA and the energy-innovation and infrastructure measures in the BIL, these two laws combined will reduce the cost of future state, federal, Tribal, local, and private actions to drive towards a 100% clean electricity system paired with rapid and efficient end-use energy electrification.

The IRA and the BIL also support the strategies necessary to achieve 100% clean electricity: helping build clean energy supply chains; supporting good-quality jobs for workers, with the free and fair opportunity to organize unions and collectively bargain, and with emphasis on communities that have high concentrations of fossil fuel jobs; and enhancing energy and environmental justice through focused investments.[2]

Ten Actions Toward 100% Clean Electricity

Several challenges must be addressed to achieve these levels of clean generation while maintaining or enhancing reliability and affordability, and to realize the benefits of 100% clean electricity. Deployment of new power generation, transmission, distribution, and storage technologies at the scale and pace required will have widespread impacts on communities, job creation, industrial supply chains, equity, and ecosystems—all of which require careful management.

For example, at the end of 2022, more than 2,000 GW of total generation and storage capacity was seeking transmission interconnection, of which more than 95% is for clean generating resources and storage [13]. Based on historical experience, many of these specific projects are at risk of not reaching construction due to siting, transmission, or other challenges. Nonetheless, these data confirm the appetite for deploying large volumes of clean capacity and storage projects, if these challenges can be addressed.

Recognizing the scale of the challenges and the scope of impacted stakeholders, an all-of-society approach is needed that strengthens and expands on current government efforts, and includes state, local, Tribal, and private sector actions. In addition, decisions and actions in the U.S. energy system are highly decentralized. Achieving a 100% clean electricity system will rely on the coordination and results of many different regional and local plans and private sector efforts, reflecting a diversity of local priorities, constraints, technology mixes, market and regulatory frameworks, and other key drivers.

Here we propose ten key actions needed to achieve 100% clean electricity. These actions are designed to provide high-level organization to the key stakeholders outlined above while being universal to any

[2] See implementation guidance for the Inflation Reduction Act at: https://www.federalregister.gov/documents/2022/09/16/2022-20210/implementation-of-the-energy-and-infrastructure-provisions-of-the-inflation-reduction-act-of-2022; see also the Biden Administration's Justice40 Initiative at: https://www.whitehouse.gov/environmentaljustice/justice40/

specific technology pathway and reflect the diversity of decisionmakers and priorities of any given region. These actions focus on those in the U.S. electricity sector and provide an organizing framework for stakeholders and policymakers to coordinate plans and activities.

Clean generation—nuclear, hydropower, wind, solar, and more—is currently responsible for approximately 40% of the nation's electricity supply and forms the foundation on which clean energy growth can build. Although wind and solar generation is growing rapidly, nuclear and hydropower provide almost two-thirds of clean electricity generation and are the primary source of the clean electricity serving base load. Nuclear plants, in particular, regularly operate for more than 90% of the year and can provide electricity in extreme situations when other resources may not be available.

Moreover, existing sources of power-system flexibility, including storage, are already helping to further integrate variable renewable energy. Though all plants age and eventually retire, retirements of sources of clean generation increase the amount of new capacity needed to reach 100%, increasing costs and deployment challenges in some cases. In the near term, ensuring that the current fleet of nuclear reactors and hydropower facilities continue to operate will reduce new deployment needs; over time, this will also entail refurbishing aging wind, solar, and other renewable energy assets, with a core focus on plants otherwise at risk of retirement.

To reach 100% clean electricity, an immediate increase of clean power and storage deployment rates is needed, followed by continued rapid growth in the pace of deployment. This growth rate reflects a significant acceleration of historical trends in clean energy capacity additions. This would rely on clean technologies that are already cost competitive and being deployed at scale, including wind and solar, and evolve over time to include a range of technologies, including advanced nuclear, fossil fuels with carbon capture and sequestration, and other forms of renewable energy.

The total amount of these technologies needed to reach 100% clean electricity varies by pathway, but studies demonstrate that rapid near-term increases in wind and solar are a core strategy to power sector decarbonization [14,15]. To accommodate these increases, a wide variety of deployment barriers will need to be addressed—perhaps most crucially, lengthy siting, permitting, and interconnection timelines. Wait times for generation interconnection, for example, are already increasing for new projects to connect to the power grid, and costs are rising [13].

Increase options for clean generation, storage, and carbon management technologies 3

Given uncertainty around the technology portfolio that will ultimately be used, it is important in the near-term to continue to invest in a full suite of clean power technologies. Although the exact pathway is uncertain, studies find that higher levels of clean electricity can be achieved at lower cost when developing and deploying a diverse set of technologies than when classes of technologies are restricted or unavailable [5,14,15,16,17]. In particular, deployment of technologies that provide high levels of firm capacity—that is, capacity that can be relied upon to generate during times of system need—such as from advanced nuclear, fossil and biomass with CCS, geothermal, hydropower, and/or long-duration storage options, can help ensure that resource adequacy and reliability are maintained at high levels of clean electricity.

Technologies that can be flexibly dispatched during times of need will be especially important. Many of these technologies are available. They could also benefit from enhanced research, development, deployment, and demonstration (RDD&D) investments to deploy them at a greater scale. Continued investment in direct air capture and carbon dioxide removal more broadly can also be valuable for the power sector by offsetting any residual emissions that otherwise may be costly to abate, especially when trying to reach net-zero emissions from the power sector while maintaining power-system reliability. Improving cost and performance even further for various technologies through continued investments in RDD&D can realize significant cost savings benefits given the sizable contributions to be made by these resources in 100% clean electricity scenarios [18].

Plan and deploy enabling infrastructure 4

Transmission investment—intra-state, regional, and inter-regional—as well as advanced distribution systems, are needed to access clean power resources and to enhance reliability and resilience. For example, one study shows long-distance transmission capacity increasing by 30% to 190% compared to today's network in scenarios reaching 100% clean electricity [5]. More broadly, transmission expansion is often a core component of decarbonization, providing benefits even in studies and scenarios that use larger amounts of clean firm resources [19]. Given emerging trends in distributed energy resources, a sufficiently robust communication infrastructure system will be needed to support a secure and reliable electrical grid.

Along with the build out of the electrical grid, some pathways to 100% clean electricity require enabling infrastructure for the storage and delivery of captured carbon and clean fuels such as hydrogen. Storage and delivery infrastructure projects have long planning, permitting, and construction timelines, so identification and design for these infrastructure systems needs to begin immediately. Without adequate planning and investment, alternative decarbonization approaches would be required. For example, lower levels of electric transmission buildout would lead to lower contributions from wind power, and greater contributions from resources that can be flexibly located closer to existing transmission infrastructure. Similarly, inadequate investment in pipelines to transport carbon or hydrogen would constrain technology options.

Proactively invest in and engage with disadvantaged and energy communities to ensure the impacts and benefits of 100% clean power are distributed equitably 5

Continuation and strengthening of current efforts to prioritize targeted investment in energy communities and energy workers, alongside new investment in long underserved communities, is needed to ensure benefits of 100% clean power are shared broadly. With thousands of gigawatts of clean capacity and associated infrastructure needed, reaching target deployment rates will likely require a reduction in permitting and siting timelines, without compromising stakeholder engagement or review of potentially adverse environmental, cultural, health, or justice impacts [16,22].

Communities, especially underserved populations, need an expanded voice in decision making and access to the benefits of the transition. Energy development has historically been inequitable [20,21] and continued policy action is required to ensure that new inequities are not created in the buildout of a 100% clean power grid [22]. Careful, community-engaged siting, wide access to clean energy assets, novel community ownership structures, and investments that prioritize reducing energy burdens can all help broaden the benefits of a clean power transition. The federal government will continue to play a critical role by providing technical assistance and funding to states, local governments, rural and remote communities, and Tribes to expand their capacity to participate in planning activities [23], with the IRA creating several new programs and opportunities toward that end.

Augment planning, operations, and markets to enable 100% clean grids 6

The United States already meets more than 40% of its electricity demand with clean energy, with some regional wholesale markets managing more than 25% of generation from wind and solar. Nonetheless, the rapid deployment of clean generation and associated storage needed to reach 100% clean electricity will result in major changes to the sources of electricity generation, with new sources requiring different planning methods, technical standards, operating strategies, and market incentives.

Wholesale electricity markets may need to be modified to enable rapid deployment of clean energy resources while ensuring resource adequacy and reliability [5,14,24,15,23]. Changes may include a recalibration of necessary grid services, how those services are compensated, and how markets are employed to deliver them. Important grid services will need to be well planned and provided through a varied portfolio of renewable energy and clean firm generation to storage and end-use demand.

Important new engineering challenges will also arise, requiring proactive resolution. With the significant addition of inverter-based generators, such as wind, solar, and batteries, the development and deployment of advanced technologies, such as grid-forming inverters, will be required [26]. Distributed energy resources need to be able to reliably support power system operations. Utilities and power-sector regulators will, naturally, play an outsized role in helping manage this complex transition. Enhanced RDD&D can help ensure that the necessary technologies, planning tools and operating strategies are available when needed. Advanced transmission and distribution systems, planning, and operations are critically important as reflected in being listed as one of the top five priorities in the

recent report *U.S. Innovation to Meet 2050 Climate Goals*.[3]

Ensure system security and resiliency as new technologies and threats emerge 7

As the power system transitions to 100% clean electricity, it will do so in the broader context of a fundamentally changing economy and climate, as well as increasing digitalization. From cyber and physical attacks to growing climate change-induced threats, the U.S. power system and its supporting infrastructure systems are facing an unprecedented and evolving threat landscape. Incidents like Winter Storm Uri, Hurricanes Ian and Fiona, and wildfires caused by severe drought in the West are causing billions of dollars in damage and are demonstrating how these threats can disrupt energy supplies, the economy, and Americans' everyday lives.

Over the entire decade of the 1980s, there were 31 climate disasters that cost $201.5 billion; in 2021 alone, there were 20 climate disasters that cost $152.6 billion.[4] Furthermore, extreme weather disasters like hurricanes, wildfires, heat waves, and freezes disproportionately hurt communities of color, who are more likely to live in vulnerable areas and without access to air conditioning, heat, and critical services. Significant action will be needed to ensure the U.S. power system is inherently resilient and secure against cyberattacks able to withstand and maintain critical functions and quickly recover from disruptions; and all electricity-adjacent enabling infrastructure is hardened against existing and emerging vulnerabilities.

Dramatically accelerate electric energy efficiency and demand flexibility 8

Energy efficiency and load responsiveness are important grid resources [25], and are core strategies for economy-wide decarbonization, as shown in the U.S. Long-Term Strategy and in many other analyses [1,26]. Efficiency investments are often cost effective, providing consumer savings and environmental benefit while also reducing overall demand and the capacity build needed in the power sector. As the grid approaches 100% clean and efficiency technologies and strategies evolve, a wider range of energy efficiency technology—such as cold climate heat pumps—could open opportunities for new and more effective energy-efficiency investments.

Demand flexibility is valuable as it can shift demand away from peak periods, provide another resource for grid management, and support integration of variable resources, enabling 100% clean electricity to be achieved with lower costs and less new capacity. The efficient electrification of end-use loads will present important new opportunities for load management and demand flexibility, given the vast expansion of demand-side devices (e.g., via Virtual Power Plants), but will also present new cybersecurity, data privacy, and control challenges. Transportation electrification can offer the grid an important new flexible resource, but only if charging infrastructure and operations are managed wisely. Utilities and utility regulators will play a key role in the deployment of demand resources, including

[3] https://www.whitehouse.gov/wp-content/uploads/2022/11/U.S.-Innovation-to-Meet-2050-Climate-Goals.pdf
[4] https://www.ncei.noaa.gov/access/billions/

managed EV charging, as rate structures and incentives will impact customer participation.

Strengthen domestic manufacturing capabilities and develop resilient and sustainable supply chains 9

Existing energy sector supply chains are already strained and, in many cases, concentrated in particular countries or regions. Energy supply chains will need to further scale up rapidly in terms of raw material extraction, manufacturing, development and construction, maintenance of unprecedented levels of clean power, and infrastructure deployment. Additionally, diversification to reduce risk of disruption on the path to 100% clean electricity will be needed. Emerging supply chains should also ensure minerals, materials, components, construction, maintenance, and operation are environmentally sustainable, low-waste, efficient, and produced in a socially responsible manner, and that remediation and recycling are an integral part of the technology lifecycle. Achieving this will involve leaning on the capabilities of trusted partners while, in parallel, rapidly building out domestic capabilities [27].

Careful planning can minimize stresses or shortages in energy supply chains and the associated workforce [15]. Common risks and vulnerabilities to U.S. energy supply chains that need to be addressed include: domestic raw material availability (e.g., cobalt, rare earth elements); U.S. manufacturing capabilities; workforce readiness; and a lack of current capacity in key areas of production (e.g., neodymium magnets).

Equitably expand the U.S. clean energy workforce 10

A skilled, diverse, trained workforce is essential. The U.S. must continue and expand actions to ensure equal access to expanding job opportunities, especially to those in disadvantaged communities and energy communities.[5] Workforce needs could constrain growth absent proactive solutions. In addition, both power and non-power sector decarbonization strategies need to use a variety of technology solutions that can take advantage of the existing skillset of workers in the fossil fuel sector. For example, district heating and cooling networks using geothermal or waste heat can both provide these jobs while reducing power sector loads on extreme hot and cold days.

Beyond current investments though the BIL and IRA, additional investments must continue to support energy communities more broadly, including in transportation, telecommunications, water, power, and health care infrastructure arenas in which economic modernization and development may be needed. Bolstered by provisions in the IRA, efforts will need to focus on building demand-driven, accessible, and equitable training programs and partnerships; they will need to ensure that jobs offer family sustaining wages, access to benefits, the right to join a union, safe working conditions, and advancement opportunities [28] to ensure historically underrepresented populations that have equitable access to quality clean energy jobs and training.

[5] See https://energycommunities.gov/

An All-of-Society Approach

Achieving 100% clean electricity will require action and coordination from all levels of society. The actions presented above are intended to provide an organized framework of high-priority items and support the needed coordination across key stakeholders and policymakers.

States, Tribal governments, local governments, grid planners and operators, private sector investors, property owners, and consumers' participation is needed

States, Tribes, local governments, and companies across the country have made and continue to make decarbonization targets and pledges. Local actions motivated by these targets are critical to continuing to push toward a decarbonized electricity system. While governmental actions are crucial, private sector involvement and investment are needed. Electricity market rules, regulations, and structures define potential value streams and modes of operation for energy resources, significantly impacting their deployment and highlighting the role and impact of regulators, as well as regional transmission organizations, independent system operators, and utilities. Buy-in from property owners and everyday people is also necessary for developers and utilities to deploy clean energy generation equitably and wisely, and consumer adoption is required to realize building and transportation electrification, reduce demand through energy efficiency, and utilize demand-side resources such as demand response.

State governments and public utility commissions have an important role in driving towards higher levels of clean electricity

States already play a leading role in driving toward 100% clean electricity. The adoption of state clean energy targets has been one of the most important energy and climate change policy developments of the past several years. Twenty-one states plus the District of Columbia and Puerto Rico have now set 100% clean energy goals for electricity, either through legislation or governors' actions. Other states have created clean energy standards with important targets; have created programs to support existing nuclear plants otherwise at risk of retirement; have facilitated tariff and institutional structures that allow end-use customers to purchase clean electricity; and have developed customer-facing programs to support clean, distributed generation, energy efficiency, and end-use demand electrification. State utility regulators and energy offices often manage or implement these programs while also overseeing state energy planning, regulating local electric utilities, and more. The continued proactive engagement of state governments, utility regulators, and energy offices will be essential in achieving 100% clean electricity.

Enhanced coordination across all relevant stakeholders, governments, and communities is essential

Independent actions by all relevant stakeholders are important, but so is coordination among those stakeholders. Coordinated policy across all levels of government, the private sector, and the public will be critical for rapid deployment of clean energy infrastructure, especially infrastructure that spans jurisdictions or impacts multiple sectors. The federal government can continue to play an important role by facilitating across stakeholders, Tribal nations, states, localities, and developers to determine policies and programs necessary to address the challenges and opportunities with clean energy development

and ensure regular electricity customers and frontline communities have power and a voice in these discussions. Coordination among grid planners, operators, and regulators will also be critical in enabling rapidly increasing clean electricity shares and supporting infrastructure while maintaining power-system reliability.

The United States Government is already working to achieve this ambitious power-sector decarbonization goal, building on efforts by state and local governments and the private sector, while maintaining an affordable and reliable system. The IRA and the BIL provide many of the tools necessary to accelerate clean electricity deployment, while meeting the nation's energy security, climate, economic, and equity goals. DOE is committed to continuing work across the government and with these partners in all parts of society to achieve 100% clean power.

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