# The Top Paths to Decarbonization

*Surveying National Decarbonization Strategies*

## Introduction

In the United States, the conversation around decarbonization generally centers around the same handful of options. In large part, the policy approaches include tax, subsidy, grants, or favorable regulatory emphasis. The technological and industrial tools for decarbonization often include wind and solar as the popular energy generators, batteries as the backup and facilitating asset, electric vehicles for transportation, and electrification of the entire economy as the end goal. Hidden within these popular paths to decarbonization are certain assumptions, social and economic costs, and varying degrees of political, economic, and logistical feasibility.

To get a better handle on the paths to decarbonization, we surveyed the top 10 most discussed decarbonization pathways. While this brief does not rank the strategies as most or least effective, we do lay out some costs and benefits for each that may go unnoticed by proponents and adversaries alike.

## Paths to Decarbonization

Because carbon is so central to plant and animal life and the global economy, strategies for decarbonizing must take aim at multiple areas. In this brief, we look at decarbonization options that include generating power without carbon, building out infrastructure that will facilitate low and zero carbon energy and industry, and technology and techniques for removing carbon that is already in the atmosphere. We frame these in three groups. Those that center on power generation, those that support or facilitate a decarbonized economy, and those that address carbon directly.

## Energy Resources and Technology

Under the umbrella of energy, there are multiple key decarbonization options. These vary in their level and ability of decarbonization, especially when it comes to the different scopes of emissions. This means that some produce energy with zero carbon emission, but there are varying carbon footprints to source, build, and deploy those energy options as well as to retire them – or their lifecycle impacts.

Electricity generation alone represents 25 percent of all carbon dioxide emissions in the United States.[1] When industrial and commercial uses of energy – including heat – are added, this figure balloons to around half of all domestic $CO_2$ emissions.[2] Transportation accounts for another quarter of emissions, either relying on fuels directly or electricity from the grid.[3] This makes energy the primary target of decarbonization efforts.

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[1] Environmental Protection Agency. (2022). *Sources of Greenhouse Gas Emissions.* United States Government. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

[2] *Id.*

[3] *Id.*

**Natural Gas and Hydrogen**
Natural gas has long been labeled a “bridge fuel” to a carbon-free future. When burned, natural gas emits around half the carbon dioxide as burning coal, which helped lower U.S. carbon emissions since 2000. While it is a preferred hydrocarbon, it still emits carbon dioxide, making it useful for lowering emissions by displacing coal, but not preferred for complete decarbonization. However, renewable natural gas or biogas is a carbon-neutral fuel, and while it still emits carbon, it is carbon that was previously emitted and captured by agriculture or waste rather than extracted from the ground. In this way, biogas is a renewable source that does not add to the carbon balance of the atmosphere while still providing economic value.[4]

Moving toward fuller decarbonization, hydrogen is another combustible gas. Unlike methane, hydrogen burns without emitting any carbon dioxide. However, hydrogen is not naturally occurring and must be produced. The most common way to produce hydrogen is steam methane reforming, which utilizes natural gas and therefore generates carbon emissions. This can be paired with carbon capture technology to achieve “blue hydrogen.” The preferred production method is electrolysis, where hydrogen is split off from water molecules. When facilitated by nuclear or renewable power, this is labeled “green hydrogen” and has been prioritized and favored in recent infrastructure legislation.

Both blue and green hydrogen tend to be centralized production methods, which will require extensive new infrastructure components to produce, transport, and store hydrogen. An alternative option that also utilizes natural gas is known as methane pyrolysis. This method can be decentralized (or distributed) and produces a powder carbon byproduct rather than carbon dioxide emissions. By decarbonizing natural gas at its point of use, methane pyrolysis may not require any new infrastructure – which could facilitate faster decarbonization and preclude carbon-intensive and specialized infrastructure development.

Treatment of natural gas, hydrogen, and decarbonization goals on the power sector through public policy has changed the underlying costs and incentives over time, but policy can also lead to a clearer pathway forward. These may include incentives as well as permitting reforms to streamline new infrastructure builds to facilitate biogas and hydrogen.

**Nuclear Energy**
Nuclear energy utilizes a fission reaction that splits atoms apart and releases energy as heat. This is paired with steam spinning a turbine to generate electricity. The process is highly efficient and can produce heat and electricity continuously for baseload power. Public policy is partially responsible for restraining nuclear energy, even though it is the cleanest and the second safest form of power generation.[5]

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[4] While hardline advocates may disapprove of burning renewable methane or biogas because it emits carbon dioxide, it is carbon neutral and value positive. It is essentially like hydrocarbon recycling, cycling the same carbon through the economy. Advocates disagree if this qualifies as “decarbonization” because it continues the use of carbon. However, using renewable methane with carbon capture would be carbon negative, fully decarbonizing the process. Also using a renewable methane for hydrogen products may provide additional decarbonization options depending on the technique and technology utilized.
[5] Ritchie, H. (2020). *What are the safest and cleanest sources of energy?* Our World in Data. https://ourworldindata.org/safest-sources-of-energy.

The high startup costs for new nuclear facilities include rigorous engineering and material specifications, regulatory compliance and permitting, legal fees and insurance, and other policy-induced barriers. On the other end, opponents of nuclear energy also point to a lack of national centralized waste disposal location, but this too is a public policy challenge that could be resolved with no change in the level of technology or best practices in the industry.

Meanwhile, advancements in small modular reactors promise to decentralize nuclear power and even provide more sustainable access to carbon-free power across the entire country in the near future with less transmission infrastructure needed. Fusion breakthroughs may also put another form of nuclear on the table in the foreseeable future.

**Wind and Solar Energy**

While separate pieces of the decarbonization puzzle, both wind and solar have similar benefits and limitations and are often discussed in tandem. Each offers carbon-free power generation but require significant mining and supply chain activity, while having limited options for waste disposal. Wind power can be onshore or offshore, providing flexibility to capture more natural energy. Solar can also be arrayed in different settings, both at rooftop or utility-scale.[6] Wind and solar both tend to be placed in open land away from cities, which mean each require electricity transmission infrastructure to connect these to the grid.

Wind and solar also both have intermittent power generation potential. This hinders their ability for baseload or for providing peak demand unless tied into a storage system. Due to natural intermittency of wind and sunlight, it also means that deploying new wind and solar farms and increasing potential capacity does not necessarily equate to increasing actual power.[7] This makes strategic deployment of new assets critical, including the location of wind turbines and solar farms to capture the maximum natural energy but also the capacity and scale of battery storage, transmission infrastructure, and related components.

A key benefit of wind and solar power is that they are technology-based power generation sources, unlike traditional hydrocarbon power generation, which is commodity-based. This means that over time, the technology used to harness natural resources can fall in price and improve in quality like other technologies. This also insulates wind and solar power from swings in commodity pricing.[8] However, these technologies are still reliant on critical minerals and mining activity, as well as foreign governments and supply chains. To further insulate them, public policy can emphasize domestic mining and supply chains. Ultimately, on a lifecycle basis, solar is the safest and the third cleanest power source, with wind coming in as third safest after solar and nuclear, and the second cleanest.[9]

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[6] As well as through photovoltaics or concentrated solar techniques.

[7] 100 wind turbines and 1,000 wind turbines both produce zero power when the wind is not blowing, despite the latter having 10 times the capacity.

[8] It is worth noting that technology can also influence commodity pricing. See for example the low cost and price of natural gas after the innovations to horizontal drilling and hydraulic fracturing. As well as technology and techniques for capturing biogas and other renewable hydrocarbons.

[9] *Supra* note 5.

## Supporting and Facilitating Assets

A key element to making systemic decarbonization feasible is ensuring the infrastructure is in place to support it. Certain assets are needed to support renewable energy, such as batteries, while others are needed to displace energy and fuel that emits carbon, such as electrified appliances and vehicles.

In practice, these too will be energy intensive and material intensive, as they will require significant build out of electricity transmission infrastructure and raw materials and rare earth minerals. The mining needed for industrial batteries and electric vehicles along with the manufacturing and supply chains to produce usable products must be accounted for in their scope of emissions – pushing back the date on achieving true decarbonization and requiring policy that streamlines permitting, emphasizes domestic resources, and allows a transition period for maximum flexibility and feasibility.

**Batteries**

At both small and industrial scales, batteries will be essential for achieving an electric and decarbonized economy. At-home batteries have helped support rooftop solar and microgrid applications, while commercial and industrial batteries will be essential for smoothing the reliability of wind and solar at grid-scale. This will require wind and solar generation to outpace demand unless the power is being diverted primarily to batteries with another source like nuclear, hydro, or geothermal providing baseload.

**Electric Vehicles**

Batteries are also vital to facilitating another decarbonization strategy: displacing internal combustion engine vehicles on the roadway with electric vehicles (EV). Battery-electric vehicles do not produce tailpipe emissions nor combust fuel in the way traditional gasoline or diesel vehicles do. Instead, they draw electricity from a battery (or a fuel cell) to turn electric motors. For widescale EV use, the vehicles must be cost competitive with gasoline vehicles, which is not currently the case without significant tax or subsidy treatment. Charging station infrastructure is also needed around the country in greater density. These are both already being addressed through public policy.

**Electrification**

The ultimate goal of a decarbonized economy must also be an electrified economy, where carbon-emitting fuels are removed or decarbonized across power generation, cooking and heating, industrial processing, transportation, and more. Presently, there is not enough electricity generation capacity on the nationwide grids to support universal electrification. Stoves, ovens, water heaters, heating units, and far more, alongside electric vehicles all drawing on the same grid would strain it in its current state.

These demands engineering as well as public policy solutions to make the grid more resilient, decentralized, smarter, and to increase its capacity by tying in more sources of power. To provide such power and remain consistent with decarbonization, this means new nuclear plants, hydropower, geothermal, and increased wind and solar alongside batteries and the new infrastructure to tie in hydrogen and the additional transmission and distribution infrastructure to move the electricity around.

## Carbon Management

A true all-of-the-above decarbonization strategy focuses not only on new emissions being added, but also how to mitigate and reverse carbon dioxide and methane already in the atmosphere. The back-end decarbonization solutions are either carbon-negative or focused on capping new emissions to address the overall carbon balance in the atmosphere.

### Carbon Taxes, Credits, and Offsets

A key public policy tactic for decarbonization is to set rules for industry. In some cases, by taxing carbon emissions, capping them, or offering credits, this public policy approach uses pricing to allow industry to make its own economic decisions inside the framework of a set of rules. Taxing or cap and trade techniques drive down emissions by incentivizing (both positively and negatively) businesses to invest in more efficient processes, innovative technology and fuels, carbon capture, or carbon offsets. The overall level of decarbonization can be set or revised overtime with these type of programs, but there are economic risks that can raise costs of energy or goods on lower income individuals.

### Carbon Capture

Many processes that are currently essential to the economy emit carbon dioxide or other particles. Carbon capture is an at-source technique for mitigating and limiting the fugitive emissions entering the atmosphere. High quality carbon capture technology can capture more than half of the would-be emissions, which are concentrated at the source. It is more economical to capture $CO_2$ at this stage because of its concentration. Some have argued that carbon capture is a half measure in the decarbonization strategy, because it prolongs or enables continued-emission activity like coal or natural gas-fired power generation. Nevertheless, it is a way to reduce carbon entering the atmosphere and therefore a necessary piece of the decarbonization conversation. It may also be used with renewable methane or biogas, which is already carbon neutral so that the net effect is carbon negative.

### Direct Air Capture

Further removed from the source, carbon dioxide can be extracted directly from the ambient atmosphere. This is the least efficient method for removing carbon dioxide because it is so diluted in the atmosphere, but the technology is improving and scaling over time. This process is being explored to reverse emissions, so that as the economy continues to emit carbon into the atmosphere, direct air capture can mitigate it; and if the economy is fully decarbonized, this technique can address the concentration already in the air. In this way, carbon capture helps address the flow of $CO_2$ into the atmosphere, while direct air capture addresses the stock. This method is technological, which may achieve faster results than tree planting, which takes years to sequester carbon as trees mature.

## Beginning the Transition

With so many sources of carbon in the economy and throughout the country, decarbonization will happen slowly and in different forms. The transition toward a low carbon future will necessarily include small changes in the short term and larger systemic changes over time. This survey included some of the most discussed and prominent solutions, but many other options can also decrease carbon intensity. It is not intended as exhaustive, and many unlisted solutions like geothermal power[10] are of critical importance in the overall energy mix and decarbonization pathway.

There remain many options that do not make headlines, but which can mitigate the carbon intensity of the economy in the short-term. Policymakers should consider ways to begin the transition by encouraging industry actions that do not require systemic shifts or economic shocks but can achieve measurable reductions in carbon emissions. Among these are: increased use of pipelines for hazardous materials to limit leaks and emissions associated with rail or truck accidents; increased use of rail relative to trucking to move freight; improved damage prevention and protection of buried utilities to limit construction site visits, emergency response vehicles, and emissions associated with excavation damage to pipelines and buried infrastructure; increased use of drones to accomplish inspections, surveys, and agricultural uses, including tree planting.

## Conclusion

Carbon is a critical component in our existing energy mix, infrastructure, and transportation sectors. Through all of these, we must focus on understanding and managing our impact on the environment and the world. Decarbonization is one private sector and public policy approach to do so, by limiting and addressing atmospheric concentrations of carbon.

The pathways surveyed here demonstrate that effective systemic decarbonization cannot be achieved through a single technology or public policy proposal, but a network of interlocking and interdependent strategies. These span energy production, supporting and facilitating infrastructure assets, and management plans that mitigate continued emissions.

Ultimately, the public policy approaches to these will include varying levels of taxation, subsidy, grants, pilot programs, and regulatory intervention, but these must be carefully calibrated. To settle those calibrations, policymakers must take into account the data and factors including economic feasibility, existing assets, the need and extent of future infrastructure buildouts, and the legal and regulatory realities that must be confronted or reformed.

[10] While carbon-free, geothermal currently represents the lowest percentage of electricity generation of any single source at only 0.4 percent of the U.S. energy mix for power generation. *See*, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

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# Recommended Citation for this report

B. Dierker. (April, 2023). *The Top Paths to Decarbonization: Surveying National Decarbonization Strategies.* Alliance for Innovation and Infrastructure.

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The Alliance for Innovation and Infrastructure (Aii) is an independent, national research and educational organization that explores the intersection of economics, law, and public policy in the areas of climate, damage prevention, energy, infrastructure, innovation, technology, and transportation.

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