How to Decarbonize the United States for Free

By Glenn Weinreb

How decarbonize for free? In short, don't waste money.

Currently, there is no mechanism that favors the lowest cost approach to climate, and this has led to wasted money. Alternatively, traditional climate money could be redirected to focus exclusively on cost-effective measures. In other words, more could be done for less money. Yet what might this look like numerically? We ran the numbers and placed the results in an open-source spreadsheet that readers can download {https://drive.google.com/drive/folders/1FqOFgYgICS6iPayHW5MNkmj1DkE-BeNk?usp=sharing} for free.

This spreadsheet calculates the cost to reduce U.S. carbon dioxide emissions 1/30th each year, over 30 years, in lowest cost order. This applies to carbon dioxide from all energy, not just electricity.

The spreadsheet assumes decarbonization is driven by government requirements, with additional costs being passed onto consumers. This can be done without subsides and without additional taxes. The analysis is based on U.S. government data {https://ma2life.org/g/eet/eetcs_plan/decarb_plan/resources.pdf} and, for brevity, it assumes GDP growth is zero, electricity generation is built over one year, and electricity demand does not change over time.

Decarbonization Law

An example requirement law is the U.S. Clean Air Act in 1972. This required power companies and refineries to emit less air pollution. To comply, they filtered more, and passed additional costs onto consumers. Requirements such as these are the lowest cost way to reduce carbon dioxide emissions, and they can be instituted without engagement from *each* citizen, company, city and state. In other words, one can focus on a few control points within an economy, and annoy as few people as possible.

Lowest Cost Order

There are many initiatives that reduce carbon dioxide emissions. Each initiatives has a cost to society and an amount of carbon dioxide that is reduced. One can divide these two numbers to calculate the cost to reduce emissions by one metric ton of carbon dioxide. One can think of these parameters as cost and impact. If one decarbonizes in lowest cost order, they might tackle $10-per-ton initiatives first, followed by $12-per-ton initiatives, for example.

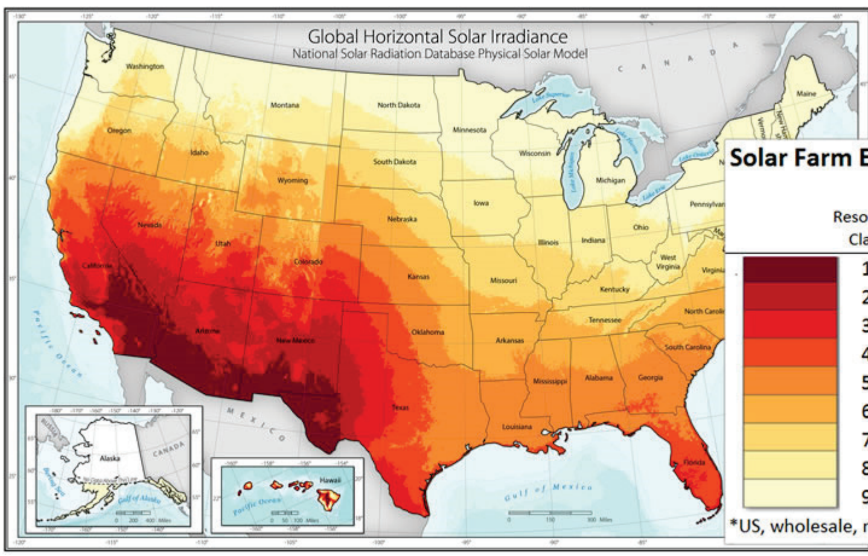
Electricity Costs

On most home electric bills, electricity consumption is specified in units of kilowatt-hours (kWh). The typical U.S. home consumes 10,000 kWh each year, at 14 cents per kWh, for a total of $1,400 per year. Homeowners typically work with kWh units, while utilities typically work with megawatt-hour (MWh) units, which are 1000-times larger.

At one end of the grid is homeowners that pay $.14/kWh retail for generation plus transmission, while at the other end is power generation facilities that receive approximately $0.05/kWh wholesale for large volumes of electricity available at their front gates.

Solar Farms and Wind Farms

Some regions in the U.S. are more sunny, while others are more windy. As one might imagine, it cost less to generate electricity with a solar farm {https://atb.nrel.gov/electricity/2024/utility-scale_pv} in a sunny region, and it cost less to generate electricity with a wind farm {https://atb.nrel.gov/electricity/2024/land-based_wind} in a windy region. Yet by how much? The following tables show the wholesale cost of electricity from wind farms and solar farms built in the year 2025 and the year 2033, as estimated by the U.S. National Renewable Energy Laboratory (NREL {https://en.wikipedia.org/wiki/National_Renewable_Energy_Laboratory}).

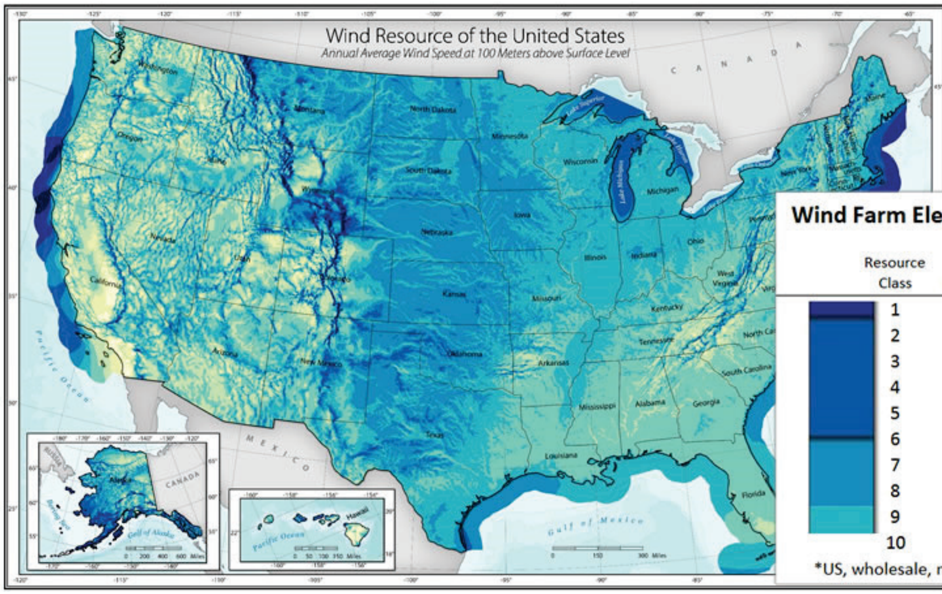


Solar Farm Electricity Cost*

Resource Class	Heat Energy (kWh/m^2/ Day)	AC Capacity Factor	Electricity Cost 2025 $/MWh	Electricity Cost 2033 $/MWh
1	> 5.75	32%	$39	$25
2	5.5–5.75	31%	$41	$26
3	5.25–5.5	29%	$43	$27
4	5–5.25	28%	$45	$28
5	4.75–5	27%	$47	$30
6	4.5–4.75	25%	$50	$31
7	4.25–4.5	24%	$52	$33
8	4–4.25	23%	$54	$34
9	< 4	22%	$57	$36

*US, wholesale, no tax credits, NREL 2024 data, Moderate

Fig 1: This map {https://ma2life.org/g/eet/eetcs_plan/solar-annual-ghi-2018-usa-small.png} shows the cost to generate electricity with a solar farm.



Wind Farm Electricity Cost*

	Resource Class	Wind Speed Range (m/s)	Capacity Factor %	Electricity Cost 2025 $/MWh	Electricity Cost 2033 $/MWh
	1	> 9.0	51%	$29	$23
	2	8.8 - 9.0	48%	$31	$25
	3	8.6 - 8.8	47%	$32	$25
	4	8.4 - 8.6	45%	$32	$26
	5	8.1 - 8.4	44%	$34	$27
	6	7.6 - 8.1	42%	$35	$28
	7	7.1 - 7.6	38%	$39	$32
	8	6.5 - 7.1	35%	$45	$35
	9	5.9 - 6.5	34%	$49	$40
	10	1.7 - 5.9	26%	$72	$55

*US, wholesale, no tax credits, NREL ATB 2024 data

Fig 2: This [map](https://ma2life.org/g/eet/eetcs_plan/US_Wind_Power_Resource_BIG.jpg) {https://ma2life.org/g/eet/eetcs_plan/US_Wind_Power_Resource_BIG.jpg} *shows the cost to generate electricity with a wind farm.*

It tends to be windy at high altitudes; therefore, windmill are technically feasible in many areas. However, due to noise and other factors, they cannot be placed close to people. Therefore, they are typically set up in remote areas. For example, windmills for U.S. east coast cities are likely to reside 200 miles inland.

The following map shows how many windmills one could potentially build at each location and generate electricity at a cost less than $50/MWh.

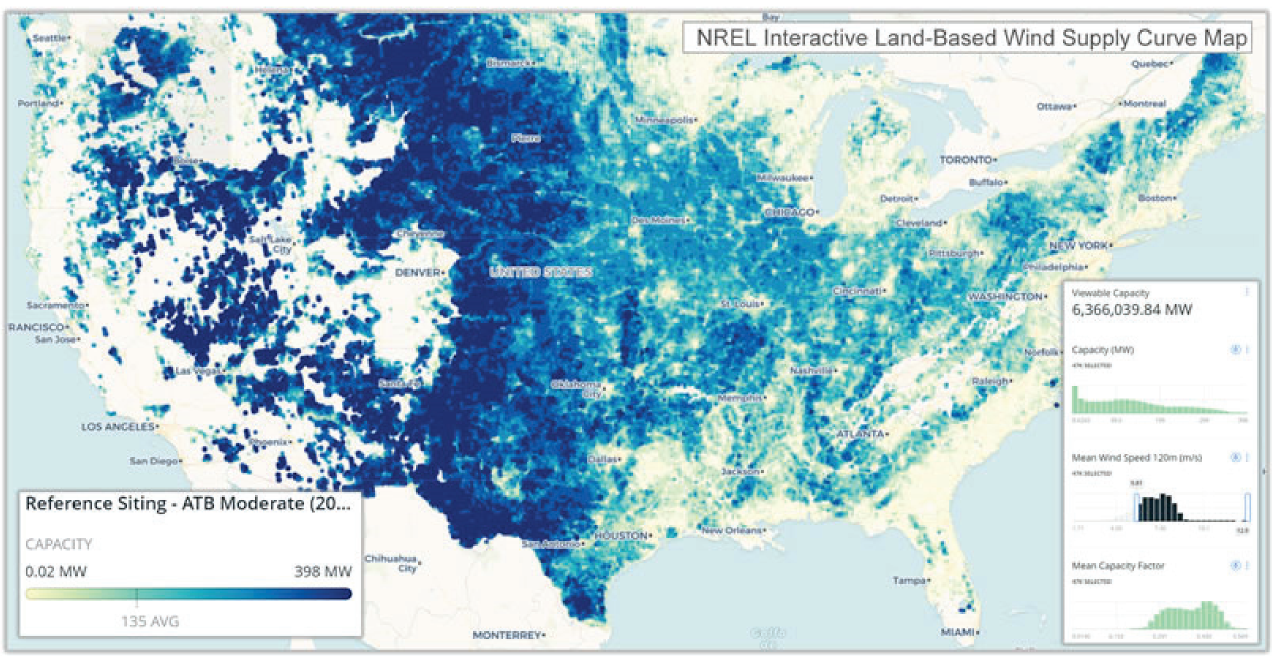


Fig 3: This [map](https://nrel.carto.com/u/alopez/builder/df165aba-7760-4e88-aa99-2e38667bb1a7/embed) *https://nrel.carto.com/u/alopez/builder/df165aba-7760-4e88-aa99-2e38667bb1a7/embed?state=%7B%22map%22%3A%7B%22ne%22%3A%5B23.18186819770262%2C-122.06909179687501%5D%2C%22sw%22%3A%5B54.35565594771057%2C-73.20190429687501%5D%2C%22center%22%3A%5B40.548113311332045%2C-97.635498046875%5D%2C%22zoom%22%3A5%7D%2C%22widgets%22%3A%7B%2268d02c83-4aab-4a95-809e-f6b27938e914%22%3A%7B%22normalized%22%3Atrue%7D%2C%22392cdb16-a8e7-4c2c-99c3-cc884413b717%22%3A%7B%22normalized%22%3Atrue%2C%22min%22%3A6.1792364597320715%7D%2C%2271768ab6-91ed-4aa6-88c0-911ca0762be1%22%3A%7B%22normalized%22%3Atrue%7D%7D%7D* *shows the number of windmills in megawatt (MW) units one*

could build at each location, with ≥ 5.8m/sec wind speed at 120m height. *Courtesy: NREL 2024 Interactive Land-Based Wind Supply Curve Map*.

The following map shows the lowest cost sources of electricity from new construction. Solar farms are shown in purple, wind farms are shown in green, and natural gas is shown in orange. Over time, green electricity costs decrease faster than carbon-based electricity costs. Therefore, we can expect the green and purple areas to expand over the next decade.

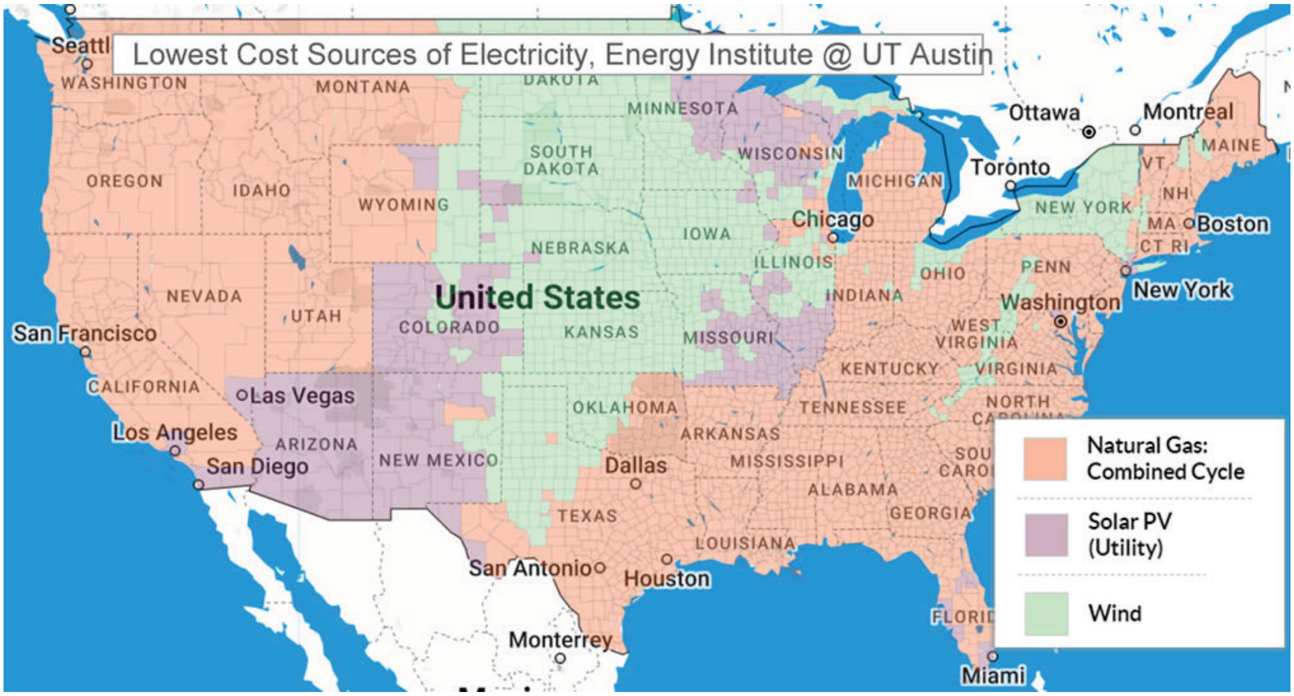


Fig 4: This [map](#) shows the lowest cost sources of new power generation. Courtesy: Electricity [Viewer](#), Energy Institute at UT Austin.

Decarbonization Cost

When replacing fossil fuel based electricity with green electricity, the additional cost to the consumer is the cost of the green electricity (Fig 1 or Fig 2) minus the cost of the fossil fuel that is not burned plus variable costs (Fig 5). In other words, to calculate the cost to go green, subtract a red number from a green number in these figures.

Fuel + VC ($/MWh)	Fuel+VC (¢/kWh)	% of US Electricity	Type of Power Plant
$25	**2.5¢**	38%	Natural Gas Combined Cycle
$32	**3.2¢**	8%	Natural Gas Steam Turbine
$39	**3.9¢**	4%	Natural Gas Combustion Turbine
$43	**4.3¢**	14%	Coal

Fig 5: Wholesale fuel cost plus variable cost at carbon based power plants. Source: NREL 2024 ATB

The Limits of Solar Power and Wind Power

Replacing carbon based electricity with solar/wind power does have limits. For example, there are only so many fossil fuel-based electrical power plants to decarbonize, and solar/wind only supports a portion of each day's needs.

Solar farms typically produce electricity 25% of the time, while wind farms typically produce electricity 44% of the time. In other words, one can build up solar farms and wind farms until the point where green supply meets demand. If one builds further, green electricity is discarded due to having too much. This is referred to as "saturation", and at this point, one can still build more solar/wind to decarbonize further when electricity demand is high; however, decarbonization cost increases due to occasional discarding.

When decarbonizing coal fired power plants with solar/wind, one eventually hits saturation. At this point, one can either decarbonize further with more expensive 24x7 green electricity, described in the next section, or replace the coal plant with less expensive natural gas. Due to internal chemistry, natural gas emits approximately half as much CO_2 as coal. However, if one replaces coal with natural gas, they'll still need to decarbonize the new natural gas plant within a few years, and a short duration mortgage is expensive.

Ideally, one wants coverage from both wind farms *and* solar farms, to avoid the higher cost 24x7 green sources. For example, if 30% of electricity is generated by a solar farm, 30% by a wind farm, and they overlap one-third of the time, then 50% of fossil fuel-based electricity could be decarbonized at close to no additional cost (30% + 30% - 30%/3). One might think of this as "the easy years."

The Easy Years

If one focuses exclusively on building solar farms and wind farms at large scales, the first seven years are easy. More specifically, during this time, the additional cost to go green is less than $1B/yr for the entire US, which equates to $3 per American ($1B / 330M population).

In summary, the low hanging fruit of large-scale decarbonization is to build up solar power and wind power until saturation, and do so at a rate that reduces total CO_2 emissions by 1/30th per year.

China's Solar Spree

A coal shortage in China recently drove up the cost of their coal-based electricity to the point where it is roughly twice the cost of their solar farm electricity. To reduce coal demand, reduce coal price, and save money, the Chinese built 277 GW {https://www.enerdata.net/publications/daily-energy-news/china-installs-record-capacity-solar-45-and-wind-18-2024.html} of solar power in 2024. This is approximately 10-times {https://www.pv-magazine.com/2025/01/28/us-added-34-gw-of-pv-capacity-in-2024} more than that built in the U.S. over the same time period.

The Chinese are demonstrating that large amounts of solar are feasible, and their immense volumes are driving down solar costs via economies of scale.

For reference, solar panels made in the U.S. cost approximately [$170/kW](https://www.nrel.gov/docs/fy24osti/88780.pdf) {https://www.nrel.gov/docs/fy24osti/88780.pdf} more than solar panels made in China—which equates to $4/MWh more for electricity.

The Next Layer of Fruit

After the low hanging fruit has been digested, one can focus on more expensive green electricity that is available 24x7. This includes nuclear {https://atb.nrel.gov/electricity/2024/nuclear} power, wind/solar with battery storage {https://atb.nrel.gov/electricity/2024/utility-scale_pv-plus-battery}, wind/solar with pumped {https://atb.nrel.gov/electricity/2024/pumped_storage_hydropower} hydro storage, and Carbon Capture & Sequestration (CCS {https://atb.nrel.gov/electricity/2024/fossil_energy_technologies}). These provide support when the wind does not blow and the sun does not shine, at a higher cost. According to the U.S. government, these costs are expected to range between $55 and $75/MWh eight years from now.

The Achilles Heel of Electrical Power

The hardest part of electrical power decarbonization involves several weeks each year that receive little wind and little sun. In theory, fossil fuel-based power plants could address these cases; however, underutilization of large facilities is costly. This is why more R&D is needed to develop low cost sources of persistent green energy.

Decarbonizing All Energy

Roughly one-third of carbon dioxide emissions are from electrical power generation, one-third from material and chemical fabrication, and one-third from transportation. If a nation decarbonizes over 30 years in lowest-cost order, then electrical power would be addressed first, over approximately 10 years, followed by easy material and chemical fabrication, followed by more costly opportunities.

The plan builds intermittent green sources for roughly seven years at close to no additional cost, and then builds more persistent green sources for an additional four years, to fully decarbonize electrical power. The remaining 19 years are handled mostly by next generation fission and fusion, described below.

Automating the Construction of Nuclear Fission Power

In theory, custom machines could be developed that automate the construction of nuclear power plants. This would drive down the cost of persistent green energy, and help decarbonize the last two decades of a 30-year decarbonization. Developing custom machines costs little, relative to the $4000B-per-year global cost of fossil fuel (i.e. $2,500B/yr for oil, $1,000B/yr for coal, and $500B/yr for natural gas). Also, if several billion dollars is spent on custom machine R&D, significantly more could be saved due to reduced construction costs.

So why don't we see these? A company would not build them due to not having a customer that wants to build many nuclear reactors; and foundations and governments rarely provide the leadership needed to push this forward. For details, click here {https://www.eetimes.com/how-ai-might-automate-nuclear-power-construction/}.

Accelerate the Development of Fusion Energy

Currently, scientists are exploring how to generate energy within a hot plasma inside a donut-shaped structure. This is referred to as "tokamak fusion," and some scientists believe it will not be commercially available for another 20 years. However, a billion-dollar sized R&D initiative, overseen by the world's top scientists, could potentially accelerate development. For details, click here {https://www.eetimes.com/how-to-solve-the-climate-problem-with-fusion-energy/}.

Co-Locating Industrial Processing with Nuclear Power

66% ….

More R&D

To prepare for the future, the plan spends $11B over five years to develop custom machines that automate the construction of nuclear fission reactors (ref {https://www.eetimes.com/how-to-solve-the-climate-problem-with-nuclear-fission-power/}), spends $11B over five years to accelerate the development of commercial fusion (ref {https://www.eetimes.com/how-to-solve-the-climate-problem-with-fusion-energy/}), and spends $1B over five years to develop custom machines that place solar material directly onto soil (ref {https://www.powerelectEETicsnews.com/mechanizing-pv-solar-on-land/}).

Decarbonization Strategy

Lawmakers are concerned about energy security, energy economics, and climate change. Energy security involves reducing dependence on other nations who might withhold energy to gain influence, energy economics involves reducing energy costs to gain economic advantage, and climate change involves reducing carbon dioxide emissions.

In theory, the U.S. electrical power industry could be required to reduce carbon dioxide emissions from all energy 1/30th each year, until wind farms and solar farms saturate. This would take roughly seven years and not degrade economic competitiveness.

Lawmakers are not inclined to support decarbonization laws unless they are based on plans that have been validated by power company engineers. This is easy during the first seven years, since they would rely on familiar gadgetry. However, 24x7 green sources are less well understood since there is little demand for more costly options. In other words, it is easier to enact decarbonization requirement laws for a handful of years at a time, and do R&D to prepare for future years.

Global Climate Strategy

If the U.S. fully decarbonizes, and other nations do not, little will be accomplished. Also, many climate models say runaway climate change is more likely than not, even with decarbonization. Obviously, this is bad. To deal with this, the plan allocates $10M/yr to build a website that summarizes the climate problem with several graphs, after the user specifies a climate model and number of years they expect our society to emit carbon dioxide. In many cases, this will show runaway climate change even with decarbonization.

Sunlight Reflectivity Research Center

In theory, more sunlight could be reflected back into outer space, to cool the planet, to block climate tipping points {https://en.wikipedia.org/wiki/Tipping_points_in_the_climate_system}. To better understand how to do this, scientists would need an airplane that injects different candidate materials {https://www.eetimes.com/why-spraying-sulfur-into-the-sky-is-not-crazy/} and then measures impact. More specifically, it would create faint streams of material that wrap around the planet, and then monitor them over weeks. This would be done in the upper atmosphere where warmer temperatures cause materials to remain elevated. A potential test site would be at a 40K ft altitude, in the stratosphere {https://en.wikipedia.org/wiki/Stratosphere}, above Alaska.

The plan allocates $500M over five years to support a sunlight reflectivity research center, to determine how to reflect approximately 1% of sunlight back into outer space, at a reasonable cost, without harm.

An Engineered Approach to Climate

For the most part, decarbonization has been undersized relative to what is needed. To decarbonize at large scales, new laws would be needed that require it. Such laws are not popular today; however, this is likely to change as evidence of climate-related problems increases. Subsequently, one can do R&D and plan development today, to prepare for a time when lawmakers are more nervous about climate.