A framework for localizing global climate solutions and their carbon reduction potential

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Localized carbon reduction strategies are especially critical in states and regions that lack top-down climate leadership. This paper illustrates the use of coupled systems in assessments of subnational climate solutions with a case study of Georgia, a state located in the southeastern United States that does not have statewide climate goals or plans. The paper illustrates how robust place-specific plans for climate action could be derived from foundational global and national work and by embedding that research into the context of socio-ecological-technological systems. Our replicable methodology advances the traditional additive sectoral wedge analysis of carbon abatement potential by incorporating solution interdependencies and by spanning both carbon sources and sinks. We estimate that a system of 20 solutions could cut Georgia’s carbon footprint by 35% in 2030 relative to a business-as-usual forecast and by 50% relative to Georgia’s emissions in 2005. We also produce a carbon abatement cost curve that aligns private and social costs as well as benefits with units of avoided CO2-e. The solutions are affiliated with various social co-benefits that highlight societal concerns extending beyond climate impacts, including public health, environmental quality, employment, and equity.

Achieving the carbon reduction necessary to avoid costly climate change necessitates actions at every political scale and across all sectors of the economy. To realize such goals will require the promotion and adoption of high-impact solutions that appeal to different subnational localities, including states, regions, and municipalities. Local businesses and consumers must also find such solutions appealing because they are suitable for the economy, the wallet, and the climate. Thus, climate action plans must be highly tailored and site-specific. One lesson from the development of the Paris Climate Agreement is that countries want to design their own site-specific solutions (1). To date, 191 parties to the Paris Climate Agreement have committed to Nationally Determined Contributions (NDCs). The United States’ original NDC pledged to reduce emissions 26 to 28% below 2005 levels by 2025; within just a few months of taking office in 2021, President Biden introduced a more stringent at least 50% carbon reduction goal for 2030. The Paris Agreement also formalized the role of subnational and nonstate actors in pushing national climate commitments forward (2).

Localized climate goals have been enacted in countries with robust federal climate goals (3). This is true, for example, in the European Union, where subnational goals have emerged alongside the bloc-wide goal of net-zero carbon emissions by 2050 (4). In the United States, subnational climate commitments have formed in the absence of coordinated federal climate policy (5). Several US states have taken a wide range of climate actions. Some have adopted climate action plans that set greenhouse gas (GHG) reduction goals as well as policies and programs aimed at achieving those goals. This includes individual state actions and collective actions, such as the Regional Greenhouse Gas Initiative in the northeastern United States that sets a cap on power sector emissions. America’s Pledge, for example, brings together public and private leaders to mobilize a wide range of actors to take action on climate change. Collectively, subnational and nonstate actors, including states, regions, cities, and businesses, have the potential to make meaningful GHG reductions that could help bring national commitments in line with the 2-degree or 1.5-degree pathways (6). There has also been a great deal of qualitative research on subnational actions to address climate change, including the development of design principles for frameworks that link multilateral and nonstate governance to avoid overlapping and redundant efforts and to fill gaps that might otherwise remain unaddressed, such as adaptation (7, 8).

However, in the United States, many states have no formal climate goals and have not adopted policies to reduce emissions systematically. Those with goals vary in detail and structure. Currently, 25 US governors have committed to meeting the goals carbon footprint | carbon neutrality | equity | climate roadmap


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impacts on societal priorities that extend beyond climate con-
that consider a range of linkages and interactions as well as
complicated by the need to study a system of climate solutions
localities. The conversion to state and local planning is further
To meet the unique needs, resources, and preferences of specific
powerful points of departure, their perspective must be tailored
research is required. While global and national studies provide
larities of a specific region, state, city, or community, additional
increasingly standardized (12), making them more challenging to
However, Bromley-Trujillio et al. (11) found that, as the public
majorities have tended to adopt climate goals and emulate cli-
emissions (the difference between carbon emissions and se-
(10). Twenty-two of these same states have climate plans. A
sions have been more strongly featured. The state of Georgia
(19). Some of these focus on emission reductions, while others
standard engineering options (such as on-shore wind, geother-
mal heat pumps, insulation, and high-speed rail), as well as
nontraditional opportunities linked to culture and behavioral
choices (such as educating women and girls, adopting plant-rich
diets, and reducing food waste). As a whole, these solutions
address all 17 of the UN Sustainable Development Goals (20).
What Project Drawdown does not do is explain how a particular
subnational locality can identify the solutions that are the best fit
for its particular circumstances. It also does not show how to
design integrated systems of solutions.
Examing solutions in isolation can lead to overestimates or
underestimates of the carbon reduction potential of solution
bundies. For instance, less electricity will be generated from
combusting landfill methane if organic waste is diverted to pro-
ductive uses such as soil amendments in conservation agriculture
and by creating new composting markets. Isolated approaches
can also overlook high-priority collateral costs and benefits. If a
solution can simultaneously tackle food insecurity, childhood
asthma, and systemic unemployment, its likelihood of success
could be greatly boosted. Additionally, solving climate change
requires action at multiple nested levels, and involving multiple
stakeholders responding to local conditions (21). Brown and
Sovacool (22) describe eight case studies of GHG reduction
programs that illustrate the benefit of such polycentrism—
engaging multiple scales of intervention and a broad array of
constituencies, including the business sector, layers of governance,
civil leaders, and more. This is especially true in electricity
and transportation sectors that account for most carbon emis-
sions in a majority of industrialized countries, where tightly
coupled supply systems with high entry barriers can be powerful
inhibitors to sustainable transitions (23).
Transitions theorists often presuppose that disruption is a
necessary requirement to alter systems characterized by strong
incumbents with vested interests in the status quo (24). However,
some technology transitions, such as the introduction of solid-
state lighting, can be accomplished with limited disruption be-
cause of its strong links to existing industries and its Edison bulb
design that is familiar to consumers (25). On the other hand,
other technology innovations, such as precombustion carbon
capture, have more significant disruptive potential because of
their links to competing supply chains (e.g., hydrogen markets),
and a lack of familiarity by decision makers (26). By embedding
these scales of disruptive potential into broader SETs framing
(10), it is possible to distinguish between adaptive and trans-
formational capacity. Adaptive capacity is the ability to confront
potentially disruptive change in ways that keep systems opera-
tional, while transformative capacity reflects the ability to shift a
system between regimes—for example, out of regimes support-
ing unsustainable pathways of development and into regimes
supporting sustainable ones (27). In the case of subnational
 states with no climate goals and no carbon reduction strategy,
holistically enhancing the transformative capacity of local sys-
tems and demonstrating the business case is essential.
The literature on SETs framing for climate action is growing
rapidly, arguing sustainable solutions that benefit both people
and nature (28, 29). However, operationalizing these systems has
been challenging. Our paper illustrates how understanding the
functioning of coupled systems can help assess drawdown op-
tions for subnational actors aiming to transform the status quo.

of the Paris Climate Agreement (9), and 23 of these, and the
District of Columbia, have set economy-wide GHG reduction
targets using statutory and/or legally binding executive action
(10). Twenty-two of these same states have climate plans. A
review of these plans indicates that only 15 states focus on net
emissions (the difference between carbon emissions and se-
questration), only 9 discuss equity issues, and only 6 address both
net emissions and equity issues. The number of comprehensive
state plans shrinks further as the treatment of other societal
priorities such as ecosystem diversity and employment impacts
are considered.
To date, states with Democratic governors and state legislative
majories have tended to adopt climate goals and emulate cli-
mate policies of states with similar political leadership (11).
However, Bromley-Trujillio et al. (11) found that, as the public
becomes more concerned about the dangers posed by climate
change, more states begin to respond. When they do so, national
and global mitigation frameworks often offer the most robust
resources.
National mitigation and adaptation strategies are becoming
increasingly standardized (12), making them more challenging to
localize for subnational purposes. When applied to the particu-
larities of a specific region, state, city, or community, additional
research is required. While global and national studies provide
powerful points of departure, their perspective must be tailored
to meet the unique needs, resources, and preferences of specific
localities. The conversion to state and local planning is further
complicated by the need to study a system of climate solutions
that consider a range of linkages and interactions as well as
impacts on societal priorities that extend beyond climate con-
cerns. The localized system’s frame helps subnational actors to
prioritize and plan for scaling climate solutions in their communi-
ities. More can be achieved at lower costs by exploiting
socio-ecological-technological systems (SETS) that are mutually
supportive (13), and by considering their multidimensional im-
pacts (14). For instance, charging electric vehicles (EVs) with
power from coal plants is counterproductive—it would increase
carbon emissions and worsen air pollution. However, operating
EVs with electricity from solar charging stations located in the
retail centers of historically marginalized communities would
enable ultralow emissions mobility that also creates local jobs.
Few comprehensive analyses are available that translate national and global frameworks for climate action to
the subnational level, particularly in the absence of state lead-
ership. This paper begins to fill that gap by describing a repli-
cable framework for translating the global Project Drawdown
solutions (15) to a set of solutions for reducing net emissions
over the next decade in Georgia, a state located in the south-
eastern United States, where state climate policies have lagged
behind the rest of the nation.
Many different approaches have been used to identify strate-
gies for reducing GHG emissions. They vary by geographic scale,
the type of solutions considered, and the articulation of these
solutions in embedded systems. Technocentric approaches in-
clude Princeton’s Stabilization Wedge Framework (16), the
National Laboratory report on “scenarios for a clean energy
future” (17), the United Nations (UN) emissions gap reports
(18), the America’s Pledge (2), and the McKinsey cost curves
(19). Some of these focus on emission reductions, while others
also include natural and technological sinks, such as forest trees,
wetlands, soils, and direct air capture. Recently, social dimen-
sions have been more strongly featured. The state of Georgia
represents an ideal model to adapt global Drawdown solutions to
a local-regional scale. Given the importance of agriculture and
forestry, the occurrence of legally protected habitats, fast grow-
ing human populations spanning a wide range of socioeconomic
backgrounds, and containing one of the nation’s largest urban
centers hosting international corporations, Georgia serves as a
compelling test case to consider a broad range of potential
Drawdown solutions to reduce state carbon emissions and en-
hance carbon sequestration by 2030 in ways that are economi-
cally practical and equitable, given an appropriate framing.
Hawken (15) offers a systems-oriented global study of carbon
abatement approaches. Included in its 100 solutions are the
standard engineering options (such as on-shore wind, geother-
mal heat pumps, insulation, and high-speed rail), as well as
nontraditional opportunities linked to culture and behavioral
choices (such as educating women and girls, adopting plant-rich
diets, and reducing food waste). As a whole, these solutions
address all 17 of the UN Sustainable Development Goals (20).

Results

Georgia’s net GHG emissions in 2017 are estimated to have been 128 megatons (i.e., 128 million metric tons of CO$_2$-e) (SI Appendix). Net emissions are calculated as total GHG emissions in CO$_2$-e minus CO$_2$ sequestered in natural carbon sinks. The largest component of net emissions in 2017 was from Georgia’s energy systems, which accounted for 142 megatons of emissions; in addition, there were 13 megatons from nonenergy CO$_2$ emissions and 19 megatons from three non-CO$_2$ GHG emissions (NO$_x$, methane, and fluorinated gas). Due to the abundance of forest trees and soils, Georgia benefits significantly from natural carbon sinks; the State is almost 60% forested in private lands with an additional 3 million acres of public forests (30). We adopt the estimate of the World Resources Institute (WRI) of 46 megatons of carbon sequestered in Georgia’s land sinks (31). We estimate that net GHG emissions in Georgia were much higher in 2005—at 156.5 megatons according to WRI (31)—and that they declined to 123 megatons in 2020.

The baseline scenario forecasts that Georgia’s net CO$_2$ emissions will decline to 122 megatons as the electricity sector continues to decarbonize, which more than compensates for an increase in emissions from greater transportation fuel consumption. In 2030, based on the Georgia Tech–National Energy Modeling System (GT-NEMS)’s baseline forecast, CO$_2$ emissions from energy consumption in Georgia are estimated to come 41% from electricity and 39% from transportation, making these two sectors key targets of carbon-reduction opportunity (32). Residential and commercial buildings are expected to account for 22% and 21% of energy-related CO$_2$ emissions in 2030, much of which comes from their consumption of electricity. The manufacturing of materials such as aluminum, chemicals, and paper, along with other industrial activities are expected to emit 17% of energy-related CO$_2$ emissions in 2030. The baseline scenario assumes no change to the carbon sequestered in Georgia’s forest, soils, and coastal wetlands.

We consider a set of climate solutions to reduce CO$_2$-e emissions and enhance sequestration over the next decade in Georgia. The 2030 time frame highlights pathways for immediate action that can help put subnational jurisdictions onto a path toward net-zero emissions by midcentury. It is therefore a useful analytic frame for helping subnational decision makers prioritize climate action. However, it is essential to note that post-2030, additional solutions will likely be cost-effective and necessary for deeper reductions. Furthermore, some solutions that are technologically and economically feasible were not selected if their achievable carbon reduction was less than one megaton in 2030. For example, we did not include solutions related to more sustainable construction practices, such as carbon-neutral buildings and building with wood. Not enough new buildings will be constructed in Georgia over the next 10 y to meet the 1-megaton reduction threshold. If the analytic time frame were 2050, these solutions might have been retained.

Down-Selection of 20 Solutions. We identified 20 high-impact solutions for Georgia, spanning five sectors (Table 1). They address a combination of traditional sources of carbon emissions from electricity generation, transport, and the energy consumption of buildings. In addition, they tackle emissions from agriculture and food systems, and they focus on the carbon absorbed in trees and soils. These solutions are diverse, spanning the interests of a wide array of stakeholders. Many of them depend on the actions of consumers—such as rooftop solar, EVs, recycling, plant-rich diets, and composting organic waste. Others depend on the actions of businesses and industry, such as refrigerant management, conservation agriculture, increasing forest cover, and generating electricity via waste heat using cogeneration. Some depend on significant public funding, such as mass transit, and they all would benefit from private investments and supportive public policies.

To compare and contrast the solutions, we quantified the actions to produce a megaton of carbon reduction in Georgia in the year 2030. For initial consideration, a solution needed to have an achievable potential to avert at least 1 megaton in Georgia relative to the statewide baseline forecast in 2030. The profiles in Table 1 display an interesting span of possible carbon-reduction activities and investments normalized to a standard megaton unit of abatement in 2030.

Carbon Abatement Potential and Costs. By comparing the baseline forecast, achievable and technical scenarios for each of the 20 high-impact solutions, we estimated their potential to contribute to carbon abatement in 2030 (SI Appendix). The achievable scenario estimates how emissions could fall if each solution was deployed at an ambitious but achievable level that considers costs, impacts, and stakeholder acceptance. The technical scenario estimates the maximum realistic deployment of each solution without regard to cost or other impacts, up to the hard limits on resources such as available land and materials. In addition, we estimate the net present cost (NPC) of a t CO$_2$-e of abatement in 2030, specified as follows:

$$\text{NPC} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{B_t}{(1+r)^t},$$

where $C$ is cost in year $t$, $B$ is benefit in year $t$, $r$ is time (year) of the cash flow analysis, $n$ is number of years of the financial analysis, and $r$ is discount rate.

Due to their local specificity, we believe the economic uncertainty of our estimates is directionally more manageable than it would be for national or international approaches.

Summing the results over the decade produces the “wedge” diagrams shown in Fig. 1 (SI Appendix). The gray band across the top shows carbon sinks at about 46 megatons, Georgia’s current carbon footprint of about 122 megatons, which is also the baseline forecast for 2030. The colored wedges below the gray band represent the carbon abatement associated with each of the 20 solutions, showing how much each solution could contribute over the next decade, by year from left to right. For example, the largest wedge represents utility-scale solar that increases from 3.9 megatons in 2021 to 11.2 megatons in 2030. The wedge for energy-efficient trucks grows from 0.5 megatons in 2021 to 3.3 megatons in 2023. When all 20 abatement estimates are included and two major interactions are taken into account, the projected total GHG emissions in 2030 would fall from the forecast of 122 megatons to 79 megatons, a 35% reduction. Relative to Georgia’s 156.5 megatons of net emissions in 2005, this would be a 50% reduction, which is consistent with the 2015 Paris Climate Agreement and follow-up commitments made on behalf of the United States in April 2021 by President Biden.

If Georgia were to pursue the technical potential for all 20 solutions, the state could achieve a net-zero carbon footprint in 2030, indeed possibly overshooting carbon neutrality by 11%. Georgia stakeholders could then hypothetically sell carbon credits into carbon offset markets, helping other states meet their goals and collecting revenues to cover the cost of their drawdown investments. Alternative mobility, retrofitting buildings, and afforestation would be large contributors to this future technically possible scenario. It is worth noting that a longer time horizon may have made certain opportunities for carbon reductions even more attractive. For example, an extended time frame might have put increased emphasis on carbon-neutral building construction given potential turnover rates in building stock, and increased focus on off-shore wind given technology
breakthroughs and US experience with offshore wind farms that is likely to occur over the next decade.

The next step involved assessing the economics of these solutions and creating a carbon abatement cost curve (Fig. 2) that aligns costs and benefits with megatons of carbon reduction. We include only private costs and benefits and not social impacts such as public health, coastal land protection, and clean air, or the equity consequences, which will be discussed next. The solutions range from net savings of $336 to net costs of $144 per megaton of abatement, and the financial impact of achieving a 35% reduction of CO$_2$-e in 2030 ranges from net benefits of $1.3 billion to net costs of $148 million.

On the left side of the abatement cost curve are the solutions that deliver the largest net benefits (reduced food waste, rooftop solar, and cogeneration). Consumers and businesses can make money by investing in them. For example, companies in many industries can cut their energy bills by buying their own generation equipment and running it primarily on waste heat. On the right side are the solutions that deliver the highest net costs (EVs and mass transit, in particular). Mass transit requires significant public investments, but based on the array of key benefits, the expenditures are justifiable.

In sum, putting all the parts together, we show that this scenario of 20 solutions could reduce Georgia’s carbon footprint at no net financial cost. However, implementing some solutions will require public support through information/outreach and technical assistance programs, while others will require direct financial outlays from private individuals/firms or public institutions. This conclusion is independent of the co-costs (such as the handling of hazardous waste streams) and co-benefits (such as improved public health and coastal land storm protection) that can result from implementing these solutions, which are discussed next.

**Other Societal Priorities.** Our research also assessed other societal impacts across the environment, equity, economic development, jobs, and public health dimensions for each solution. We conducted a literature search on all solutions to identify benefits and concerns, which also benefited from the strong stakeholder engagement ([SI Appendix](https://doi.org/10.1073/pnas.2100008118)). In Fig. 3, we align the cost abatement curve’s “ranking” of solutions with an initial multicriteria assessment of societal attributes to acknowledge the hard-to-monetize costs and benefits of each solution and to consider equity as it relates to their distribution ([32](https://doi.org/10.1073/pnas.2100008118), using a similar analysis as [Cowlin et al.](33)). Non-CO$_2$ environmental impacts of most solutions are expected to be positive, with air quality being the most prominent cross-cutting benefit, although there are some issues to manage, such as land use changes and hazardous waste generation. There are also clear and substantial benefits in the public health dimension across most solutions. A number of solutions also offer overall net positive economic development and job benefits (noting transitioning from one technology to another may create net losses in particular job segments and/or potentially higher system or infrastructure costs impacting customers or others in the value chain).

In this assessment, we pay special attention to the “equity” dimension, which relates to the distribution of societal impacts. In states like Georgia with large historical and ongoing inequities across demographic groups, this is particularly important. Ideally, implementation paths should not mitigate existing environmental injustices and institutional barriers to access solution benefits, but should also go beyond that to erase those inequities.

**Table 1. A megaton of abatement from 20 solutions implemented in Georgia in 2030**

<table>
<thead>
<tr>
<th>Category</th>
<th>Solution</th>
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<tbody>
<tr>
<td>Electricity</td>
<td>Cogeneration</td>
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<tr>
<td>Demand response</td>
<td></td>
</tr>
<tr>
<td>Landfill methane</td>
<td></td>
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<tr>
<td>Large-scale solar</td>
<td></td>
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<tr>
<td>Rooftop solar</td>
<td></td>
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<tr>
<td>Transportation</td>
<td>Alternative mobility</td>
</tr>
<tr>
<td></td>
<td>Electric vehicles</td>
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<tr>
<td></td>
<td>Energy-efficient cars</td>
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<td></td>
<td>Energy-efficient trucks</td>
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<td></td>
<td>Mass transit</td>
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<tr>
<td>Buildings and materials</td>
<td>Recycling</td>
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<td></td>
<td>Refrigerant management</td>
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<tr>
<td></td>
<td>Retrofitting</td>
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<tr>
<td>Food and agriculture</td>
<td>Composting</td>
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<tr>
<td></td>
<td>Conservation agriculture</td>
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<tr>
<td></td>
<td>Plant-rich diet</td>
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<td></td>
<td>Reduced food waste</td>
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<tr>
<td>Land sinks</td>
<td>Afforestation and silvopasture</td>
</tr>
<tr>
<td></td>
<td>Coastal wetlands</td>
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<td></td>
<td>Temperate forest stewardship</td>
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</tbody>
</table>

This study was conducted by beyond the University of Georgia and was supported by the National Science Foundation. The authors declare no competing interests.

**Author Contributions.** J.H.B. and P.W.O. oversaw the project and contributed to the research design, data analysis, and paper writing. J.H.B. carried out the majority of the research. The authors have no competing interests.
health benefits along with solution-specific equity concerns and opportunities such as affordability and access. While not an explicit criterion in selecting solutions, we scanned for any potential “no-go” equity-related issues and sought to document both issues and opportunities as we proceeded through the process. Where feasible, we also identified promising approaches to expanding equity benefits and mitigating potential adverse impacts. The inputs for this work came from the approaches described in SI Appendix (and included qualitative literature reviews, stakeholder input, and expert engagement).

**Systems Summary of Seven Solutions.** We highlight system effects and illustrate social costs and benefits by weaving our findings into short narratives describing seven of our 20 solutions. For context, we note that in many regions of the United States, electricity systems are being strained by four trends. The grid is expanding its renewable portfolio, transportation and buildings are increasingly reliant on electricity, many coal plants are being retired, and distributed energy resources are proliferating. The result is a challenging era for the orchestration of power management. This has resulted in an increased interest in flexible demand, our first example solution.

**Demand response.** Demand response (DR) has traditionally involved cutting consumption during peak hours, when electricity is most expensive and polluting. With a combination of innovative rate designs and the direct load control of heat pumps, water heating, air conditioning, and EV charging, demand response also allows power providers to enhance system reliability and resilience. System peaks may be reduced by clipping demand during peak hours or shifting load from on-peak to off-peak hours. In either case, DR changes the standard electricity usage patterns of consumers, allowing utilities to reduce their use of expensive and carbon-intensive peaking resources and thereby decreasing GHG emissions. DR can be seen as a type of decentralized energy storage that enhances demand-and-supply flexibility, by separating the timing of electricity production from energy consumption. In Georgia, peak demand is met primarily by natural gas plants, but more polluting and inefficient single-cycle diesel combustion turbines also contribute. We modeled demand response using GT-NEMS by allowing consumers to shift 20% of their on-peak demand for electricity to off-peak hours. The result is a reduction of 1.7 megatons of CO$_2$ and a cut in utility bills across all customer classes, averaging $2.4 million annually over the next decade, reducing energy burdens. However, for low-income households, bill reductions may be limited without policy adjustments to target renters as well as owners and the lower penetration of targeted appliances such as clothes washers, dryers, and dishwashers (34). All income groups would benefit from the improved public health from cleaner air, estimated to be worth $21 million annually over the next decade, principally from curbing childhood asthma and reducing adult lung and heart diseases.

**Rooftop solar systems.** A second way to reduce emissions from the electricity sector is to expand green electricity such as rooftop solar systems. In 2020, Georgia had less than 2,000 home solar systems (displacing a fraction of 1-megaton CO$_2$), mostly located in large cities that have hosted Solarize Campaigns—community-based solar purchasing programs. Based on Google Project Sunroof data (35) on existing flat and south-facing angled roofs located in Georgia and analyzed by county, Georgia has the technical potential for 24.3 GW of solar rooftop nameplate capacity, similar to an earlier National Renewable Energy Laboratory (NREL) analysis by Lopez et al. (36). This technical capacity would cut Georgia’s carbon footprint by 12 megatons, making it an important target for future action. Fitting a generic logistic growth curve (see below) to past adaption trends and the estimated technical potential, we estimate that by 2030, Georgia could achieve close to 1 megaton of abatement by 2030. The generic logistic growth curve that was fitted to historic growth rates and the technical potential for rooftop solar in Georgia, is specified below:

$$ R_t = \frac{TP}{1 + Ae^{-bt}} $$

where $R_t$ is reduction (MtCO$_2$) in year $t$, $TP$ is technical potential (MtCO$_2$), and $A$ and $b$ are the logistic parameters.

Such an expansion of rooftop solar would deliver a sizeable reduction in air pollution as new solar systems displace fossil-fueled power plants. We estimate that CO$_2$, NO$_x$, SO$_x$, PM$_{2.5}$, and PM$_{10}$ pollutant reductions through this solution would result in cumulative monetized benefits worth $67 million in the achievable case in 2030 (37). While rooftop solar also is a job generator (38), the solar workforce lacks diversity (39). Strategies are emerging through Solarize campaigns that use community solar to bring solar to renters and minorities (40). Success depends on overcoming the financial challenges of high upfront installation costs, misaligned incentives between owners and renters, and underlying racial barriers (41).

**Alternative mobility.** In the transportation sector, alternative mobility involves reducing vehicle miles traveled by walking, biking,
or teleworking. Prior to the coronavirus pandemic, adults in the United States spent an average of 1 h driving every day, and 91% of the workforce commuted in personal vehicles (42). These numbers dropped substantially during the pandemic as many offices adopted telework policies. For the achievable scenario, an additional 5–10% uptake in bike/walk share to replace auto trips in urban environments would result in 45–55% of trips under a one-half mile and 22–32% of trips under 4 miles being taken by walking or cycling by 2030, in line with current figures achieved in some parts of the United States. This increase in walking and cycling is combined with an additional 10 to 20% of telecommuting by workers who have jobs that can be done remotely (roughly 50% of the population) (43) to achieve total emissions reductions of between 1.8 and 3.6 Mt CO$_2$-e. Technical potential (21.5 Mt CO$_2$-e) is modeled as 45% of all trips taken by alternative transportation and 50% additional telecommuting by 2030. It demonstrates a large potential that is constrained by societal choices around the design of urban and suburban

![Fig. 2. Carbon cost abatement curve. (Note: Abatement costs and potentials have ranges for some solution, which are highlighted by dividing boxes vertically and horizontally. Recycling has a range of both abatement costs and potential.)](image)

![Fig. 3. The outcome of qualitative multicriteria assessment for selected attributes. Green, material positive impacts with few negative impacts. Orange, heterogeneity in the impacts across population subgroups, with some negative impacts that require attention. Blank, not material; not expected to have substantive positive or negative impacts.](image)
enough to result in meaningful CO₂ reductions, but not so am-
EV growth in Georgia, in that the deployment is aggressive
crease in EVs compared to the achievable scenario), but CO₂
the share of EVs in the cumulative fleet reaches 8.3% (a 125%
sions reductions from EVs would not maintain this same pace of
in 2030, reaching a 3.7% share of the cumulative fleet under our
fleet. If EVs were to grow to 21% of new light-duty vehicle sales
be used to meet demand) or cost efficiency (e.g., require excessive/
specifically to low-income communities (44).
are several promising trends and tools underway to address this
challenges associated with this transition to EVs, including the lack of
affordability by resource-challenged consumers. Fortunately, there
there are several promising trends and tools underway to address this
barrier, including steadily declining battery and EV prices, sub-
sidies to help defray upfront investments, and programs geared
specified locally to low-income communities (44).

Building retrofits. Turning to the energy-consuming built environ-
ment, deep building retrofits offer sizeable potential energy
savings at reasonable costs. The achievable scenario for retro-
fitting considers a 2% per year market penetration (above the
baseline forecast) of smart thermostats, improved insulation, and
light-emitting diode (LED) lighting for the residential sector and
retro-commissioning, building automation, and LED lighting for
the commercial sector. The result is an abatement potential of
2.4 to 4 megatons in 2030. This is significant in the technical
scenario, with the addition of improved windows in the
residential sector; high-efficiency heat pumps, hybrid heat pump
water heaters, and improved insulation in the commercial sector;
and the assumption of a 5% per year market penetration. Building retrofits are especially important to help deal with other
solutions that could raise electricity rates and exacerbate
household energy burdens (45). The following points explain the
magnitude of our estimated carbon-reduction potential: 1) the
additional energy-efficiency gains are estimated with respect to a
thorough business-as-usual scenario for existing buildings that is
anticipated to deliver an estimated 9.6% decrease in energy per
household over the next decade; 2) more efficient new buildings
would deliver additional carbon reductions; 3) we considered the
potential for a carefully selected subset of cost-effective tech-
nologies; 4) we rely on retrofit rates achieved by best-in-class retrofit programs; and 5) as more renewable energy penetrates
the grid, we model the fact that carbon reduction from energy
efficiency declines because the energy that is being avoided has
lower carbon content. We estimate and discuss these interaction
effects in the paper and its SI Appendix, to clarify some of these
limitations. Indeed, with a more comprehensive approach to
promoting energy efficiency, a longer time horizon, and aggressive
incentives, it would be possible to go beyond our “achievable”
scenario.
However, a majority of energy-efficiency programs require
upfront customer investments to leverage rebates and associated
savings, which makes them unaffordable to low-income house-
holds (46). When access to energy becomes difficult, the burden
is felt in every facet of life—housing, mobility, health, work,
education, and much more (47). Thus, policy innovations are
needed for this solution to be equitable. These innovations in-
clude programs such as utility financing via “Pay As You Save”
and on-bill financing initiatives. There are also efforts that ex-
tend beyond financing and bill assistance to addressing root
causes through, for example, correcting funding disparities be-
tween the federal Low-Income Home Energy Assistance Pro-
gram, which supports short-term energy bill assistance; and the
Weatherization Assistance Program, which funds more perma-
nently beneficial weatherization and energy efficiency for low-
income households (48).

Reducing food waste. In the food and agriculture sector, reducing
food waste is a major potential contributor. More than one-third
of food every year is wasted globally and nationally (49, 50). In
the United States, more than 55 million tons of food is wasted
annually at the retail and consumer levels, and that is on top of the
losses occurring throughout the production, processing, and
transportation chain (51). When food waste ends up in landfills,
some is broken down to CO₂ where oxygen levels are high
enough, but most degrades into methane, which is a particularly
potent GHG (45). Furthermore, there are significant GHG emissions throughout the food supply chain that could be avoided
by reducing the throughput associated with waste. By our
estimate, reducing food waste by 20% could avoid almost 2
megatons of emissions in Georgia. To achieve this, we need
comprehensive consumer education campaigns, institutional
food reduction programs, more effective food donation pro-
grams, improved refrigerated storage and capacity, standardized
date labeling, and robust data analytics on food waste measure-
ment and monitoring (48). In the end, reducing waste along the
supply chain can benefit farmers, processors, wholesalers,
retailers, restaurants, and consumers. Furthermore, it can help
tackle the problem of food insecurity that has been made so
visible by COVID-19. However, there also can be affordability
challenges and/or cost pressures for individual actors in the
value chain.

Afforestation and silvopasture. Afforestation and silvopasture is a
solution that illustrates the importance of expanding land sinks.
Earth has three natural carbon “sinks” where carbon can be
stowed. The atmosphere is the most common waste repository for
carbon (52), which is causing the climate change that we now
must manage. Carbon can also be absorbed by the ocean, but this
causes issues of ocean acidification that harms shellfish and
other aquatic life. Land sinks, on the other hand, can absorb
carbon safely and securely. Almost 60% of land in Georgia is
composed of naturally recruited and planted temperate forests,
and Georgia is the number one forestry state in the nation (29).
Increasing forest cover in Georgia by 10% would increase the
state’s carbon storage by 2.8 megaton in 2030. In addition, more
forests mean more wildlife habitats and low-cost recreational
lands, as well as cleaner water and air because trees deliver
powerful pollutant filtration ecosystems (48, 53, 54).

Solution Interactions. A key contribution that we formalize is the
assessment of systems of solutions to maximize synergies and
minimize competitive effects. Synergies occur when the suc-
cessful deployment of one solution magnifies the carbon reduc-
tion potential of another. In contrast, competitive effects occur
when the deployment of one solution undermines the ability of
other solutions to reduce carbon emissions. As outlined in ref.
32, we distinguish between synergies and competition based on
emissions vs. implementation. Synergistic emissions occur when
the implementation of one solution (such as large-scale solar)
boosts the emissions reduction of another, as occurs when EVs
operate on lower-carbon electricity. With synergistic implementation,
expansion of one solution such as afforestation, accelerates the implementation of another solution, such as coastal wetlands, which are a more robust carbon sink as the result of the pollution filtering of upstream forests.

Solutions can also be competitive. With competitive emissions, implementing one solution (such as large-scale solar) reduces the potential for another solution to cut emissions. This is the case with building retrofits, because the electricity that would be “saved” from insulating structures and upgrading appliance efficiencies, would be less carbon intensive. With competitive implementation, the uptake of one solution undermines opportunities for another. For instance, reducing food waste or adopting composting, reduces organic waste streams and therefore shrinks the potential to produce landfill methane. Similarly, limited common resources can lead to competition, as with the competition for land, which is needed to plant trees, build solar farms, and expand mass transit.

Fig. 4 identifies notable bilateral competition and synergies. Competitive and synergistic impacts are one of the motivations for economy-wide modeling of emissions strategies. The literature also often deals with co-benefits and competing goals (55–57). At the same time, addressing the full range of macro-economic effects will require general equilibrium models for each solution, the specification and results of which will be highly dependent on how the solution is implemented. While some solutions like mass transit warrant a full-scale macroeconomic analysis before significant investments are made, considering the urgency of the climate crisis, we should also be mindful of “paralysis by analysis.”

We have modeled two of these interactions, and the results are embedded into our analysis of abatement potential and costs and are summarized below (SI Appendix). The first example—the interaction between EVs and large-scale solar—is complex, but primarily complementary, with the scale and timing of deployment impacting potential synergies. This result is consistent with that of Hoarau and Perez (58) who find synergies in the interaction between EVs and solar photovoltaics across the academic literature. A major motivation for EVs is the goal of shifting prime energy resources from liquid hydrocarbon fuels to grid power. With this shift, large-scale solar in Georgia could improve the environmental impact of EVs by reducing the average CO₂ intensity of grid electricity. Three relevant interactions have been modeled: the average reduction of grid CO₂ intensity from solar, the decrease of light-duty vehicle (LDV) CO₂ emissions, and the increase in electricity demand due to LDVs. This interaction was modeled using the following quantities and formula using MATLAB (the code is reproduced in SI Appendix). We conceptualize the relationship based on Eq. 1:

$$\Delta S = \Delta DC + \Delta E,$$

where $\Delta D$ is increase in electricity demand from LDVs (in gigawatt hours) in the EV scenario, $\Delta E$ is decrease in emissions from LDVs (in megatons) in the EV scenario, $C$ is CO₂ intensity of the grid (megatons/gigawatt hour) assuming the achievable potential of large-scale solar, and $\Delta S$ is emission reduction from the combined large-scale solar and EV achievable scenarios relative to the baseline (megatons).

In sum, if large-scale solar were to reach the deployment levels modeled in the achievable scenario in 2030, EVs would reduce CO₂ by an additional 14% (that is, 0.2 more megatons of CO₂ avoided). The modeling of this specific interaction is limited by our assumed use of average grid-CO₂ emissions. It should be noted that marginal CO₂ emission rates (e.g., on an hourly basis) can become important, and would be higher than average rates, if EV charging is not managed carefully throughout the day (e.g., solar energy will not directly charge EVs at night, but instead offset other forms of generation). This would erode some of the potential synergies of this interaction. Additional erosion could occur if/when future EV deployments and charging needs surpass a certain threshold wherein electricity generation must be derived from higher CO₂ resources, i.e., if low carbon generation is fully utilized and insufficient to meet additional EV demand, requiring additional fossil generation.

The second example—the interaction between retrofitting and large-scale solar—also complex, but primarily competitive.

![Fig. 4. Solution interactions.](https://doi.org/10.1073/pnas.2100008118)
Retrofitting reduces carbon emissions through the reduction of building energy consumption. The growth of large-scale solar to replace fossil fuel-based grid power generation decreases the carbon intensity of the grid, lowering the avoided emissions from retrofitting as every unit of power saved is now equivalent to less CO₂. This model uses the ratio of CO₂ intensities to scale the known CO₂ reduction from retrofitting cases. This interaction was modeled using the following quantities and formula in MATLAB2. We conceptualize this relationship based on Eq. 2:

$$\Delta S = \Delta E \times I_b$$

where $\Delta E$ is emissions reduction from retrofitting cases, relative to baseline (megatons), $I_b$ is baseline CO₂ intensity of grid power (megatons/gigawatt hour), $I_s$ is drawdown scenario CO₂ intensity of grid power (megatons/gigawatt hour), and $\Delta S$ is emissions reduction from combining the retrofitting and large-scale solar cases, relative to the baseline (megatons).

In sum, if large-scale solar were to reach its achievable potential in 2030, retrofitting would produce 0.7 megatons (27%) less CO₂ savings from its achievable case. These two examples illustrate why strategies need to consider interactions and “systems” of solutions. Economy-wide modeling of synergies and interactions across solutions remains an enormous challenge for Integrated Assessment Models, and more limited regional or systems-level economic models (39). The research team plans to conduct follow-on research that will explore these interactions in greater detail, with higher resolution, in particular, relative to marginal CO₂ considerations as well as costs and benefits that accrue when considering more complex systems of solutions.

Discussion

Our results are broadly consistent with approaches like Project Drawdown and America’s Pledge, yet highlight some differences as well that reflect our modeling choices and problem context. America’s Pledge attributes lower potential to states and localities, suggesting 25% potential reductions relative to 2017 levels, with many of these embedded in existing policies and programs rather than new efforts. In contrast, our analysis finds opportunities to reduce emissions by 37% in 2030 relative to 2017 levels, and by 47% relative to Georgia’s 2005 net emissions. While these differences are likely the result of disparate assumptions about state, local, and federal responsibilities, as well as assumptions about potential penetration rates of various technologies, it is worth noting that America’s Pledge finds three largely similar levers for potential reductions to carbon. America’s Pledge relies primarily on renewable electricity, energy efficiency, afforestation, land use, and EVs. These efforts align closely with our most promising solutions.

Relative to Project Drawdown, we find that there are significant differences in context that highlight the potential for carbon reductions. For example, while refrigerant management features quite prominently in Project Drawdown, refrigerant management was a much less promising solution in Georgia. This is due to various regulatory requirements in the United States that require proper disposal of refrigerants, regulatory initiatives designed to reduce leakage, and efforts made to find lower global warming potential alternatives. In addition, our state-level focus attributes many of these efforts to federal policy that exists outside the purview of local officials, highlighting the importance of different approaches to these types of analyses. This analysis was finalized prior to the passage of the 2020 omnibus appropriations bill that included legislation to phase down hydrofluorocarbons nationwide.

To benefit the climate planning of other states and communities, we summarize the strengths and weaknesses of our analytical approach. Key among the strengths is its use of open-source data and publicly available analytical tools. Another strength is our assessment of SETs, which led us to closely examine interactions across solutions and to consider carbon-reduction actions in the context of other societal priorities. A third strength is our elaboration of the role of nested solutions that can be acted upon at the state and local level, independently or in conjunction with federal policies. Individual solutions fit with specific institutions that are already in place, and by tying them into nested polycentric institutional frameworks, the likelihood of success is strengthened.

Several limitations warrant consideration as our findings are examined by stakeholders. First, carbon reductions by the year 2030 are a key metric for down-selecting solutions for Georgia. In subsequent decades, additional solutions will be needed to achieve net-zero carbon emissions by midcentury, possibly including renewable hydrogen fuels, offshore wind, and direct air capture of CO₂. Such mid- and long-term solutions can be difficult to translate into large-scale options if today’s choices make them more costly to develop in the future—an example of near-term solutions becoming barriers to the deployment of alternative and potentially more transformative changes (32).

This concern can be mitigated in several ways. First, while the solutions are specific enough to target near-term impact, their ultimate scalability will benefit from continued research and development that supports a broad range of uses and solutions beyond those that we down-selected. One example relates to battery storage and associated technologies, which via improvements, will enhance the benefits of solar and EVs, as well as wind energy. Second, solutions may be scoped to describe the achievement of the carbon impacts we identified but allow for the application and deployment of a broad subset of technologies. For example, retrofitting buildings refers to a range of possible interventions that can also be applied to deepen impact in both commercial and residential sectors. Third, we would recommend that any policy adoption of our 20 solutions (in support of a 2030 target) also include explicit R&D funding for new innovations that might be deployed over the next decade and/or a longer-term horizon. Similarly, we recommend that even solutions with smaller annual impacts in the near term should be nurtured through local community initiatives, innovation competitions, student-focused opportunities at all educational levels, and other forms of outreach that support a broad level of engagement.

Second, our analysis to date does not consider all of the potential leakage, rebound effects, or life cycle impacts of each solution. Our treatment of solution interactions considers only first-order effects and not the second-order macroeconomic impact of prices and quantities. To address the full range of macroeconomic effects requires general equilibrium models for each solution, the specification and results of which will be highly dependent on how the solution is implemented. However, some solutions such as mass transit warrant a full-scale macroeconomic analysis before significant investments are made, considering the urgency of the climate crisis.

Third, the abatement cost estimates for each solution are average costs that may not be applicable across all scales, and the inclusion of transaction costs across solutions is variable. In many cases (e.g., food waste and recycling), there are institutional, or information barriers that would require significant costs to overcome that may not be fully incorporated into cost estimates. These limitations result from the fact that we have only partially and incompletely considered the full range of policy levers available to promote climate technologies. We are now launching a follow-on phase of policy research that will reveal new insights when overlaid upon this foundational effort.

Finally, the deployment of these 20 solutions can assist or thwart other societal priorities. The broad inclusion of stakeholders in policy decision-making and implementation is particularly important in addressing the needs of communities in
Georgia that are more vulnerable to climate change (59), including people at risk due to their locations, available services, and economic situations (60). In the wake of the coronavirus pandemic, it is particularly important to focus on how the deployment of high-impact solutions can help communities build back better. Ultimately, the activities of subnational actors—governors and their state agencies, local communities, municipalities, businesses, nongovernmental organizations (NGOs), and civic leaders—need to be stitched together with national initiatives to collectively drive down net emissions while simultaneously addressing other societal needs.

**Materials and Methods**

The systematic and replicable methodology used to down-select 20 high-impact solutions for Georgia from Project Drawdown’s original list of 100 options (15) involved five steps that are described in SI Appendix.

The Drawdown Georgia project engaged experts and stakeholders at multiple points in the research process to ensure that community preferences were considered and that relevant climate solutions were thoroughly vetted. This engagement took multiple forms (expert and public surveys, webinars, conferences, expert working groups, expert forums, etc.) (SI Appendix). Underpinning the analysis of all 20 solutions is a characterization of Georgia’s current carbon footprint, which is created using traditional government and NGO data sources and is further described in ref. 32 (SI Appendix). We then standardize our analysis of the 20 high-impact solutions by defining three scenarios of their likely future market penetration. The baseline scenario reflects the status quo forecast with no new policies, assuming continued market and technological trends. The Reference Case of the GT-NEMS defines our forecast for Georgia’s carbon footprint from energy usage in 2030, and other sources are used to provide further details particular to individual solutions. The achievable scenario reflects ambitious action at levels of future penetration. In aggregate, it assumes that businesses expand their sustainability goals, governments create stronger policies, and consumers are committed to more sustainable lifestyles. In many instances, these estimates are derived from modeling the implementation of supportive public policies and programs and by benchmarking the achievements of state and local leaders across the United States that have shown what is possible. The scenario of technical potentials estimates the maximum possible adoption of each of the 20 climate solutions. Adoption rates are not constrained by assumptions around cost or other impacts and are assumed to be deployed up to hard limits on resources, such as available land and materials. (SI Appendix, Table S1) provides a description of data sources and methods for each of the 20 solutions.) The same data sources and modeling approaches were used to create a standard metric to characterize what each solution would look like if scaled to deliver a megaton of abatement.

**Data Availability.** All study data are included in the article and/or SI Appendix.

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