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 CO_2-e. The solutions are affiliated with various social co-costs and co-benefits that highlight societal concerns extending beyond climate impacts, including public health, environmental quality, employment, and equity.

carbon footprint | carbon neutrality | equity | climate roadmap

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

Significance

Only 22 states in the United States have climate action plans, and of these, only six consider carbon mitigation, negative emissions, and equity issues. In the absence of robust federal or state policy action, there is a need for subnational carbon abatement planning. However, many of the most robust frameworks for carbon abatement are at a global or national scale. We provide a framework for localizing an existing global roadmap of climate solutions for Georgia, a state located in the southeastern United States. We thereby provide a replicable model that documents how subnational actors can evaluate high-potential emission reduction and carbon removal solutions while considering systems of solutions and taking into account social, ecological, and technological issues and priorities.

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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 sequestration), 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 majorities have tended to adopt climate goals and emulate climate 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 particularities 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 concerns. The localized system's frame helps subnational actors to prioritize and plan for scaling climate solutions in their communities. More can be achieved at lower costs by exploiting socio-ecological-technological systems (SETs) that are mutually supportive (13), and by considering their multidimensional impacts (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 robust and comprehensive analyses are available that translate national and global frameworks for climate action to the subnational level, particularly in the absence of state leadership. This paper begins to fill that gap by describing a replicable 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 southeastern United States, where state climate policies have lagged behind the rest of the nation.

Many different approaches have been used to identify strategies 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 include 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 dimensions 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 growing 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 enhance carbon sequestration by 2030 in ways that are economically 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, geothermal 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.

Examining solutions in isolation can lead to overestimates or underestimates of the carbon reduction potential of solution bundles. For instance, less electricity will be generated from combusting landfill methane if organic waste is diverted to productive 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 emissions 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 because 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 transformational capacity. Adaptive capacity is the ability to confront potentially disruptive change in ways that keep systems operational, while transformative capacity reflects the ability to shift a system between regimes—for example, out of regimes supporting 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 systems 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 options for subnational actors aiming to transform the status quo.

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, transportation, 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:

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

where C is cost in year t, B is benefit in year t, t 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 2030. 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

SOCIAL SCIENCES

ENVIRONMENTAL SCIENCES

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

Category	Solution
Electricity	
Cogeneration	Sixteen additional 25-MW combined heat and power plants generating electricity with waste heat from industrial processes
Demand response	187,000 households shift 10% of their peak electricity use to off-peak
Landfill methane	Four additional typical landfill facilities with 5-MW gas-to-energy systems
Large-scale solar	Ten new 100-MW utility-scale solar installations and 36 new 5-MW community solar projects
Rooftop solar	295,000 new 5-KW home solar systems
Transportation	
Alternative mobility	Eliminate 2.5% of vehicle miles traveled
Electric vehicles	Replace 250,000 gasoline-powered vehicles with electric vehicles (EVs)
Energy-efficient cars	Improve fleetwide fuel economy for light-duty vehicles by exceeding baseline fuel economy by 3%
Energy-efficient trucks	Reduce diesel fuel use in medium and heavy-duty trucks by 10%
Mass transit	320,000 additional households in transit-oriented developments
Buildings and materials	
Recycling	Recycle at least 20% of currently disposed paper waste annually
Refrigerant management	Retrofit refrigeration systems in all Georgia grocery stores to refrigerant leakage rate of 8%
Retrofitting	Retrofit 20% of Georgia's homes to save 20% of energy annually
Food and agriculture	
Composting	Divert 2 million tons of organic and food waste to composting
Conservation agriculture	Adapt an additional 1.6 million acres of cropland into conservation agriculture practices in Georgia
Plant-rich diet	25% of Georgians adopt plant-rich or lower carbon-emitting diet
Reduced food waste	Reduce about 12% of Georgia's current food waste
Land sinks	
Afforestation and silvopasture	Plant 7% of current pasture lands with mixed hardwood and loblolly (*Pinus taeda*) tree species
Coastal wetlands	Increase Georgia's coastal wetland area by 71%
Temperate forest stewardship	Increase forest cover by 3.5% with mixed hardwood and loblolly (*Pinus taeda*) tree species

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*). 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), 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. Issues identified in our work that will need to be addressed include solution access, affordability (such as changes in energy and water burdens), and expanding diversity among workforce and business owners. On the positive side, the public health benefits of solutions can reduce health inequities by offering improved air quality and public health benefits for under-resourced communities. With this context, our primary objective was to be intentional about capturing (in shaping solution summaries and related communications) both broad-based generalized benefits such as improvements in air quality and related

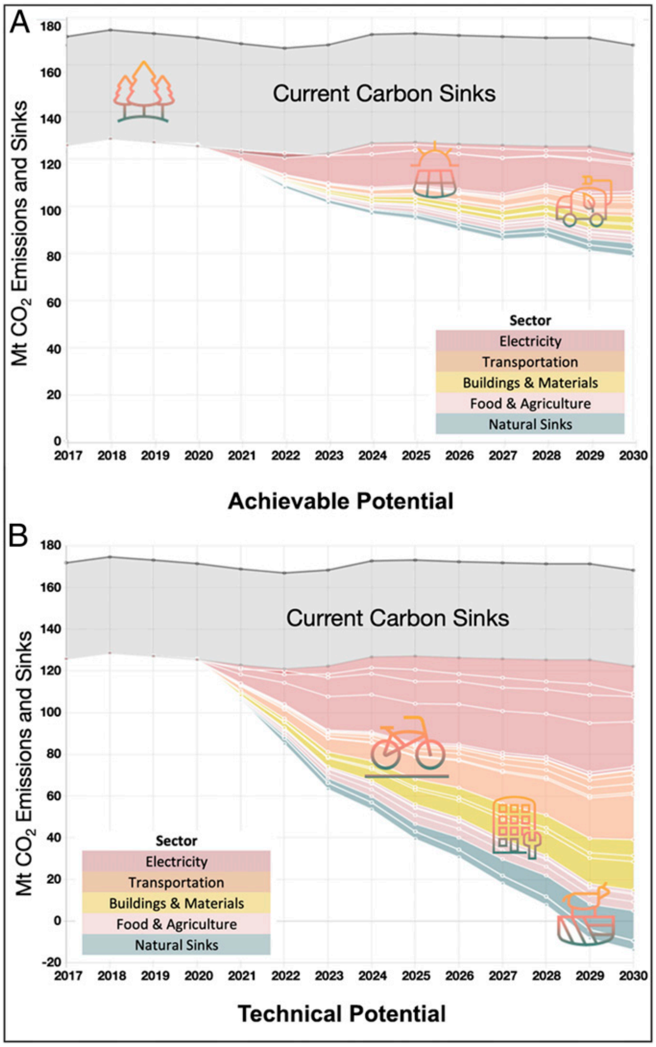

Fig. 1. The achievable and technical abatement potential of 20 high-impact solutions for Georgia.

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 systems 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 adoption 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^2, $PM_{2.5}$, 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,

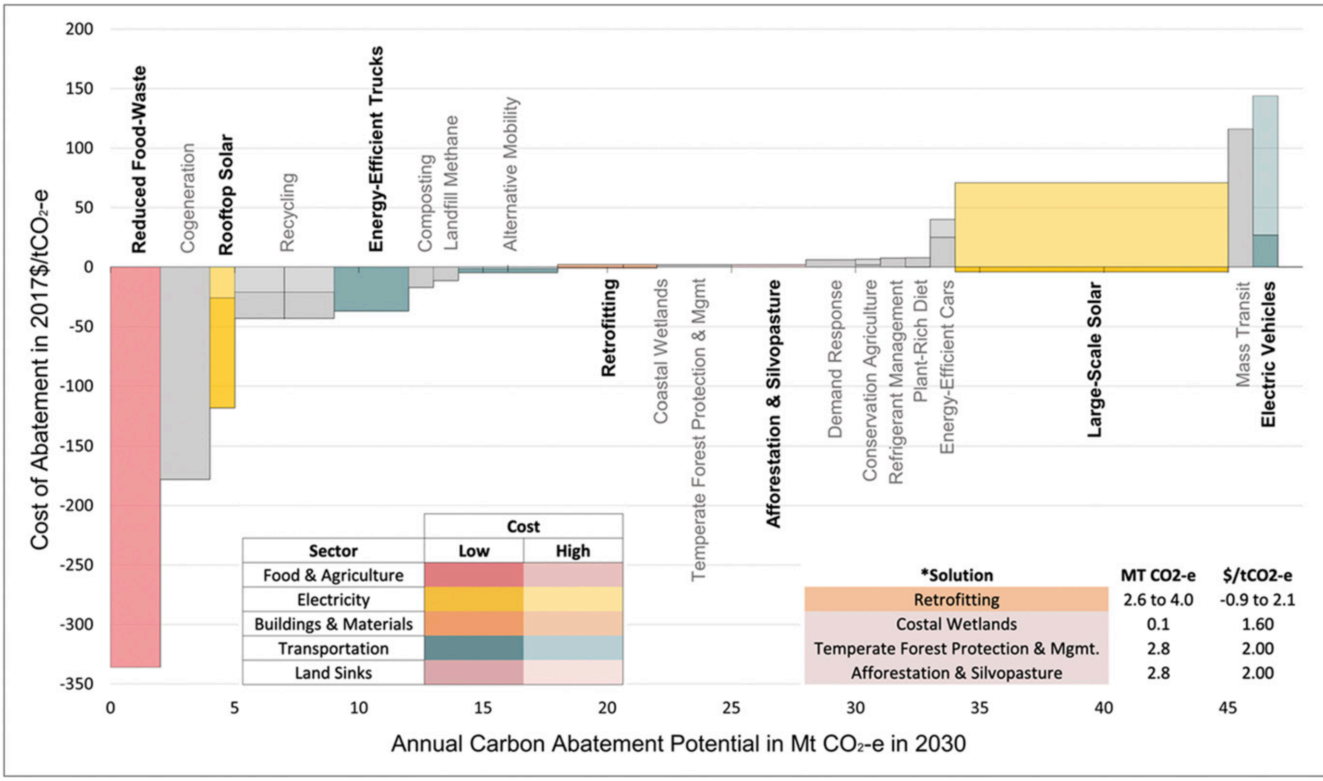

Fig. 2. Carbon cost abatement curve. (Note: Abatement costs and potentials have ranges for some solution, which are highlighted by dividing boxes vertically and horizontally. Recycling has a range of both abatement costs and potential.)

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

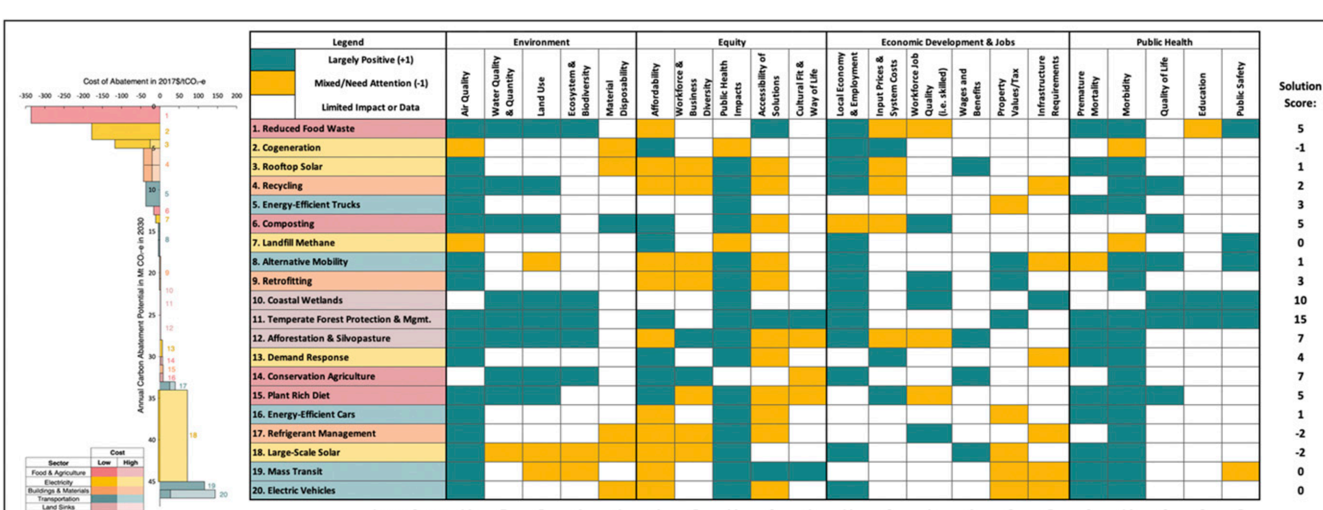

Fig. 3. The outcome of qualitative multicriteria assessment for selected attributes. Green, material positive impacts with few negative impacts. Orange, heterogeneity in the impacts across population subgroups, with some negative impacts that require attention. Blank, not material; not expected to have substantive positive or negative impacts.

environments and current dependence on automobiles. While we expect that trends toward teleworking are likely to continue, telecommuting does not play a large role in the achievable or technical potential because, according to the National Household Transportation Survey, work-related trips make up just 16.6% of total car trips (33). However, in combination with telework, opportunities for teleshopping, telemedicine, and other forms of internet-enabled transactions make this solution one of the largest contributors to the technical scenario.

EVs. EVs are another attractive transportation solution. In 2020, EVs comprised less than 0.5% of Georgia's light-duty vehicle fleet. If EVs were to grow to 21% of new light-duty vehicle sales in 2030, reaching a 3.7% share of the cumulative fleet under our achievable scenario, Georgia's carbon emissions would drop by 1.4 megatons by 2030. Our analysis further suggests that emissions reductions from EVs would not maintain this same pace of reduction at greater penetration rates. In the technical scenario, the share of EVs in the cumulative fleet reaches 8.3% (a 125% increase in EVs compared to the achievable scenario), but CO_2 emissions are reduced by only 2.3 megatons in 2030. Our achievable scenario represents a kind of "Goldilocks" state for EV growth in Georgia, in that the deployment is aggressive enough to result in meaningful CO_2 reductions, but not so ambitious as to jeopardize decarbonization (e.g., force fossil fuels to be used to meet demand) or cost efficiency (e.g., require excessive/redundant infrastructure, or violate reserve capacity margins). (See *SI Appendix* for further details.) There are additional challenges associated with this transition to EVs, including the lack of affordability by resource-challenged consumers. Fortunately, there are several promising trends and tools underway to address this barrier, including steadily declining battery and EV prices, subsidies to help defray upfront investments, and programs geared specifically to low-income communities (44).

Building retrofits. Turning to the energy-consuming built environment, deep building retrofits offer sizeable potential energy savings at reasonable costs. The achievable scenario for retrofitting 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 increases to 13.7 megatons 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 technologies; 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 households (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 include programs such as utility financing via "Pay As You Save" and on-bill financing initiatives. There are also efforts that extend beyond financing and bill assistance to addressing root causes through, for example, correcting funding disparities between the federal Low-Income Home Energy Assistance Program, which supports short-term energy bill assistance; and the Weatherization Assistance Program, which funds more permanently 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 CO_2 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 wastage. 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 programs, improved refrigerated storage and capacity, standardized date labeling, and robust data analytics on food waste measurement 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 stored. 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 successful deployment of one solution magnifies the carbon reduction 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,

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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 macroeconomic 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 CO_2 intensity of grid electricity. Three relevant interactions have been modeled: the average reduction of grid CO_2 intensity from solar, the decrease of light-duty vehicle (LDV) CO_2 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**:

$$\mathbf{\Delta S = \Delta DC + \Delta E}, \qquad [1]$$

where $\mathbf{\Delta D}$ is increase in electricity demand from LDVs (in gigawatt hours) in the EV scenario, $\mathbf{\Delta E}$ is decrease in emissions from LDVs (in megatons) in the EV scenario, $\mathbf{C}$ is CO_2 intensity of the grid (megatons/gigawatt hour) assuming the achievable potential of large-scale solar, and $\mathbf{\Delta S}$ 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 CO_2 by an additional 14% (that is, 0.2 more megatons of CO_2 avoided). The modeling of this specific interaction is limited by our assumed use of average grid-CO_2 emissions. It should be noted that marginal CO_2 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 CO_2 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.

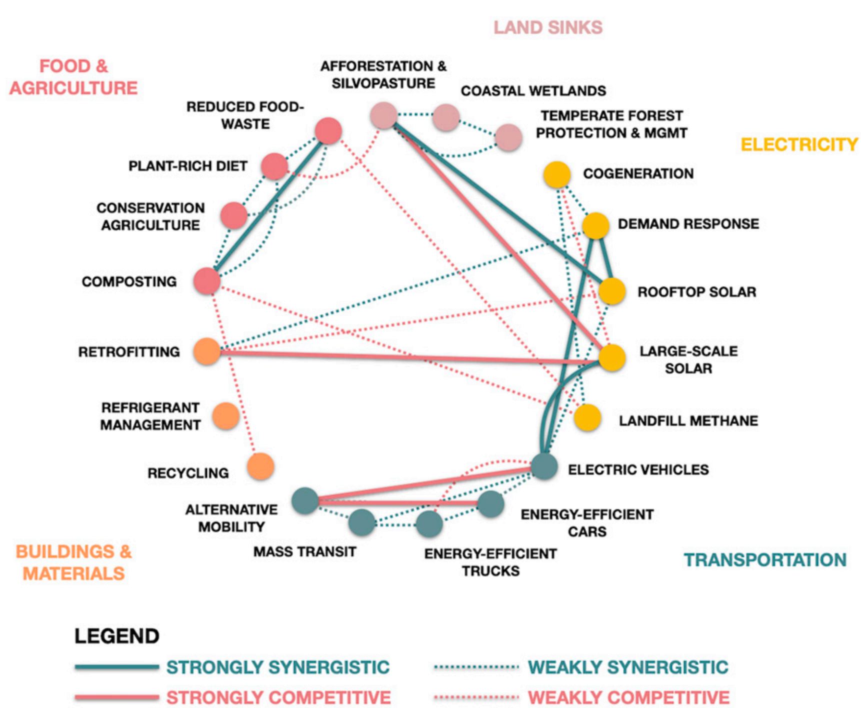

Fig. 4. Solution interactions.

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 CO_2. This model uses the ratio of CO_2 intensities to scale the known CO_2 reduction from retrofitting cases. This interaction was modeled using the following quantities and formula on MATLAB2. We conceptualize this relationship based on Eq. **2**:

$$\mathbf{\Delta S = \Delta EIsIb}, \qquad [2]$$

where $\mathbf{\Delta E}$ is emissions reduction from retrofitting cases, relative to baseline (megatons), **Ib** is baseline CO_2 intensity of grid power (megatons/gigawatt hour), **Is** is drawdown scenario CO_2 intensity of grid power (megatons/gigawatt hour), and $\mathbf{\Delta S}$ 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 CO_2 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 CO_2 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 CO_2. 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 over 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

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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 but realistic 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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1. United Nations Framework Convention on Climate Change, Paris Agreement Conference of the Parties Report No. 21, Addendum. FCCC /CP/2015/10/Add.1. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/FCCC_CP_2015_10_Add.1.pdf. Accessed 9 July 2021.
2. T. Hale, All hands on deck: The Paris Agreement and nonstate climate action. *Glob. Environ. Polit.* **16**, 12–22 (2016).
3. M. Roelfsema *et al*., Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat. Commun.* **11**, 2096 (2020).
4. European Commission, EU Climate Action and the European Green Deal (2021). https://ec.europa.eu/clima/policies/eu-climate-action_en. Accessed 5 April 2021.
5. R. Bromley-Trujillo, M. R. Holman, Climate change policymaking in the states: A view at 2020. *Publius* **50**, 446–472 (2020).
6. A. Hsu, N. Hohne, T. Kuramochi, V. Vilarino, B. Sovacool, Beyond states: Harnessing sub-national actors for the deep decarbonization of cities, regions, and businesses. *Energy Res. Soc. Sci.* **70**, 10.1016/j.erss.2020.101738 (2020).
7. A. Hsu *et al*., A research roadmap for quantifying non-state and subnational climate mitigation action. *Nat. Clim. Chang.* **9**, 11–17 (2019).
8. S. Chan *et al*., Reinvigorating international climate policy: A comprehensive framework for effective nonstate action. *Glob. Policy* **6**, 466–473 (2015).
9. N. Hultman *et al*., Fusing national and sub-national climate action is central to rapid near-term decarbonization: The case of the United States. *Nat. Commun.* **11**, 5255 (2020).
10. Center for Climate and Energy Solutions, State climate policy maps. https://www.c2es.org/content/state-climate-policy/. Accessed 17 December 2020.
11. R. Bromley-Trujillo, M. R. Holman, Climate change policymaking in the states: A view at 2020. *Publius* **50**, 446–472 (2020).
12. F. Alves *et al*., Climate change policies and agendas: Facing implementation challenges and guiding responses. *Environ. Sci. Policy* **104**, 190–198 (2020).
13. S. A. Markolf *et al*., Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earths Futur.* **18**, 1 (2018).
14. G. Skogstad, M. Wilder, Strangers at the gate: The role of multidimensional ideas, policy anomalies and institutional gatekeepers in biofuel policy developments in the USA and European Union. *Policy Sci.* **52**, 343–366 (2019).
15. P. Hawken, *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming* (Penguin Press, 2017).
16. R. H. Socolow, S. W. Pacala, A plan to keep carbon in check. *Sci. Am.* **295**, 50–57 (2006).
17. Interlaboratory Working Group, Scenarios for a clean energy future. https://www.nrel.gov/docs/fy01osti/29379.pdf. Accessed 9 July 2021.
18. United Nations Environment Program, Emissions gap report 2019. https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf?sequence=1&isAllowed=y. Accessed 9 July 2021.
19. McKinsey and Company, Climate math: What a 1.5-degree pathway would take. *McKinsey Quarterly*, **30** April 2020. https://www.mckinsey.com/business-functions/sustainability/our-insights/climate-math-what-a-1-point-5-degree-pathway-would-take. Accessed 9 July 2021.
20. C. Frischmann *et al*., "Drawdown's 'system of solutions' helps to achieve the SDGs" in *Partnerships for the Goals, Encyclopedia of the UN Sustainable Development Goals*, Leal Filho, Ed. (Springer Nature, 2020), pp. 1–25.
21. E. Ostrom, Polycentric systems for coping with collective action and global environmental change. *Glob. Environ. Change* **20**, 550–557 (2010).
22. M. A. Brown, B. K. Sovacool, *Climate Change And Global Energy Security: Technology and Policy Options* (MIT Press, Cambridge, MA, 2011).
23. M. Winskel, Beyond the disruption narrative: Varieties and ambiguities of energy system change. *Energy Res. Soc. Sci.* **37**, 232–237 (2018).
24. F. W. Geels, B. K. Sovacool, T. Schwanen, S. Sorrell, Sociotechnical transitions for deep decarbonization. *Science* **357**, 1242–1244 (2017).
25. S. Franceschini, F. Alkemade, Non-disruptive regime changes: The case of competing energy efficient lighting trajectories. *Environ. Innov. Soc. Transit.* **21**, 56–68 (2016).
26. F. Bowen, Carbon capture and storage as a corporate technology strategy challenge. *Energy Policy* **39**, 2256–2264 (2011).
27. W. C. Clark, A. G. Harley, Sustainability science: Towards a synthesis. *Annu. Rev. Environ. Resour.* **45**, 331–386 (2020).
28. A. J. Duff, P. H. Zedler, J. A. Barzen, D. L. Knuteson, The capacity-building stewardship model: Assessment of an agricultural network as a mechanism for improving regional agroecosystem sustainability. *Ecol. Soc.* **22**, 45 (2017).
29. H. M. Leslie *et al*., Operationalizing the social-ecological systems framework to assess sustainability. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 5979–5984 (2015).
30. US Department of Agriculture, *Georgia's Land: Its Use and Condition Fourth Edition* (Natural Resources Conservation Service, Athens, GA, 2016).
31. World Resources Institute, CAIT 2.0. Climate Analysis Indicators Tool: WRI's Climate Data Explorer (World Resources Institute, Washington, DC, 2014). https://www.wri.org/data/climate-watch-us-states-greenhouse-gas-emissions. Accessed 9 July 2021.
32. M. A. Brown *et al*., Translating a global emission-reduction framework for subnational climate action: A case study from the state of Georgia. *Environ. Manage.* **67**, 205–227 (2021).
33. S. Cowlin, J. C. Shannon, S. Cox, C. Davidson, W. van der Gaast, "Broadening the appeal of marginal abatement cost curves: Capturing both carbon mitigation and development benefits of clean energy technologies" (NREL/CP-6A20-54487, National Renewable Energy Laboratory, 2012).
34. X. Xu, C. Chen, Energy efficiency and energy justice for U.S. low-income households: An analysis of multifaceted challenges and potential. *Energy Policy* **128**, 763–774 (2019).
35. Google, Project Sunroof: Data explorer. https://www.google.com/get/sunroof. Accessed 9 July 2021.
36. A. Lopez, B. Roberts, D. Heimiller, N. Blair, G. Porro, "U.S. renewable energy technical potentials: A GIS-based analysis" (Report No. NREL/TP-6A20-51946; Contract No. DE-AC36-08GO28308; National Renewable Energy Laboratory, Golden, CO, 2012).
37. M. A. Brown, J. Hubbs, V. Gu, M.-K. Cha, Rooftop solar for all: Closing the gap between the technically possible and the achievable potentials. *Energy Res. Soc. Sci.*, in press.
38. M. A. Brown, Y. Li, A. Soni, Are all jobs created equal? Regional employment impacts of a US carbon tax. *Applied Energy* **262**, 114354 (2020).

39. The Solar Foundation, National solar jobs report. https://www.thesolarfoundation.org/national/. Accessed 2 June 2020.
40. L. Shaver, R. Shea, Solarize campaigns: Helping communities of color access rooftop solar. https://rmi.org/solarize-campaigns-helping-communities-of-color-access-rooftop-solar/. Accessed 9 July 2021.
41. D. A. Sunter, S. Castellanos, D. M. Kammen, Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nat. Sustain.* **2**, 71–76 (2019).
42. Bureau of Transportation Statistics, National household travel survey daily travel quick facts. https://www.bts.gov/statistical-products/surveys/national-household-travel-survey-daily-travel-quick-facts. Accessed 9 December 2020.
43. E. Brynjolfsson, J. J. Horton, A. Ozimek, D. Rock, G. Sharma, H. Y. TuYe, "COVID-19 and remote work: An early look at US data" (No. w27344, National Bureau of Economic Research, 2020).
44. A. Song, K. Cline, L. Lyshall, "Facilitating low-income utilization of electric vehicles: A feasibility study" (Washington State Department of Transportation, Innovative Partnerships Office, 2018). https://wsdot.wa.gov/publications/fulltext/LegReports//17-19/FacilitatingLowIncomeUtilizationOfElectricVehicles.pdf. Accessed 9 July 2021.
45. E. Johnson *et al*., Peak shifting and cross-class subsidization: The impacts of solar PV on changes in electricity costs. *Energy Policy* **106**, 436–444 (2017).
46. R. Cluett, J. Amann, O. Sodavy, "Building better energy efficiency programs for low-income households" (Report No. A1601, American Council for an Energy-Efficient Economy, 2016). http://www.southeastsdn.org/wp-content/uploads/2016/11/Building-Better-Efficiency-Programs-for-Low-Income-Households.pdf. Accessed 9 July 2021.
47. M. A. Brown, A. Soni, M. V. Lapsa, K. A. Southworth, M. Cox, High energy burden and low-income energy affordability: Conclusions from a literature review. *Progress in Energy* **2**, 10.1088/2516-1083/abb954 (2020).
48. J. Lewis, D. Hernández, A. T. Geronimus, Energy efficiency as energy justice: Addressing racial inequities through investments in people and places. *Energy Effic.* **13**, 419–432 (2019).
49. Food and Agriculture Organization of the United Nations, Global food losses and food waste: Extent, causes, and prevention. http://www.fao.org/fileadmin/user_upload/ags/publications/GFL_web.pdf. Accessed 9 July 2021.
50. J. C. Buzby, H. F. Wells, J. Hyman, "The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States" (EIB-121, US Department of Agriculture, Economic Research Service, 2014).
51. ReFed, A roadmap to reduce US food waste by 20 percent. https://www.refed.com/downloads/ReFED_Report_2016.pdf. Accessed 9 July 2021.
52. W. H. Schlesinger, E. S. Bernhardt, "The global cycles of carbon and oxygen" in *Biogeochemistry: An Analysis of Global Change* (Academic, London, UK, ed. 4, 2020), chap. 11, pp. 1297–1399.
53. P. V. Bolstad, W. T. Swank, Cumulative impacts of land use on water quality in a southern Appalachian watershed. *J. Am. Water Resour. Assoc.* **33**, 519–533 (1997).
54. P. Baas, J. D. Knoepp, D. Markewitz, J. E. Mohan, Areas of residential development in the southern Appalachian mountains are characterized by low riparian zone nitrogen cycling and no increase in soil greenhouse gas emissions. *Biogeochemistry* **133**, 10.1007/s10533-017-0318-9 (2017).
55. V. Viguié, S. Hallegatte, Trade-offs and synergies in urban climate policies. *Nat. Clim. Chang.* **2**, 334–337 (2012).
56. A. Sharifi, Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *Sci. Total Environ.* **750**, 141642 (2021).
57. H. B. Dulal, Making cities resilient to climate change: Identifying "win–win" interventions. *Local Environ.* **22**, 106–125 (2017).
58. Q. Hoarau, Y. Perez, Interactions between electric mobility and photovoltaic generation: A review. *Renew. Sustain. Energy Rev.* **94**, 510–522 (2018).
59. K. C. Binita, J. M. Shepherd, C. Johnson, Climate change vulnerability assessment in Georgia. *Appl. Geogr.*, 10.1016/j.apgeog.2015.04.007 (2015).
60. US Global Change Research Program, *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* (US Global Change Research Program, Washington, DC, 2018), Volume II.

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