Quantifying the Socio-Economic Impacts of Decarbonization Policy using Integrated Assessment Modeling

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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***Abstract*—With net-zero emission goals by 2050 becoming the standard in climate policy initiatives at regional, national, and international scales, policymakers and business leaders are left with the questions of how to implement change. Achieving these emission goals requires quantitative tools for understanding how potential policies impact net emissions and existing economic and industrial systems. Computable general equilibrium (CGE) models are often used as a tool for analyzing the response of an economy to policy, technology, or other shocks, but CGE models are not capable of techno-economic modeling of the renewable energy and carbon dioxide removal technologies that will need to be deployed to achieve warming limits. Integrated models, in contrast, such as the Global Change Analysis Model (GCAM) are able to simulate emerging technologies but lack the resolution and regional fidelity of CGE models. In this study CGE and GCAM are soft linked to analyze the effect of implementing high, low, and zero carbon taxes on the electricity generation technologies and labor demand for these technologies by 2060. We find that the implementation of a carbon tax results in significant growth in labor and investment in the electricity sector, with a large proportion of this growth in the wind and solar industries.**

I. INTRODUCTION

Efforts to decarbonize the economy are critical to limit climate change. However, these plans will require large scale shifts in the economy on the order of $11-$21 trillion through 2050 in order to build out renewable energy capacity, electrify our transportation sector, and decarbonize industrial sectors such as ammonia, cement, plastics and steel [1]. Institutions want to decarbonize, but this is a big and complex challenge. Modeling can inform institutions of the optimal way to reach decarbonization goals. Many models exist to achieve this, each with different strengths. We use GCAM and CGE modeling in this study.

The Global Change Analysis Model (GCAM) is a widely used IAM that simulates the interactions between the economy, energy systems, land use, and the climate system. GCAM is designed to evaluate the potential impacts of policies and technologies related to climate change mitigation and adaptation, energy systems, land use, water resources, and air quality [2]. A CGE model provides a more detailed representation of the economy by disaggregating economic sectors, and the impacts of a specific policy shock are analyzed by comparing the state of the economy before and after the policy shock [3]. We built upon an existing CGE model originally created for the Chinese economy and adjusted it to US data. We then created a soft linkage between the CGE results and GCAM to investigate how the implementation of a carbon tax affects the US economy, particularly the energy sector. The electricity sector is the largest contributor to greenhouse gas emissions in the United States. To combat climate change, policymakers have proposed implementing a carbon tax as a means of reducing emissions. GCAM and CGE modeling are both widely used tools for analyzing the potential impacts of climate policies on the electricity generation sector. The following section highlights existing literature in both modeling fields.

II. LITERATURE REVIEW

Computable general equilibrium (CGE) models analyze the behavioral response of different agents using economic data, so the use of such a model for informing policy making in the realm of renewable energy is not novel. For example, Mu et al. [4] inform Chinese policymakers by analyzing the response of the labor market to the introduction of renewable energy policies. Using the China Hybrid Energy and Economic Research (CHEER) model, which is the basis for the model used in this project, Mu and co-authors explore the employment impacts from renewable energy policies in China. They established a CGE-based method to analyze the employment impacts of renewable energy – decomposed into direct, indirect, and induced impacts and discovered that most jobs are created in the construction, installation, and manufacturing stage. Our work mainly differs in scope and granularity of results. As opposed to analyzing renewable energy policies and their impact on employment we focus on carbon taxes and their impact on multiple sectors, across different variables, including household consumption and demand for labor and capital, between different geographical regions.

Using the same model as Mu et al. [4], Huang et al. [5] analyze the impacts of low carbon policies across different types of employment as well as on income migration between urban and rural areas. By comparing a traditional energy scenario (i.e., business as usual) to a low carbon development scenario, Huang et al. [5] find that the labor movement in energy-related industries from the traditional energy sectors to the renewable energy sectors ultimately lead to a decrease in the income gap between rural and urban residents, but an eventual increase in the income gap among urban residents. Our work differs in that Huang et al. create low carbon scenarios by combining two low-carbon policies: transformation of the power industry and the introduction of carbon cost via the purchase of carbon credits, while our scenarios are different carbon tax levels.

Existing literature, including the work done by Mu et al. [4] and Huang et al. [5], similarly establish datasets from CGE models in the sustainability scope, but both pertain to China and neither explore the impacts of different carbon tax scenarios as we have done for the United States. Additionally, our work is novel in that little to no literature exists on the linkage between GCAM and CGE results to investigate techno-socio-economic aspects of carbon mitigation as we have done.

As with CGE modeling, GCAM has been widely used in studies to inform policy in the realm of sustainability and renewable energy sources. Many of these studies focus on the implementation of a carbon tax (and/or carbon price) and its impacts in the energy sector, just as we have done. Jeon et al. [6] used GCAM-Korea to derive sectoral and provincial implications from power sector scenarios in Korea. The study analyzes the impacts of four power sector scenarios on the Korean economy and environment. The results show that the carbon tax scenario and renewable portfolio standard scenario can effectively reduce CO2 emissions. In the United States, another study using GCAM conducted by Wilkerson et al. [7] found that a carbon price of around $25 to $30 per ton of CO2 would be sufficient to achieve a 17% reduction in greenhouse gas emissions by 2020 compared to 2005 levels.

Both of these studies suggest that a carbon tax can effectively reduce CO2 emissions from the electricity sector in the United States. Combining a carbon tax with other policies can lead to even greater emissions reductions. While a carbon tax may have economic costs, policies such as output-based rebates can help to mitigate these costs. Both GCAM and CGE modeling are valuable tools for policymakers and researchers to evaluate the potential impacts of climate policies on the electricity generation sector. We leverage both models to analyze the effect of implementing high, low, and zero carbon taxes on the electricity generation technologies and labor demand for the technologies by 2060.

III. METHODS

The model we developed throughout the course of this project is a dynamic energy-economy- climate CGE model of the United States that allows us to analyze the economic effects of implementing a carbon tax. The original structure was developed by students at Tsinghua University in Beijing [8]. We modified certain input parameters to reflect the differences between the Chinese and US economies. These input parameters include a social accounting matrix (SAM), population trends, and GDP growth. The SAM was constructed using data from the Global Trade Analysis Project (GTAP) version 11 database, population trends from the United Nations' Department of Economic and Social Affairs, and projected GDP growth from the shared socioeconomic pathways (SSPs). Emissions factors and substitution elasticities were contributed by our colleagues at Tsinghua[1]. Using this data, we explored the effects of three decarbonization scenarios, which were defined as follows: business as usual (no carbon tax), the introduction of a low ($17/ton CO2e) carbon tax, and high ($130/ton CO2e) carbon tax in the United States starting in the year 2025. These specific dollar amounts were chosen based on the range in price of existing carbon taxes in other countries, which, if present, ranged anywhere from ¡$1 to $137/ton CO2e. Under these three scenarios, we analyze changes in the following areas: household consumption, employment, and investment.

A. GCAM Modeling

The GCAM model includes a representation of the global energy system, including the electricity sector. The electricity sector in GCAM is divided into multiple sub-sectors, each representing a different aspect of the sector. These sub-sectors are:

Electricity generation: This sub-sector includes all technologies and fuels used to produce electricity. It includes both conventional and renewable technologies, such as coal-fired power plants, natural gas-fired power plants, nuclear power plants, wind turbines, solar photovoltaic panels, and others.

Electricity transmission and distribution: This sub-sector represents the infrastructure used to transport electricity from the point of generation to the point of consumption. It includes transmission lines, transformers, and distribution networks.

Electricity end-use: This sub-sector includes all the different ways in which electricity is used, such as lighting, heating, cooling, and other appliances.

The electricity generation technologies defined in GCAM are divided into three categories: conventional thermal, nuclear, and renewable. The conventional thermal category includes coal-fired, natural gas-fired, and oil-fired power plants. The nuclear category includes both light water reactors and advanced reactors. The renewable category includes wind, solar, hydro, geothermal, and biomass technologies.

GCAM also includes a detailed representation of the costs and performance of each technology, which allows the model to simulate the deployment and use of each technology under different scenarios and policy conditions. Additionally, GCAM allows for the implementation of various policies related to the electricity sector, such as carbon pricing, renewable energy standards, and technology-specific subsidies.

To model the US electricity generation system by 2060, GCAM considers different types of electricity generation technologies, including fossil fuels, nuclear power, and renewable energy sources. The model also considers different types of

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[1] Because of time limitations, the elasticities and emission factors used here are the same as those defined in the model of the Chinese economy. Although these are not specific to the United States, these values will not alter the trends observed in our experiments but may affect the magnitudes slightly when they are adjusted at a later time.

electricity generation plants, including baseload, intermediate, and peaking plants, as well as different types of electricity storage technologies. More detailed information about the US electricity generation system is provided in the GCAM documentation [2].

To simulate the impacts of a carbon tax on the electricity generation sector, a constant price on carbon emissions over time is set in the GCAM model. This carbon price is implemented as a tax on carbon dioxide emissions from fossil fuel combustion and industrial processes. The revenue from the carbon tax can be used to reduce other taxes, to fund renewable energy and energy efficiency programs, or to provide rebates to households and businesses.

The model evaluates different carbon tax rates (0, 17, and 130 $/tCO2e) to assess the impacts on the electricity generation sector over time. To evaluate the impacts of a carbon tax on the electricity generation sector, GCAM considers a range of economic and technological factors, including the costs and availability of different energy sources and technologies, the competitiveness of different electricity generation technologies, and the demand for electricity across different sectors of the economy. The model also considers the impacts of the carbon tax on greenhouse gas emissions, air pollution, and public health, as well as on economic growth and employment.

In this study, GCAM and our CGE model are linked by combining the ratio of electricity generation by technology from GCAM outputs with monetary labor demand for the electricity sector which is one of the CGE outputs. Evaluating the impacts of carbon taxes on the electricity generation sector in the United States is provided using GCAM. By considering the policy options, the linked CGE-GCAM model can provide valuable insights in terms of labor demand specified by the electricity generation subsector for policymakers and stakeholders as they work to address climate change and transition to a low carbon economy.

B. Data Acquisition

The social accounting matrix (SAM) is the primary data source used to calibrate the CGE model to the US economy. The SAM is a square matrix that possesses input/output accounts by sector of an economy as well as national and external accounts representing value added sectors (labor and capital), and factor payments. The original data included 72 production sectors, which were pulled from the GTAP version 11 database. These sectors were then further aggregated into 42 sectors. Five factors of production were consolidated into two: labor (combining unskilled and skilled labor), and capital (combining capital, land, and natural resources).

The household component of the SAM was broken out into two groups to represent rural and urban consumers. The choice to disaggregate into rural and urban consumers in the United States was made to build on current efforts of regional modeling. In the future, this could be expanded to account for differences in US states, regions, etc., given the correct data. The disaggregation process drew on demographic and consumption data from the Consumer Expenditure Surveys conducted by the Bureau of Labor Statistics in 2019 [9]. This data provides mean annual expenditures per consumer unit classified by type of area: urban and rural. It further provides mean incomes for the country (rural and urban split) by a factor of production (i.e., labor and capital), which are used to split household income into rural and urban within the SAM. The Consumer Expenditure Surveys provided data for 25 sectors; for the remaining 17 we applied ratios from similar sectors to split consumption. The ‘rest of world’ (ROW) account was then used to balance any residuals. This process of aggregating production sectors and disaggregating household expenditures resulted in a 50x50 SAM. Finally, some slight adjustments were made in terms of accounting choice. Rather than taxes on value added sectors, this sum is accounted for as a payment from households to the government.

In addition to the SAM, GDP and population growth trends were used for further calibration to the US economy. GDP growth trends were taken from the shared socioeconomic pathways (SSPs), which are five scenarios developed by the climate change research community that outline different narratives of global socioeconomic development [10]. The GDP growth rates used in this model are the annual average GDP per capita growth rates for high income countries [11]. Population growth trends were sourced from the Population Division of the United Nations Department of Economic and Social Affairs [12]. These growth rates are assumed to be the same for both rural and urban areas in the US. Finally, the remaining data used in this model (substitution elasticities, emissions factors and trends, and total factor productivity growth) are from the original model calibrated to the Chinese economy.

C. Model Structure

The data described in the previous section are used to calibrate the model, which consists of four main components: production, consumers, commodity markets, and factor markets. The production bundle includes functions that describe inputs and outputs resulting from production activities, including: intermediate inputs from the 42 commodity sectors, energy, capital, and labor. In the consumer bundle, consumers are represented by households (both urban and rural) and the government. These consumers invest in factor markets, which include labor, energy, and capital, using the income received from taxes and wages. Household income is also allocated to goods and services in sectors at a rate defined by the social accounting matrix.

Given what constitutes each component of the model, the flows are defined as follows: producers invest in intermediate inputs and production factors (energy, capital, labor), which are used to provide goods and services to consumers (households and government) through commodity markets. Taxes from these activities are paid as income back to consumers, and wages earned through labor are paid to households. Consumers invest in factors of production and provide labor, and ultimately determine the total level of consumption of goods and services by adhering to budgetary constraints. Prices adjust such that the market for all factors and commodities is in equilibrium, where supply is equal to demand. This model structure is derived from Huang et al. [5].

D. *Analysis Procedure*

We analyze the effects of decarbonization scenarios on household consumption and demand for labor and capital. Labor and capital demand are related in regards to energy sectors and are linked with results obtained from GCAM. Decarbonization scenarios in this study are defined as the value of a carbon tax implemented in the United State: none ($0), low ($17/tCO2e), and high ($130/tCO2e). Within our model, the low and high carbon tax begin in the year 2025. Due to project constraints, we focus on a pre- and post-tax view of the results rather than a yearly view. This before-and-after framework provides insights into overall trends set by our decarbonization scenarios, which are more reliable than true values on a time axis given the information/time limitations.

The model outputs values for the variables of interest by year and scenario. We used multiple pivot tables to extract information relevant to consumption, labor demand, and capital demand for the years 2020 and 2030 (before and after a tax is implemented). For household consumption, the total value (in million USD) was calculated across all sectors and tax scenarios for the years 2020 and 2030 for urban and rural households. This data was then normalized across each sector, allowing us to identify the impact of the presence of a tax in two areas by comparing the difference in consumption between no tax and a low tax (which we describe as 'generally reactive'), and then a low tax and high tax (which we describe as 'price sensitive'). Within each of these categories, we compared the sectors that experienced the most and least change in terms of consumption for both urban and rural households (Table I).

Labor demand was analyzed by looking at the percentage change in energy sectors (electricity, natural gas, coal, and petroleum), so that the results of our model could be compared with those of the Chinese economy described in this paper [5]. Electricity is the sole non-fossil energy sector represented in our CGE model. To understand where emerging renewable technologies may be represented in electricity generation, our findings were linked to GCAM results to understand how electricity may be broken out between various renewable energy sectors, including, wind, solar, and others. Analysis on changes in investment (capital demand) is included to support our findings in terms of labor.

IV. RESULTS

A. *Household consumption*

Table I compares which sectors exhibited the most and least change as a result of different carbon tax prices across rural and urban households. The direction of change across all sectors is a decrease in household consumption. In both rural and urban households, consumers do not change their consumption of health services and insurance in a significant way – an intuitive result that builds credibility in our model's results. More compelling analyses can be done on sectors that differ from their rural or urban counterparts.

TABLE I
CARBON TAX EFFECTS (DECREASES) ON SECTOR HOUSEHOLD CONSUMPTION

Sector Designation		Rural Households	Urban Households
Generally Reactive	Least	Health	Health
	Most	Electricity	Water & air Transport
Price Sensitive	Least	Insurance	Health
	Most	Transportation Services[a]	Other transport

[a] Includes all types of transportation, including water & air.

The extreme decline in rural household consumption in the Transportation Services sector but not in urban household consumption when the price of a carbon tax is raised indicates rural areas do not change their consumption of transportation services until the tax is higher. This result is corroborated by the lack of substitutes for transportation services available in rural US households compared to urban US households.

Rural household consumption of electricity is similarly more sensitive to change than urban consumption of electricity but is so with the introduction of a carbon tax – even a small one – rather than increasing the price point. This implies rural households are more sensitive to a rise in price. The introduction of a carbon tax would drive up the price of electricity coming from coal-powered plants. The economy was not previously accounting for carbon emissions when determining the cost of electricity, but when accounting for them, the price of electricity increases.

Consumption in urban households in sectors related to transport (water & air transport and non-water & air transport) decreases the most across both tax pricing scenarios. This seems an intuitive result given how petroleum intensive these sectors are. However, we would like to note a limitation of this model in that it does not account for the substitutability that comes from exogenous factors such as new technology. Given that change in consumption would be where substitutability is the highest, the next iteration of the model may seek to account for such factors and in turn, more accurately predict sectoral responses to a carbon tax.

B. *Electricity generation in GCAM*

GCAM allows us to better understand what renewable technologies may emerge under each carbon taxation scenario, by including electricity generation subsectors not present within the CGE model. Results from GCAM under each tax scenario are shown in Figures 1-3.

Without a carbon tax, six renewable electricity generation technologies in the subsectors of biomass, coal, gas, and refined liquids will not phase in, due to the cost of the carbon capture and storage (CCS) process. CCS is an expensive process that requires financial support to be implemented in larger scales; this financial support could come from revenues on a carbon tax should one be implemented. With a tax on carbon, the largest negative impact is in the coal power

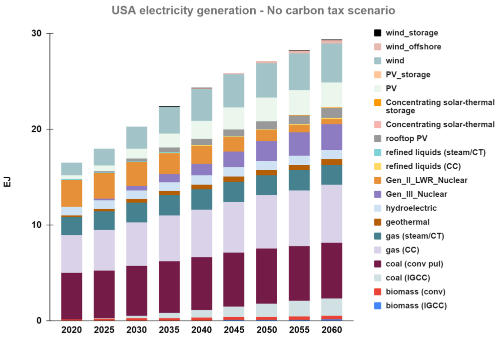

Fig. 1. US electricity generation without a carbon tax, 2020-2060.

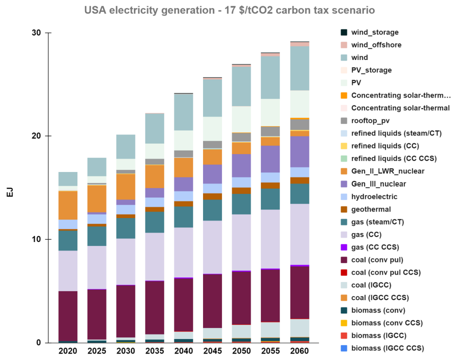

Fig. 2. US electricity generation with a 17 $/tCO2e carbon tax, 2020-2060.

generation subsector. Wind and solar power generation have significant growth from 2020 to 2060 under both a low and high tax scenario. A 17 $/tCO2e tax results in wind power for electricity doubling (a 222.04% increase) and solar power generation growing over six times its value in 2020 (a 621.56% increase). A high tax yields similarly significant growth in these sectors: an increase of 160.32% in wind and 677.44% in solar.

C. Labor demand

The implementation of a carbon tax results in significant decreases in labor demand in fossil fuel energy sectors, and a significant increase in labor demand in the electricity sector. However, even with the growth in the electricity sector, a tax on carbon results in a net decrease in employment in the energy sector as a whole. Compared with the demand in 2020 (prior to any tax being implemented), coal experiences the largest reduction: 85.02% under a low tax scenario and 97.53% under a high tax scenario. Natural gas and refined petroleum experience reductions of 29.65% and 14.37% under a low carbon tax, and 59.79% and 30.90% under a high carbon tax. As the only non-fossil fuel energy source included in this model, labor growth related to energy is concentrated in the electricity sector. Given a low tax, labor demand for the electric sector increases by 21.75% and 45.25% under a high tax. In a baseline scenario with no carbon tax introduced, each of these four energy sectors experiences moderate positive growth: 6.17% (natural gas), 2.36% (petroleum), 6.21% (coal), and 5.95% (electricity). These changes can be observed in Fig. 4.

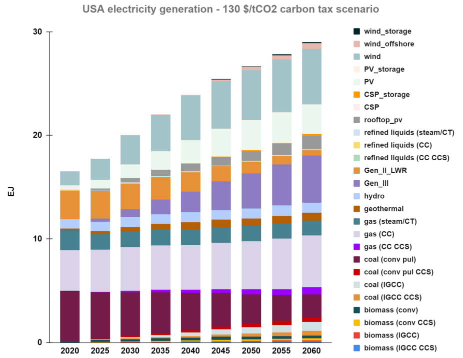

Fig. 3. US electricity generation with a 130 $/tCO2e carbon tax, 2020-2060.

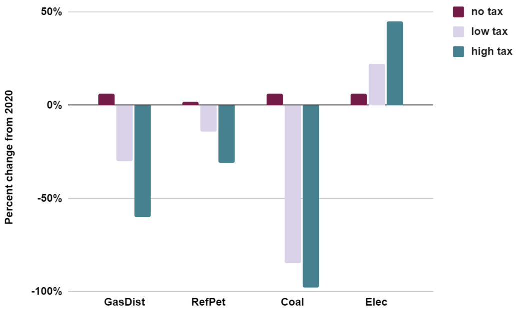

Fig. 4. Labor demand changes in US energy sectors under carbon tax scenarios.

The changes in labor demand above can be compared with other CGE models, specifically, the study done by Huang et al. on the income gap in the Chinese economy [5]. Under a low carbon development scenario, labor demand in the coal sector decreases by 92.96% and 52.37% in the petroleum sector. While the results in these two fossil fuel sectors are comparable with those highlighted in Fig. 4, Huang et al. find that the natural gas sector experiences 86.6% growth with the implementation of a low-carbon policy. The reason for this disparity between the two models is that the US has already substituted natural gas for coal; the US is a larger producer of natural gas than China. This explains why the findings of Huang et al. show growth in the natural gas sector while our model shows a decline. Further, in their model, natural gas is broken out along with renewables (wind, solar, and nuclear), so gas grows along with these in the lower-carbon scenario. In our model, the growth of renewables is reflected in the electricity sector. Growth in the electricity sector as a result of a carbon tax being implemented has implications on the level of investment as well. The introduction of a [high] carbon tax requires a considerable amount of capital investment in the electricity sector. When a tax of $130/tCO2e is implemented,

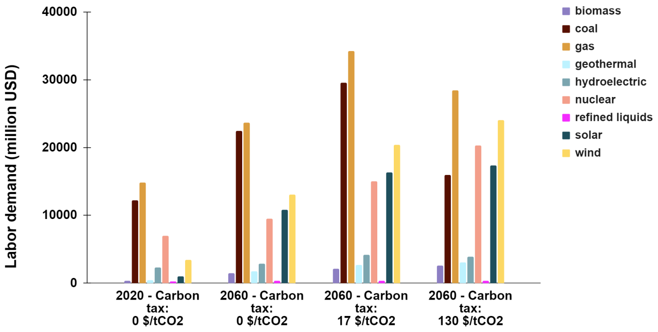

Fig. 5. Changes in US labor demand per electricity generation subsector, 2020-2060.

capital demand in the electricity sector grows 16.58% from 2020 to 2030.

D. Labor demand under CGE-GCAM linkage

Using the results obtained from the CGE and GCAM models separately with respect to labor demand and electricity generation technologies, we connect the two to understand how the total growth in the electricity sector (Fig. 4) can be attributed to different renewable technologies. Fig. 5 shows the changes in labor demand per electricity subsector.

We find that in order for labor demand in the coal and gas subsectors to decrease, a carbon tax priced at $130/tCO2e must be set. Coal's resistance is especially interesting when comparing the results in the previous section, which show that coal will experience the largest decrease in power generation. While labor demand for both refined liquids and biomass subsectors remain relatively unchanged across different tax scenarios, nuclear experiences increasing growth with a higher tax on carbon. Additionally, wind experiences higher growth compared to solar when the tax is increased from 17 to 130 $/tCO2e.

V. CONCLUSION

This study investigates the technological, economic, and social aspects of carbon mitigation through the implementation of a carbon tax in the United States by soft linking GCAM and CGE modeling. Our general finding is that the implementation of a carbon tax will result in new investment and employment in the electricity sector, whereas fossil fuel energy sectors will experience a reduction in these areas. Household consumption of transportation related sectors in both rural and urban households will be negatively impacted unless policy and/or new technology is introduced to change the substitutability of these goods and services towards their renewable counterparts. Additional research may be explored using this coupled modeling approach and data. Further, the establishment of the US SAM may serve as the basis for other modeling and explorations and CGE may be linked with GCAM in additional ways.

Our research serves as an important step towards improving modeling capabilities to analyze implications of decarbonization pathways at the regional level using linkage between CGE and GCAM modeling. In the future, we would like to investigate further policy implementations related to carbon taxation. Our (CGE) model returns revenue created from the carbon tax back to households, but to support the development of renewables an alternative policy would be to invest this revenue into new renewable technology, which would also improve the substitutability of renewable and non-renewable energy related goods and services. Another future direction of this work lies in the data: the SAM may be manipulated to represent smaller regions of the United States, and also adjusted to include emerging sustainable technologies such as carbon dioxide removal (CDR).

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