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&
OFFICE OF MANAGEMENT AND BUDGET

Methodologies and Considerations for Integrating the Physical and Transition Risks of Climate Change into Macroeconomic Forecasting for the President's Budget

March 13, 2023

SUMMARY

The changing climate, and the rapid transformation of energy systems—including electricity generation, as well as energy used in buildings, transportation, and industrial uses—required to mitigate climate change, will have widespread and long-lasting economic effects. These present risks and opportunities for the U.S. economy, financial system, and fiscal position, particularly if these effects are unexpected and not integrated into institutional planning. In May 2021, the Executive Order (EO) on Climate-Related Financial Risk (EO 14030) directed agencies across the Federal government to begin addressing these risks. Climate change—and the energy-system transition required to address it—present a number of risks relevant to the President's Budget, including effects operating via impacts to future GDP growth and other economic outcomes. Under Section 6(a) of the EO, the Council of Economic Advisers (CEA), Office of Management and Budget (OMB), and an Inter-Agency Technical Working Group (ITWG) have been working to develop methodologies to assess these risks and integrate them into the macroeconomic forecast of the President's Budget. This White Paper describes how physical climate risks have been assessed for the Long-Term Budget Outlook for Fiscal Year 2024 and considerations for more fully integrating climate risks into future Budget forecasts. This integration will require a triangulation that accounts for 1) requirements and constraints of the current macroeconomic forecasting performed by Treasury, CEA, and OMB; 2) the ways in which climate change and the energy transition could affect macroeconomic outcomes; and 3) the ability of existing climate–energy–economy models to capture these effects. The second part of this paper describes these three considerations in more detail and develops a two-track plan to quantify the macroeconomic risks of climate change in future Budgets.

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1. Introduction

The intensifying impacts of climate change create challenges for the environment, public health, and the economy. President Biden set an ambitious target for the United States to achieve a 50-52 percent reduction in annual greenhouse gas emissions[1] from 2005 levels by 2030, and is mobilizing a whole-of-government approach to climate action, capitalizing on major legislative achievements, through policies in the 2024 fiscal year budget that hasten and smooth the transition to a net-zero economy.

As part of this effort, President Biden signed an executive order on Climate-Related Financial Risk (EO 14030) that directed work across the Federal Government to quantify, disclose, and mitigate climate-related financial risks. Climate change presents many economic, financial, and fiscal risks across the United States. Prudent, forward-looking planning requires that we understand, quantify, and accurately price these risks. Recognizing that climate risks have implications for the fiscal position of the United States, Section 6(a) of EO 14030 establishes an objective to "identify the primary sources of Federal climate-related financial risk exposure and develop methodologies to quantify climate risk within the economic assumptions and the long-term budget projections of the President's Budget."

The Council of Economic Advisers (CEA), Office of Management and Budget (OMB), and an Inter-Agency Technical Working Group (ITWG) are working together to pursue this objective. A year ago, the FY 2023 Budget presented a long-term fiscal outlook under a climate-risk scenario with a high-emissions, high-risk estimate of physical climate change damages (OMB 2022a).[2] An accompanying White Paper reviewed research on the relationship between climate risks and the macroeconomy and identified relevant resources across the Federal government that could be deployed to quantify the climate change risks relevant to the economic assumptions (CEA and OMB 2022).

Climate-related financial risks relevant to the macroeconomic projections in the President's Budget are composed of two types (Carney 2015): physical risks associated with the effects of climate change on economic outcomes (for instance, capital destruction in extreme events or reduced labor, capital, or land productivity in hotter temperatures) and transition risks associated with the transition to a zero-carbon economy (for example, the costs of mitigation policy or sudden changes in the valuation of assets, such as energy infrastructure with accelerated depreciation).[3] Both have economic implications for important macroeconomic variables related to labor, trade, capital services, and productivity.

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[1] Greenhouse gases covered by the U.S. net-zero commitment are carbon dioxide, methane, hydrofluorocabons, perfluoro chemicals, sulfur hexaflouride, nitrous oxide, and nitrogen trifluoride (White House 2021).

[2] Specifically, this analysis projected physical climate damages under a very high emissions trajectory (RCP 8.5) and assumed economic damages to be at the 95th percentile of those projected for the U.S. by Kalkuhl and Wenz (2020).

[3] For example, EO 14030 describes how "the global shift away from carbon-intensive energy sources and industrial processes presents transition risk to many companies, communities, and workers."

Acknowledging these risks, a wide range of institutions—including the IMF (IMF 2022), World Bank (Burns et al. 2021), central banks (NGFS 2022b), and Moody's (Licari et al. 2021)—are working to integrate explicit consideration of these effects into macroeconomic projections. In fact, since 2019, the Congressional Budget Office has integrated estimates of costs from changing temperature, rainfall and hurricane patterns into its baseline macroeconomic forecast (CBO 2020, 2021). As part of the Coalition of Finance Ministers for Climate Action, over 80 finance ministries from around the world, including the United States are working to, among other things, develop tools to support the assessment of the macroeconomic effects of climate change impacts as well as adaptation and mitigation policies (CFMCA n.d.). This range of ongoing work reflects the widespread recognition that climate change and the policy responses to it will shape economic growth pathways over the near-, medium-, and long-term.

Macroeconomic climate risks are relevant to the Federal fiscal position because government revenues and spending depend on macroeconomic conditions. CEA, OMB, and the Treasury lead a process to produce the economic assumptions that underlie the President's Budget, producing 10-year projections of important economic variables such as GDP growth, interest rates, and employment. These economic assumptions play a critical role in the Budget-making process, as they ensure that all agencies rely on the same macroeconomic forecast when projecting programs' receipts and outlays over the 10-year Budget window. OMB extends these economic assumptions an additional 15 years for the Long-Term Budget Outlook (LTBO) to assess various risks to the United States' long-term fiscal position. Although relevant to the economic trajectory over the next 25 years, climate risks are not currently explicitly integrated into these economic assumptions.

This White Paper outlines methodologies and considerations for integrating climate risks into the U.S. Government's forecasts of macroeconomic conditions. Currently, the Long-Term Budget Outlook captures the fiscal effects of climate change by accounting for estimates of how climate damages affect longer-run GDP growth and how these changes in GDP growth, in turn, affect estimates of Federal revenues and spending. Importantly, climate risks could have a number of other more specific and directed effects on the Federal Budget, for instance through spending required to respond to climate change impacts or via differentiated effects on specific tax revenues,[4] which are outside the scope of this work on macroeconomic channels. Efforts to quantify the direct implications of climate change for Federal spending via specific programs in a bottom-up manner is proceeding under Sections 6(b) and 6(c) of EO 14030 (OMB 2022b).

While linking climate risks to macroeconomic variables like GDP growth is useful for projections of Federal revenues and spending, there are nonetheless important limitations of a focus on GDP. By design, GDP measures the market value of transactions across the economy; it is not a measure of well-being or wealth and, in particular, excludes many of the most serious impacts of climate change, including some forms of damage to ecosystems and human health. While GDP is a valuable metric for economic forecasting and budgeting applications, estimates of the effect of climate change on GDP are limited in nature and are not appropriate for some applications, such

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[4] The transition to electric vehicles, for example, will have particular implications for revenue from the Federal gas tax while increases in severe flooding will have implications for expenditures on real Federal property.

as benefit-cost analysis. The Biden-Harris Administration recently released a 15-year strategy for developing a set of environmental-economic statistics that would allow the United States to better track changes in natural assets, addressing some of the short-comings of GDP as an economic indicator (White House 2023). Notably, addressing the impacts of climate change will also have several substantial non-market benefits that are not measured through economic parameters, including benefitting human health globally, reducing the risk of conflict and migration, and ensuring the viability of ecosystems.

This paper proceeds by first describing the assessment of physical climate change costs to U.S. macroeconomic growth included in the FY 2024 long-term budget outlook. The second section of this paper then lays out considerations for more fully quantifying climate-related macroeconomic risks for future budgets. This requires a modeling framework that is able to provide input into the U.S. Government process for developing the macroeconomic forecast and capture the main pathways by which climate change and the energy-transition affect the macroeconomy over the 10- and 25-year timeframes of the budget forecast. This section of the paper describes these requirements, develops criteria for a modeling framework able to credibly provide climate risks as an input into the economic assumptions of the President's Budget, and evaluates alternative models with respect to these criteria. Lastly, the paper concludes by outlining next steps, in light of the model assessment.

A. Physical Climate Risks in the FY 2024 Long-Term Budget Outlook

The long-term budget outlook (LTBO) provides projections of fiscal indicators such as the deficit and debt-to-GDP ratio over the next 25 years. These projections depend on long-run economic projections that are likely to be affected by climate change.[5] In FY 2023, the President's Budget included a single estimate of the effects of physical climate risks: changes to the debt-to-GDP ratio implied by impacts to GDP under a high-emissions, high-warming scenario. The FY 2024 analysis expands on this by presenting three future emissions scenarios and estimates damages based on a comprehensive review of published estimates (Figure 1), rather than using a single, high-end damage estimate. This section describes how these damage estimates were derived.

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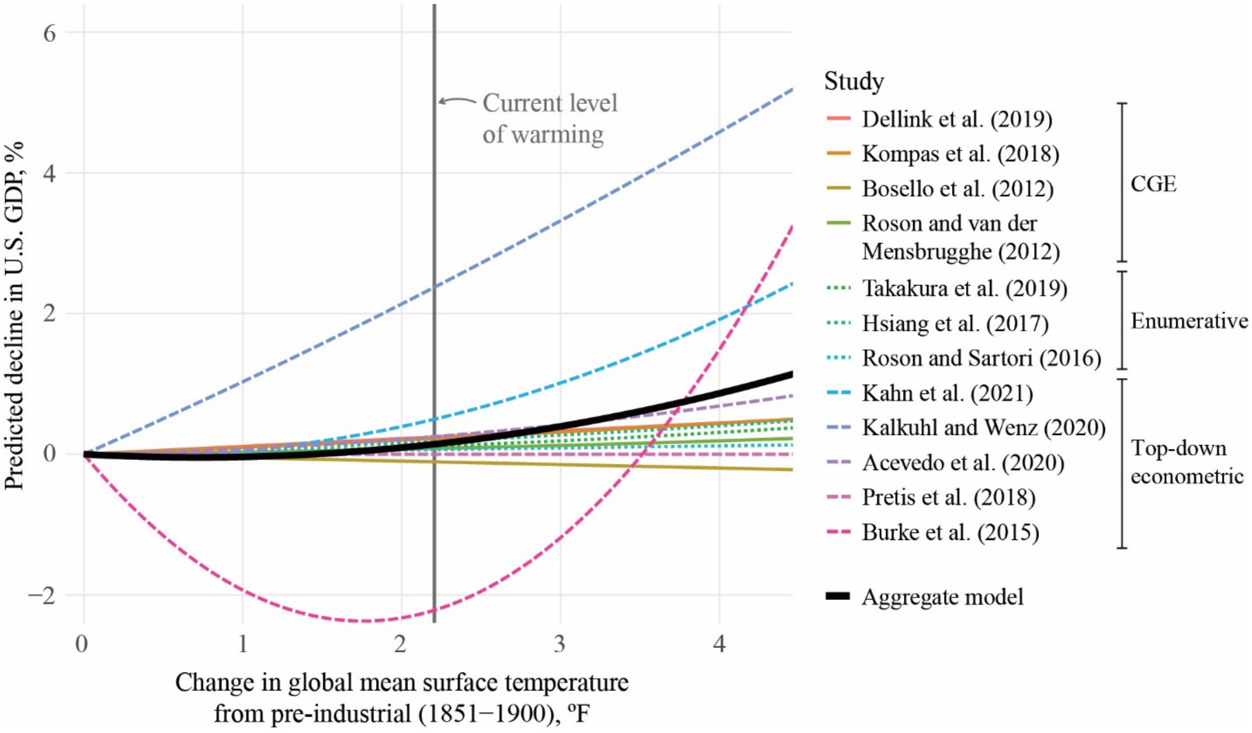
[5] Additional information on the process for developing the LTBO is given in the second section.

Figure 1: Individual Damage Functions and Aggregate Function Used for Scenarios including Physical Climate Risks in the FY 2024 Long-Term Budget Outlook



i. Methods to Assess Risk

The United States has committed to reducing its annual greenhouse gas emissions by 50–52 percent relative to 2005 levels by 2030, which will lower the physical risks of climate change. But the magnitude of climate damages in the United States depends on the level of *global* climate policy ambition and associated global greenhouse gas (GHG) emission trajectories, which determine the magnitude of climate change and associated damages. Therefore, the LTBO presents debt-to-GDP ratios under three scenarios that differ in terms of how global GHG emissions evolve over the next 25 years. In the "low global emissions" scenario, global emissions reduction policies roughly follow U.S. long-term commitments along a net-zero 2050 trajectory (Shared Socioeconomic Pathway [SSP] 1-2.6); in the "moderate global emissions" scenario, those policies roughly stay at current levels of ambition (SSP 2-4.5); and in the "high global emissions" scenario, the rest of the world reduces their climate policy ambition, producing higher emissions (SSP 3-7.0). We use an ensemble of the latest climate models from the Sixth Coupled Model Intercomparison Project (CMIP6) to project global temperature change associated with these three scenarios (Gergel et al. 2022; Hersbach et al. 2020; Muñoz Sabater 2019; Muñoz Sabater 2021; Xin et al. 2018; Lovato et al. 2021; Ziehn et al. 2019; Hajima et al. 2019; Tatebe and Watanabe 2018; Wieners et al. 2019; Seland et al. 2019; Krasting et al. 2018) relative to the pre-industrial temperature baseline of 1850–1900 (Morice et al. 2021).[6] The model ensemble includes only CMIP6 models that report values for all three SSPs and that do not suffer from the "hot model" problem in which some models, when predicting the past climate, tend to be too warm relative to observations (Hausfather et al. 2022). The three SSP temperature paths are shown in Appendix Figure 2.[7]

To convert these temperature changes into economic damages, we survey the academic literature for published relationships between temperature change and economic output, commonly called a "damage function" (e.g., Piontek et al. 2021). We only include estimates from studies that meet the following set of criteria: (a) the study must have been published in a peer-reviewed journal in the last 10 years (2012 or later); (b) it must report market damage estimates (we include studies that report non-market damages so long as they can be separated from market damages); and (c) it must either report U.S.-specific damages or report otherwise spatially disaggregated damages (in which case damages for regions that include the United States are used). Table 1 below gives details of the 12 estimates of physical climate change costs included in the analysis.

This literature on the relationship of climate change to economic output derives from three primary methodologies, identified in the second column of Table 1.[8]

One set of studies estimates the historical relationship between year-over-year variations in weather and annual economic output ("top-down econometric" studies), abstracting away from the question of how particular components of the macroeconomy are affected by climate. There are limitations to this approach. First, while these studies implicitly include impacts to every sector of the economy, to the extent those impacts are reflected in GDP, this method does not allow those estimated damages to be broken down by sector. Second, GDP is not a direct measure of welfare and therefore does not capture many economically relevant impacts of climate, such as the destruction of infrastructure, the creation of new goods, or innovation. Further, because these studies mostly consider only temperature variation, they do not include effects of climate change unrelated to interannual variation in temperature, such as sea-level rise, CO_2 fertilization, ocean acidification, or changing rainfall patterns. Lastly, the validity of extrapolating from local, short-term weather fluctuations to estimate the effects of long-term global changes in climate is unclear.

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[6] CMIP6 is the latest set of climate scenarios produced by climate modeling groups around the world and used as input to Working Group 1 of the Intergovernmental Panel on Climate Change.

[7] In the near future, natural variability in the climate system dominates the signal from changing greenhouse gas emissions under the SSPs, even averaging over the multi-model ensemble; to aid visual representation and clarify interpretation of the different temperature trajectories, we locally smooth (LOESS) each of the three ensemble average temperature paths.

[8] Further details on the methods for generating aggregate damage estimates and comparisons of the different approaches are available in a number of review papers (Piontek et al. 2021; Howard and Sterner 2017; Diaz and Moore 2017).

Table 1: Summary of studies assessing physical climate risks to the U.S. used to develop an aggregate damage function used for the climate risk scenarios in the FY24 budget

Model	**Model type**	**Geography**	**Included damages**						**Notes**
			Agriculture	**Energy**	**Tourism**	**Sea level rise**	**Labor productivity**	**Other**	
Hsiang et al. (2017)	Enumerative	United States	X	X			X	Interaction of cyclones and sea-level rise	Figure 5B
Takakura et al. (2019)	Enumerative	North America	X	X		X	X	Nutrition, flooding	Supplementary Figure 4, all scenarios
Roson and Sartori (2016)	Enumerative	United States	X	X	X	X	X		Table A-1.1
Dellink et al. (2019)	CGE	United States	X	X	X	X	X	Fisheries, cyclones	Figures 4 and 5
Kompas et al. (2018)	CGE	United States	X			X	X		Table 2
Roson and van der Mensbrugghe (2012)	CGE	United States	X	X	X	X	X		Figure 5
Bosello et al. (2012)	CGE	United States	X	X	X	X	X	Forest productivity, flooding	Figure 5
Acevedo et al. (2020)	Top-down econometric	United States	Any variation in economic output associated with interannual temperature variation						Estimated from Fig. 9
Kalkuhl and Wenz (2020)	Top-down econometric	United States							Adjusted output from IIASA
Kahn et al. (2021)	Top-down econometric	United States							Table 6
Pretis et al. (2018)	Top-down econometric	United States							Figure 4
Burke et al. (2015)	Top-down econometric	United States							Adjusted output from online supplement

Note: Model types are described in more detail in the main text; "CGE" = computable general equilibrium

A second set of studies enumerates the effect of climate change on various sectors of the economy and combines these to arrive at an estimate of the overall macroeconomic effect ("enumerative" studies). While this method can provide more granularity on the mechanisms through which climate affects macroeconomic output, these studies only capture effects on sectors explicitly included in their analysis, and are hence limited in their ability to fully quantify all of the effects of climate change. For example, while the effects of climate on agriculture and energy demand are estimated by all studies of this type, tourism and flooding impacts are only included in a subset (Table 1). In the sector-by-sector approach taken by these studies, difficult-to-quantify climate change effects—such as infrastructure damage, disruption caused by extreme rainfall, and changes in migration trends—are often missing. Another limitation of these sector-by-sector studies is that they cannot fully capture the potential interactions and general equilibrium effects across sectors, which could result in undercounting or double-counting various impacts.

A third set of studies pursues a similar strategy to the enumeration approach but attempts to avoid double-counting and to account for interaction and general equilibrium effects by including the enumerated estimates in a computable general equilibrium model ("CGE" studies). Integration of multiple sectoral impact relationships into a unified CGE model allows these estimates to account for interactions between various climate change damages and for adjustments within the economy that could affect aggregate costs in ways that the enumeration approaches cannot. However, these methods have similar weaknesses as the enumeration approaches: they account only for the most easily identified and quantified damages and may miss potentially significant channels that allow for the propagation of damages, including those important for understanding macroeconomic effects of climate change (see Table 2 for more details).

Figure 1 above shows the estimated U.S. GDP response reported by each study and an aggregate across these 12 studies, plotted as a function of changes in global mean surface temperature relative to the 1851–1900 average. For each study, we plot all reported damages and corresponding temperatures and fit a smooth, continuous function through these values. All studies report estimates of damages throughout the range of the x-axis in Figure 1. To calculate our aggregate estimate of the relationship between the level of climate change and the change in U.S. output over time, we generate a large number of equally spaced points along each of these damage functions and fit a penalized spline through the complete set of these points. The aggregate function is shown with a solid black line in Figure 1 above.[9]

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[9] Our aggregate estimate uses equal-weighting of the 12 estimates. If estimates are not independent of each other, then a more-accurate weighting scheme would account for this dependency by placing more weight on relatively more independent estimates. Howard and Sterner (2017) provide a detailed discussion of the dependencies in damage estimates supporting the damage functions in integrated assessment models. However, since that paper was published there have been many more recent, original estimates from a range of researchers using different methodological approaches, and the 12 studies used here have no direct dependencies on each other (i.e., one study is not the input for another). To address sensitivity to the equal weighting assumption, however, Appendix Figure 1 also shows an alternative hierarchical weighting scheme, which places equal weight across the three methodologies rather than individual papers. This alternative weighting approach yields similar results as the equal-weighting one.

Global mean temperature changes resulting from each emissions scenario (Appendix Fig 2) are put into the aggregate damage function, resulting in a mapping between time and the predicted change in U.S. GDP for each emissions scenario. These projected changes to U.S. GDP are integrated into the long-term budget modeling by OMB to produce alternate debt-to-GDP pathways.

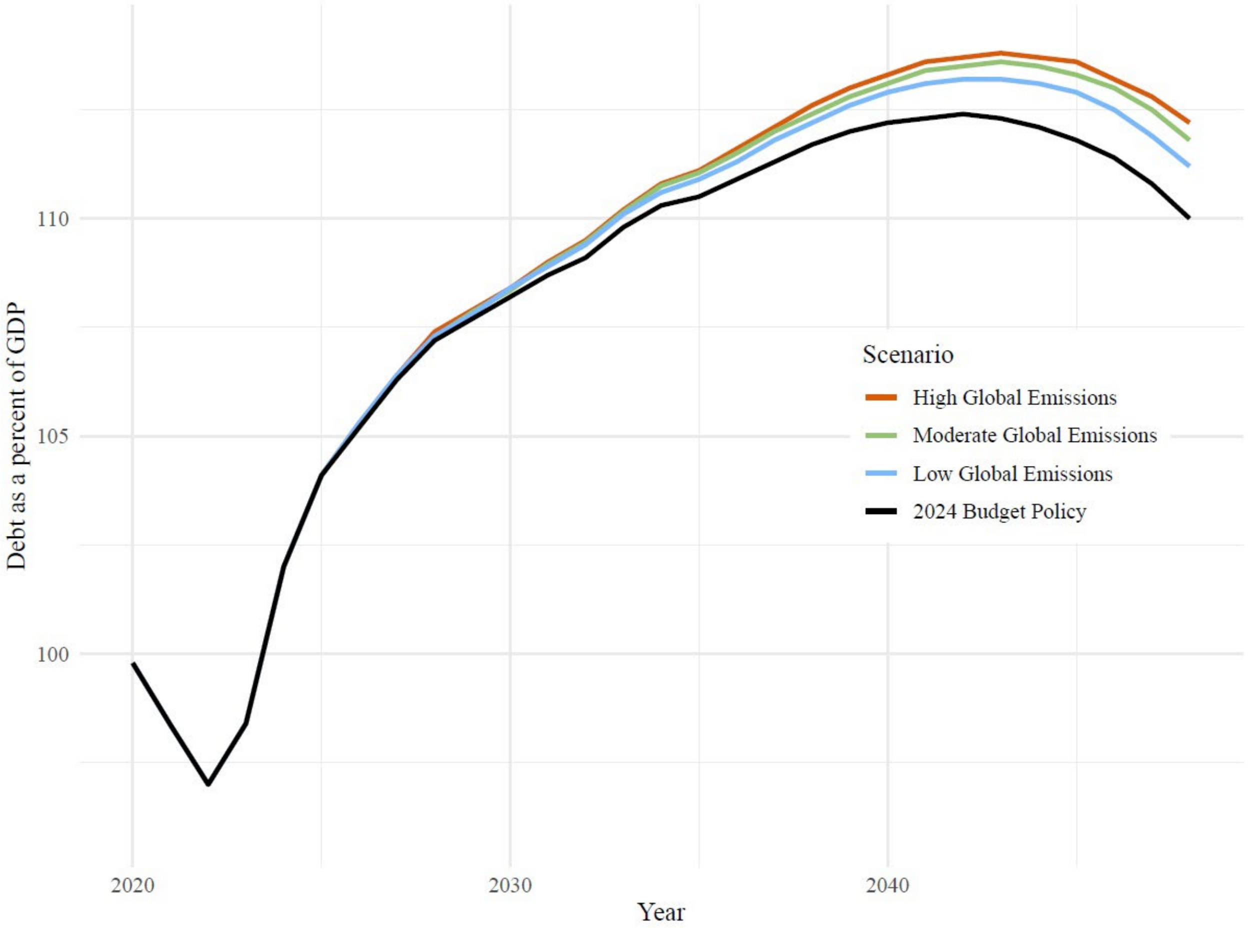
ii. FY 2024 Long-Term Budget Outlook

Figure 2 presents the projections of debt as a share of GDP resulting from the physical impacts of climate change (as quantified in studies in Table 1) under three different global greenhouse gas emission scenarios and the policy baseline scenario, in which the economic assumptions do not explicitly account for climate risk. Even under the low global emissions scenario, the consequences of physical climate damages for the macroeconomy weaken the fiscal outlook. Debt to GDP under the low global emissions scenario is projected to reach 111.2 percent by 2048, compared to 110.0 percent in the policy baseline. The debt-to-GDP ratio is projected to be even higher under the middle and high global emissions scenarios, reaching 111.9 percent and 112.6 percent, respectively, by 2048. Beyond the 25-year window considered in the LTBO, the macroeconomic outlooks under these emissions scenarios diverge further over time. As a consequence, the high global emissions scenario, in particular, would lead to even further deteriorations in the longer-term fiscal outlook. These results illustrate the sensitivity of fiscal measures to different emissions scenarios given the costs estimated as described above.

It is important to interpret these values in the context of the substantial uncertainty that underlies them and to understand these estimates as almost certainly a lower bound on total climate change costs. The macroeconomic effects of climate change that have been quantified in the studies used to assess physical risks are a strict subset of all possible climate change effects (Table 1) and the studies show a range of estimate (Figure 1). In addition, Rising et al. (2021) provide a characterization of the many risks currently missing from climate damage estimates. This includes the omission of biophysical processes such as climate system feedbacks, imperfect accounting of the effects of spatial or temporal extremes, limited inclusion of feedback processes or cross-sector interactions, and the effects of deep uncertainty or tail events. Improving the quantification of climate change costs to better support the economic assessment of climate risks should be a high priority for the near-term.

Further uncertainty in the debt-to-GDP metric shown in Figure 2 arises because changes in GDP are themselves just an input into the long-term budgetary projections, which rely on well-informed assumptions that nonetheless cannot fully anticipate future trends. Climate outcomes could have material effects on a wide range of macroeconomic variables, such as migration trends and demographics, which influence fiscal conditions above and beyond their effects on GDP. Lastly, this exercise does not explicitly account for other implications of climate on Federal revenues or outlays. In particular, climate change impacts may have particular implications for certain categories of Federal spending such as disaster relief or medical expenditures due to climate-induced declines in individuals' health. These are not captured here, but work to assess these potential risks is proceeding in a complementary workstream at OMB (OMB 2023).

Figure 2: Debt-to-GDP Ratio Projections under Scenarios including Physical Climate Risks in the FY 2024 Long-Term Budget Outlook



2. A Proposal to Develop Climate-Informed Economic Assumptions for Future President's Budgets

The section above describes the current, limited assessment of physical climate risks to the U.S. macroeconomy that was incorporated as a climate risk alternative into the FY 2024 LTBO. This assessment was guided by the current literature and built upon the analysis in the FY 2023 Budget. In order to more comprehensively assess the full range of macroeconomic risks climate change presents to the macroeconomy over the short-, medium-, and longer-term, more robust methods are needed. Specifically, a fuller accounting of climate risks in the economic assumptions would address the macroeconomic effects of the net-zero energy transition (transition risks) in addition to physical risks and capture climate risks over both the 10-year budget window as well as longer horizons.

This section lays out how the U.S. Government could begin explicitly incorporating both physical and transition risks of climate change into its macroeconomic projections. Subsection A describes the current U.S. Government process for developing the economic assumptions for the President's Budget. Subsection B then describes how key macroeconomic variables relating to labor, capital, and productivity could be affected by climate change and the energy transition. Subsection C outlines considerations and challenges in integrating climate modeling within macroeconomic forecasting exercises. These, in turn, inform the general approach considered for how to integrate climate risks within the U.S. Government's macroeconomic forecasting process in Subsection D. Subsection E develops sets of essential and desirable criteria for models to integrate within this approach. Then, Subsection F describes the five existing models considered here, which are evaluated relative to the essential and desirable criteria in Section G.

A. Developing the Economic Assumptions in the Federal Budget

In the President's Budget, OMB publishes a set of 10-year economic assumptions, which inform projections reported in the Budget of the trajectory of fiscal indicators under current law and proposed policies.[10] OMB extends these economic assumptions in the Long-Term Budget Outlook, which provides a 25-year forecast of the Budget and assesses various risks to the fiscal projections. OMB and agencies also use the Budget's economic assumptions in the development of scores for proposed policies in the President's Budget.

The process to generate the economic assumptions is led by CEA, OMB, and the Treasury—commonly referred to as the Troika. The methods for this macroeconomic forecast are well-established and consistent with those of other forecasters. The Troika forecasts the 10-year economic assumptions through use of a primary model, inputs from secondary models for specific economic indicators, and expert opinion.

The primary model that informs the Troika process is S&P's U.S. Macro Model, which is often referred to as the Macroeconomic Advisers U.S. (MAUS) model.[11] MAUS is a large-scale, structural econometric model: "structural" because it is grounded in macroeconomic theory, with relationships imposed between certain variables, rather than derived from micro-foundations, and "econometric" because those relationships are estimated using historical data. These relationships predict how near-term deviations from a long-run equilibrium will impact the components of the

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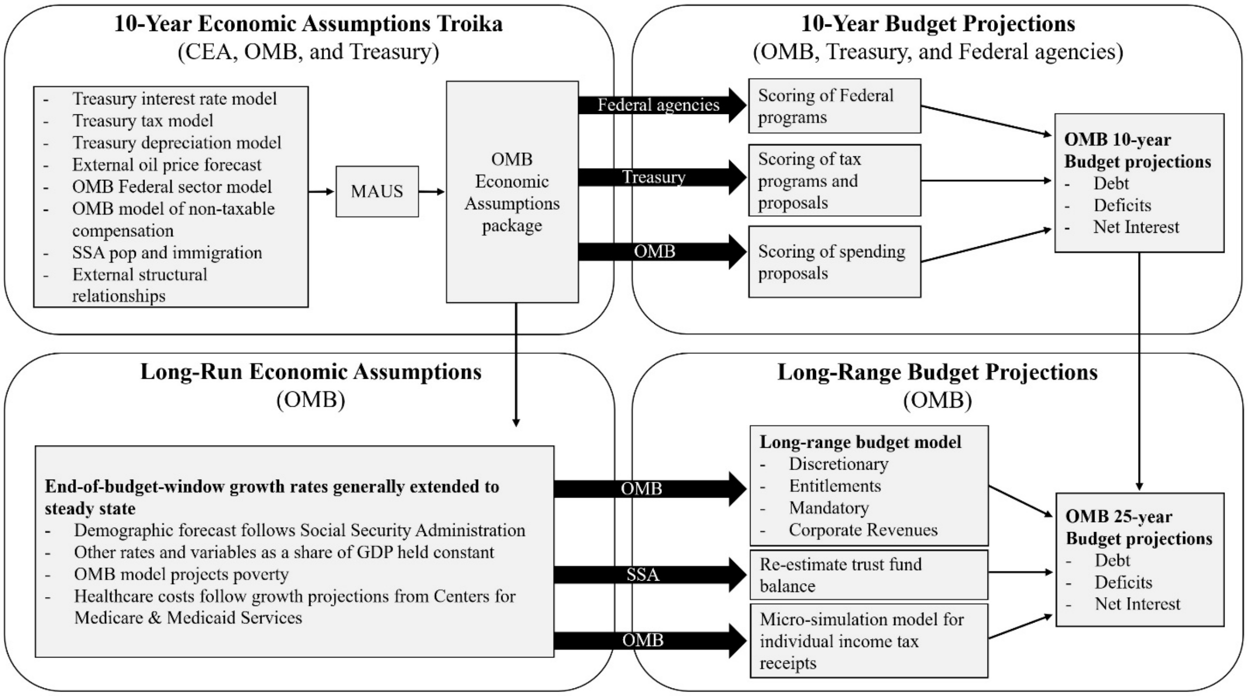
[10] This differs from other forecasts such as that performed by the Congressional Budget Office, which makes projections based on current law, not including proposed policies.

[11] Macroeconomic Advisers developed the model, but have since been acquired by IHS Markit, which has since been acquired by S&P.

National Income and Product Accounts[12] as well as other key macroeconomic variables, such as inflation, labor market indicators, and financial market measures.

The Troika applies secondary modeling and expertise from across the U.S. Government to derive and impose the trajectories of certain variables within the MAUS framework. For example, the Troika accounts for the macroeconomic effects of the policies proposed in the President's Budget; new proposals, in particular, will not be anticipated by the baseline MAUS forecast. Additionally, the Treasury models interest rates and international flows, which are largely external to the structural relationships in MAUS. Expertise from outside the Troika is also leveraged: for example, Social Security Administration's (SSA) Trustees report data are used as input for demographic projections, and external forecasts are relied upon as reference points in developing projections for certain variables.

Figure 3: Illustration of the process for developing economic assumptions and 10- and 25-year Budget projections



The 10-year economic forecast and budget projections are extended over a 25-year horizon to create the Long-Term Budget Outlook chapter of the Analytical Perspectives volume in the

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[12] NIPA and the associated national economic balance sheet do not include air emissions, climate, land or other stocks of natural capital in the United States. This gap is part of the reason that connecting climate or other environmental change to macroeconomic forecasts is challenging. The Federal Government has initiated work to fill this gap within the scope of national accounting standards (https://www.whitehouse.gov/wp-content/uploads/2022/08/Natural-Capital-Accounting-Strategy.pdf).

President's Budget (see Figure 3). OMB extends the 10-year economic assumptions by assuming the economy is broadly on a balanced growth path at the end of that window.[13] In practice, that means many variables are held constant. For example, interest rates, the unemployment rate and various measures of income as a share of GDP remain unchanged after the 10-year window. As climate and transition risks become more integrated into the development of the Budget's economic assumptions, some of these variables will likely respond to changes in climate risks and energy policy.

At present, the Troika process does not explicitly model the impacts of climate-change-induced transition and physical risks. However, to the extent they have historically influenced economic outcomes, some climate effects may already appear implicitly. For instance, recent decades have seen a substantial slowing of multi-factor productivity growth, both in the Unites States and globally, and several papers have suggested that climate change might be a contributing factor (Sprague 2021; Dieppe 2021; Diffenbaugh and Burke 2019; Ortiz-Bobea et al. 2021; Letta and Tol 2019). This setting of sluggish productivity growth forms the backdrop for economic forecasts projecting growth over the next 10 years, including the Budget's economic assumptions. To the extent some portion of this recent productivity slowdown can be attributed to a changed climate, this is therefore reflected implicitly in lowered expectations of future productivity growth incorporated into the forecast.

On the transition risks side, the economic assumptions do not currently include any explicit consideration of the direct macroeconomic effects of decarbonization efforts. For example, the existing MAUS framework does not contain the structural relationships that would be necessary to estimate the macroeconomic impact of various Inflation Reduction Act (IRA) clean-energy subsidies. At present, the Troika considers the impact of those subsidies only through standard fiscal policy channels (that is, as the macroeconomic impact of increased government spending). The Budget estimates do already include estimated fiscal effects of existing policies, including major climate bills such as IRA. It also includes the fiscal effects of any climate policies proposed within the Budget, though not the effects of any additional policies that may be necessary to meet the 2050 net-zero GHG goal that have not been proposed. However, if realized or anticipated decarbonization efforts have impacted key producer and consumer behavior in the past and, hence, have impacted important macroeconomic variables, such as energy prices, there are some implicit effects already included in the Budget's economic assumptions.

B. Climate Risks to the Macroeconomy

Having walked through the current U.S. Government process for producing the economic assumptions, the next steps are to assess the most critical pathways through which climate change and the energy transition affect the macroeconomy and to assess the capacity of the U.S. Government to quantify these effects. While the U.S. Government has some of the best analytic

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[13] Not all variables' growth rates are held constant, so this is not an assumption of a balanced growth path in the strict sense. For example, the Long-Term Budget Outlook incorporates the Social Security Administration's longer-term demographic projections.

capabilities in the world, the capacity to model and quantify these macroeconomic effects, both within the U.S. Government and in the academic community more generally, is still early in its development.

This section details pathways through which climate change impacts (physical risks) and decarbonization efforts (transition risks) could affect future macroeconomic conditions, and identifies new concerns that the integration of climate risks brings to the construction of the economic assumptions. For both the physical and transition risks of climate change, we look separately at each of the three traditional drivers of growth: labor, capital services, and total factor productivity (TFP)[14] and assess the current capacity, both within the U.S. Government[15] and within the academic community more generally, to model and quantify these effects. Because these macroeconomic outcomes are not always the focus of climate and energy modeling, the connections between them may not be obvious and so we aim to elaborate them below.

i. Physical Risks

A substantial literature documents the existence of and damage from climate change, including efforts to quantify the implications of these effects on human welfare (Nordhaus 1994; Howard and Sterner 2017; USGCRP 2018; Pörtner et al. 2021). One challenge of relying on the current literature for this application is that most estimates of marginal climate change costs take economic growth as exogenous, effectively assuming there are no substantive macroeconomic feedbacks from climate change. In addition, some of the existing assessments of climate change costs are not readily applicable to current macroeconomic modeling applications because they either examine only physical outcomes (such as number of people displaced, frequency of droughts, or changes in crop yields) and do not quantify effects economically, or they examine non-market effects (such as mortality risks or effects on natural ecosystems) that are only indirectly relevant to near-term macroeconomic outcomes. Table 2 therefore describes the sub-set of climate change impacts that are directly related to key macroeconomic drivers and the documented evidence for the existence of these pathways. Reduced emissions will lower the magnitude of climate change and therefore provide benefits in terms of reduced physical risks.

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[14] TFP growth is measured as the residual of GDP growth after accounting for changes in the factors of production, typically labor and capital. If this accounting is missing factors of production, such as natural capital, then changes in those factors will be mis-attributed to TFP. Although addressing this issue is beyond the scope of this work, parallel efforts to improve quantification of natural capital changes in economic accounting are relevant for this work (e.g., White House 2023).

[15] Existing capacity within the USG for physical risk modeling comes from work done by the Climate Change Impacts and Risk Analysis project at EPA to value damages within the United States from a large number of sectors (Martinich and Crimmins 2019; Neumann et al. 2020), work done at the National Center for Environmental Economics at EPA to quantify global climate change costs as part of estimating the social cost of carbon (Greenstone et al. 2013; NCEE 2022), and various other USG efforts (for example, NOAA Billion-Dollar Disasters and the National Climate Assessment (USGCRP)). For transition risk, modeling capacity includes the energy-systems modeling capability at the Department of Energy Pacific Northwest National Lab, macroeconomic forecasting capacity within the Executive Office of the President and Treasury, as well as capabilities that may be possible through external contracts.

Table 2: Examples of pathways by which climate change can affect macroeconomic variables

Broad Pathway	**Specific Climate Pathway**	**Discussion**	**U.S. Government Analytic Capacity**	**References**
Labor	Migration	Climate change, including displacement from sea-level rise, could affect the propensity to migrate to and from the United States in complex ways, as well as the distribution of population within the United States	Limited	Benveniste et al. 2020; Benveniste et al. 2022; Jessoe et al. 2018
	Workweek	Changes in extreme temperatures alter hours worked, particularly in more exposed industries (e.g., construction, agriculture)	Good	Rode et al. 2022; Graff-Zivin and Neidell 2014
	Population Growth - Fertility	There is some suggestion climate change may affect fertility decisions, though magnitudes may be small for a services-led economy with high air conditioner penetration like the United States	Limited	Casey et al., 2019; Barreca et al., 2018
	Population Growth – Mortality	Substantial evidence that temperature extremes lead to premature mortality, though effect sizes are smaller for prime work-force ages. Other mortality effects operate through changes in disease and extreme weather events	Good	Carelton et al. 2022; Cromar et al. 2022; Bressler et al. 2021
Capital Services	Destruction	Climate-change-related extreme events could destroy capital investments. Resources required for recovery may be diverted from productive investments.	Partial	Hallegatte et al. 2007; Otto et al. 2023; studies referenced in Martinich and Crimmins 2019
	Uncertainty	Additional uncertainty from climate-change-related weather extremes raises risk premia on certain assets and	Limited	Fernando et al. 2021; Otto et al. 2023

		financing costs for related investments. Climate uncertainty could limit availability or increase costs of disaster insurance in certain markets, slowing recovery.		
Factor Productivity	Labor	Extreme hot temperatures lower labor productivity in highly exposed industries	Good	Lima et al. 2021; Kjellstrom et al. 2010
	Capital Services	Changing climate may alter the productivity of climate-sensitive capital such as dams, electricity transmission and generation, and roads.	Partial	Studies referenced in Martinich and Crimmins 2019; EPRI 2022
	Land	Higher temperatures and CO_2 concentrations affect agricultural yields and forest productivity	Good	Beach et al. 2015; Moore et al. 2017; Baker et al. 2022

Note: Modeling capacity definitions: "None" = potential pathway but not quantified or modeled; "Limited" = pathway has been fully or partly modeled in the academic literature, but adapting results for Budget forecasting purposes remains challenging; "Partial" = capacity exists to quantify some but not all of these effects; "Good" = capacity exists to quantify the bulk of these effects and/or used in existing U.S. Government work

ii. Transition Risks and Opportunities

Energy is an essential input into much of the modern economy.[16] From transportation, to heating and cooling, to electricity, to industrial production, energy infrastructure underpins a large fraction of economic activity. Changes in the availability of energy inputs can require shifts in production methods; fluctuations in energy prices, in turn, can affect broader price movements. Further, achieving the global temperature goals under the Paris Agreement, supported by climate science, requires a rapid decarbonization of the global economy. Limiting temperature rise to 1.5 degrees Celsius will require reductions in global greenhouse gas emissions of 73–98 percent by 2050 (Riahi et al. 2022, p.298), relative to levels in 2019. As such, policymakers must have a firm grasp of interim economic dynamics. Assessing and quantifying transition risks, as well as a range of other U.S. Government activities to manage climate-related financial risks directed by E.O. 14030, are aimed at managing the energy transition and aligning investor expectations to enable an orderly transition and lower transition risks.

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[16] Full decarbonization will require changes to food systems to address agricultural greenhouse gas emissions as well as emissions of greenhouse gases in industrial production (via cement production for instance). While such changes are also important, the discussion here focuses on the energy-system transition (including transport, heating and cooling, electricity generation, and industrial energy use) as it is both the largest part of the decarbonization effort and the most macroeconomically relevant due to the central economic role of energy in developed economies.

The transition to net-zero will affect the macroeconomy by changing capital markets, energy price levels and volatility, and labor allocation. Recent work on the macroeconomic costs and financial risks of climate change has distinguished between orderly and disorderly energy transitions, with the latter defined by rapid changes in policy producing stranded energy assets or divergent policies across sectors (NGFS 2022a). As with physical risks, while there is a long tradition of modeling the energy transition, this has historically focused on energy system models that typically take macroeconomic conditions (projections of energy demand, for instance) as a given. Table 3 therefore describes specific pathways through which the energy system transition may affect macroeconomic variables and qualitatively assesses current U.S. Government capacity to quantify these effects.

Table 3: Examples of pathways by which the energy transition can affect macroeconomic variables

Broad Pathway	**Specific Energy-Transition Pathway**	**Discussion**	**U.S. Government Analytic Capacity**	**References**
Labor	Skill and Geographic Mismatch	The energy transition will decrease labor requirements in some industries while increasing them in others. Differences in the skill requirements and location of growing compared with shrinking sectors, combined with labor market frictions, could lead to localized unemployment or labor shortages	Limited	Council of Economic Advisors 2022; Hafstead et al. 2022; Greenspon and Raimi 2022; Castellanos and Heutel 2019
Capital Services	Investment	A rapid energy transition requires large investments in new energy infrastructure. Macroeconomic effects of this investment might result from diversion of investment from other productive uses and economic stimulus under certain circumstances. Capital adjustment frictions could lead macroeconomic costs to increase with the speed of the transition.	Good	See discussion of macroeconomic models in following sections.
	Policy Uncertainty	Energy infrastructure investments are forward-	Limited	IMF 2022 (Chapter 3)

		looking and depend on investor expectations regarding future returns. Policy uncertainty around the speed and nature of the energy transition could lead to higher financing costs and under-investment in energy generally, with implications for energy prices and volatility.		
Factor Productivity	Energy and Energy-Intensive Infrastructure	Rapidly changing policy conditions could lead energy infrastructure to under-perform relative to expectations. Capital in downstream, energy-intensive industries may also be rendered prematurely obsolete or less productive as energy markets and technology change.	Partial	A substantial literature on asset stranding associated with energy transitions exists, including Fofrich et al 2020; van der Ploeg and Rezai 2020; Grubert 2020
Energy	Price Levels	Energy prices can affect macroeconomic conditions. For instance, oil prices are a standard factor in macroeconomic forecasting (Figure 3). The energy transition may change energy prices in the near-term, particularly if it is disorderly. The longer-term effects on energy prices are unclear, as they depend on future technological evolution and policy that could lead to either decreases or increases in energy prices.	Partial	McKibbin et al. 2020
	Price Volatility	Volatile energy prices increase uncertainty for producers and consumers, potentially with macroeconomic implications. A disorderly transition could increase	Limited	

		energy price volatility in the short- to medium-term. In the longer-run, the declining share of fossil fuels in the energy mix could lower price volatility.		

Note: Modeling capacity definitions: "None" = potential pathway not quantified or modeled; "Limited" = pathway has been fully or partly modeled in the academic literature, but adapting results for Budget forecasting purposes remains challenging; "Partial" = capacity exists to quantify some but not all of these effects; "Good" = capacity exists to quantify the bulk of these effects and/or used in existing U.S. Government work

C. Approaches and Challenges in Modeling Climate Risks to the Macroeconomy

The mandate laid out in EO 14030 is to "develop methodologies to quantify climate-related financial risk within the economic assumptions and the long-term budget projections of the President's Budget" (White House 2021). This entails finding and deploying the best-available tools, given the limitations of current models, while also encouraging the development of more appropriate models and partnering with external experts to enhance the dissemination of knowledge and best practices. Not all models are able to capture the pathways shown in Tables 2 and 3 or are able to credibly speak directly to the macroeconomic effects of climate risks on the U.S. economy.

The task here differs from prior applications of climate-economy models. Most notably the timeframes involved (10 years for the main Budget window and 25 years for the long-run budget projections) are considerably shorter than the century-scale timelines typically examined in climate policy modeling. Over the Budget's timeframes, transitory economic dynamics such as business cycles, as well as adjustment processes in response to new regulations and incentives, could play a dominant role. Models able to capture these dynamic adjustment processes are needed to quantify effects over these short- and medium-run timescales.

Another difference between previous applications of existing climate-macro models and the budget process is the spatial scale of interest. Because climate change is global phenomenon, a most climate modeling has been done at the global scale. The climate risks the United States faces are global because they partly depend on actions taken by other countries, which are in turn influenced by U.S. actions. The U.S. macroeconomy could also be affected by climate change impacts outside U.S. borders via effects on trade, migration, national security channels, as well as direct economic interests abroad (NCEE 2022; National Intelligence Council 2021). Further, the energy transition could affect global trade patterns. Modeling for U.S. budget projections, however, is currently informed by the MAUS model, a single-region model of the U.S. economy (Figure 3).

This policy application is also very different from modeling that informs estimates of the social cost of greenhouse gas emissions (SC-GHG), which is a summary metric quantifying the net present value of the damages from an additional ton of greenhouse gas emissions. The SC-GHG focuses on the social welfare changes from greenhouse gas emissions over very long time-frames (Rennert et al. 2022). While the SC-GHG is critically important for quantifying the social welfare benefits of emissions reduction, calculation of the SC-GHG is a fundamentally different from the exercise described here. For instance, some climate change effects may have large implications for social welfare but limited near-term implications for economic production and macroeconomic variables of interest in the U.S. budget process. SC-GHG estimates also focus exclusively on the physical impacts of climate change and do not capture the macroeconomic effects of mitigation policies. And finally, modeling underlying current SC-GHG estimates does not, for the most part, incorporate the potential macroeconomic effects of climate change damages.[17]

Given the importance of integrating climate risks into macroeconomic planning, a number of institutions have made efforts to overcome these limitations by exploring options for how best to measure these effects over budget-relevant timescales and regions (several examples are discussed in CEA and OMB 2022). Several institutions, including the Network for Greening the Financial System (NGFS) and Moody's, have connected carbon price trajectories produced from partial-equilibrium multi-sector dynamics models (MSDs) and physical risk damage functions into macroeconomic models similar to MAUS (NGFS 2022a; Licari et al. 2021). On the transition side, this approach has the drawback of deriving characteristics of the transition using partial-equilibrium models that abstract from the fact that the macroeconomy and the energy system are coupled.[18] An NFGS exercise comparing MSD results with a hybrid CGE- macroeconomic model, G-Cubed, showed that the effects of climate policy on aggregate energy demand and on substitution between high- and low-carbon economic sectors can be important determinants of energy transition dynamics (NGFS 2022b). A second limitation is that these approaches, like much previous modeling of the economic effects of the energy transition, typically focus on carbon pricing, missing the range of different climate policy tools that governments are using to draw down emissions, which could have different macroeconomic implications.

The IMF and World Bank are using multiple modeling approaches to understand climate change. The IMF has used both the G-Cubed model (IMF 2020) and, more recently, an extension of its Global Macroeconomic model (IMF 2022) to understand the macroeconomic effects of the energy transition. The World Bank is integrating climate change into its macrostructural model, MFMod, to understand how physical and transition risks affect country development pathways (Burns et al. 2021). Both institutions are also using CGE models to understand the long-run effects of both types of climate risk on economic growth (IMF 2022; Benitez et al. 2018).

i. Developing Scenarios for Understanding U.S. Macroeconomic Climate Risk

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[17] Interim SC-GHG estimates from a U.S. government interagency working group on this issue are currently based on three models (U.S. Interagency Working Group on Social Cost of Greenhouse Gases 2021): DICE 2010, PAGE09 and FUND 3.8. DICE allows indirect effects of climate damages on the capital stock via effects of lower economic production on investment, but assumes exogenous pathways of both TFP growth and labor (see Moore and Diaz 2015 for a discussion). FUND and PAGE both specify GDP growth exogenously (Hope 2011; Anthoff and Tol, 2014).

[18] Partial equilibrium models capture adjustments in certain economic sectors while keeping other parts of the economy fixed. General equilibrium models allow for adjustments across the whole economy.

Integrating climate risks into the macroeconomic forecast will require the development of policy and climate scenarios that raise particular issues distinct from other climate-economy modeling exercises.

First, understanding transition risks and benefits to the U.S. economy requires developing future domestic climate policy scenarios. The United States has committed to a 50–52 percent reduction in annual greenhouse gas emissions relative to 2005 levels by 2030—and to reach net-zero emissions by 2050 (UNFCCC 2021). Further policies will need to be developed in the future to meet the longer-term goal; the domestic macroeconomic effects and global competitiveness effects of climate policy depend on the specifics of policy design and the full set of policies the United States will implement to achieve these medium- and long-term goals is not yet clear. Near-term U.S. climate policy, as reflected primarily in the 2022 IRA, relies on a combination of demand and supply subsidies to low-carbon energy technologies. These subsidies, in combination with existing policies, are projected to reduce U.S. emissions to 40 percent below 2005 levels by 2030 (DOE 2022). Whether additional policies to achieve U.S. emissions targets continue this subsidy-based approach alone or pursue alternative approaches will have implications for the total costs and macroeconomic effects of the energy transition.

Second, both transition and physical climate risks in the United States depend on the ambition and nature of climate action in the rest of the world. On the transition side, these effects operate through global energy and financial markets, where prices and capital flows will be determined by climate policies across all countries. On the climate damages side, worldwide greenhouse gas emissions and therefore climate damages to the United States are determined by global climate policy action. Climate policy in other countries, however, is interdependent with U.S. actions. Global climate action constitutes a strategic setting where, as the wealthiest country in the world and the second-largest greenhouse gas emitter, U.S. actions will likely be important in shaping climate ambition in other countries (Nordhaus 2015; Kotchen 2017). The interrelationships between U.S. and international action should be integrated into scenario development, reflecting a belief that more aggressive U.S. climate action may raise climate policy ambition and action globally, resulting in lower total climate damages as well as a more orderly transition pathway.

D. Approaches for Integrating Climate Risk Information into the Current Macroeconomic Modeling for the President's Budget

The current processes that the Troika uses to develop the Budget's economic assumptions constrains how climate risks can be incorporated. As noted above, the Troika currently uses the MAUS macroeconometric model as part of developing the 10-year economic assumptions and for informing the 25-year forecast. This section focuses on how to work within the current Troika process, as any information on climate risks to be incorporated into the process must have this end-use in mind.

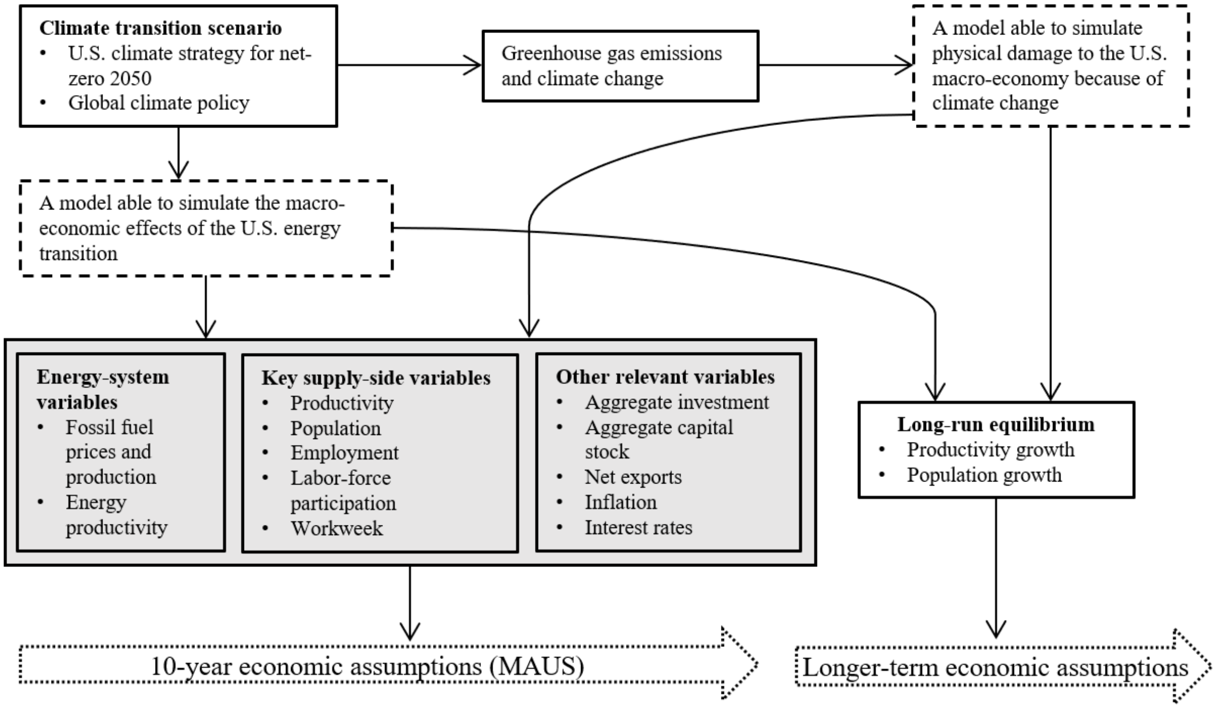
On its own, the MAUS model cannot simulate the macroeconomic effects of climate risks. Because MAUS was not designed for the evaluation of energy and climate policies, it has neither a detailed representation of energy-system variables nor specific sectors relevant for the incorporation of climate change impacts. MAUS does contain some variables that will be particularly affected by the energy transition, such as prices and production of oil, natural gas, and coal, but these mostly enter exogenously and importantly are not linked to the key supply-side variables for macroeconomic growth—namely productivity, the employment rate, average workweek, population, and labor force participation. Although the measures are not sector- or location-specific, MAUS does track the total capital stock and investment flows, which will be affected by the energy transition.

Given these facts, the effects of climate impacts and the energy transition on the key macroeconomic variables will have to be determined externally and provided as inputs to MAUS (Figure 4). This approach mirrors the ways in which other specialized information such as population, migration, and interest rate forecasts are provided into the Troika process (Figure 3).

In terms of geography, MAUS has limited spatial coverage as it only estimates macroeconomic aggregates for the United States. However, climate damages and transition risks are both global—with foreign emissions, transition efforts, and international economic responses all impacting the U.S. macroeconomy—and hyper-local—with very localized climate damages and transition policy impacts—neither of which MAUS captures. Currently, international trade and capital flows are captured only through their effect on U.S. international accounts and there are no State or regional impacts modeled in MAUS. While sub-national estimates are not required for producing the Budget's economic assumptions, such capacity would make the framework more useful for the formulation and analysis of the clean energy transition and climate policy more generally.

In the long-run projection extending beyond the 10-year forecast developed using MAUS, the current assumption of the economy being along a balanced growth path also presents constraints for representing climate damages and transition risks. For example, the U.S. net-zero emissions commitment is for 2050, currently slightly beyond the end of the 25-year long-run budget window. Additionally, the underlying structural relationships between many variables are not extended for the long-term budget outlook and so all modifications to account for climate must be imposed exogenously on the supply-side economic growth factors included in the forecast (this is similar to the current approach taken by NGFS). The current OMB model also does not include the effect of capital on labor productivity, but this could be introduced to help capture transition dynamics and the capital costs of climate change-related weather extremes.

Figure 4: Illustration of modeling framework able to integrate climate risks into the economic assumptions.



Note: Boxes with dashed outlines denote required modeling capabilities. Boxes with solid lines indicate input or output variables from modeling process

Finally, the budgeting framework also constrains the degree to which uncertainty can be represented in the final estimates. Troika produces a single set of economic assumptions, which agencies use for budgeting purposes, with some sensitivity analysis examined in the Analytical Perspectives section of the President's Budget. Considering the mechanisms through which climate risks affect the macroeconomy (as opposed to climate impacts more generally) suggests a focus on uncertainty and the energy transition. Ideally, models used would be able to represent the endogenous effect of changing risks on macroeconomic outcomes, for instance in a dynamic stochastic framework (e.g., Cai and Lontzek 2019). The computational complexity of these models, however, requires trade-offs in the form of simpler representations of the energy system and climate policy. If a dynamic stochastic framework is not used, uncertainty could instead be partially but imperfectly captured by sampling over the distributions of input variables, producing a distribution of macroeconomic outcomes and taking the expected value, or other relevant statistics, of this distribution.

E. Modeling Framework Criteria

The process described above for generating the economic assumptions and the pathways through which climate change may affect macroeconomic outcomes (Tables 2 and 3) imply the need for a specific modeling framework (Figure 4). Such a framework would incorporate several distinct models in order to capture both physical and transition risks as well as overall macroeconomic dynamics. This framework needs to be able to represent some of the key pathways shown in Tables 2 and 3 in order to estimate how the key variables for macroeconomic forecasting could be affected by the physical and transition risks of climate change.

This section describes a set of criteria identified by the ITWG for a modeling framework that could credibly simulate the macroeconomic effects of climate change and the energy transition for the United States. While Figure 4 illustrates modeling the physical and transition risks separately, in practice these are inter-related phenomena. For instance, climate change impacts on energy infrastructure could affect the pace and costs of the energy transition (EPRI 2022). These would ideally be combined into a single model that could simulate the interacting macroeconomic effects of different climate risks. However, on an interim basis the framework could be more tractable if it treated these risks distinctly. It is also possible that more than one model could provide input on either physical or transition risks into the forecasting process, allowing for assessments of model uncertainty. These analytical capabilities would complement the existing Troika forecasting framework. Essential and desirable criteria are as follows:

Essential attributes

1. Produces macroeconomically relevant variables related to labor, capital and productivity

Existing climate change analyses that quantify damages in specific sectors (physical risks) and detailed energy-system models (transition risks) usually take macroeconomic trajectories as given. In some cases, these risks are relevant for macroeconomic outcomes (e.g., capital destruction due to intensifying storms), but in other cases they are less relevant over the short term (e.g., non-market welfare losses from climate change such as increased mortality risks). Given the goal of informing macroeconomic forecasting, the modeling framework must be able to quantify the key linkages that connect the energy system and climate impacts with macroeconomic drivers.

2. Ability to represent U.S. climate policy approach

The vast majority of climate policy modeling to date has examined the effects of carbon pricing on the energy system (for example, McFarland et al. 2018). This approach has analytic advantages in capturing cost-effective abatement strategies across multiple emitting sectors in a single policy variable. However, the United States' climate policies to date have largely followed a different approach, as exemplified by the Inflation Reduction Act. Focusing on demand and production subsidies to clean energy technologies, the Act aims to stimulate deployment so as to drive down costs over time and improve U.S. competitiveness in the clean energy industry.

Models used for this application must have sufficient flexibility to represent the full and complex range of climate policies that the United States is adopting to accurately assess the macroeconomic implications. For instance, there is a substantial literature documenting the "learning by doing" effect (whereby initial deployment of new technologies lowers costs leading to further deployment) as well as network effects, whereby more widespread adoption of a new technology lowers costs directly or indirectly for other adopters (Li et al. 2017; Way et al. 2022). Provisions within the IRA and the Bipartisan Infrastructure Law (BIL) such as consumer and producer subsidies, loan authority to boost deployment of new energy technologies, and funding for electric vehicle charging infrastructure are targeted at these particular technological externalities to accelerate the energy transition. Many other countries have similarly used green technology subsidies or other types of standards or regulation as part of their climate strategy. Modeling the effects of these policies requires sufficient technological and sectoral detail within the energy sector, as well as representations of technological change, learning dynamics, and network effects that investments are targeting.[19]

Future U.S. climate policy will likely also continue to rely on various forms of regulation and standards such as fuel-economy standards, energy-efficiency standards and emissions regulations. One example is the EPA's proposed rule to address methane emissions from the oil and gas industry (EPA 2022), which again requires models with sufficient technological, sectoral, and economic detail to capture the macroeconomic effects of specific regulations.

3. Representation of climate damages and flexibility to incorporate additional information

Although several existing models address both the transition and physical risks of climate change, energy system modeling and studies of climate damages have traditionally been siloed in different academic disciplines meaning that most models focus primarily on one type of risk. Historically, aggregated integrated assessment models (IAMs) used to calculate the SC-GHG have focused most on economic valuation of climate damages while more disaggregated, multi-sector dynamic models (MSDs) have focused on the energy system and generally have not quantified climate change costs.[20]

Given the charge in this work of considering both physical and transition risks, an ideal modeling framework would be able to assess the macroeconomic effects of both risks. In addition, given the particular context of this work, damages within the United States that affect the drivers of macroeconomic growth are especially important. The flexibility to integrate additional detail and information on these types of damages from outside analysis will be a necessary capability.

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[19] Carbon pricing and clean energy subsidies also differ in their effects on government financial flows, which can affect the macroeconomic outcomes of climate policy. Carbon pricing schemes do not involve direct government spending and can, depending on details of design, raise revenue. Prior modeling studies have shown that the ways revenue is returned into the economy can substantively affect macroeconomic costs of the policy (Goulder and Hafstead 2013; McFarland et al. 2018). A subsidy-based approach instead relies on government spending that must be paid for by increased revenue, debt-issuance, or spending cuts elsewhere that could all have macroeconomic effects. For instance, clean energy subsidies in the IRA are paired with increases in the corporate income tax and improved tax enforcement that could result in net deficit reduction, which could have subsequent macroeconomic effects, though these have been estimated to be small (Penn-Wharton Budget Model 2022).

[20] Aggregated IAMs used to calculate SC-GHG include DICE, PAGE, and FUND. Process-based IAMs include GCAM and IGSM-EPPA, and are sometimes referred to as multi-sector dynamic models (MSDs). For a discussion of the distinction between aggregate and process-based IAMs see Weyant (2017) and Wilson et al. (2021)

Desirable attributes

4. Produces results at a sub-national level within the United States

The effects of both the energy transition and climate change will be felt unequally across the United States (Hsiang et al. 2017; Grubert 2020; CEA 2022, 221–249). Programs such as the Justice40 initiative (White House 2022a) and provisions within the IRA directing benefits towards particular, disadvantaged localities are designed to address the disparate effects of climate change and the energy transition within the United States. Improving capacity within the U.S. government to analyze the regional and distributional, as well as aggregate, effects of climate policies is a high priority. Therefore, although the Budget's economic assumptions only project U.S. economic activity at the national level, a modeling framework that allows representation of sub-national effects is desirable for general analytic capability and policy formulation. Physical and transition risks are thought to have larger effects on lower-income groups, as they have higher vulnerability than higher-income populations (Dennig et al. 2015; EPA 2021). Therefore, desirable disaggregation would not only be for spatial and political units (i.e., States or regions within the United States), but also be by income groups within sub-national regions.

5. Includes capital and labor frictions

Meeting the Administration's commitment to net-zero greenhouse gas emissions by 2050 will require one of the largest and fastest transformations of the U.S. energy system in history. Ultimately a carbon-free energy system could yield large benefits in the form of lower energy costs, reductions in air and water pollution, and improvements in health in addition to a stable climate. However, as we transition to this new equilibrium, many forces will have important implications for macroeconomic dynamics over the next few decades (Roy et al. 2022). The current energy infrastructure constitutes a large stock of capital. Unplanned or premature retirement of existing infrastructure (i.e., asset stranding) can create unexpected costs for asset owners (Fofrich et al. 2020). In addition, to the extent the path of the energy transition or future climate policy is uncertain, investors may under-invest in energy infrastructure generally, potentially leading to shortages and higher prices. Labor markets can exhibit frictions if the locations or skill-sets required in new jobs do not match those in declining industries, producing temporary increases in unemployment as workers take time to search for or retrain for other jobs (Hafstead et al. 2022; Greenspon and Raimi 2022; Hanson 2023). Such labor-market frictions could also delay the deployment of new energy infrastructure, which would impede the energy transition. Given the anticipated speed of the energy transition and the importance of understanding capital and labor dynamics for macroeconomic forecasting, the ability to model these dynamic frictions is highly desirable.

6. Model is open-source and peer-reviewed

Openness and transparency are important to generating confidence in government analysis and enabling equitable participation in public processes. The Administration is committed to principles of open government (White House 2022b). Models used for climate, energy, and macroeconomic analysis vary substantially in their degree of openness. Public accessibility is not a binary measure: for instance, model equations may be publicly documented, but the datasets or software required to run the model may require licenses. While proprietary models may by necessity play a role for some government applications, public accessibility and peer-review is a desirable criterion.

F. Models Considered

Through discussions with the ITWG, CEA, and OMB identified a set of models that meet many of the essential and desirable criteria. These models are described below, along with some considerations about the ways in which they can and cannot address the criteria required to inform Budget projections. We then provide a table summarizing the performance of models with respect to the criteria identified above (Table 4).

E3ME (Energy-Environment-Economy Macro-Econometric model)

E3ME is a macro-econometric model developed by Cambridge Econometrics. E3ME estimates economic activity, energy supply and demand, emissions, and trade for 61 regions worldwide (including a single U.S. region) across 43 industries. The model relies on top-down, empirically estimated econometric equations to simulate the behavior of sectors and households. To address energy and technology transitions not represented in the historical data, E3ME links to bottom-up, technology-specific economic diffusion models for key sectors such as electricity supply, passenger vehicles, household heating, and steel production.

E3ME is demand-driven such that supply adjusts to meet demand, subject to labor and capital constraints. E3ME endogenously models voluntary and involuntary unemployment. A unique attribute of E3ME is that it allows for unused labor and capital resources to be deployed under certain policy and economic conditions. For example, in some cases, regulation can increase short-run investment, output, and employment. E3ME also represents research and development (R&D) through a knowledge stock, which allows for spillovers. State-level detail may be obtained by downscaling national results from the E3ME global model using the 50-State E3-US model.

EPPA (Emissions Prediction and Policy Analysis Model)

EPPA is an open-source CGE model of the world economy developed by the MIT Joint Program on the Science and Policy of Global Change. EPPA simulates the human dimensions—economics, demographics, and trade—within MIT's Integrated Global System Modeling (IGSM) multi-sector dynamic modeling framework that aims to analyze the complex interactions with the MIT Earth System Model. EPPA is a recursive-dynamic (i.e., myopic) model with 18 regions globally (including a single U.S. region) and 16 sectors (8 energy, 8 non-energy). The model projects economic activity and energy system transitions as well as CO_2, non-CO_2, and criteria air pollutant emissions.[21] EPPA's recursive-dynamic framework allows for more regional, sectoral, and technological detail at the expense of omitting forward-looking behavior.

In EPPA, population and total factor productivity (TFP) growth vary across regions and sectors, but are exogenous. Labor markets in EPPA do not exhibit frictions. However, EPPA employs capital market frictions through capital vintaging, using the so-called putty-clay formulation. In this formulation, new capital within a sector may substitute with other factors. However, existing capital is largely sector-specific with fixed input proportions. Notably, the MIT Joint Program has other complementary models including the USREP (U.S. Regional Energy Policy) Model, a recursive-dynamic model that represents individual States, multi-State regions, and up to nine household income groups.

GCAM (Global Change Analysis Model)

GCAM is an open-source global multi-sector dynamics model developed by the Pacific Northwest National Laboratory. GCAM includes a typical energy–economy model that integrates regional information on land, population, and current technology, as well as the supply and demand of various resources (energy sources, water, crops, livestock, forests), and expands on this by also including a climate module that tracks emissions and concentrations of a rich set of greenhouse gases and provides estimates of associated climate impacts (limited to agriculture and energy demand). GCAM prioritizes computational tractability by using recursive-dynamic solving to solve all resource markets simultaneously.

GCAM's economic module begins with exogenous projections of population, labor force participation, labor productivity growth rates, and base-year GDP. It then produces estimates for future values of GDP, commodity prices, energy use, land use, water use, and greenhouse gas emissions for each of its regions, as well as global greenhouse gas concentrations. As the key labor variables in GCAM are exogenous, it cannot speak directly to the sensitivity of climate-affected economic assumptions in the President's Budget. However, a more robust macro module is under active development. Recent updates to GCAM allow it to represent a wide range of climate policies, from emissions pricing to subsidies to low-emission technologies, though behavioral changes induced by these policies do not induce second-order changes in relative technology costs. Notably, a derivative version, GCAM-USA, expands on GCAM by separately modeling the energy and economic systems of the 50 States and Washington, D.C.

G-Cubed

G-Cubed is a hybrid DSGE (dynamic stochastic general equilibrium)[22] and CGE model developed by Warwick McKibbin and Peter Wilcoxen since the mid-1980s. G-Cubed integrates both emissions and energy data and is distinct from a number of other models in that it handles financial and physical capital separately (which differ greatly in terms of their mobility). Despite being a

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[21] Criteria air pollutants (e.g., ozone and carbon monoxide) are the pollutants subject to EPA's National Ambient Air Quality Standards, as directed by the Clean Air Act.

[22] DSGE models are standard macroeconomic tools to capture the general equilibrium responses of the economy to shocks.

forward-looking intertemporal model, G-Cubed is able to represent uncertainty and errors in the formation of expectations. This prevents the macroeconomy in G-Cubed from responding to policy changes in an unrealistically fast manner; rigidity is also provided by nominal wage stickiness, short-run inflexibility of physical capital, and the imposition of monetary and fiscal rules on model agents. These features, and the model's rich micro-foundations, allow G-Cubed to more fully specify the intertemporal evolution of investment and savings, improving the consistency of its representation of the transition between the short- and long-run time horizon. Notably, a number of variants of the model have been developed that trade off computational tractability with aggregation or disaggregation across regions and sectors. Recent versions of the model have also integrated some climate change impact pathways (Fernando et al. 2021).

SAGE (SAGE is an Applied General Equilibrium model)

SAGE is an open-source CGE model of the U.S. economy developed by a team at the EPA starting in 2017.[23] SAGE is resolved at the subnational level, with each of the four U.S. Census Regions represented by five types of households reflective of national income quintiles and 23 types of firms reflective of the national economy.[24] In SAGE, the United States functions as a large open economy, meaning changes in the United States can affect the global market with which the U.S. trades. SAGE is a forward-looking intertemporal model with perfect information, so its modeled agents know exactly how their decisions will impact the future. In SAGE, population and productivity growth vary across regions and sectors, but are exogenous.

When CGE models are used to analyze the effect of particular policies, they may exhibit instantaneous reallocation toward a new equilibrium that overstates the rate at which the economy can change. To avoid this, SAGE differentiates the flexibility of capital reallocation by its vintage: existing capital can only be reallocated with sufficiently strong price signals, while new capital is substantially more flexible (i.e., a partial putty-clay dynamic). As currently specified, labor markets in SAGE do not exhibit frictions and SAGE does not model greenhouse gas emissions, air pollution, or associated climate damages.

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[23] The source code and all data needed to run the SAGE model are publicly available, though some of the underlying source data used in building the model are not publicly available.

[24] Overall output employs a nested constant elasticity of substitution production function, with greater disaggregation in the energy and manufacturing sectors.

Table 4: Model Framework Criteria

Characteristics	*E3ME*	*MIT-EPPA*	*EPA SAGE*	*G-CUBED*	*GCAM*
Purpose	Energy and environmental policy modeling	Energy and environmental policy modeling	Regulatory analysis	Macroeconomic modeling	Energy/water/land and environmental policy making
Model type and solution method	Macroeconometric; simulation	CGE; recursive dynamic optimization	CGE; fully dynamic optimization	CGE and DSGE; fully dynamic optimization	Multi-sector dynamics model; dynamic recursive optimization
Scope - spatial and sectoral	43 industries; 61 regions worldwide with single U.S. region	16 sectors (8 energy; 8 non-energy); 18 regions worldwide with single U.S. region	23 sectors (5 energy; 12 manufacturing); 4 sub-U.S. regions and 1 for the rest of the world	20 sectors (5 energy; 8 electricity; 7 non-energy); 10 regions worldwide with single U.S. region	32 regions worldwide with single U.S. region
Essential Features	*E3ME*	*MIT-EPPA*	*EPA SAGE*	*G-CUBED*	*GCAM*
1. Produce macroeconomically relevant variables related to labor, capital and productivity	Yes, it has a macro-econometric framework.	Yes, it is a micro-founded CGE model.	Yes, it is a micro-founded CGE model.	Yes, it is a structural global model combining CGE and DSGE frameworks.	Presently no, energy- and agricultural commodities only. Integration of a macro framework in progress.
2. Ability to represent current U.S. climate policy approach	Yes, can introduce subsidies, has learning curves; R&D represented	Yes, can include subsidies and regulation. Includes	Partly, includes taxes, subsidies, and regulation. No learning	No, primarily just a carbon price. Some representation of	Yes, can represent technology-specific subsidies, tax credits,

	through knowledge stock.	endogenous learning effects in standard model.	curves in standard model.	technology change via changing catch-up rates across countries and has sector-specific productivity.	performance standards. Can capture technology change from investment decisions and through capital investment-retirement dynamics.
3. Representation of climate damages and flexibility to incorporate additional information and improve climate damages	No representation of physical damages in default model, but could be introduced exogenously.	Some damages already incorporated through Earth System (IGSM) - EPPA linkages; in process of developing more linkages.	No representation of physical damages in default model, but could be introduced exogenously.	Recent versions include agricultural, sea-level rise, labor productivity, disease, and extreme-event impacts.	No representation of physical damages in default model, but could be introduced endogenously for agricultural and energy systems and exogenously for other impacts.
Desirable Features	*E3ME*	*MIT-EPPA*	*EPA SAGE*	*G-CUBED*	*GCAM*
4. Produce results at a sub-national level for the United States	No, but E3-US can do State-level.	No, but MIT-USREP can do State-level and up to 9 income classes.	Yes, has four regions and five income groups.	No, the United States is a single country.	No, but GCAM-USA can do State-level.

5. Include capital and labor frictions	Not endogenously, though some frictions in historical relationships within framework.	Capital frictions captured in putty-clay capital framework; labor frictions are not.	Capital frictions captured in putty-clay capital framework; labor frictions are not.	Yes, short-run unemployment with restrictions on labor mobility and capital adjustment costs.	No, no current macro framework.
6. Open-source and peer-reviewed	Peer reviewed; documentation describes model in detail, but code not publicly available; input data not fully public.	Peer reviewed; documentation describes model in detail; code for past version publicly available; input data not fully public.	Reviewed by EPA Scientific Advisory Board; model code—but not solver (GAMS)—publicly available; input data not fully public.	Peer reviewed; model code—but not solver (proprietary) —publicly available; input data not fully public.	Peer reviewed; all model code and input data open-source.

G. Model Evaluation

Table 4 shows the variety of modeling platforms able to inform questions of how the energy transition and climate change impacts affect the macroeconomy. The models show variation in their fundamental design and therefore the phenomena they are able to represent. For instance, MIT-EPPA and EPA SAGE are both CGE models. As a class of models, these are designed to examine the economy-wide, equilibrium effects of policy or other changes. They excel at modeling the economic interconnections that produce adjustments across multiple sectors in response to shocks. They are not, however, able to simulate the pathway of adjustment as the economy transitions to a new equilibrium. E3ME and G-Cubed in contrast are able to simulate transition dynamics: E3ME because it is driven by statistical relationships in historical time-series, and G-Cubed because of its DSGE components. An additional fundamental difference between the models is the degree of agent foresight and technological detail. GCAM and MIT-EPPA are myopic models; their agents optimize one period at a time without taking into account the effects of their current decisions on future outcomes. However, they have relatively more technological detail, allowing representation of more decarbonization options. In contrast, EPA SAGE and, to some extent, G-Cubed are forward-looking models in which agents optimize over all time periods[25]—a useful feature when representing decisions about long-term issues and long-lived capital assets.

The models also show a range of desirable features for the purpose of integrating climate within the economic assumptions of the President's Budget. For instance, EPA SAGE resolves multiple geographic regions and income quintiles within the United States, as well as a detailed treatment of the U.S. tax system, valuable for understanding tax interaction effects. The DSGE elements of G-Cubed allow it to represent investor behavior under uncertainty and the risk premia associated with climate policy or impact uncertainty. GCAM has detailed representation of the energy system and mitigation technologies, while E3ME and G-Cubed have more stylized energy systems that capture economic dynamics but not necessarily the details of specific technologies.

Table 4 also reveals general limitations across modeling platforms, for our purposes. Given the importance of labor-market variables in driving the macroeconomic forecast (see Figure 3), it is notable that only G-Cubed includes explicit representation of short-run labor market frictions.[26] This is a known weakness of CGE models, which generally assume full employment and are therefore not able to simulate the economic processes that produce involuntary unemployment (Hafstead et al. 2022). In part, this is a reflection of the equilibrium nature of these models; over the typical time-step used in CGE models—five years—critical policy-relevant labor market frictions can form and dissipate.

The models also show general weaknesses in the representation of physical climate risks, with only MIT-EPPA and G-Cubed integrating a limited set of climate change damages in the default

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[25] G-Cubed represents expectations using a mixture of forward-looking and myopic agents.

[26] E3ME may implicitly include some effects based on historical relationships due to the macro-econometric nature of the model.

model. This is reflected by the fact that the primary application of most of these frameworks has been to understand energy-system transitions, not to estimate damages from climate change. Most models, however have sufficient flexibility to model the macroeconomic effects of climate damages if information on sectoral productivity, capital, or labor effects could be provided into the model.

The first row of Table 4 highlights that the most of these models' purposes are very distinct from the climate/ macroeconomic forecasting we are interested in. Good model development entails crafting the framework to suit the specific needs of the exercise. The criteria on which we are evaluating these models can differ substantially with those pertinent for these models' intended use. Consequently, the limitations we highlight are only limitations for our ability to repurpose these models, not for what these models were originally designed for.

3. Next Steps

In order to meet the directions of EO 14030 to develop methodologies for the integration of climate risks within the economic assumptions and long-term projections of the President's Budget, CEA, OMB, and the ITWG will proceed on a two-track approach. In the near-term, we can draw on the most applicable and high-quality set of resources within the U.S. Government to provide an initial assessment of both the physical and transition risks of climate change in the economic assumptions over the 10- and 25-year Budget windows.

On the transition-risks side, GCAM has a rich representation of the global energy system and provides a valuable, open-source framework for understanding the effects of the energy transition. The model plays an important role in U.S. energy planning and has the ability to represent both technology-specific subsidies and regulation via its detailed representation of energy technologies. Scenarios initially developed for the U.S. Long-Term Energy Strategy (U.S. Department of State and EOP 2021) adjusted to account for the effects of the Inflation Reduction Act could be used as a basis for exploring policy effects. Macroeconomically relevant variables that GCAM produces include energy prices and energy productivity, as well as capital-related variables such as investments and plant retirements. In addition, GCAM model developers are in the process of building out the integration of the energy system with the macroeconomy that will provide additional macroeconomically relevant variables.

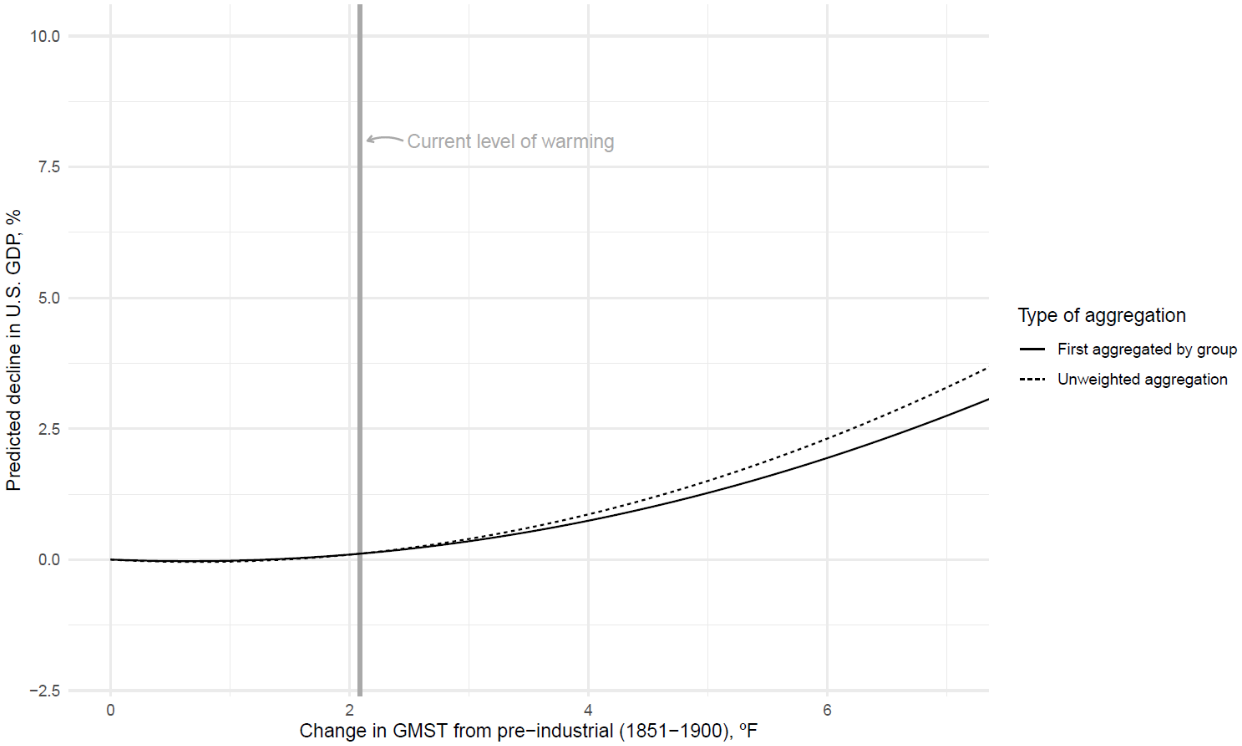
On the physical-risks side, existing work at EPA could be combined with other estimates from the academic literature of climate change effects on key macroeconomic variables (specifically population, labor supply, and productivity), as well as relevant information in the National Climate Assessment (USGCRP 2018) and from the U.S. Global Change Research Program more generally.

These near-term opportunities to quantify transition and physical risks over the 10- and 25-year Budget timeframes would not analyze physical and transition risks in a fully integrated framework but could nevertheless be organized to ensure comparability. For instance, consistent emissions-temperature scenarios representing U.S. emissions reduction commitments as well as comparable commitments from the rest of the world would ensure some consistency. Combined information from these the physical and transition risk workstreams could be provided as input to the Troika process for development of the economic assumptions.

Over the medium-term, partnership with other modeling groups, such as one or more of those described above, would further improve the ability to quantify macroeconomic climate risks, including integrating physical and transition risk factors and examining the sub-national distribution of impacts. CEA and OMB are exploring ways to further build this capacity for the analysis of macroeconomic risks to the United States.

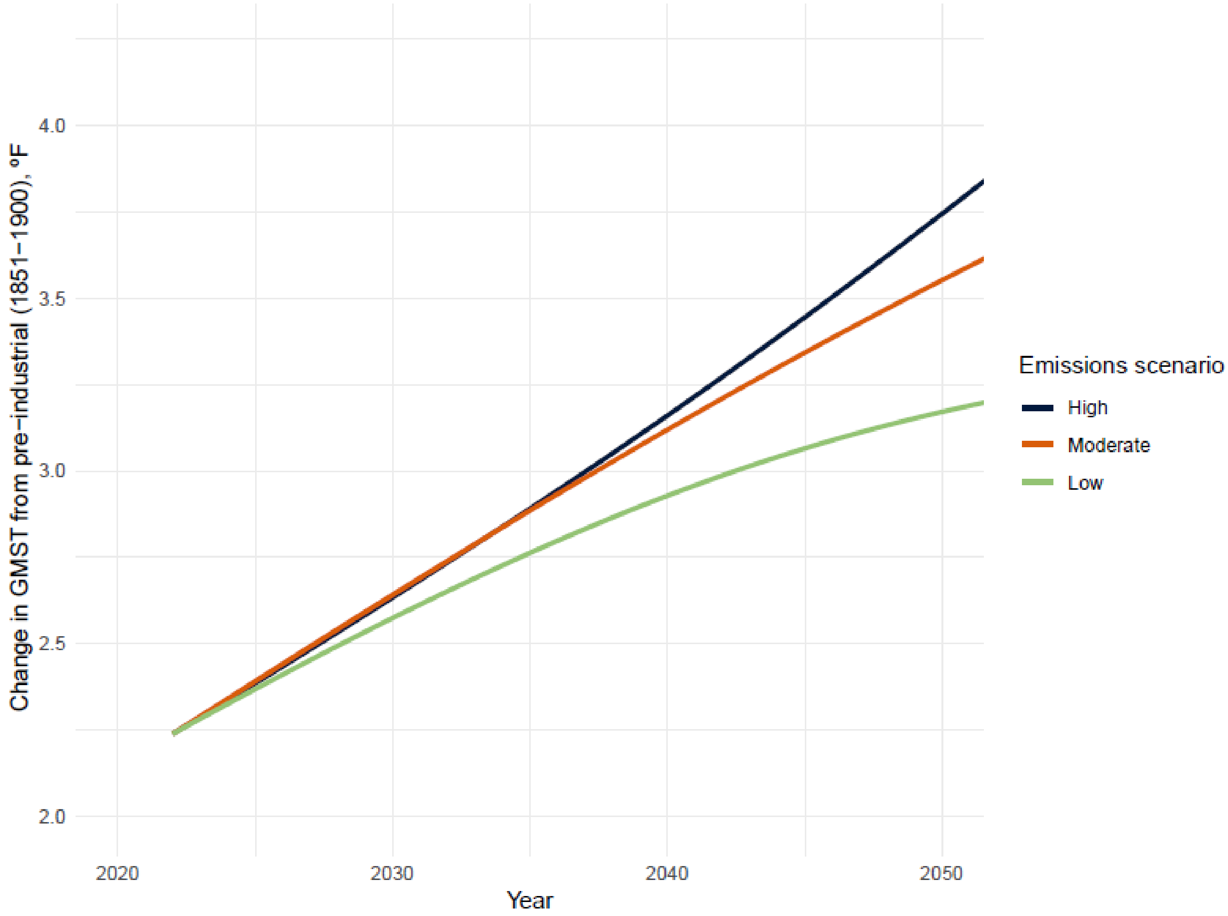
Appendix

Appendix Figure 1: Aggregate Damage Functions using Different Aggregation Methods



Note: Dotted line shows the aggregation across studies using an equal weighting for all papers (black line in Figure 1). Solid line shows an alternate weighting scheme that places equal weight on the three different methodologies (top down econometric, bottom-up enumeration, and CGE).

Appendix Figure 2: Changes in Global Mean Surface Temperature resulting from Different Emission Scenarios, Relative to a Pre-Industrial (1851–1900) Baseline



Note: Projected changes in global mean surface temperature (GMST), relative to the pre-industrial (1851–1900) global average temperature, under three greenhouse gas emission scenarios by a subset of the latest climate models (CMIP6). By 2022, GMST had already increased by about 2.2 degrees Fahrenheit relative to its pre-industrial level.

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