# Multi-Scale Economic Methodologies and Scenarios Workshop


**August 2016**

Report of a workshop on April 20-21, 2016, organized under the auspices of the Scenarios and Interpretive Science Coordinating Group, U.S. Global Change Research Program, and sponsored by the U.S. Department of Energy and U.S. Environmental Protection Agency

Prepared by ICF International under contract to EPA | Contract Number EP-C-14-001

U.S. Global Change Research Program

## Disclaimer

# Acknowledgements

The U.S. Global Change Research Program (USGCRP) Scenarios and Interpretive Science Coordinating Group (SISCG) would like to thank the Scientific Leads and participants for contributing their time and expertise to the workshop. This report reflects their invaluable contributions. The SISCG would especially like to thank Jae Edmonds and Richard Moss for their help in organizing and leading the workshop sessions. The SISCG is grateful to the Oak Ridge Associated Universities team for their logistical support. We extend sincere gratitude to the ICF International author team, led by Jessica Kyle and Frances Sussman, for their assistance in developing the workshop report. Finally, the SISCG would like to express a special thanks to Alison Delgado for her help in coordinating the workshop and report development process.

## About the Scenarios and Interpretive Science Coordinating Group

The U.S. Global Change Research Program's (USGCRP) mission is "to build a knowledge base that informs human responses to climate and global change through coordinated and integrated federal programs of research, education, communication, and decision support" (USGCRP, 2014). Within USGCRP, the goal of the Scenarios and Interpretive Science Coordinating Group (SISCG) is to build a foundation for a science-based scenario enterprise that responds to shared agency needs for quantitative and qualitative scenarios-related products. In particular, the SISCG aims to:

- Advance collaborative science on critical gaps.
- Enhance methodologies for use-inspired scenario development, risk framing, and contextual interpretation.
- Develop the next generation of scenario work products for model inter-comparisons, assessments, and analyses, including coordinated uses such as for the National Climate Assessment (NCA), Intergovernmental Panel on Climate Change (IPCC), and the Coupled Model Intercomparison Project (CMIP).
- Improve interagency communications, coordination, and accessibility to knowledge, work products, and technical resources.

As part of its ongoing efforts, the SISCG is conducting a series of workshops to elicit expert opinion on the state of the science and for further defining long-term needs for the science. In the near term, one of the SISCG's top priorities is to better understand the human dimensions of climate and global change scenarios.

# Table of Contents

# Exhibits

# Executive Summary

The impacts of climate change on the United States depend not only on the rate and magnitude of climate change, but also on the evolving socioeconomic landscape. Changes in technology, economic growth, institutions, lifestyles, and policy will all affect our ability to limit climate change effects and the effectiveness of adaptive and other responses. Thus, the availability of a consistent set of forward-looking economic scenarios for the United States is an important component of research and policy efforts to model, understand, and assess evolving impacts, the interactions of human and physical systems, and response options, in both the near and long terms.

Despite their potential importance, however, economic scenarios at fine geographic scales and for the very long term needed to analyze climate effects are not widely available; moreover, available economic scenarios do not take into account the effects of extreme events or provide probabilities or uncertainty information regarding the scenarios. (See Exhibit 1 for a definition of the term "scenario.") In addition, for Integrated Assessment (IA) and Impacts, Adaptation, and Vulnerability (IAV) models, scientifically defensible projections of economic variables are increasingly critical for analyses of alternative mitigation scenarios—that is to say, scenarios for reducing greenhouse gas (GHG) emissions over time. Similarly, projections of economic variables are central to understanding and estimating potential damages associated with climate change and the effects of adaptive responses.

To address the need for economic scenarios, the SISCG convened the Multi-Scale Economic Methodologies and Scenarios Workshop in College Park, Maryland, on April 20 and 21, 2016. The workshop was coordinated and supported by member agencies, co-sponsored by Robert Vallario of the U.S. Department of Energy and Anne Grambsch of the U.S. Environmental Protection Agency, and chaired by Jae Edmonds of the Joint Global Change Research Institute. The workshop brought together 28 experts, who collectively represented an array of relevant disciplines and professional affiliations, and possess expertise in key topics such as climate impact assessment, economic modeling, integrated assessment modeling, decision analysis, and uncertainty analysis. Background materials distributed to participants in advance of the workshop helped to frame key issues for the workshop discussions, and short presentations throughout the workshop provided additional content.

The workshop had several objectives. For the longer term, an objective was to identify necessary research that would allow the development of a fully realized integrated system of scenarios, with interactions and feedbacks between physical and economic domains and across sectors, and developed at fine geographic and long temporal scales. It was also an objective of the workshop to identify immediate and intermediate steps that could be taken in support of the longer term research goal. In addition, a key objective was to consider the character of economic scenarios that are needed for assessments and to develop a strategy for leveraging currently existing data, models, and analytical methods to develop viable and defensible scenarios in the short term.

These objectives were reflected in the four key discussion questions that were posed to participants:

1. What are the needs of potential users of economic scenarios?

2. What are the current capabilities for meeting user needs for economic scenarios?

3. What might a long-term research agenda look like?

4. What is a viable short-term path forward to develop economic scenarios for assessments and other uses in research?

A workshop session was devoted to each of these multidimensional questions, providing considerable insight into each question. During the discussion, participants voiced a diverse set of perspectives, touching on a range of themes (See Section 2 of this report for additional information on the discussion). Topics that were discussed included:

- ***The "Wants" of the User Community:*** The diverse uses of economic scenarios by the members of the user community, which includes both researchers and policy makers at all levels of government and in the private sector, and the similarly diverse set of desirable scenario characteristics and temporal, spatial, and sectoral scales.
- ***Data:*** Existing sources of data and the potential for developing high-quality data at the level of detail needed to support the development of models and analytical methods, including new sources of data that might be developed and existing data that could be shared or combined.
- ***Models and Analytical Methods:*** Existing modeling capabilities and analytical methods, limitations and key areas for improvement, and potential pathways and directions for developing and expanding these capabilities and methods over time.
- ***Model Evaluation:*** Methods for evaluating models, both existing models and those being developed, including model comparisons, backcasting (sometimes referred to as hindcasting), and other approaches.
- ***Extremes and Disruptive Events:*** The nature, sources, and potential for extreme and disruptive events occurring in the economy, in technological developments, in other socioeconomic systems/features, or in the natural and physical world (including climate and weather patterns), as well as the potential importance of these events to decision-making and assessment.
- ***Uncertainty Characterization:*** The drivers of uncertainty in economic scenarios and economic futures; ways to characterize, represent, and analyze uncertainty; and decision making under uncertainty spanning both the human and natural systems.
- ***Feedback Effects and Co-evolving Trends:*** Complexities and interactions between and among human and natural systems, the potential for capturing these with models and methods, and the co-evolution of economic scenarios with other domains.
- ***Scenario Development for the United States:*** A viable process for developing meaningful economic scenarios for the United States that are tailored to U.S. conditions and the needs of the user community.

Key insights that arose during the discussion of these themes are clustered below, roughly following the first two questions identified above: Users and User Needs, and Tools and Resources.

***Users and User Needs.*** Many participants pointed to the diversity of the user community—ranging from city planners to integrated modelers and researchers—and suggested a similar diversity of potential user needs. Some participants suggested that these needs will vary depending on the local, regional, and sectoral context and the types of analysis or decisions that are being made, and will also reflect considerations of timing and cost. Consequently, scenarios that are tailored to the needs of U.S. decision makers and researchers, and reflect local and regional conditions and knowledge, may need to be developed both at finer spatial scales and over longer time periods than currently available scenarios (such as the "Shared Socioeconomic Pathways" (SSPs)).[1] A few participants suggested that overlap among user needs may make it possible to develop a smaller set of user types; scenarios designed around this typology could provide the foundational information for researchers and other users of scenarios. Many participants noted that a need is emerging for scenarios that provide usable information about a wide range of potential disruptive/extreme events, along with trained science interpreters who can help navigate the available information on risks and uncertainty. One participant also pointed out that although scenarios are often thought of as a data product, they can also be a service.

***Tools and Resources.*** Data, models, and analytical methods together comprise the means for producing economic scenarios that serve user needs, as well as the means for using these scenarios in assessments and other research efforts. Many participants identified issues with existing tools and resources. First, while user needs range across multiple dimensions, the available data collected by academics, government agencies, and other organizations are often collected in varying units, with varying definitions, and at differing spatial and temporal intervals. Given the need for information across multiple dimensions and scales, some participants identified an associated need for the development, documentation, and dissemination of publicly available and reconciled data sets. A few participants also noted that quantitative products from research models and analytical results that use scenarios as inputs are also "data," and need to be archived, documented, and made available for use.

Second, many participants discussed existing models and analytical methods, the potential for developing new capabilities that better serve user needs, and what those new capabilities might look like. Some participants identified changes that would be beneficial to the current economic models that provide quantitative scenarios as outputs, including the importance of incorporating the lessons of behavioral economics and other advances in economic theory into these models. A few participants also noted the importance of model validation, and of methods such as hindcasting that are infrequently or inconsistently applied to economic models. A few participants noted that it is unrealistic to expect a single economic model to meet the needs of all users, since different types of models and even different functional forms within model types have their own strengths and weaknesses in terms of modeling the future. In addition, some participants discussed possibilities for developing complex and integrated models that incorporate linkages and feedback effects across sectors, economic regions, and physical and human systems, and that span multiple scales. Some participants identified the challenges of

[1] Developed through an international process, the SSPs are described as "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies" and consist of two elements: a narrative storyline and a limited set of variables (including GDP) that have been quantified at a national-level. For more information see: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/parallel_nat_scen.html

developing and deploying a multi-scale, multi-model capability, such as the difficulty of developing multi-sector and multi-scale computational architectures capable of coupling models. Some participants also noted the difficulty of effectively communicating and reconciling information across models and scales.

***Beyond the Workshop.*** During the discussion, many participants provided insights into the third and fourth workshop questions. Participants at the workshop identified a number of directions along which data, models, and analytical methods could be improved in order to develop economic scenarios that might better serve the user community. (See Section 3 of this report for additional discussion of these ideas.) Specifically, many participants identified viable opportunities and important next steps as well as potential longer-term research goals and activities that could productively be pursued. The ideas expressed at the workshop are clustered below into three groups: immediate opportunities (i.e., in the next year), intermediate-term opportunities, and fundamental science challenges.

- ***Immediate opportunities:*** Suggestions from some participants included reviewing available economic data and scenarios in order to identify scenarios that might be immediately available to support the upcoming Fourth U.S. National Climate Assessment (NCA4) and related or similar research and assessment efforts. Other suggestions included providing guidance on the use of qualitative scenarios (such as storylines), and on the application and limitations of economic scenarios. A few participants also identified steps that can be taken in the near term to begin to build a foundation for longer-term actions, including starting to reconcile economic data across diverse sources, and identifying classes of problems that use different types of scenarios, including scenarios that support risk framing and the incorporation of uncertainty into analysis.
- ***Intermediate-term opportunities:*** Several participants suggested opportunities for research and the enhancement of data, models, and analytical methods that could move the development of economic scenarios forward in several key directions. First, several participants suggested that it is important to develop a better understanding of the drivers of economic results and the implications of using different types of economic models through model evaluation, possibly including model comparison projects and expert elicitation. Second, several participants indicated that data, models, and methods can be enhanced and improved in the intermediate term by, for example, exploring uncertainty and decision making, identifying opportunities for combining scenarios with formal uncertainty analysis, revisiting the underlying drivers of economic growth, and developing scenarios and other information that focuses on tipping points and extreme events. Last, a few participants identified the opportunity to begin developing synthesized products that conform to community standards for both the data underlying models and scenarios and the outputs produced by models.
- ***Fundamental science challenges:*** A number of participants described the challenges to developing economic scenarios at the spatial and temporal scales identified as important to the user community, that possess other desirable characteristics (such as the types of variables included or the sectors covered), and that reflect the realities of how the economy functions and co-evolves with other systems over time. A number of these challenges involve model development, e.g., developing computational platforms that can accommodate multiple interoperable models, validating or understanding the behavior and usefulness of coupled modeling systems, and incorporating feedback effects and co-evolution of human and physical earth systems into complex modeling systems. Some participants identified challenges to developing scenarios for extreme events that are scientifically

defensible and believable, but also are informative for decision makers and can be appropriately communicated to potential users. Some participants identified the importance of building the community of practice for integrated assessment researchers and modelers, which could ultimately produce standards and protocols (e.g., protocols that define inputs and outputs), a common language across disciplines, and enhanced core capabilities and tools.

# 1 Context, Goals, and Organization of the Workshop

## 1.1 Workshop Process and Goals

The USGCRP's SISCG convened the *Multi-Scale Economic Methodologies and Scenarios Workshop* in College Park, Maryland, on April 20 and 21, 2016. The workshop was coordinated and supported by USGCRP member agencies, including the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA). Acknowledging the need for a coordinated, multidisciplinary effort across the fields of climate change and economics, the SISCG planned the workshop in consultation with researchers at the Pacific Northwest National Laboratory. The workshop was co-sponsored by Robert Vallario of DOE and Anne Grambsch of EPA, and chaired by Jae Edmonds of the Joint Global Change Research Institute. (Appendix A lists members of the committees involved in workshop development.)

The objectives of the workshop reflected both near- and long-term goals for developing scenarios, and the diverse aims of scenario users and ongoing climate research and assessment in the United States. For the longer term, the objective was to identify research that would allow the development of a fully realized integrated system of scenarios, with interactions and feedbacks between physical and economic domains and across sectors, developed at geographic and temporal scales of interest. (See Exhibit 1 for a definition of the term "scenario.") The workshop also sought to identify immediate steps that could support the longer term goals. For the near term, the objective was to identify opportunities, using existing methods and models, to find a possible path toward developing economic scenarios that are scientifically defensible and are independent of—but consistent with—other scenario efforts.

The overarching science question with which workshop participants grappled was:

> *How might the economic character of the United States evolve at time scales ranging from annual to decadal, at spatial scales ranging from national to local, and taking into account the multitude of drivers and stressors that could shape the path, e.g., climate change, demographics, migration, and technology?*

To consider this multi-dimensional question, the workshop brought together 28 experts (listed in Appendix C). Participants were chosen to represent an array of relevant disciplines (including economics, geography, engineering, and climate and other physical sciences), and a range of professional affiliations (including government, consulting, and academic and other research institutions). Participants' expertise spanned a number of important topics, such as sectoral impacts in water, agriculture, and energy; regional economics; economic modeling; integrated assessment modeling; scenario development; and decision analysis, risk analysis, and uncertainty analysis. Background materials were distributed to participants in advance of the workshop to help frame key issues for the workshop discussions. (Appendix E contains these background materials.)

This workshop report will serve as a technical input to the SISCG for strategy formulation and research planning.

**Exhibit 1. Characterizing the Future**

The Intergovernmental Panel on Climate Change (IPCC) has developed a typology of terms for describing future characterizations, including *scenario*, *storyline*, *projection*, and *probabilistic futures*. The terms reflect typical usage in climate change impact, adaptation, and vulnerability studies. They describe a range of approaches to describing plausible futures, with one key difference among the approaches being the extent to which probabilities are ascribed to the future. This typology and the figure below were not developed specifically for economic futures, but are indicative of the dimensions along which different types of futures can vary.

The IPCC definitions, with clarifications added from other sources, are given below.

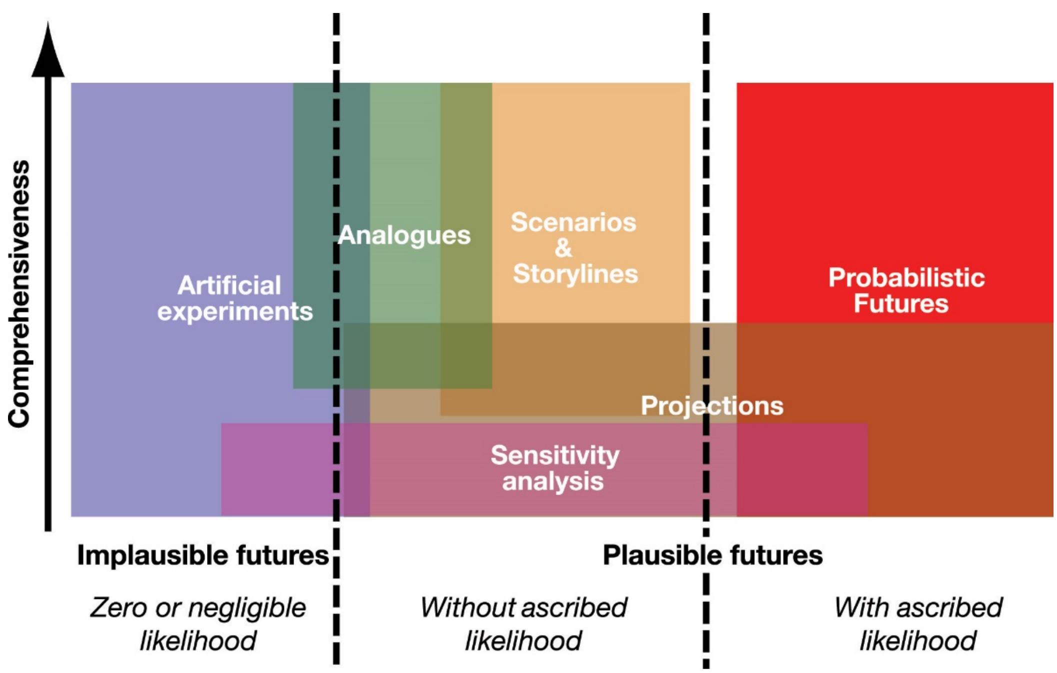
**Scenario** is a coherent, internally consistent, and plausible description of a possible future state of the world, which may be quantitative, qualitative, or both. The components of a scenario are often linked by an overarching logic, such as a storyline that represents a qualitative, internally consistent narrative of how the future may evolve.

**Storylines** describe the principal trends in key drivers and relationships among these drivers. Storylines may be stand-alone, but more often underpin quantitative projections.

**Projection** is any description of the future and the pathway leading to it. In the climate world, projections are often model-derived estimates of future conditions for an element (such as population) of an integrated system. Projections are generally less comprehensive than scenarios. Projections may be probabilistic, while probabilities are not ascribed to scenarios.

**Probabilistic futures** are futures with ascribed probabilities. Conditional probabilistic futures are subject to specific underlying assumptions. Assigned probabilities may be imprecise or qualitative, as well as quantitative.

A **prediction** or **forecast** is a statement that something will happen in the future, based on what is known today, and on the initial conditions that exist. An important part of a prediction is our degree of belief that it will come true.




*Sources:* Carter et al., 2007; Solomon et al., 2007; Weaver et al., 2013.

## 1.2 Workshop Agenda and Format

The workshop was held over two days; see Appendix B for the workshop agenda. The first day began with an opening session on the drivers, needs, and broader context for economic scenarios; background on the SISCG and NCA scenario strategy; and brief introductions to the goals and format of the workshop. Following the opening session, the workshop was organized into four sessions, as described further below.

Each of the four sessions opened with short presentations or brief comments, followed by dialogue around key issues and topics. Presentations and discussions were guided by a set of questions that were developed and distributed prior to the workshop. (Appendix D provides these questions.) Sessions 3 and 4 were closed by "round-robin" discussions during which all participants had an opportunity to speak; these discussions resulted in many participants raising a wide range of ideas surrounding alternative uses, development paths, research opportunities, and other features of economic scenarios.

- **Session 1: Use-inspired Needs and Drivers**. The morning of the first day focused on the "demand" side of the scenario development process, exploring what research and assessment questions economic scenarios are intended to inform and what that implies for the character of economic scenarios. The discussion centered on the needs of the IAV community, extending from operations to planning and deep research on long-term systems dynamics.
- **Session 2: Current State of the Art: Process Understanding, Data, Models, and Analytical Methods**. The second session focused on the current understanding of underlying dynamic processes and identifying existing data, models, and methods to deploy in support of near-term assessments—i.e., the "supply" side of the scenario development process. The first mini-presentation offered insights on integrated scenarios, the user context, and scenario development processes for the SSPs[2] and NCA; the second presentation provided background on the USGCRP strategy for scenarios for research and assessment, including information on efforts to develop population and sea-level rise scenarios. Building on these presentations, discussions covered current capabilities in terms of models, methods, and data.
- **Session 3: Current Gaps and Research Needs: A Research Agenda for the Future.** At the end of the first day of the workshop, Session 3 examined gaps that exist between the present capabilities to provide economic scenarios and multi-scale economic projections (Session 2) and the capabilities that the IAV research and assessment community would like to have (Session 1). The discussion focused on ideas for a foundational research agenda that would facilitate improved data, models, and analytical methods.
- **Session 4: Near-term Opportunities: The Nearer-term Challenges of Economic Research, Scenario Development, and Next Steps.** The second day opened with rapporteurs

[2] Developed through an international process, the SSPs are described as "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies" and consist of two elements: a narrative storyline and a limited set of variables (including GDP) that have been quantified at a national-level. For more information see: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/parallel_nat_scen.html

providing a recap of key messages from the first day of the workshop. Then, in this final session, participants considered how to support near-term assessments while laying the foundation for the longer term. The discussion focused on relevant challenges and research opportunities that could be tackled in the very near term (six months).

Although the workshop was convened to share information to inform both near- and longer-term strategies for developing economic scenarios, it is important to note that USGCRP did not expect workshop participants to reach consensus; instead it emphasized the importance of individual contributions and viewpoints.

## 1.3 Structure of the Workshop Report

The remainder of this report is divided into two sections:

- **Section 2: Workshop Summary**. This section provides a narrative of the ideas and discussion across the workshop, organized by key themes.
- **Section 3: Beyond the Workshop**. This section offers perspectives from the participants regarding opportunities and challenges accompanying a near-term path for developing U.S. economic scenarios for use in interdisciplinary analysis of social and environmental issues, and a long-term research agenda for advancing the science for integrated scenarios.

These sections are followed by references cited and five appendices that provide additional information from the workshop.

# 2 Workshop Summary

Over the course of the workshop, participants wrestled with the multidimensional question of economic scenarios, touching on many of the questions listed in Appendix D. The discussions often focused on data, models, and analytical methods, particularly the improvements that need to be made to capture the real-world complexities that shape how the economy grows and changes over time. Discussions also centered on the types of scenarios that would be meaningful for different analyses. Finer geographic-resolution scenarios, extreme events (the tails of the economic distribution), and uncertainty arose as specific areas that are not adequately captured by current scenario approaches. At the same time, these features were identified as core requirements for many types of users—particularly those who are making decisions, such as climate adaptation planners at state and local levels. Discussion touched on the potential for developing new modeling techniques and analytical methods to capture these important attributes, including the application of branches of the economics discipline, such as agent-based modeling, and interdisciplinary work with geographers, urban planners, and other social scientists.

While some participants indicated a need to capture additional facets of the real world with more integrated and comprehensive models and a wider array of scenarios, others pointed out that a "simpler" approach will be more transparent and easier to apply, and in some circumstances may be sufficient for providing robust analytical results. Discussion pointed out the difficulty of communicating and applying these more complex outputs (as well as the practicality of meeting the data and resource requirements to develop them). In addition, some participants noted that the need for near-term and timely results for some user groups would suggest adopting an approach that can be more quickly implemented, taking into account both the characteristics of a scenario and its credibility or reasonableness. The discussion raised a number of ideas about how the scenarios themselves, underlying data sets, and the results of analyses using the scenarios could be clearly communicated and more widely disseminated to the research, policy, and assessment communities.

The discussions at the workshop have been clustered into eight topic areas:

- **The "Wants" of the User Community**—the characteristics of scenarios desired by user groups as inputs into the types of analyses being conducted for assessment, research, and policy purposes.
- **Data**—existing sources of data and the potential for developing high-quality data at the level of detail needed to support the development of models and analytical methods.
- **Models and Analytical Methods**—existing capabilities and pathways and goals for developing additional capabilities over time.
- **Model Evaluation**—the state of the art and ways for validating existing models and those being developed.
- **Extremes and Disruptive Events**—capturing disruptive or extreme events (e.g., climate or technological change) and other sources of non-linearity in economic growth.
- **Uncertainty Characterization**—drivers of uncertainty, capturing uncertainty in economic scenarios, and decision-making under uncertainty.

- **Feedback Effects and Co-evolving Trends**—complexities and interactions between and among human and physical systems, and the co-evolution of economic scenarios with other domains.
- **Scenario Development Tailored for the United States**—identifying a viable process for developing meaningful economic scenarios for the United States with appropriate characteristics.

Each of these areas is discussed in more detail below.

## 2.1 The "Wants" of the User Community

User groups for economic scenarios are diverse, including researchers and analysts from academia; national, state, and local governments; the not-for-profit community; and private-sector individuals and businesses. These users conduct a wide array of types of analyses, such as planning for impacts and adaptation, qualitative and quantitative impact assessment, and policy analysis of alternative mitigation and adaptation strategies. In turn, these analyses are indicative of the types of economic variables and economic futures that are (or might be) used and the types of economic scenarios that might be developed to assist this community.

The users and developers of economic scenarios represent a community of practice, one that can provide information on the available sources of data for developing economic scenarios as well as the factors influencing how economic futures develop and evolve in reality. In addition, the community may provide a means for sharing the experiences of those applying and using economic scenarios.

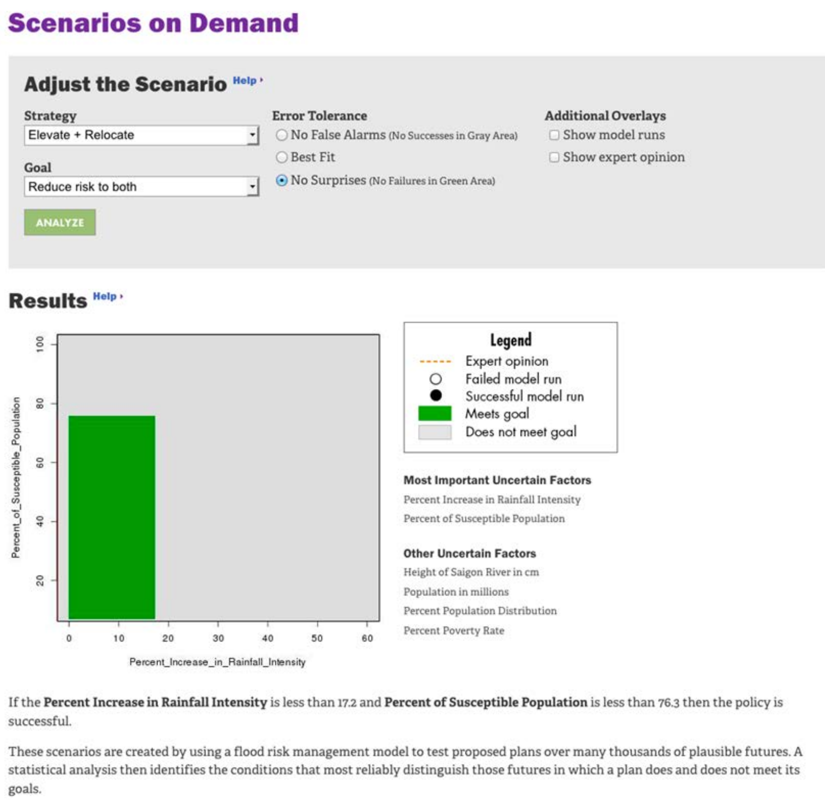
Recurring discussions throughout the workshop centered on the types of scenarios that users need in order to support planning and analytical efforts, ways to develop scenarios that address diverse needs, and how to engage the community of practice. These issues came up particularly during Session 1, which explicitly raised these questions. Discussants at the workshop covered topics such as the diversity of potential users—ranging from integrated assessment models (IAMs) to regional planners—and the consequent diversity in the types and characteristics of scenarios that would be needed, the communication of scenarios and scenario uncertainty, and how to make scenarios more "usable" by the user community.

- ***User groups and needs are diverse.*** A recurring theme at the workshop was the difficulty of designing a single set of scenarios to serve the needs of diverse users, implying that the variety of users and user needs could lead to the development of multiple types of scenarios. Different users are asking different research questions, which drives the diversity of analytical needs. Many participants described a variety of potential users, from researchers conducting impact and adaptation analyses at the sectoral level to those conducting national analyses, as well as policy makers, planners, and analysts working at the local, state, and national levels. The user community includes not only those conducting impact studies or adaptation planning, but also the developers of IAMs, which use scenarios as inputs. Some participants noted that while certain users may choose simple scenarios to support their analyses, the same cannot be said for all users; some may want additional variables, longer time scales or more detailed time steps, or the flexibility to incorporate changing policies or economic patterns and develop conditional economic futures. Further, some may want economic futures that cover a small geographic region or single sector, while others may want multi-scale futures or integrated approaches. Some participants were also intrigued by the concept of a typology of representative user groups or classes of problems, with the idea that it could be feasible to develop a limited set of scenarios, models, or analytical techniques that could nonetheless serve the needs of specific user groups or be useful for approaching certain sets of problems. (See also the discussion of U.S. economic scenarios in Section 2.8.)

- ***Different questions require different scenarios and methods.*** Several participants commented on the relationship between the nature or type of scenario that is needed and the specific questions or decisions being addressed by a particular analysis—i.e., demand-driven scenarios. Some participants observed that problems can be worked both forward and backward. One participant noted the usefulness of working the problem backward in some cases; this involves identifying the key consequences of interest, and then analyzing the relationships to identify the variables that are critical to those consequences. (See Exhibit 2 and also the discussion on characterizing uncertainty in section 2.6.) This approach can help reduce the dimensionality of the scenarios and the variables that need to be well-characterized and understood.
- ***User-driven characteristics.*** A portion of the discussion focused on the characteristics of scenarios that would be useful to particular types of analyses and user groups. Many participants described the usefulness of developing scenarios at fine geographic scales, such as the state, county, or municipal level, but also indicated that analyses are conducted on all scales, and that an analysis could be multi-scale; e.g., providing results both nationally and at finer resolution. With regard to timeframe, some participants noted that a 20- to 30-year time horizon could be long enough for some policies. In the longer term, however, where economic models are coupled with climate models, scenarios could extend to 2050 and to 2100 to maintain consistency between economic and climate scenarios. Several participants commented on specific variables that might be useful in economic scenarios; these included variables that relate to spatial and temporal distributions of people, such as household income, per capita income, land values, housing values, employment, and sectoral output; as well as jobs, market behavior and change, finance conditions, and indicators of economic resilience. Several participants suggested that, at the USGCRP level, there could be a guiding document providing standard gross domestic product (GDP) projections.
- ***Addressing the needs of the community of practice***. Some participants discussed a need to make scenarios more readily "usable" by users, and stressed the importance of providing support and guidance for users. Ideas ranged from providing good, basic guidance on what is contained in the scenarios and how they can be used, to providing information on how to interpret the scenarios or think of uncertainty in the context of scenarios. One participant suggested that this translational work could extend to standards or quality requirements to improve communication and clarity across researchers; e.g., developing standards for reporting and transparency in modeling work and research studies, and developing documentation requirements for datasets. The idea of providing centralized support for the community of practice was also raised; e.g., encouraging community of practice meetings, or providing a central location for a library of citations to published scenario applications by user groups, case studies, or available tools in the literature. Some participants cautioned, however, that providing such a wide range of guidance and support could be very resource-intensive over a long period of time.

**Exhibit 2: Which Scenarios are Needed to Support Decision-making?**

"Working the problem backwards" helps researchers identify variables critical to the consequences about which decision makers are concerned. In the study from which the figure below is taken, key variables to the success of policies being considered are the city population and the amount of rainfall. Consequently, it may be important to incorporate high-quality projections of these variables in order to assist decision makers. An analogous approach may reveal the relative importance of different economic variables to analyses conducted in different sectors, at different scales, or with different goals.




*Source*: Lempert, 2016.

## 2.2 Data

The previous section described growing user needs—and a diversity of potential users—for economic scenarios that are relevant for climate impacts, adaptation, and vulnerability research and assessment. Those user needs motivate demands for more detailed subnational data, techniques to address gaps in datasets, data quality, harmonization among different data sources, and overall data sharing and access issues. The complexity of socioeconomic processes necessitates assimilating data from multiple sources, sectors, and disciplines, making these data demands even more challenging.

The topic of data came up during each session of the workshop. In identifying near-term opportunities, some participants focused on the availability and quality of data at different temporal and spatial scales that could support the development of economic scenarios. With regard to longer-term research, some participants discussed ways to meet needs for high-quality data at the necessary level of detail to support model and analytical methods development. Several participants noted that there are many different users of data within the IAV, IAM, and earth systems model (ESM) communities, and that ideally researchers should have access not only to the data, but also to the assumptions behind their development or synthesis. (See also the discussion on community of practice in Section 2.1.)

- ***Integration or harmonization of data across federal agencies.*** Several participants described the difficulty of compiling compatible and complete data sets across time and federal agencies. They also indicated a general need for data to be harmonized across different federal agencies that collect and report similar or related data. One participant pointed out, for example, that U.S. Bureau of Economic Analysis (BEA) and U.S. Bureau of Labor Statistics (BLS) employment data (for the same industries) have only recently become consistent. One participated explained that he often mixes and matches data; for example, using BEA industry data, but removing industries related to energy and splicing in energy data from the U.S. Energy Information Administration (EIA). Another participant noted that federal agencies have historical data on paper that needs to be digitized.
- ***Fine-scale data.*** The availability of fine-scale data was identified as an important area for improvement by some workshop participants. Multiple participants pointed out that regional or local planning boards are good sources of data that could be further examined. However, one participant noted that there is no current effort to bring these datasets together and they are not readily comparable, giving the example that some of them are cross-sectional data, while others are time series.
- ***Acquiring datasets and processing data***. Many participants noted that researchers often find publicly available regional datasets to be of lower quality than national datasets, inconsistent with other data sources, sparse, or not in a usable format. As a result, regional data often need to be processed to fill gaps in the data, or datasets need to be combined to create panel datasets from time series and cross-sectional datasets. While allocation procedures exist to address data gaps, a few participants noted that such procedures are tedious and time-intensive, and may require expert involvement to ensure quality. Several participants noted that developing these data sets is an extremely time-consuming aspect of research, and that it would be beneficial if the results of such compilations could be shared across researchers. An alternative is for researchers to purchase regional data from providers such as IMPLAN; however, one participant noted that a disadvantage of purchasing these data is that it makes it difficult, or impossible, to publicly release models or underlying data.
- ***Internally consistent data***. Several participants pointed out the usefulness of different modeling teams having consistent underlying data in order to have consistency in results, enable model comparisons, and provide robustness. Many comments were made that while plenty of datasets have been compiled by individual researchers, these data are not made available to others in the community. One participant felt that the research community needed to do a better job of collecting data, synthesizing data, making data consistent, and making data available, including the data used to develop tools and assessments.
- ***Big data and the potential to crowd-source data.*** A few participants raised the idea of using surrogate data or "big data"—such as information obtained from satellite imagery—to develop

socioeconomic information. One participant pointed to the potential that big data offer to incorporate data analytics into research. Another viewpoint was that while big data have potential, the analysis of those data should be grounded in theory. In a related discussion, the idea of "crowd-sourcing" to develop new sources of data was raised. Some participants were skeptical of the ease with which crowd-sourced data might be used, given difficulties involved in cleaning up existing data sources obtained through more formal processes.

## 2.3 Models and Analytical Methods

Many models and analytical methods currently in use are capable of producing projections that could inform economic scenarios. These models and methods have been developed for a variety of purposes, ranging from theoretical explorations of policy questions, to practical applications of the results in a governmental regulatory or programmatic context, to forecasting for business and government planning purposes. Increasingly, these models have been expanded and drawn into the climate change arena, and used to inform questions about optimal global paths for GHG emissions, the importance of adaptation in reducing impacts, and other questions. In particular, IAMs of global climate change study the interlinkages between human systems and natural systems, and include representations of the economy that range from simple to complex.

However, developing economic projections at the subnational level over the long and very long terms—as is often required by climate change impact and adaptation analyses—is challenging. As many participants emphasized, no single model is likely to meet all the needs of researchers for these types of projections. Developing a viable path forward, therefore, may involve building on current capabilities and combining different approaches and models to provide a set of projections that meets researchers' and policy-makers' needs, and does so in a way that is scientifically defensible, believable, and transparent.

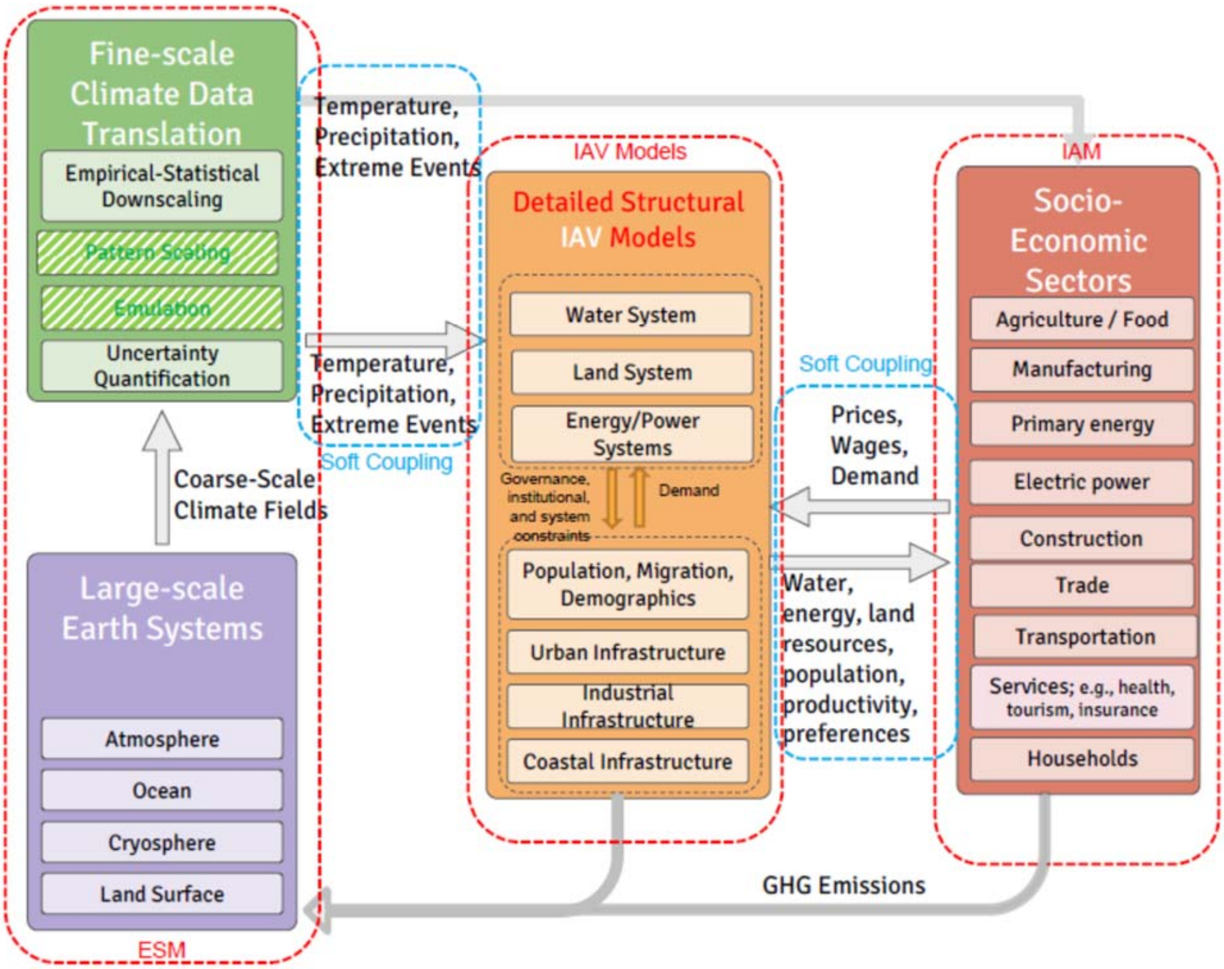
Models and analytical methods to develop economic scenarios were significant topics of discussion, spanning all four sessions of the workshop. With regard to short-term needs, participants discussed currently available methods to develop fine-scale economic projections, as well as the current state of development for IAMs. For a longer-term research agenda, participants considered the types of model advances and complementary modeling capabilities that are needed, as well as opportunities to move in the direction of a fully integrated modeling system. There were many ideas for improvements to models and methods at the workshop, with calls for simpler models, more complex models, different coupling approaches, and mixing of methods and models, including qualitative approaches.

- ***Simpler versus more complex models.*** Discussions in several of the workshop sessions indicated a need for both simpler and more complex models. Several participants explained situations in which simpler models that adhere to first principles may be appropriate and preferable. Examples ranged from how reducing complexity in one system can enable coupling with other systems of similar complexities, to how more stylized models can allow for the incorporation of more complex economic behaviors (e.g., oligopolistic competition), to how adding complexities can sometimes detract from believability. The need for models to capture reality, including complexity across different temporal and geographic scales and variables, was another topic of discussion. Many participants noted that an "uber" model that meets all needs is unlikely to exist or be practical to develop. Some participants felt that the interconnectedness of different spatial scales (e.g., telescoping), the economy, and physical systems was a reason to introduce more detail to models or more interactions within models. Some participants also called for models that were more spatially specific and based on behavioral analysis. One participant pointed out the importance of including sector detail in models addressing climate issues, given that there are winners and losers, and highlighted the variability among models in terms of sectoral coverage; for example, some models have five sectors while others have several hundred.

- ***Approaches for coupling models***. Many different approaches are available to couple earth systems models, physical system models, and socioeconomic models.[3] One participant presented three current approaches, including a robust IAM soft-coupled with climate, aggregated IAM/IAV/ESM individual model approach, and an IAV-IAM soft-coupled approach; the third approach is illustrated in Exhibit 3 below. The participant also noted several future research opportunities, including identifying advantages and disadvantages of different coupling approaches, and better understanding what research questions can be answered using one approach versus another.

[3] A subsequent Snowmass workshop on Climate Change Impacts & Integrated Assessment (XXII), held on July 20-29, 2016, discussed model coupling approaches and terminology in considerable detail.

**Exhibit 3: Example of Soft Coupling Approach for Components of an Integrated IAV System within an Integrated Assessment Framework**




*Source:* Developed by Karen Fisher-Vanden and Robert Nicholas (Pennsylvania State University), and Robert Vallario (DOE).

- ***Interoperability***. Related to coupling was a discussion about interoperability of models. While many relevant tools and models exist, they are not always interoperable, due partly to different languages and native scales. One participant noted that using emulators or reduced-form models can help reduce the work required to link models, while another participant emphasized the potential for translational tools (e.g., software) to enable model coupling. A few participants also discussed the concept of "plug-and-play" models; an advantages of these models is transparency but they also require guidance and a community of practice to ensure that tools are used correctly and that results are interpreted in light of model characteristics and limitations. (See also the discussion on community of practice in Section 2.1.)
- ***Mixing and matching models and methods, including qualitative approaches***. Many participants recognized that many data, models, and analytical methods already exist and could be

mixed and matched in different ways to answer different questions. One participant called for more experimentation with mixed methods, both quantitative and qualitative. Several participants highlighted an important role for qualitative components, including to frame quantitative modeling results, capture broader interactions than models can capture, and describe cascading damages, which are highly uncertain and may lack quantitative results.

- ***Role for array of models and methods***. Many types of models and methods are available and could be used to develop economic scenarios, including macro-econometric forecasting models,[4] computable general equilibrium (CGE) and partial equilibrium models,[5] and behavioral economics approaches, such as agent-based frameworks. Some participants made the point that a major determinant in model selection is the question being asked, so a broad suite of models can help address a variety of questions and research needs. One participant described the role of different economic model types and methods for different timeframes. For the short term, statistical models such as vector autoregression are often used; in the medium term, structural models use underlying economic theory to give more robust results, with key drivers of demography and population growth; and in the long term, in addition to the use of structural models, methods such as expert elicitation can be explored.[6] One participant pointed out that CGE models perform best in developed countries or in regions or countries where the economy is more market-oriented.
- ***Needed improvements***. There were many comments on ways to improve economic models. Some participants commented on the possibility of near-term research opportunities that could improve modeling to support decision-making under uncertainty. (See also the discussion on uncertainty in Section 2.6.) A few participants noted that CGE models can use a stochastic dynamic approach, although it is computer-resource intensive and may require significant model simplification (see, for example, Cai et al., 2016). One participant noted that most modeling assumes that policymakers make optimal decisions—an assumption that history often disproves. Some discussions focused on the assumption of perfect competition in many CGE models. A few participants found this assumption problematic and unrealistic; for example, one participant pointed out that many of the short-term fluctuations of imperfect markets (e.g., oil prices) can have important and lasting impacts on the economy. Another participant identified the allocation of non-market resources (e.g., such as water quality or carbon sequestration) as a key research issue for CGE models.
- ***Inter-method comparisons***. Some participants identified inter-method comparisons as a research opportunity. (See also the discussion on model validation in Section 2.4.) A few participants noted that the IAV/IAM community does conduct some inter-model comparisons via forums such as the Energy Modeling Forum (EMF) or CMIP, but that comparisons between models of different types or across methods (e.g., qualitative or quantitative, coupling approaches) are rare. One participant

---

[4] For example, Moody's Macro Model (see Appendix E for more information).

[5] For example, the MIT Economic Projection and Policy Analysis (EPPA) model, Dynamic Integrated Economy/Energy/ Emissions Model (DIEM), Global Change Assessment Model (GCAM), All-Modular Integrated Growth Assessment Model (AMIGA), Intertemporal General Equilibrium Model (IGEM), and MIT US Regional Energy Policy Model (USREP). See Appendix E for more information.

[6] The short, medium, and long term in the context of projections and scenarios were not explicitly defined at the workshop. Interpretations can depend on the model type, among other considerations. In general, short term can range from months to a couple of years; medium term may range from a few years to a couple of decades; and the longer term can reach from a couple of decades to a century.

noted that some inter-method comparisons have been done by a researcher comparing different models used to determine the social cost of carbon, running the models piece by piece and comparing results.

## 2.4 Model Evaluation

Model evaluation processes can involve comparisons of model outputs with observational data, using sensitivity tests to understand model behavior better, conducting model intercomparisons, and analyzing or producing common scenarios or metrics against which models can be benchmarked. Such processes are important for understanding model behavior and assessing model skill, especially as models incorporate new capabilities and move to finer geographical scales. The climate and integrated assessment model communities have experience in model comparison and evaluation, including community projects such as CMIP, EMF, the Agricultural Model Intercomparison and Improvement Project (AgMIP), the U.S. DOE Program on Integrated Assessment Model Development, Diagnostics and Inter-Model Comparisons (PIAMDDI), and the Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates (AMPERE) project in the EU. The economics community, on its own, however, has not yet established such coordinated efforts or processes to validate models, outside of the peer review of model methodology.

At the workshop, model validation and evaluation was considered in the context of economic model capabilities and future development needs. Many participants discussed the role of hindcasting as one tool for evaluating models, model comparison studies to determine the relative importance of model structure, downscaling (or upscaling) methods, and model diagnostic test cases.

- ***Hindcasting.*** Hindcasting[7] refers to using models to forecast the past, and comparing what a model produces to actual historical data. To illustrate the need for hindcasting, one participant presented studies of the poor performance of forecasts of U.S. primary energy consumption and coal prices to electric generating plants, when compared with observed data (Smil, 2003; Newcomer, 2007). Some discussion focused on the appropriateness of hindcasting in the context of economic models. One participant noted that while hindcasting is used extensively in the climate modeling community, economic models are fundamentally different in that they are based on less-predictable laws of human behavior rather than laws of thermodynamics. Other participants pointed out that while economic models may not hindcast as accurately as climate models do, knowing where models perform poorly in the past can help to set future research agendas for improvements. Some participants also noted the influence of model structure on hindcasting results: statistical models (which are based on historical data and econometrically estimated relationships) would be expected to predict the past more accurately than structural models (which are usually calibrated and based on economic theory), even though structural models will perform better for long-term future projections, particularly when assessing the effects of unprecedented policy shocks that are not present in the historical data such as high carbon prices."

[7] The issue of hindcasting was also discussed at length by the U.S. EPA's Scientific Advisory Board Panel on Economy-wide Modeling of the Benefits and Costs of Environmental Regulation.

- ***Model comparison studies.*** A few participants emphasized the importance of testing the structure and integrity of models to see where they "break." For example, when models are run under extreme policy scenarios, they might generate misleadingly high $CO_2$ prices as a result of limitations in the underlying functional form. One participant suggested that models could have diagnostic or evaluative scenarios (i.e., common standards or test cases for which the community thinks models should produce similar results). Another participant noted that diagnostic scenarios can shed light on model assumptions (e.g., comparing price elasticities that come out of the model versus the same elasticities reported in the literature).

## 2.5 Extremes and Disruptive Events

In general, economic projections used in impact/adaptation assessments and climate modeling tend to be trend-based, assuming that economic change will be relatively monotonic and steady. In reality, upward and downward movement of the economy occurs due to business cycles and economic and financial shocks, and the rate of growth changes over time. The economy also responds to extreme natural and climate events, such as storms, earthquakes, flooding, or droughts (such as the one in 2015 illustrated in

below). The economy may also change in a non-linear manner due to disruptive events involving technological change, institutional or legal change, and structural economic changes. These extreme or disruptive events could represent a singular occurrence, or might reflect repeated or prolonged change.

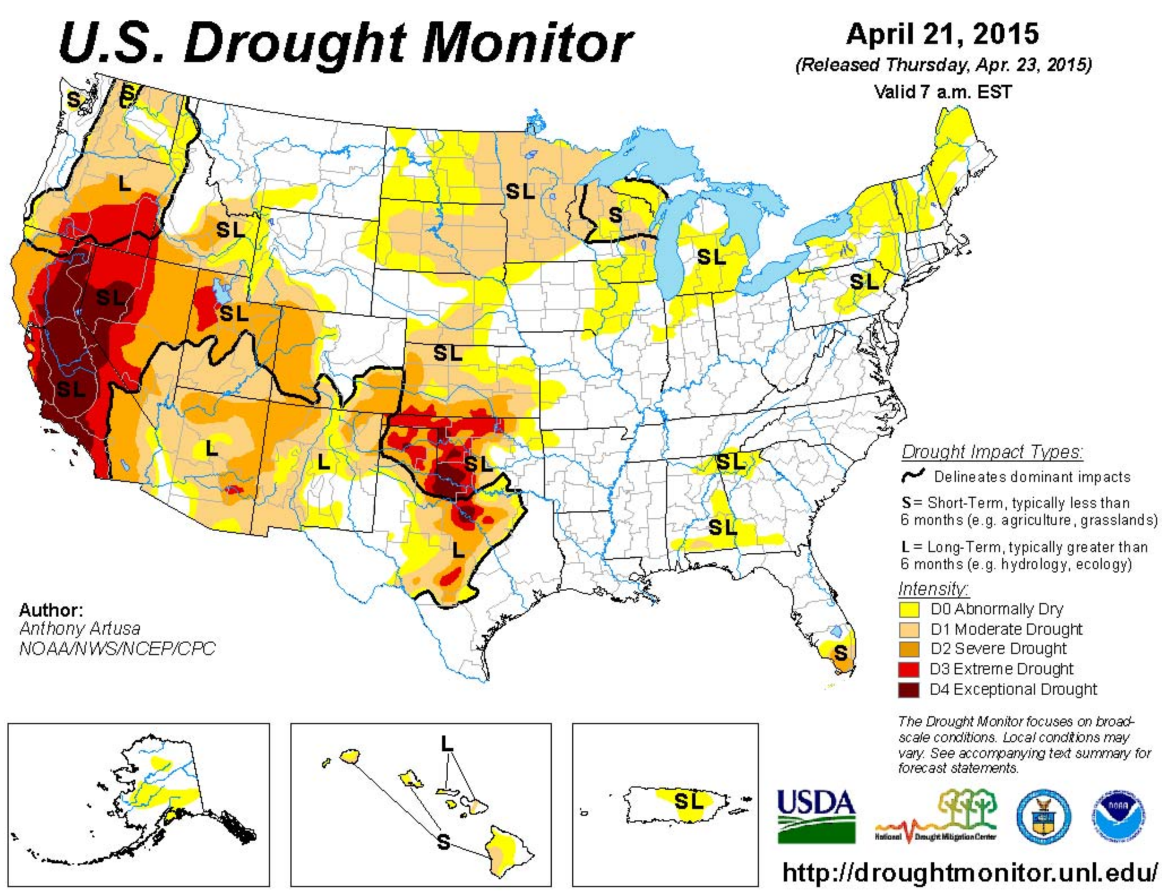
Throughout the workshop, some participants raised the topic of non-linear changes (e.g., extreme or disruptive events) as an important area that requires more research, inclusion into models, consideration in scenarios, and appropriate contextual framing. Some participants focused on what could be done in the short, medium, and longer terms to capture or incorporate the potential for disruptive change in economic models and economic scenarios.

- ***Data, models, and analytical methods.*** Many participants indicated that our current **c**apability for modeling or analyzing extreme events is extremely limited, and represents an important area for improvement. Some participants discussed the implications of different model types vis-à-vis representing extreme events. One participant noted that model structure is particularly important when future events may take the economy and economic drivers outside boundaries indicated by the historical record. Several participants pointed out, for example, that structural economic models, such as CGE models, can be designed to model responses to changing events and policies, in contrast to macroeconomic forecasting models, which are based on relationships derived from the historical record. Some participants also suggested that incorporating approaches from the behavioral economics literature, or from other disciplines, could be fruitful in understanding how socioeconomic futures and extreme events are linked. For example, one participant described the potential of agent-based models to capture decision-making approaches and decision-making mistakes.
- ***Disruptive events and stochasticity in scenarios.*** A few participants noted that the use of smooth, long-term socioeconomic trends in scenarios misses potential damages from low-probability events such as mass migrations or pandemics. One participant raised the idea of incorporating disruptive events into scenarios by nesting an extreme event within the framework of a longer-term economic

trend scenario. Another participant suggested that embedding stochasticity and modeling shocks needs to be done in a scientifically defensible manner.

- ***Contextual framing.*** The framing of extreme events and scenarios that may depict extreme events was also identified as an important issue by several participants. A few participants pointed out that scenarios or models of extreme events should be presented in a way that contextualizes why the extreme event is being analyzed and emphasizes the low probability of such an event occurring. (See also the discussion on uncertainty in Section 2.6.)
- ***A "reasonable" range for extreme events.*** One participant described the difficulty of constructing scenarios for extreme events, since combining all the sources of extreme events could result in an overwhelmingly alarmist scenario; rather, the goal is for scenarios to be scientifically defensible, believable, and salient to decision makers. The participant also discussed the importance of communicating the idea that the scenarios represent extreme events from the tails of the probability distributions, and so are less probable than other scenarios.

**Exhibit 4: Monitoring U.S. Drought**




*Source*: NOAA National Centers for Environmental Information, 2015.

## 2.6 Uncertainty Characterization

Uncertainty is an intrinsic characteristic of economic modeling and economic scenarios of the future. Uncertainty arises, in part, because the future is unknown and therefore difficult to characterize. Uncertainty also results from the inherent variability of systems, whether climatic, economic, or social. But uncertainty also arises because economic and other complex processes are modeled using our current understanding of systems, in light of available data and modeling capabilities, and facing computational limitations. (See Exhibit 5 for an illustration of the difficulty of projecting the future.) The choice of models and analytical methods may influence the uncertainty of the scenario outputs; for example, uncertainty may depend on whether scenarios are qualitative or quantitative, and whether quantitative projections are developed using downscaling or regional or sectoral models. Together, all these conditions may create uncertainty in the economic scenarios produced using these methods.

The question of uncertainty was discussed during the workshop from different perspectives, including the drivers behind uncertainty, how researchers and decision makers might (or do) account for uncertainty about the future in their analyses, and how uncertainty should be reflected in approaches to constructing and describing economic scenarios. Uncertainty was viewed by many participants as an important and growing topic, and one to which attention should be paid in developing scenarios and refining data, models, and analytical methods over time.

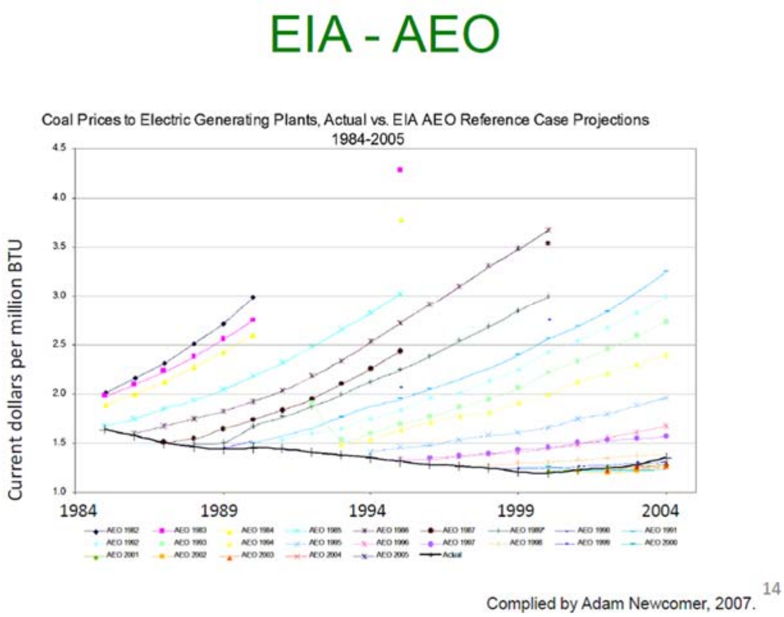
- ***Understanding and reducing uncertainty.*** Several participants noted that a scenario with greater detail (i.e., developed for finer spatial scales or over a longer term) will be more uncertain. One participant suggested that the uncertainty associated with fine-scale scenarios would be reduced if researchers used higher-resolution variables in analyses, where doing so could produce scientifically defensible and believable results. Another participant suggested that the uncertainty associated with projecting economic growth over a long time frame (e.g., to the year 2100) makes it particularly important to focus on and revisit the key drivers of economic growth. One participant referred to research on model and parametric uncertainties for population, total factor productivity, and climate sensitivity using integrated assessment models (Gillingham et al., 2015). A few participants also questioned how to reconcile different sources of uncertainty in a common analytical framework, and how to constrain uncertainty as models become more complex and incorporate more feedbacks. (See also the discussion on feedback effects in Section 2.7.) Several participants stressed the potential benefits of hindcasting, in order to look at how a model performs when it "projects" the past; although the climate community does this activity routinely, economic modelers hindcast only infrequently. (See also the discussion on model evaluation in Section 2.4.)
- ***Supporting decision-making and planning.*** Many participants viewed the needs of decision makers for decision support under uncertainty as a key consideration in the context of scenario development. Several participants discussed decision-making in the presence of "deep uncertainty" (sometimes referred to by economists as "Knightian" uncertainty after seminal work by Frank Knight). Deep uncertainty refers to a situation where the future is essentially unknowable (because it includes "unknown unknowns" as well as "known unknowns") and is therefore difficult to project. One participant explained that under conditions of deep uncertainty, it can be useful to conduct analyses backwards (See also the discussion of user needs in Section 2.1.)

- ***Developing a range of outcomes.*** Several participants emphasized that a risk-framing approach to decision-making requires developing a full range of outcomes (e.g., outcomes that reflect the potential for significant disruptions and non-linear changes). (See Section 2.8 for a discussion of assigning probabilities to scenarios.) They pointed out that users rely too often on one model or one set of results; it would be helpful to encourage users to think about uncertainty (e.g., by providing them with scenarios that bound an uncertainty range). One participant also pointed out that scenario development can lead to "overconfidence" and an underestimate of the range of possible future outcomes; the more detail that one adds to the storyline of a scenario the more probable it will appear and the greater difficulty users may have in imagining other, equally or more likely, scenarios. (See also the discussion on developing scenarios in Section 2.8.) Two participants presented the result of research suggesting that the range of scenario outcomes ought to be wider than is typical in current scenarios. In particular, one participant presented the results of a study indicating that the empirical prediction intervals[8] for EIA's oil price forecasts often span a wider range than EIA's high and low scenarios (Kaack, 2016). Another participant presented research indicating that using expert elicitation to project annual global output to 2100 yields a wider range of results for GDP per capita than the SSPs do (Christensen et al., 2016).
- ***Informing the process of developing scenarios.*** Uncertainty analysis could also inform the process by which scenarios are developed. A typical approach to developing a scenario is to create the storyline and then identify parameters or drivers that span the range of that storyline. One participant suggested that storyline scenarios should be a product of uncertainty analysis (both parametric and structural uncertainty analyses). In this view, scenarios could be developed and structured around the results of the uncertainty analysis; this approach might be particularly useful when scenarios are focused on low-probability, high-consequence events. (See also the discussion on developing scenarios in Section 2.8.)
- ***Exploring uncertainty and research opportunities.*** Many ideas were raised for future research on uncertainty in the context of economic scenarios. In terms of models, some participants pointed out that uncertainty in decision-making is beginning to be incorporated via dynamic stochastic programming approaches (in contrast to deterministic models); these are more computer-resource intensive and often require making simplifying assumptions in certain parts of a model (e.g., aggregating sectors and regions) in order to represent stochastic decision making in another part (e.g., the electric power sector) (see, for example, Morris, 2016; and Cai et al., 2016). Another participant pointed out that uncertainty can also be explored using sensitivity analysis (e.g., for CGE models). A few participants observed that expert or professional elicitation methods may be able to define distributions for key parameters, which can then be used as model inputs or for Monte Carlo type analyses. One participant suggested that, given uncertainty across many variables, a Value-of-Information type approach could be used to identify key factors influencing the uncertainty of results; efforts to develop scenarios could then focus on those factors.

[8] This method uses the distribution of past errors to create a probability density forecast around an existing point forecast (Kaack, 2016).

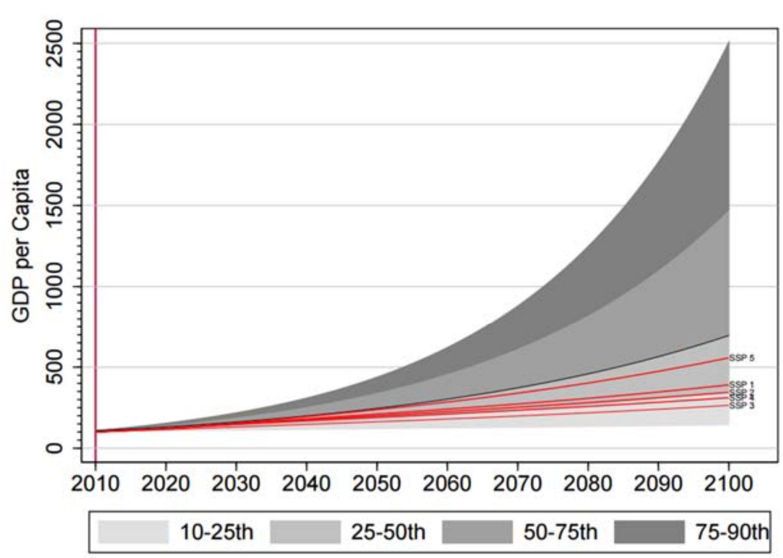
**Exhibit 5: The Difficulty of Projecting the Future**

In the first figure, the historical record of projections in coal prices versus actual prices illustrates how the future can be difficult to predict, even with experience. The second figure shows the results of a study by Christensen, Gillingham, and Nordhaus (2016), which found that a sample of expert-elicited long-run forecasts of productivity growth and uncertainty yielded wider bands than the SSPs.




*Source:* Compiled from EIA Annual Energy Outlook data by Adam Newcomer, Department of Engineering and Public Policy, Carnegie Mellon University, 2007.

Figure 4: Comparison of Projections of Annual Global Output to 2100 with SSP Scenarios




**Note:** Grey shaded areas illustrate per capita growth projection using combined quantile distribution F(x; $\hat{\theta}_{p=10}$, $\hat{\theta}_{p=25}$, $\hat{\theta}_{p=50}$, $\hat{\theta}_{p=75}$, $\hat{\theta}_{p=90}$) for global rates (2010-2100). Red lines illustrate per capita growth projections using SSP projections of global rates. Global rates are geometric means of national growth rates, weighted by share of global income in 2006.

*Source:* Christensen et al., 2016.

## 2.7 Feedback Effects and Co-evolving Trends

Projecting economic futures—whether qualitative or quantitative—is made more complicated by the complexities and interactions between human and physical systems. Feedback effects between economic sectors can change the trajectories of prices, output, and other economic variables in these sectors, and have implications for the broader economy as well. Feedbacks between physical and human systems can also influence the trajectory of economic variables. Additional complexity is introduced by the connections among socioeconomic variables and between physical and human systems, which can result in the co-evolution of demographic and economic trends at regional scale, and also the co-evolution of socioeconomic trends with climate policy and, thus, changes in climate.

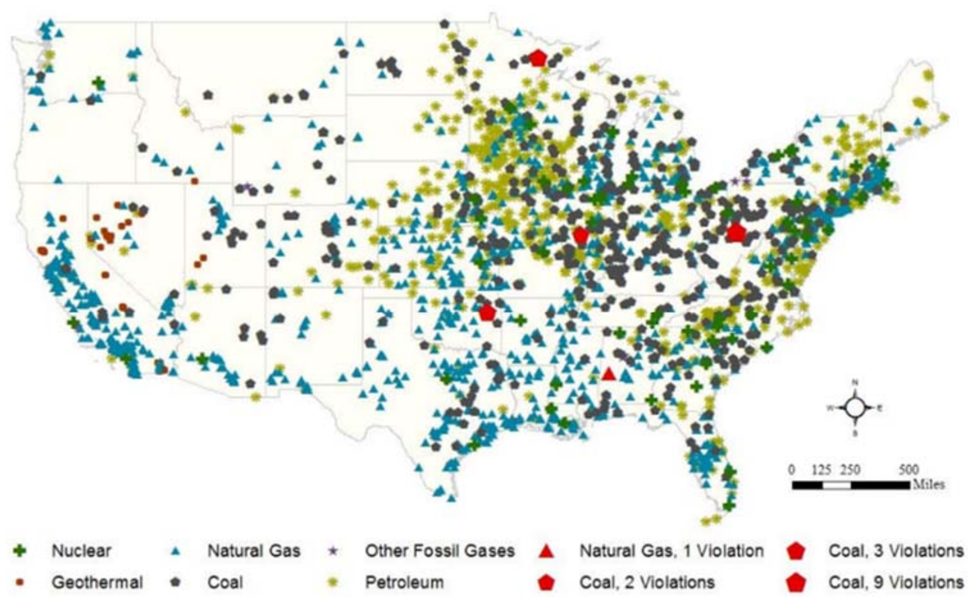
Some participants at the workshop observed that while existing models may capture one-way linkages between sectors and systems, feedback effects and co-evolution are poorly captured in existing economic models and in models that integrate economic and physical systems. However, some discussants also gave examples illustrating the extent to which improvements are already being made in order to introduce more real-world complexities into modeling systems. Topics of discussion included incorporating feedback effects among climate and socioeconomic variables (e.g., capturing both the impacts of economic systems on physical processes and the impacts of physical processes and climate impacts on economic development), needs for research into the development of model and methodological architectures capable of capturing these feedbacks, and a call for research on how systems co-evolve over spatial scales and over time.

- ***Interactions among human and physical systems***. Many participants noted the important implications for economic projections associated with significant feedbacks between and among human and physical systems. They stressed the need to better represent these interdependencies in economic models and in modeling systems that include economic models. Several participants provided examples to illustrate the importance of these feedbacks in the context of the energy-water-land (EWL) nexus. One participant highlighted research on thermoelectric vulnerabilities (see Exhibit 6 below) as an example of bi-directional feedbacks, where water is needed for energy production, but energy is also needed to move water (e.g., inter-basin pumping). Another participant described the effects of national energy policy, agricultural policy, transportation systems (that import fertilizer and animal feed), population, diet composition, and other factors on nutrient pollution.
- ***The potential for incorporating linkages and feedbacks.*** Some participants highlighted examples of feedback effects that are particularly important to capture, and others provided examples of models where such feedbacks are already being researched and in some case incorporated into projections or models. For example, one participant indicated the importance of strengthening the economic models used in integrated assessments, particularly with respect to the agriculture sector. Another participant indicated that the influence of climate change on total factor productivity growth could be important for making long-run economic projections. Some discussion focused on climate influences on population migration, and advances that are being made in that arena. One participant noted that a new version of EPA's Integrated Climate and Land-Use Scenarios (ICLUS) allows population migration to be influenced by a dynamic climate, via changing amenity values.

Another participant mentioned ongoing research on climate-induced migration and second-order effects, illustrating how wage rates can dampen first-order migration effects.

- ***Architecture to capture feedbacks.*** The discussion focused on the state-of-the-science on this topic. One participant emphasized that more work is needed on incorporating feedbacks, spillovers, and interactions into integrated assessment modeling. Another participant pointed out that efforts have been made to link economic models, but without fully incorporating feedback effects.
- ***Co-evolving scenarios.*** A related discussion focused on the potential for co-evolving and dynamic scenarios, rather than static ones. One participant suggested that a dynamic model could create a variety of futures depending on how systems co-evolve. This participant also noted the modeling complexities that arise at a global or national scale, but suggested that an agent-based behavioral economic model might capture decision-making and help to understand co-evolution at finer scales. Another participant similarly recognized the need for research on how systems co-evolve across scales and over time, and suggested that learning from other disciplines might be useful (e.g., game theoretic models in electricity modeling).

**Exhibit 6: Example of Bi-directional Feedbacks in Thermoelectric Vulnerabilities**




*Source:* U.S. Department of Energy, 2014.

## 2.8 Scenario Development Tailored for the United States

The path forward for developing economic scenarios for the United States in both the near and longer terms may depend not only on the characteristics of scenarios identified by various user groups for different analytical purposes, but also on the data, models, and analytical methods that are currently available or may be developed in the future. Discussions at the workshop revealed the potential need for a wide range of U.S. economic scenarios with different characteristics, in terms of geographic scale, sectors that are covered, economic variables that might be included, and time frame. At the same time, discussions revealed a potential need for scenarios that reflect the inherent uncertainty in projections and potential discontinuities in economic futures, the variety of models and modeling assumptions that might be used in developing or applying futures, and the interconnectedness of sectors and of the economy with other socioeconomic scenarios and variables. (See also the discussions on user needs, models and methods, and extreme events in Sections 2.1, 2.3, and 2.5.) Developing viable U.S. economic scenarios over time will require evaluating these diverse and competing considerations in the context of the viability and usefulness of alternative research and development paths.

The topic of economic scenarios to support research and assessments in both the near and long terms arose during all sessions of the workshop. Discussions raised a broad range of issues related to scenarios for the United States, such as how a scenario could be defined and what elements should be included in a scenario; how scenarios could be developed; needs for scenarios in terms of geographic scale, resolution, and timeframe; if and how economic scenarios could address highly disruptive, non-linear, or rapid changes; whether probabilities could or should be attached to scenarios; and the role of consistency in developing and evaluating scenarios.

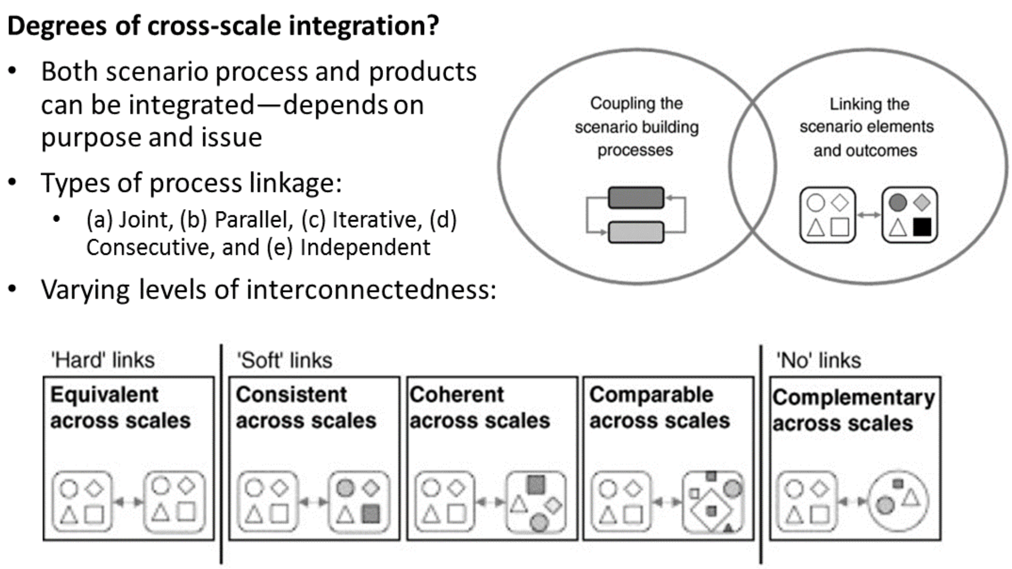
- ***Defining scenarios.*** The definition of "what constitutes a scenario" plays a key role in how scenarios are used and how they are developed. Some participants indicated that scenarios need not be quantitative, but can also be qualitative; while quantitative scenarios are particularly useful to modelers or researchers seeking to product quantitative assessments or other results, qualitative scenarios can be important for providing an overarching narrative, bridging scales, informing decision makers, and as inputs for modeling. As one participant suggested, scenarios might be better designed by first understanding if and how users are using assessment information for decision-making. Another participant pointed out that although scenarios are often thought of as a product, they can also be a service. For example, in robust decision-making, scenarios can help decision makers decide when to justify paying the incremental cost to protect against sea-level rise.
- ***Scenario geographic scales***. The geographic scale at which economic scenarios are developed for the United States will depend on user needs for economic futures, the reliability or credibility of scenarios developed at different scales, and the available data to support the quantitative development of scenarios. The appropriate scale of scenarios will also depend on the level of detail or time frame of the scenario (as discussed in Section 2.1 on user needs). Several participants pointed to a multi-scale approach or nested framework as one option to meet the needs of different user groups that work at several scales. For example, nested scenarios could follow a "subsidiary" principle, in which scenarios at the highest level could provide boundary conditions or the minimum level of information, while lower-level scenarios include more detailed quantitative or qualitative information that users need. One participant also noted that a multi-scale approach can be important because many of the issues involved have native scales (e.g., watersheds, utility grids). Another participant used an example case of nutrient pollution in the Chesapeake Bay watershed to illustrate how the scale of scenario information that may be relevant for analyses is not always immediately obvious. For example, although local agricultural, fishing, and use policies are clearly

dominant, national energy policy is also an important determinant of local nutrient pollution. (See also the discussion on user needs for characteristics of U.S. scenarios in Section 2.1.)

- ***Scenario development process.*** One participant pointed out that the process of developing scenarios has historically begun with developing descriptive storylines and then identifying parameters that span the range of the storyline. Several participants identified ways in which this process could be improved. One participant suggested that storylines could instead be constructed to capture a range of multi-dimensional impacts; specifically, more formal uncertainty, statistical, and structural analysis could be used to design a few cases or types, and storylines could be designed around them. This approach, the participant indicated, would be particularly useful for low-probability, high-impact events. Identifying policy-relevant scenarios from large ensembles of model-generated futures was a similar approach presented by another participant.
- ***Associating probabilities with scenarios***. Several comments were made on the importance of assigning probabilities to scenarios to support risk framing and decision-making. One participant noted that users assign probabilities of scenarios implicitly if the assignment is not done for them explicitly. Another participant presented results from research on judgment under uncertainty that suggests that the more detail a scenario contains, the more probable it will appear to most people (Morgan and Keith, 2008). (See also the discussion of overconfidence in Section 2.6.) Another participant pointed to existing work on probabilistic projections, including the International Institute for Applied Systems Analysis's (IIASA) stochastic population projections. One participant noted that probabilities or likelihoods have not been assigned to NCA scenarios; instead scenarios are identified as higher or lower in magnitude, and probabilities are not assigned.
- ***Stressing or disruptive event scenarios.*** Several participants expressed the importance of choosing scenarios that represent a full range of outcomes, including disruptions and major changes, especially considering their influence on economic growth rates and characteristics. This approach was seen by some as especially relevant for risk framing. (See also the discussion of extreme and disruptive events in Section 2.5.)
- ***Consistency.*** Several participants explored the importance of and limits to consistency between and across storylines and quantitative results, and the type and degree of consistency appropriate for different purposes. Some of the discussion also focused on consistency of economic scenarios with respect to other domains (e.g., other socioeconomic variables, such as population). One participant noted that one approach is to develop common assumptions or parameterization across scenario domains (i.e., "consistent with, but independent of"), where the assumptions are scientifically defensible and credibly sourced. Scenarios can also be made "consistent" or integrated by sharing spatial characteristics, focal issues, processes for development/application, and other features. A framework by Zurek and Henrichs (2007) was raised by several participants as a way of conceptualizing consistency of scenario process and products (see Exhibit 7). Some participants also discussed potential consistency with the SSPs, which have been quantified for several socioeconomic variables at the global and national levels; for example, the SSPs could be used as boundary conditions. Several participants questioned whether global storylines and quantitative SSP projections are appropriate for the United States, and whether these projections elaborate on the factors that are relevant for IAV analysis. One participant noted the extent of work that went into the SSPs and suggested that there may be opportunities to build from that scenario exercise.

- ***Resistance toward scenarios.*** A few participants noted perceived skepticism or even hostility toward scenarios among some members within and outside of the climate change research and analysis community. One participant suggested that simple parametric analysis may be sufficient for many uses, in place of a scenario approach. Other participants emphasized the value of scenarios in visualizing relationships and interdependencies, exploring uncertainties, and facilitating planning.

**Exhibit 7: A Framework for Conceptualizing Consistency**




*Source:* Zurek and Henrichs, 2007.

# 3 Beyond the Workshop: Opportunities and Challenges

Participants at the workshop identified a number of directions along which data, models, and analytical methods could be improved in order to develop economic scenarios that might better serve the user community. In some cases, participants identified specific opportunities or pathways that could productively be pursued in the near, intermediate, or longer term. The ideas expressed at the workshop are clustered below into three groups: immediate opportunities (i.e., in the next year), intermediate-term opportunities, and fundamental science challenges.

This workshop report—including the opportunities and challenges identified by workshop participants—will serve as a technical input to the SISCG in the formulation of strategies and research plan development.

## 3.1 Immediate Opportunities

Near-term opportunities take two primary forms. First, opportunities exist to develop economic scenarios by applying currently available data and making use of the capabilities of existing models and methods. If made available, scenarios and/or guidance might be used by research teams gearing up for the U.S. National Climate Assessment (NCA4), by developers of state and local climate assessments, by other assessments prepared by the international community, such as the IPCC, and for a range of coordinated modeling/research studies, such as those undertaken by the EMF. Second, there may be steps that can be taken in the near term to begin the process of improving the data, models, and analytical methods and other capabilities to produce economic scenarios in the intermediate and longer terms.

First, several participants suggested activities that could be undertaken in the near term to develop and disseminate economic scenarios or other guidance materials for assessment purposes. Suggestions from some participants included:

- Review the available sources of economic data and scenarios that are relevant to NCA4 in order to identify scenarios that might be immediately available at the national level, as well as the state and local levels, for a limited set of variables.
- Provide information on qualitative approaches such as storylines and case studies that are part of a broader, qualitative framework and can be used for some forms of assessment.
- Develop guidance and methods documents on the application and limitations of quantitative and qualitative economic scenarios.

Second, a few participants also identified steps that can be taken in the near term that begin to build a foundation for additional actions in the intermediate and longer terms. The suggestions from participants included:

- Start to identify (and ultimately reconcile) economic data across diverse sources, including data sets used and refined or built by academics; regional, state, and local governments; and planning boards.

- Begin to develop an understanding of the types of scenarios that can support risk-framing approaches to decision making and adaptation.
- Identify classes of problems that use different types of economic scenarios or represent types of users and a typology across the user community.

## 3.2 Intermediate-term Opportunities

Several participants suggested opportunities for research and the enhancement of data, models, and analytical methods that could move the development of economic scenarios forward in several key directions. These suggestions can be grouped into three categories: (1) comparing models and model results, and conducting model evaluation and validation activities, (2) enhancing model capabilities that build on activities that are already underway in the research community, and (3) advancing new and combined data sources. Together, these activities could present a promising opportunity to expand the available set of quantitative U.S. scenarios in the intermediate term.

First, several participants suggested that it is important to develop a better understanding of the drivers of economic results and the importance of different model types or methodological approaches to the economic outputs, or scenarios, that result. Specific ideas that were raised include:

- Perform various types of evaluative activities, such as hindcasting, along with developing protocols for conducting hindcasting.
- Conduct model comparisons across and within model types, in order to understand the importance of inputs, model structure, and other characteristics in determining economic outputs.
- Use expert elicitation to develop economic futures and to assess the futures developed using modeling approaches.

Second, data, models, and analytical methods clearly play an important role in developing capabilities to address problems at multiple scales and across multiple sectors. Several participants indicated that data, models, and analytical methods can be enhanced and improved in the intermediate term to address some of the user needs for economic scenarios as well as the perceived limitations of current approaches. Specific ideas that individual participants put forth include:

- Explore uncertainty and decision making, for example by using a stochastic dynamic approach and economic models that can use this approach, such as CGE models.
- Identify opportunities for combining scenarios with formal uncertainty analyses, and develop a probabilities for the scenarios using an ensemble approach, running more simplified models that may lower the computational burden of uncertainty analysis, or adopting another approach.
- Revisit the underlying drivers of economic growth that economic models assume to make long-term projections (e.g., out to 2100).
- Develop information that is targeted toward assisting local decision makers by focusing on extreme events, tipping points, and (as mentioned above), uncertainty.

Last, since reconciled data are needed to support the development and improvement of multi-sector and multi-scale modeling and research, an important opportunity exists to begin developing synthesized data products that conform to community standards, including both data underlying models and model outputs. This process is one that can be started in the intermediate term, but would be expected to continue on into the longer term.

## 3.3 Fundamental Science Challenges

A number of participants described the challenges of developing economic scenarios at the spatial and temporal scales identified as important to the user community, that possess other desirable characteristics (such as the types of variables included or the sectors covered), and that reflect the realities of how the economy functions and co-evolves with other systems over time. While these challenges are long-term in nature, steps will clearly need to be taken in the near and intermediate terms to understand and set the stage. A number of these challenges involve model development; others represent challenges to understanding and incorporating information into decision making.

Several participants identified challenges for the modeling community (see Section 2.3 for additional discussion of these challenges) and for researchers more broadly. These included:

- Developing computational platforms that can accommodate multiple interoperable models and ultimately incorporate information from other sources, such as case studies.
- Facilitating integration across models that span human and physical Earth systems, including incorporated feedback effects and co-evolution of these systems, and improved orientation of multi-model frameworks and approaches around different scientific questions, uses, and user needs.
- Adapting models to reflect economic realities (such as the absence of perfect information about the future), and the lessons emerging from behavioral economics and other disciplines.
- Developing scenarios for extreme events that are scientifically defensible and believable, but also informative for decision makers and can be appropriately communicated to potential users.

Some participants also identified the importance of building the community of practice for integrated assessment researchers and modelers. Over the long term, this could include establishing standards and protocols (e.g., protocols that define inputs and outputs for models that would enable models to be effectively coupled in an integrated, interoperable environment), developing a common language across disciplines, and enhancing core capabilities and tools. The development of protocols and platforms is a long-term challenge, which if successfully addressed could facilitate the capture and use of scientific advances in both human and physical Earth system research for use across a much wider range of potential users than is currently possible.

# References

Cai, Y., K.L. Judd, and T.S. Lontzek. 2016. The social cost of carbon with economic and climate risks. *Journal of Political Economy*. Under review.

Carter, T.R., R.N. Jones, X. Lu, et al. 2007. New assessment methods and the characterization of future conditions. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York: Cambridge University Press. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter2.pdf.

Christensen, P., K. Gillingham, and W. Nordhaus, 2016. Uncertainty in forecasts of long-run productivity growth. Working paper, Global Trade Analysis Project.

Gillingham, K., W.D. Nordhaus, D. Anthoff, G. Blanford, V. Bosetti, P. Christensen, H. McJeon, J. Reilly, and P. Sztorc. 2015. *Modeling Uncertainty in Climate Change: A Multi-Model Comparison*. NBER Working Paper No. 21637. Available at: http://www.nber.org/papers/w21637.

Kaack, L. 2016. The applicability of empirical prediction intervals to energy forecasting. engineering and public policy. Carnegie Mellon University. Working paper.

Lempert, R. et al. 2016. *Scenarios on Demand*. RAND Report TL-165. Forthcoming at https://www.rand.org/pardee/projects/scenarios-on-demand.html.

Morgan, M.G. and Keith, D.W. 2008. Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change* 90: 189-215.

Morris, J., M. Webster, and J. Reilly. 2016. *Electricity Investments under Technology Cost Uncertainty and Stochastic Technological Learning*. MIT Joint Program on the Science and Policy of Global Change. Report No. 297. May 2016.

Newcomer, A. 2007. Compiled EIA-AEO data. Department of Engineering and Public Policy, Carnegie Mellon University.

NOAA National Centers for Environmental Information. 2015. U.S. Drought Monitor Update for April 21, 2015. Available at https://www.ncdc.noaa.gov/sites/default/files/April-21-2015-US-Drought-Monitor-Map.png (accessed July 26, 2016).

Smil, V. 2003. *Energy at the Crossroads. Global Perspectives and Uncertainties*. Cambridge, Massachusetts: MIT Press.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds. 2007. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York: Cambridge University Press.

U.S. Department of Energy. 2014. *The Water-Energy Nexus: Challenges and Opportunities*. Available at: http://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities. Accessed July 28, 2016.

USGCRP (U.S. Global Change Research Program). 2014. Mission, Vision and Strategic plan. Available at: http://www.globalchange.gov/about/mission-vision-strategic-plan. Accessed August 1, 2016.

Weaver, C.P., R.J. Lempert, C. Brown, J.A. Hall, D. Revell, and D. Sarewitz. 2013. Improving the contribution of climate model information to decision-making: The value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, 4, 39–60.

Zurek, M.B., and Henrichs, T. 2007. Linking scenarios across geographical scales in international environmental assessments. *Technological Forecasting and Social Change.* 74:1282–1295.

# Acronyms and Abbreviations

| Acronym / Abbreviation | Stands For |
|---|---|
| AgMIP | Agricultural Model Intercomparison and Improvement Project |
| AMPERE | Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates |
| BEA | Bureau of Economic Analysis |
| BLS | Bureau of Labor Statistics |
| CGE | computable general equilibrium |
| CMIP | Coupled Model Intercomparison Project |
| DOE | U.S. Department of Energy |
| EIA | Energy Information Administration |
| EMF | Energy Modeling Forum |
| EPA | U.S. Environmental Protection Agency |
| ESM | earth systems model |
| GDP | Gross Domestic Product |
| GHG | greenhouse gas |
| IAM | Integrated Assessment Model |
| IAV | Impacts, Adaptation, and Vulnerability |
| ICLUS | Integrated Climate and Land-Use Scenarios |
| IIASA | International Institute for Applied Systems Analysis |
| IPCC | Intergovernmental Panel on Climate Change |
| NCA | National Climate Assessment |
| PIAMDDI | Program on Integrated Assessment Model Development, Diagnostics and Inter-Model Comparisons |
| RCP | Representative Concentration Pathway |
| SISCG | Scenarios and Interpretive Science Coordinating Group |
| SSP | Shared Socioeconomic Pathway |
| USGCRP | U.S. Global Change Research Program |

# Appendix A: Organizing and Production Teams

The following groups played a role in the organization and production of the *Multi-Scale Economic Methodologies and Scenarios Workshop.*

## Scientific Leads

**Jae Edmonds**, Pacific Northwest National Laboratory / Joint Global Change Research Institute (Scientific Chair)
**Richard Moss**, Pacific Northwest National Laboratory / Joint Global Change Research Institute

## U.S. Global Change Research Program Scenarios and Interpretive Science Coordinating Group

**Linda Langner** (Co-chair), U.S. Department of Agriculture Forest Service
**Robert Vallario** (Co-chair), U.S. Department of Energy
**Susan Aragon-Long**, U.S. Global Change Research Program / U.S. Geological Survey
**Ben DeAngelo**, U.S. Global Change Research Program
**Alison Delgado**, U.S. Global Change Research Program (National Coordination Office Point of Contact) / Pacific Northwest National Laboratory / Joint Global Change Research Institute
**Dave Easterling**, National Oceanic and Atmospheric Administration
**Anne Grambsch**, U.S. Environmental Protection Agency
**John Hall**, U.S. Department of Defense
**Allison Leidner**, National Aeronautics and Space Administration
**Fred Lipschultz**, U.S. Global Change Research Program / National Aeronautics and Space Administration
**Ron Sands**, U.S. Department of Agriculture
**Chris Weaver**, U.S. Environmental Protection Agency

## ICF International Production Team

**Jessica Kyle**, ICF International
**Frances Sussman**, ICF International
**Andrew Kindle**, ICF International
**Jessica Kuna**, ICF International
**Brad Hurley**, ICF International

# Appendix B: Workshop Agenda

## Multi-Scale Economic Methodologies and Scenarios Workshop

### Morning April 20

| | |
|---|---|
| 8:15 AM | **Coffee and Breakfast** |
| 8:45 AM | **Welcome:**<br>**Ghassem Asrar**<br>**Gary Geernaert** |
| 8:50 AM | **Introductions** |
| 9:00 AM | **Overview of the Experts Workshop and Goals of the Meeting**<br>*This session will go over the goals of the meeting; it will discuss the science drivers, the desired meeting outcomes, and the general flow of the meeting.*<br><br>*Our overarching science question is: How might the economic character of the United States evolve at time scales ranging from annual to decadal, at spatial scales ranging from national to local, and taking into account the multitude of drivers and stressors that could shape the path, e.g. climate change, demographics, migration, and technology?*<br><br>**Session Chair: Jae Edmonds**<br><br>**Drivers, Needs, and Broader Context – Bob Vallario/Anne Grambsch**<br>*Description of the workshop in the context of a larger series of workshops, initiatives, and needs.*<br><br>**Agenda, Meeting Flow, and Logistics – Jae Edmonds** |
| 9:30 AM | **Session 1. Use-Inspired Needs and Drivers: What research and assessment questions are economic scenarios intended to inform and what does that imply for the character of economic scenarios?**<br>*This session will discuss the uses to which economic scenarios will be put in a representative range of assessment processes—the “demand” side of the scenario-development process. We will particularly focus on the needs of the impacts, adaptation and vulnerability (IAV) community extending from operations, to planning, to deep research on long-term systems dynamics. The key issue to be discussed is “who wants scenarios and what types of scenarios are needed for what purpose?”*<br><br>**Session Chair: Anne Grambsch**<br>**Opening Comments**—*Each panelist will provide 5 minutes of perspective on the desired character of economic scenarios that are needed to undergird research and assessment work in various areas.*<br>• **Diana Bauer**<br>• **Ron Sands**<br>• **Jim Shortle** |

| | |
|---|---|
| | • **Amy Glasmeier**<br>• **Ben Preston**<br>• **Mike Mastrandrea**<br><br>**DISCUSSION (PART 1)** |
| 10:30 AM | **Break** |
| 11:00 AM | **Session 1: Continued Discussion**<br>**Session Chair: Anne Grambsch**<br><br>**DISCUSSION (PART 2)**<br><br>**Rapporteur**<br>• **Martin Ross** |
| 12:00 Noon | **Lunch Discussion** |

## Afternoon April 20

| | |
|---|---|
| 1:00 PM | **Session 2. Current State of the Art: Process Understanding, Data, Models, and Analytical Methods**<br>*This session focuses on current understanding of underlying dynamic processes and identifying existing data, models, and methods to deploy in support of near-term assessments—the "supply" side of the scenario-development process. The session will consider the current capabilities to deliver economic scenarios at time and spatial scales relevant to assessment needs (Session 1), illuminating economic growth, transitions, and dynamics at regional to global scales. Limitations in these capabilities are relevant to both near-term support for assessment and the identification of gaps that point to the longer-term research agenda for developing data, models and methods.*<br><br>**Session Chair: Jae Edmonds**<br><br>**Mini-presentations**—*Perspectives on current capabilities*<br>• **Richard Moss**—Integrated Scenarios<br>• **Anne Grambsch**—A scenario strategy for the USGCRP<br><br>**Comment on the current state of economic scenarios, data, methods and models**<br>• **Ken Gillingham**<br>• **Mort Webster**<br>• **Rob Lempert**<br>• **Amy Glasmeier**<br>• **Doug Meade**<br><br>**DISCUSSION**<br><br>**Rapporteur**<br>• **Ron Sands** |

<table>
<tr><td></td><td></td></tr>
<tr><td>3:00 PM</td><td>Break</td></tr>
<tr><td>3:30 PM</td><td>Session 3. Current Gaps and Research Needs: A Research Agenda for the Future<br>This session looks at the gaps that exist between the present capabilities to provide economic scenarios and multi-scale economic projections that exist (Session 2) and the capability that IAV research and assessment community would like to have (Session 1). Discussions follow regarding the research agenda that is needed to enable researchers to provide improved data, methods and models. The key question is how best to move from the current capability to deliver economic scenarios for research and assessments.<br><br>Session Chair: Bob Vallario<br>Comments—What are the research needs for advancing the next generation of economic multi-scale methods and the scientific foundations for regional-scale U.S. economic scenarios? Each panelist will provide 5 minutes of perspective.<ul><li>Karen Fisher-Vanden</li><li>Granger Morgan</li><li>Leon Clarke</li><li>Richard Moss</li><li>Ben Preston</li><li>Martin Ross</li></ul>DISCUSSION<br><br>Rapporteur<ul><li>Jae Edmonds</li></ul></td></tr>
<tr><td>5:30 PM</td><td>Adjourn</td></tr>
</table>

## Morning April 21

<table>
<tr><td>8:30 AM</td><td>Coffee and Breakfast</td></tr>
<tr><td>9:00 AM</td><td>Recap and Additional Thoughts On Day 1<br>Session Chair: Anne Grambsch<br>Panel 1—Each of the Rapporteurs from Day 1 provide a quick recap<ul><li>Martin Ross (Session 1)</li><li>Ron Sands (Session 2)</li><li>Jae Edmonds (Session 3)</li></ul>DISCUSSION</td></tr>
<tr><td>9:45 AM</td><td>Session 4. Near-Term Opportunities: The Nearer-term Challenge of Economic Research and Scenario Development, and Next Steps<br>This session will take up the question of how to support near-term assessments, while laying the foundation for the longer term. How can we develop a set of scientifically defensible and consistent scenarios (including a framework for considering uncertainty) given the limitation in our existing capabilities for the United States in the very near term (6 months), without compromising the long-term development outlined in Session 3?<br><br>Session Chair: Anne Grambsch</td></tr>
</table>

| | |
|---|---|
| | **Comments**— On *nearer-term challenge of economic research and scenario development and next steps*<br>• **Ken Gillingham**<br>• **Jim McFarland**<br>• **Henry Chen**<br>• **Doug Meade**<br>• **Granger Morgan**<br>• **Karen Fisher-Vanden**<br><br>**DISCUSSION** |
| 11:30 AM | **Round Robin Thoughts on the Way Forward**<br>Each person gets 1 minute<br><br>**Perspectives and Closing Thoughts**<br>• **Ghassem Asrar**<br>• **Anne Grambsch**<br>• **Bob Vallario** |
| 12:15 Noon | **Lunch Continued Discussion** |
| 1:30 PM | **Adjourn** |

# Appendix C: List of Workshop Participants

**Ghassem Asrar**, Joint Global Change Research Institute

**Diana Bauer**, U.S. Department of Energy

**Henry Chen**, Massachusetts Institute of Technology

**Leon Clarke**, Joint Global Change Research Institute

**Alison Delgado,** U.S. Global Change Research Program Pacific Northwest National Laboratory / Joint Global Change Research Institute

**Jae Edmonds**, Pacific Northwest National Laboratory / Joint Global Change Research Institute

**Karen Fisher-Vanden**, Pennsylvania State University

**Gerald Geernaert**, U.S. Department of Energy

**Kenneth Gillingham**, Yale University

**Amy Glasmeier**, Massachusetts Institute of Technology

**Anne Grambsch**, U.S. Environmental Protection Agency

**Lynn Kaack**, Carnegie Mellon University

**Andrew Kindle**, ICF International

**Jessica Kyle**, ICF International

**Robert Lempert**, RAND Corporation

**Michael Mastrandrea**, Stanford University

**James McFarland**, U.S. Environmental Protection Agency

**Doug Meade**, University of Maryland

**Granger Morgan**, Carnegie Mellon University

**Richard Moss**, Pacific Northwest National Laboratory /Joint Global Change Research Institute

**Benjamin Preston**, Oak Ridge National Laboratory

**Martin Ross**, Duke University

**Ron Sands**, U.S. Department of Agriculture

**James Shortle**, Pennsylvania State University

**Frances Sussman**, ICF International

**Robert Vallario**, U.S. Department of Energy

**Anthony Walker**, Oak Ridge National Laboratory

**Mort Webster**, Pennsylvania State University

# Appendix D: Workshop Discussion Questions

## SESSION 1: What are the needs of potential users of economic scenarios?

1. What are the needs for long term (e.g., 2030 +) economic scenarios for climate impacts, adaptation, and vulnerability research and assessments, in terms of:
   - Time frame or length of the analysis (2030, 2050, 2100, or beyond)?
   - Geographic scale and resolution (national, regional (multi□state), state, county, or municipality)?
   - Economic variables (GDP, income, employment, sector output)?
   - Combinations of socioeconomic variables (e.g., income by age group)?

   How do these needs vary or differ across potential user groups (e.g., assessment teams vs. state adaptation decision makers, vs. basic and applied research needs)? Across sectors of analysis or impact categories (e.g., water vs. health)?

2. Are economic scenarios needed for all sectors? Which sectors need economic projections? If all sectors need economic projections, how consistent do they need to be across sectors and the economy?

3. What are user needs with regard to different sources and types of uncertainty and how uncertainty propagates throughout the system? For example:
   - How should we represent uncertainty in an economic view of the future? What would be most valuable to users?
   - Should the view of the future include extreme climate events? Other types of extreme events? Business cycles?
   - Is there a role for qualitative as well as (or instead of) quantitative scenarios?
   - What information communicating and presenting uncertainty would be valuable to users?

4. How should scenarios reflect the possibility of disruptive or fundamental structural changes occurring in the future, e.g., climate-induced extreme events, disruptive technological change, long□term economic downturns, etc.? Does this differ across potential user groups?

5. Do users need consistent scenarios:
   - Across geographic scales (e.g., hierarchical or "nested")? What about temporal scales?
   - With non□economic scenarios (e.g., the demographic scenarios produced by the USGCRP)?
   - With the SSPs?

## SESSION 2: What are the current capabilities for meeting user needs for economic scenarios as described in Session 1?

1. Scenario projections: What is the state of the art for long-term economic projections?
   - What methods (both model-based and using other approaches) are currently available to develop regional, state- and local-level long-term economic projections? What are the strengths and weaknesses of these methods?
   - What models and other methods are available for exploring feedbacks and interdependencies across sectors and regions? What is the current state of development of integrated models?
   - How can we assess the usefulness of long-term economic projections (2030 to 2100+)?
   - What approaches are likely to be most productive when users request long-term projections at multiple geographic scales?
   - What can be done to evaluate and improve models used to develop projections? Do the priorities differ for different time scales, e.g., to 2030, to 2100?
2. Methods for evaluating the implications of an uncertain future:
   - What methods are available for evaluating uncertainties in long-term economic projections; e.g., what approaches would capture the range of "known unknowns?" How can "unknown unknowns" be addressed?
   - What are methods for evaluating (and perhaps reducing) uncertainties in models or combinations of models and methods?
   - What methods could be used to increase the usefulness of long-term economic scenarios given their inherent uncertainty? For example, decision analysis approaches, bottom-up or "backwards" methods that start from impact thresholds, and sensitivity or "stress tests?"
   - How should uncertain impacts/feedbacks be incorporated into economic scenarios, especially considering their importance to altering economic growth rates and characteristics?
   - What alternative methods (perhaps not using economic models) are available to construct scenarios, e.g., means of constructing qualitative scenarios?
3. Non-linear change:
   - How could economic models and economic scenarios address highly disruptive, non-linear, or rapid changes, such as prolonged or repeated extreme events?
   - Can models explore fundamental breaks with the past?
   - What other approaches—e.g., analogs, sensitivity/stress test cases—could be useful?
4. Data:
   - What is the availability and quality of data at different temporal and spatial scales to support the development and evaluation of economic scenarios?
   - How does the goal of consistency affect the assessment of these data?
   - Can we bring together data across distributed domains/systems in order to create an integrated set and form a new comprehensive system?

## SESSION 3: What might a long-term research agenda look like?

What do we need to do to improve in each one of the categories below? How do we set up an agenda for the future? In addition, how can we construct a research agenda so that we have "off ramps" and ensure that emerging insights from the research program can be readily incorporated into the assessment process?

1. DATA—How can needs for high-quality data at necessary level of detail to support model and methodological development be met?
   - How can the appropriate data sets be synthesized, documented, archived, and made readily available to support research?
   - Can data sets with adequate temporal and economic data be developed to support model validation and hind-cast activities?
   - Research itself will produce new data products. Can those data sets be documented, archived, and made readily available?
   - Can system boundary definitions be reconciled so that models can be compared?
2. MODELS AND METHODS—Where should model and methodological development be focused?
   - What types of economic models are used for IAV and EWL research? What model advances are needed?
   - What economic variables are needed at the different scales at which assessment is being conducted?
   - What complementary modeling capabilities are needed? For example, how should economic models interface with physical models?
   - How can other modeling paradigms be used to inform the emerging modeling capabilities? How can information from qualitative assessment be used to inform models? Can agent-based models be used in conjunction with neoclassical models?
   - What types of model comparison studies can be conducted to determine the relative importance of model structure, downscaling (or upscaling) method, and scenario or storyline in the magnitude of projections?
   - How can we explore the importance and the limits to internal and external consistency in storylines and quantitative results?
   - What can be done in the short, medium, and longer term to update and validate underlying data sources and develop new sources of data?
   - Can incentives be developed, e.g., dedicated journals, to encourage model documentation and documentation maintenance?
3. LINKED MODELING SYSTEMS—How can we move in the direction of a fully integrated modeling system, where we are modeling one set of assumptions in a single framework (in contrast to modeling different domains separately but with consistent underlying assumptions)?
   - How can economic models be linked to other physical and biological processes in integrated models? What is the role of emulators in coupled systems?

- How can different economic sectors be better linked with each other and with the macroeconomic models?
- How can "non-market" systems (especially those that have some market components, like Ecosystem Services) be integrated into the system?
- Can we develop economic models that have the flexibility to incorporate:
  - Interoperable modules?
  - The ability to telescope across a range of spatial and temporal scales (and potential sectors/systems of interest as necessary)?
  - Emulators for computationally expensive processes that are not core to addressing every problem?
  - Soft- and hard-coupled economic and physical processes?
  - Bi-directional influences, e.g., impacts of economic systems on physical processes and feedbacks of physical processes and associated impacts on economic development?
- Do we want to develop measures of net economic welfare as well as GDP?

4. UNCERTAINTY—What can/should be undertaken in the short, medium, and longer terms to understand the role of scale, time frame, and models/methodology combinations in uncertainty?
   - How do we develop tools to test or characterize uncertainty?
   - What techniques are needed to characterize uncertainty at multiple scales in a consistent manner?
   - What are the relative roles of uncertainty and sensitivity work?
5. DISRUPTIVE EVENTS—What can/should be done in the short, medium, and longer terms about capturing/incorporating the potential for disruptive change (e.g., transformational technological change, structural economic change, or extreme climate events)?
   - How can models and data be organized to better characterize events that are not occurring within the range of prior experience?
   - How much do potentially disruptive events need to be characterizable?
   - Can surprises even be modeled and/or how can different types of surprises be explored quantitatively?

## SESSION 4: What is a viable short-term path forward to develop economic scenarios for assessments and other uses in research?

1. What types of projections can be developed in a timely way in the near term (e.g., meeting the needs of NCA4, climate impacts research, etc.), and what are the characteristics of projections that could be developed? Specifically:
   - What economic variables, timeframes, and scales could be developed? What degree of consistency is possible/desirable across scales and other variables?
   - What degree of consistency with other scenarios/storylines is possible and desirable?
   - What models and methods could be used to develop these projections in the short term?
2. How can uncertainty be incorporated into scenarios in the near term? Is a higher and lower framing for uncertainty feasible? How could it be implemented? What could be done to reflect disruptive changes?
3. What guidance is necessary to improve the usability of these projections and scenarios (e.g., for climate impacts research, adaptation research, decision support, system dynamics, NCA4, and other assessments)? For example:
   - What elements could be included in the guidance (e.g., variables, timeframe, scale, boundary conditions, and methodological recommendations)?
   - How should researchers, who may be non-economists, interpret and use these scenarios to inform their assessment of impacts, adaptation, and vulnerability?
   - What process should be put into place for developing guidance for the longer term?
4. How can we ensure that emerging insights and interim progress (e.g., new scenarios, projections, or evolving capabilities) from a longer-term research program can be made available for climate research and vulnerability, impact, and adaptation research and assessments? What is a reasonable path forward to share such information on a regular basis?
5. What are the most promising research opportunities and critical next steps to pursue in the near term (e.g., under a year), in order to provide incremental results that push the envelope of both scenario development and integrated modeling forward? Where is the low hanging fruit with potential near-term, significant payoff in terms of advancing capabilities? What initial research efforts should be started sooner rather than later?

# Appendix E: Workshop Background Material

Prior to the workshop, background research was conducted to better understand the current use of projected economic inputs in impacts, adaptation, and vulnerability analyses in the United States, and to identify current capabilities in terms of models and methods for making long-term, sub-national economic projections. The results of this research were shared with participants as background material prior to the workshop and received intensive review by the organizing team members. In addition, these appendices were circulated for subsequent review by participants as part of the workshop report review package. This research is in no way intended to be a comprehensive assessment of these issues and capabilities, but rather to illustrate them and provide background for the workshop discussions.

## E.1: Background for Session 1: Current Use of Projected Economic Inputs in Impacts, Adaptation, and Vulnerability Analyses in the United States

National, regional (multi-state), state, and local analyses often identify socioeconomic data as key factors in impact and vulnerability assessments and adaptation plans. This section provides one view on the extent to which economic variables are identified as important drivers and are used as quantitative inputs in impact, adaptation, and vulnerability studies. To provide this view, an illustrative selection of available research, studies, and reports was reviewed. The selection of material reviewed included published literature (peer-reviewed journals and books) and unpublished reports undertaken by and for federal and state governments and non-governmental organizations, as well as academic working papers. The review provides evidence on several topics of interest:

- The typical use of economic variables in studies that cite economic inputs as important.
- The characteristics of studies that use economic variables quantitatively as part of estimating projected outcomes for impacts, vulnerability, or adaptation, in terms of the geographic scale, impact sectors, time frames, and other features.
- The sources of economic projections used in these studies.

More than 350 items of different types were reviewed. The search strategy is described further below.

### The use of economic inputs in impacts, adaptation and vulnerability studies: an overview

Economic variables appear as inputs into studies in three different applications: (1) qualitatively, as drivers of impacts or adaptive behavior; (2) quantitatively, in analyses of historical relationships between climate and impacts or other relevant variables; and (3) quantitative projections used as part of the process of estimating future climate impacts or adaptation costs and effectiveness. Each of these is discussed in turn below.

**First, studies cite economic variables as potential drivers of impacts or adaptive behavior.** While a few of the studies reviewed discuss the importance of economic drivers in some detail, many contain only a passing reference or short statement indicating importance. For example:

- Income is often identified as important in determining demand (for water or energy, in particular).
- Per capita income is also cited as a factor in determining impacts, particularly with regard to health, since lower income households may be more vulnerable to health effects and extreme events, and income also affects households' ability to adapt (e.g., by relocating or purchasing air conditioning or other building improvements).
- Studies also indicate indirect effects of income; for example, income may affect migration patterns, or economic growth may result in growing needs for utilities, roads, and public services, which may themselves become vulnerable to climate change.
- Last, economic growth affects both the resources available for adaptation by government entities and the *value* of structures that are vulnerable to flooding and other physical effects of climate change.

**Second, studies may use historical economic data to derive statistical relationships, e.g., between climate and health effects, or between climate and energy expenditures.** Studies in several different sectors use historical GDP, per capita income, or other economic variables in this manner. This approach is particularly common in the energy sector, where researchers use income (among other control variables) in regressions estimating the relationship between climate and energy consumption or expenditures. Researchers may use similar approaches in other sectors, including agriculture, recreation, water resources, coastal areas, and health, in order to capture the effects of economic growth or per capita income on the demand for resources, on land and property values, or on population vulnerability, as needed.

**Last, studies may use projected economic variables as part of projecting climate impacts or adaptive actions into the future.** Almost 50 studies were identified that use some sort of economic variable projected into the future as an input into the analysis. A number of these studies were conducted as part of coordinated efforts by the USGCRP and the NCA, by funding organizations such as the Electric Power Research Institute (EPRI) or Environmental Defense, or by a state government, such as California. Studies using economic projections as inputs appear as early as 1989, in the US EPA *Potential Effects* report (Smith and Tirpak, 1989), and at least one study was found in just about every year since 1994 to the most recent studies in 2015. The identified group of studies that use quantitative economic inputs is included and discussed in more detail further below. *Again, this list is not intended to be comprehensive, but rather illustrative.*

## Where and how quantitative projections of economic growth and income are used

The use of economic variables as quantitative inputs in these reviewed studies ranges across sectors, geographic scales, and time frames.

- **Sectors.**[9] The use of economic inputs is more readily found in studies that focus on physical resources—whether property or natural resources, such as water. Examples can be found in nearly all sectors, however.
  - A number of Energy sector studies define a relationship between income and energy consumption/expenditures, and analyze the relationship using historical data and statistical techniques; the studies then project expenditures or consumption using projected economic variables.
  - In Coastal Resources and other studies that look at physical damage to property or infrastructure and adaptive responses, economic inputs are used to estimate growth in the value of resources over time—e.g., the value of coastal property or infrastructure at risk of flooding, or potential damage due to extreme events, such as hurricanes.[10]
  - In Water Resources, economic inputs contribute to estimates of demand for water over time; a study of the Natural Environment sector also indicates that "population and economic growth are significant drivers of changes in resource demand and production." (USFS, 2012)
  - Methodologies that link per capita income to disease incidence (across countries) have also been developed (see, for example, Bosello, et al., 2004), although they are not applied as frequently as the economic adjustments described for the sectors above.
  - The use of economic projections may be more common in analyses coordinated across multiple sectors, which strive to provide a more consistent approach and framework across the studies.
- **Time frame.** The time frame of the reviewed studies ranges from 2030 to 2100 and beyond. While the difficulty of projecting economic growth and related variables over the very long term did not appear to limit the time frame of the overall analysis (which was often 2100), a number of studies cite problems with economic projections beyond a couple of decades. This may be, in part, the reason that studies often use very simple rules of thumb (see the discussion below regarding sources of economic data) or assume no changes beyond a particular year. Examples of limitations and approaches to the time frame include:
  - "Socioeconomic scenarios are created from population, household, and economic forecasts from regional and national sources. After 2050, we assume no further changes." (Kirshen, et al., 2006)
  - "Over the 21st century. . . it is reasonable to expect that populations will migrate, and incomes to grow or, in some cases, fall. Unfortunately, we have not identified a reliable approach to

[9] The sector typology used here is derived from the broad sector categories identified in the Global Change Resources Act of 1990: Natural Environment and Biodiversity (including non-product oriented ecosystem services, and species), Agriculture (including crops, livestock and grazing land), Energy Production and Use (both energy demand and energy supply), Land Resources (including forestry), Water Resources (including water quality and quantity, fishing, drinking water, and wastewater treatment), Transportation (both infrastructure effects and consequent effects on transportation services for business and households), Human Health and Welfare (including impacts on illness and mortality), and Human Social Systems (includes productive resources that are affected, as well as the built environment, and impacts on community and quality of life).

[10] To some extent, the predominance of the use of projections in these studies may reflect the multiple studies done by the same researchers using similar methodologies.

estimating migrations and income changes over the long time scale in which climate change and SLR will manifest." (Martinich, et al., 2013)

- **Geographic scale and resolution.** The identified studies include global studies (with the United States broken out separately or in some cases as part of larger regions), U.S. national studies, U.S. regional or multi-state studies, state studies, and a few city or county studies. While it is not always clear at what geographic resolution the analyses are performed (and the resolution may vary across types of data within a study), at least a few studies appear to produce results at the city or county level (see, for example, Stanton and Ackerman, 2007; Brown et al., 2013; and Pendleton et al., 2009).

## The sources of economic data

Studies that quantitatively project economic variables often adopt a simple assumption about growth rates in near-term decades (often based on recent historical growth rates or official estimates), and more modest rates in subsequent decades. Where possible, researchers rely on official government sources of information.[11]

- A number of studies use data provided by the federal government, in some cases building on the data. Sources include the U.S. EIA Annual Energy Outlook, the U.S. BEA, and the Congressional Budget Office. For example, Bin et al. (2007), a study of North Carolina coasts, uses per capita economic growth projections taken from the EIA. Paltsev et al. (2015) reports on the development of scenarios to support the Climate Change Impacts and Risks Analysis (CIRA) project at EPA (and studies that use the scenarios from CIRA, such as McFarland et al. (2015)); economic growth up to 2035 is based on the EIA Annual Energy Outlook, and productivity growth is assumed to be similar to that of past years in the years beyond 2035.
- A few studies begin with national estimates and then disaggregate these to the state or county level, using data such as the Regional Economic Information System of BEA (GLRA, 2000).
- In some cases, the assumptions for the SRES scenarios are used to guide the economic assumptions that are made at the national level. Some studies use the assumptions developed by the National Assessment Synthesis Team (NAST) for the 2000 NCA.[12]
- In many cases, relatively simple assumptions are made, such as a constant growth rate. For example, Neumann et al. (2010) assume 2% economic growth; Stanton and Ackerman (2007) assume an annual growth rate of 2.2% (based on historical rates in Florida) through 2030, then a drop to 1.5% for the next 70 years; and Rosenzweig et al. (2011) use a real GDP growth rate of 2.4% to extrapolate current climate impact costs out to 2080. Mansur et al. (2005) models income per

[11] The background material for Session 2 of this conference provides more information on US government sources of economic projections.

[12] For more information on these scenarios, see http://www.climateimpacts.org/us-climate-assess-2000/background/meetings/socio-econ.html

capita as continuing to grow at 2% per year (based on historical averages), and assumes that these changes are proportional across the country.

- Particularly for state-level analyses that require data at the state and/or local level, studies may rely on non-governmental sources of projections on personal income or economic growth, such as projections by IHS (Global Insight Model), Regional Economic Models, Inc. (REMI), and other modeling and forecasting firms.

In some cases high and low (or higher and lower) projections are used. For example, EPRI (2003) assumes growth rates of 1% and 2% in per capita income, for high and low population growth scenarios, respectively. In many cases, however, only a single economic projection is adopted. This raises the question of how different sources of uncertainty should be represented in the scenarios (see text box below on uncertainty).

## Search strategy

To identify literature that includes economic projections as part of impacts, adaptation, and vulnerability analyses, more than 350 items of different types were reviewed. Potentially relevant materials to be reviewed were identified from several sources: recent literature reviews on impacts and adaptation to climate change in the United States, the work coming out of the CIRA program at EPA, books and reports that have been published over the past three decades on the impacts of climate change in the United States[13], and citations from the most recent National Climate Assessment (NCA3). General internet searching provided additional published and unpublished literature, as well as a number of adaptation plans or impact assessments conducted by state and local governments. Overall, the focus was on finding items that provided quantitative estimates of future impacts, particularly those that provided assessments in dollar terms, since these materials were expected to be more likely also to use economic inputs; but the net was also cast more widely in order to identify some materials that discussed economic variables as drivers, qualitatively.

[13] See for example, Smith and Mendelsohn, 2006; Mendelsohn and Neumann, 1999; Ruth et al., 2006; CIER, 2007; Smith and Tirpak, 1999; and Mendelsohn, 2001.

**Considerations of Uncertainty in Developing and Applying Economic Scenarios**

The term "uncertainty" is used to encompass a multiplicity of concepts. Uncertainty may arise because of incomplete information (e.g., what will policies be in the future), or may refer to variability in natural or human social systems (e.g., variability in human behavior and responses to climate change or other changes over time). A quantity or measurement may be called uncertain, but so also may be the structure of a model. Many of the typologies of the sources of uncertainty in complex modeling systems contain the elements bulleted below, reflecting the conditions that give rise to uncertainty.

***Evolutionary or scenario uncertainty*** is a reflection of what is unknown about how the future will develop along any of a number of dimensions, including technology, legislation and regulation, the structure of the economy and political systems, international development, and other factors.

***Model or specification uncertainty*** (sometimes called scientific uncertainty) arises due to imperfect understanding of the relationships being modeled or specified (or erroneous theory). Model uncertainty does not always reflect insufficient understanding, but may also be introduced "as a pragmatic compromise between numerical stability and fidelity to the underlying theories, credibility of results, and available computational resources" (Curry and Webster, 2011).

***Parametric uncertainty*** refers to the uncertainty associated with quantifying the parameters and initial conditions of models. Parameter uncertainties (and consequent effects on outcomes and model outputs) can often be evaluated using statistical analysis and techniques such as Monte Carlo analysis, or other "cascading uncertainty" analyses.

***Stochastic uncertainty*** (also referred to as Ontic uncertainty) is associated with inherent variability or randomness, e.g., in climate or other physical and biological systems, or in human social systems (which reflect the variability and indeterminacy of human behavior).

***Other sources of uncertainty*** can affect model outputs, including measurement errors in the underlying data or other facets of data quality, algorithmic errors that result from computational limitations, or coding errors when writing the program for the model.

Uncertainty can be categorized across two other dimensions that may also be useful to the process of developing economic scenarios. The first dimension is the extent to which uncertainty can be statistically analyzed. The second dimension is whether uncertainty can be reduced by further study.

*Sources:* Adapted from discussion and definitions in Morgan and Henrion, 1990; Gillingham et al., 2015; Hendry and Erickson, 2001; Briggs et al., 2012; and Curry and Webster, 2011.

## Bibliography for Review of IAV Studies

The following bibliography includes the list of books, reports, and articles that were identified and analyzed to determine how economic projections were used as inputs into the analyses. These are items that passed the test of: (1) discussing economic variables as inputs into impacts, adaptation, or vulnerability assessments and analyses, and (2) using quantitative projections of economic variables in the analysis of the future. The list is not intended to be a comprehensive set of materials that use economic variables in this way, but rather illustrative and sufficiently representative to allow generalizations about the use of economics to be made.


America's Energy Coasts, America's Wetland Foundation, and Entergy Corporation. 2010. Building a resilient energy gulf coast: Executive report.

Bigano, A., Bosello, F., Roson, R., and R. S. J. Tol. 2006. Economy-wide estimates of the implications of climate change: A joint analysis for sea level rise and tourism. Fondazione Eni Enrico Mattei.

Bin, O., Dumas, C., Poulter, B., and J. Whitehead. 2007. Measuring the impacts of climate change on North Carolina coastal resources. National Commission on Energy Policy, Washington, DC.

Bosello, F. Roson, R. and R. S. J. Tol. 2007. Economy-wide estimates of the implications of climate change: Sea level rise. *Environmental and Resource Economics,* 37:549–571.

Bosello, F., Roson, R. and R. S. J. Tol. 2004. Economy-wide estimates of the implications of climate change: Human health. *Ecological Economics,* 58:579-591.

Brown, T. C., R. Foti, and J. A. Ramirez. 2013. Projected freshwater withdrawals in the United States under a changing climate. *Water Resources Research*, 49:1259-1276.

Callaway, J. M., Louw, D. B., Nkomo, J. C., Hellmuth, and D. A. Sparks. 2007. The Berg River dynamic spatial equilibrium model: A new tool for assessing the benefits and costs of alternatives for coping with water demand growth, climate variability, and climate change in the Western Cape. AIACC Working Paper No. 31, February.

Center for Integrative Environmental Research (CIER) at University of Maryland. 2007. The US economic impacts of climate change and the costs of inaction.

Electric Power Research Institute (EPRI). 2003. Global climate change and California: Potential implications for ecosystems, health, and the economy. Sacramento: Prepared for California Energy Commission, Public Interest Energy Research Program. Report No. 500-03-058CF.

Fankhauser, S. 1995. Protection versus retreat: Estimating the costs of sea level rise. *Environment and Planning A,* 27:299–319.

Fisher, A., Abler, D. , Barron, E. Bord, R., Crane, R., DeWalle, D, Knight, C. G., Najjar, R., Nizeyimana, E., O'Connor, R., Rose, A., Shortle, J., and B. Yarnal. 2000. Preparing for a Changing Climate: The potential consequences of climate variability and change. Mid-Atlantic. A report of the Mid-Atlantic Regional Assessment (MARA) Teams.

Gleick, P., and D. B. Adams. 2000. Water: The potential consequences of climate variability and change for the water resources of the United States. The report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change for the U.S. Global Change Research Program.

Great Lakes Regional Assessment (GLRA). 2000. Preparing for a changing climate: The potential consequences of climate variability and change: Great Lakes. A summary by the Great Lakes Regional Assessment Group for the U.S. Global Change Research Program.

Howitt, R. and E. Pienaar. 2006. Agricultural impacts. In Smith, J.B. and R. Mendelsohn (eds.). *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California*. Northampton, MA: Edward Elgar Publishing.

Hughes, G., Chinowsky, P., and K. Strzepek. 2010. The costs of adaptation to climate change for water infrastructure in OECD countries. *Utilities Policy*, 18, 142-153.

Hurd, B., Callaway, J.M., Smith, J.B. and P. Kirshen. 1999. Economic effects of climate change on US water resources. In R. Mendelsohn, and J. E. Neumann (eds.). *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

Jorgenson, D. W., Goettle, R. J., Hurd, B. H., Smith, J. B., Chestnut, L. G., and D. M. Mills. 2004. U.S. market consequences of global climate change. Pew Center on Global Climate Change.

Kirshen, P., Ruth, M., and M. Anderson. 2006. Climate's long-term impacts on urban infrastructures and services: The case of metro Boston. In M. Ruth, K. Donaghy, and P. Kirshen (eds.). *Regional Climate Change and Variability: Impacts and Responses*. Northampton, MA: Edward Elgar Publishing.

Lloyd, S. J., R. S. Kovats, and Z. Chalabi. 2011. Climate change, crop yields, and undernutrition: Development of a model to quantify the impact of climate scenarios on child undernutrition. *Environmental Health Perspectives*, 119 (12), 1817-1823.

Mansur, E. T., Mendelsohn, R., and W. Morrison. 2005. A discrete-continuous choice model of climate change impacts on energy (Working Paper No. ES-43). Yale School of Management. New Haven, CT.

Mansur, E., R. Mendelsohn, and W. Morrison. 2008. Climate change adaptation: A study of fuel choice and consumption in the US energy sector. *Journal of Environmental Economics and Management*, 55, 175-193.

McCarl, B. 2007. Adaptation options for agriculture, forestry and fisheries: a report to the UNFCCC Secretariat Financial and Technical Support Division.

McFarland, J., Zhou, Y., Clarke, L., Sullivan, P., Colman, J., Jaglom, W. S., Colley, M., Patel, P., Eom, J., Kim, S.H., Page Kyle, G., Schultz, P., Venkatesh, B., Haydel, J., Mack, C., and J. Creason. 2015. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change,* 131: 111-125.

Mendelsohn, R. and M. Markowski. 1999. The impact of climate change on outdoor recreation. In R. Mendelsohn, and J. E. Neumann (eds.). *The Impact of Climate Change on the United States Economy.* New York: Cambridge University Press.

Mendelsohn, R. 2006. Energy impacts. In J. B. Smith and R. Mendelsohn (eds.). *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California*. Northampton, MA: Edward Elgar Publishing.

Mendelsohn, R. and J. E. Neumann (eds.). 1999. *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

Mendelsohn, R. (ed.). 2001. *Global Warming and the American Economy: A Regional Assessment of Climate Change Impacts.* England: Edward Elgar Publishing, 2001.

Moore, C. 2015. Welfare estimates of avoided ocean acidification in the U.S. mollusk market. *Journal of Agricultural and Resource Economics,* 40 (1):50-62.

Morrison, W. and Mendelsohn, R. 1999. The impact of global warming on US energy expenditures. In R. Mendelsohn, and J. E. Neumann (eds.). *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

National Assessment Synthesis Team. 2001. Climate change impacts on the United State: Potential consequences of the climate variability and change for the United States. Foundation Report. Report for the US Global Change Research Program. Cambridge University Press, Cambridge, UK.

Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M., and D. Lee. 2010. The costs of agricultural adaptation to climate change (Discussion Paper No. 4). The World Bank.

Neumann, J. and D. Hudgens. 2006. Coastal Impacts. In J. B. Smith and R. Mendelsohn (eds.). *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California*. Northampton, MA: Edward Elgar Publishing.

Neumann, J., Hudgens, D., Herter, J., and J. Martinich. 2010. The economics of adaptation along developed coastlines. *Wiley Interdisciplinary Reviews: Climate Change* 2:89–98.

Neumann, J. and N. D. Livesay. 2003. Coastal structures: Dynamic economic modeling. In R. Mendelsohn (ed.), *Global Warming and the American Economy: A Regional Assessment of Climate Change Impacts*. Northampton, MA: Edward Elgar Publishing.

Nicholls, R. J. and R. S. J. Tol. 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical Transactions of the Royal Society A,* 364:1073-1095.

National Round Table on the Environment and the Economy (NRTEE). 2011. Paying the price: The economic impacts of climate change for Canada.

Ojima, D. S., and J. M. Lackett. 2002. Preparing for a changing climate: The potential consequences of climate variability and change. Central Great Plains. A report of the Central Great Plains Regional Assessment Group for the U.S. Global Change Research Program.

Pendleton, L., King, P., Mohn, C., Webster, D. G., Vaughn, R. K., and P. Adams. 2009. Estimating the potential economic impacts of climate change on Southern California Beaches. Draft paper. California Climate Change Center. Paper No. CEC-500-2009-033-D.

Rosenzweig, C., Solecki, W., DeGaetano, O'Grady, M., Hassol, S., and P. Grabhorn (eds.). 2011. Responding to climate change in New York State: the ClimAID integrated assessment for effective climate change adaptation in New York State. Final Report. NYSERDA Report No. 10851.

Ruth, M., K. Donaghy, and P. Kirshen (eds.). 2006. *Regional Climate Change and Variability: Impacts and Responses*. Northampton, MA: Edward Elgar Publishing.

Seattle Public Utilities. 2006. Official yield estimate and long-range water demand forecast.

Smith, J. B. and D. Tirpak (eds.). 1989. The potential effects of global climate change on the United States. Washington, DC: U.S. Environmental Protection Agency.

Smith, J.B. and R. Mendelsohn (eds.). 2006. *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California*. Northampton, MA: Edward Elgar Publishing.

Sohl, T. L., Sleeter, B.M., Sayler, K. L., Bouchard, M.A., Reker, R.R., Bennett, S. L., Sleeter, R. R., Kanengieter, R. L., and Z. Zhu. 2012. Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States. *Agriculture, Ecosystems and Environment*, 153:1-15.

Sohngen, B., Mendelsohn, R., and R. Sedjo. 1999. The impacts of climate change on the US timber market. Mendelsohn, and J. E. Neumann (eds.). *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

Stanton, E. A., and F. Ackerman. 2007. Florida and climate change: The cost of inaction. Tufts University, Global Development and Environment Institute, Stockholm Environment Institute, US Center.

Strzepek, K., Jacobsen, M., Boehlert, B., and J. Neumann. 2013. Toward evaluating the effect of climate change on investments in the water resources sector: Insights from the forecast and analysis of hydrological indicators in developing countries. *Environmental Research Letters,* 8: 044014.

Strzepek, K., Neumann, J. E., Smith, J., Martinich, J., Boehlert, B., Hejazi, M., Henderson, J., Wobus, C., Jones, R., Calvin, K., Johnson, D., Monier, E., Strzepek, J., and J. H. Yoon, 2015. Benefits of greenhouse gas mitigation on the supply, management, and use of water resources in the United States. *Climatic Change,* 131:127-141.

USFS (U.S. Forest Service). 2012. Future of America's forest and rangelands: 2010 Resources Planning Act assessment. General Technical Report WO-87. U.S. Department of Agriculture, Washington, D.C.

Yohe, G. W., Neumann, J., and P. Marshall. 1999. The economic damage induced by sea level rise in the United States. In Mendelsohn, and J. E. Neumann (eds.). *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

Yohe, G. W. and M. E. Schlesinger. 1998. Sea-level change: The expected economic cost of protection or abandonment in the United States. *Climatic Change,* 38:447–472.

Yohe, G. W., Neumann, J., Marshall, P., and H. Ameden. 1996. The economic cost of greenhouse-induced sea-level rise for developed property in the United States. *Climatic Change*, 32:387–410.

# E.2: Background for Session 2: Current Capabilities—Models and Methods

Existing climate change IAV studies that incorporate economic projections often use fairly simple methods to generate those projections. Current approaches to developing economic projections in these studies employ only a subset of available models and methods, and do not always provide the geographic, sectoral, and temporal detail that researchers would like. This background section explores the existing projections, models, and methods that could be employed to develop spatially and temporally detailed projections. Several different sources for existing economic scenarios include:

1. Projections (not related to climate change) developed by the U.S. federal and state government agencies.
2. Climate change-related projections (e.g., Shared Socioeconomic Pathways).
3. Existing models, including national economic models and IAMs.
4. Methods for disaggregating or downscaling economic projections from coarser to finer scales.

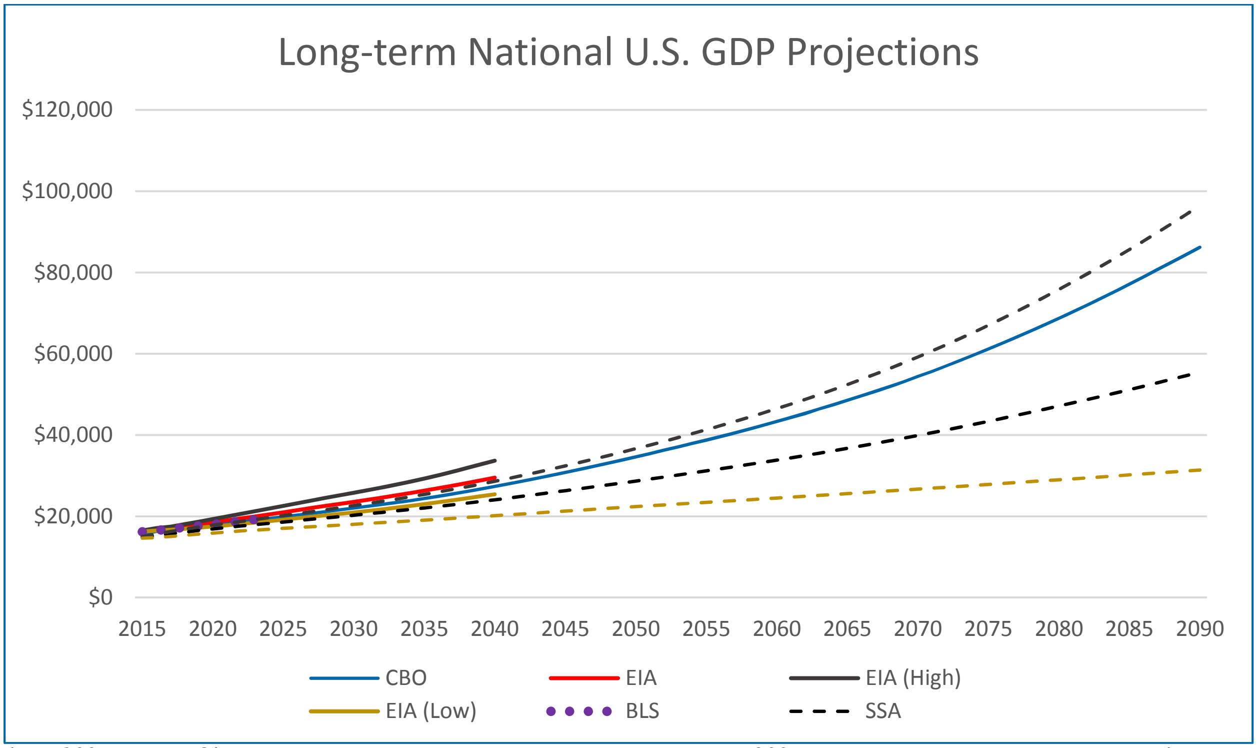
It will also be important at the workshop to consider the readiness of existing methods, models and data to provide economic scenarios that are consistent with a wide range of other concurrent developments (e.g., demographics, technology, and climate influences).

## Federal and state government projections

Projections of national U.S. GDP (and in some cases other economic variables) are available from several U.S. federal government agencies, the Organization for Economic Co-operation and Development (OECD), and the International Monetary Fund (IMF). In additional, many state governments project GDP using different methods, often for purposes of planning for development or employment. The figure below displays the national projections from federal and international sources.

At the federal level, the EIA, the Congressional Budget Office (CBO), and the BLS produce long-term projections of national GDP and other economic variables. From 1964 until 1995, the BEA also produced long-term projections, at both the national and state level.

- EIA produces the Annual Energy Outlook (AEO), which projects GDP, energy prices, energy consumption, and other variables relevant to the energy sector. The current projection extends to 2040.
- BLS publishes 10 year projections of employment, which also include GDP, personal consumption, investment, and other variables.
- CBO publishes the Long-Term Budget Outlook, which includes projections for national GDP and other economic and fiscal variables 25 years into the future.
- The Board of Trustees of the Federal Old-Age and Survivors Insurance and Federal Disability Insurance Trust Funds publish an annual report that includes projections for economic variables 75 years into the future.




All in 2005 billion US$; all source projections that were not reported in real 2005 dollars were converted using the BEA chain-type quantity index, with the exception of the SSA series, which was converted using that projection's consumer price index.

All GDP projections are from "baseline" or "reference" case scenarios except for "EIA High"; "SSA High" and "EIA Low"; "SSA Low" which, respectively, represent high and low economic growth scenarios from the EIA AEO and Social Security Administration.

*Sources:* CBO, 2015; EIA, 2015; BLS, 2015; SSA, 2015.

International organizations produce short- and long-term projections. OECD produces a long-term (through 2060) economic projection for all OECD economies and the major non-OECD economies, including GDP, employment, population, and interest rates. The IMF projects U.S. GDP, inflation, national savings, imports, exports, employment rate, and government debt 5 years into the future.

Many state governments produce state or county/city level economic projections. These generally range from around 3 to 10 years in length, although some states produce longer forecasts; notably, California currently has economic projections out to 2040 and Texas projects 30 years into the future. The variables projected depend on the source of the projection (e.g., development, transportation, or labor agencies within the state), but may include income, wages, employment, sectoral output, and other variables. Most states use commercially available models. Many states do not publish information on the methodology used to project these variables; those that do tend to have in-house models that use inputs from sources such as IHS Global Insight forecasting model, BEA and BLS data, and input-output tables.

## Climate change-related projections

Economic projections have been developed at the global and U.S. national level to inform climate change research communities, including the IAM community and the vulnerability, impacts, and adaptation community. Some notable examples of these projections are discussed below.

- Using its Integrated Global Systems Model (IGSM), the Massachusetts Institute of Technology (MIT) Joint Program on the Science and Policy of Global Change has designed scenarios for impact assessment that include economic projections and resulting GHG emissions through 2100 for a "no climate policy" scenario and two stabilization scenarios (Paltsev et al., 2015). These projections were used to assess U.S. climate change impacts as part of EPA's Climate CIRA project.
- The SSPs were developed by the international climate change community and consist of two elements: a narrative storyline and a limited set of quantified variables at the global and national levels.[14] The box below briefly describes the five future storylines. Quantified drivers include population (by age, sex, and education), urbanization, and economic development (GDP). For GDP, three interpretations of the SSPs have been modeled at the global and country levels by teams from OECD, IIASA, and the Potsdam Institute for Climate Impact Research (PIK).
- IAMs—including the Global Change Assessment Model (GCAM)—have run Representative Concentration Pathway (RCP) scenarios with associated economic growth projections. The RCPs are four radiative forcing trajectories chosen to represent a broad range of climate outcomes. Each RCP was simulated in an IAM to provide an internally consistent pathway of emissions and land use change that leads to the specific radiative forcing target.
- Three IAMs—MIT's IGSM, the Model for Evaluating the Regional and Global Effects (MERGE) developed jointly at Stanford University and EPRI, and the GCAM of the Joint Global Change Research Institute—were applied to develop scenarios for studying climate stabilization goals. These scenarios were developed using assumptions about principal drivers such as economic growth, population increase, land and labor productivity growth, and technological options (Clarke et al., 2007).

[14] The SSPs have been described as "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies" (O'Neill et al., 2014). They can be combined in a matrix architecture with assumptions about climate change (the Representative Concentration Pathways, or RCPs) and policy responses to evaluate climate change impacts, adaptation, and mitigation.

**The Shared Socioeconomic Pathways (SSPs)**

- **SSP1 (Sustainability)**—describes a world that makes progress toward sustainability, including rapid development of low-income countries, with low mitigation and adaptation challenges.
- **SSP2 (Middle of the Road)**—is characterized by continuing historical social, economic, and technological trends, and moderate challenges for both mitigation and adaptation.
- **SSP3 (Regional Rivalry)**—represents a strongly fragmented world with slow economic development, persistent or worsening inequality, and extreme poverty, subject to high mitigation and adaptation challenges.
- **SSP4 (Inequality)**—is a world with increasing inequalities and stratification both across and within countries. Concentrating power, moderate economic growth, and technology development in the high-tech economy lead to low challenges for mitigation. Adaptation challenges are high for substantial proportions of the population at low levels of development.
- **SSP5 (Fossil-fueled Development)**—is a growth-oriented world with rapid technological progress and human capital development. Reliance on fossil fuels results in high mitigation challenges. High human development, robust economic growth, and highly engineered infrastructure lead to low adaptation challenges.

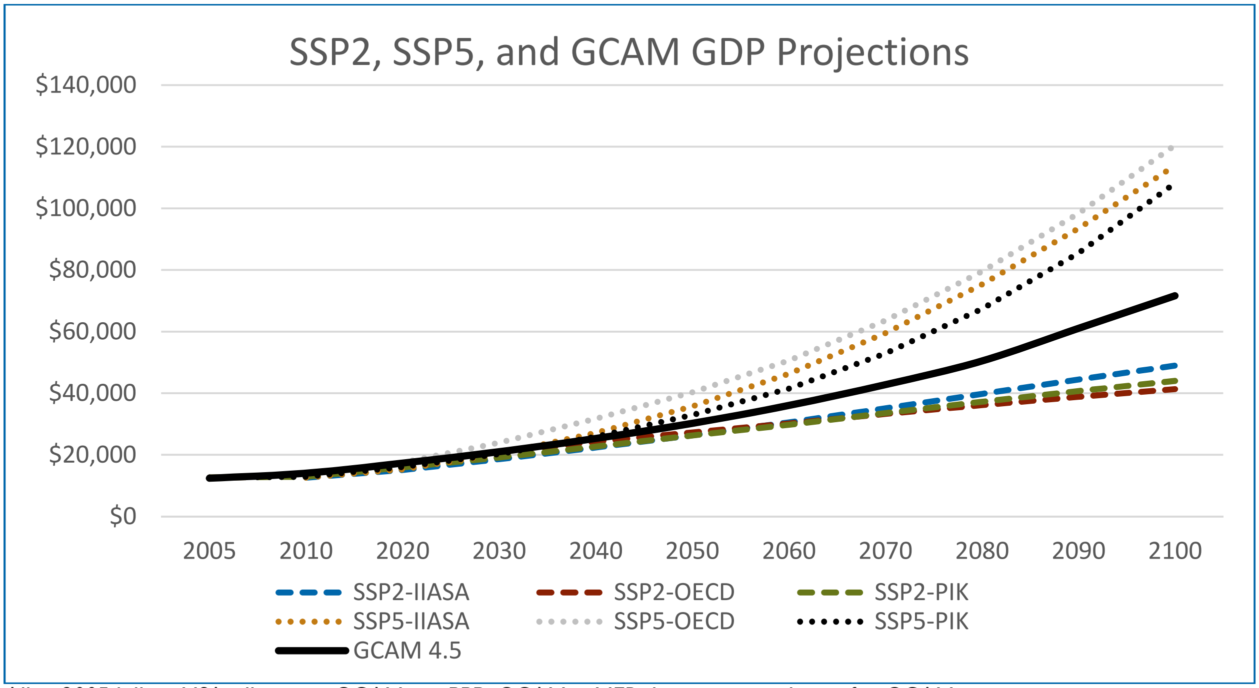
Key assumptions for modeling macroeconomic growth in the context of SSPs include total factor productivity (TFP) growth at the frontier (for the most advanced countries), and the speed of convergence of other countries to that frontier. These assumptions are given in the table below.

| **SSP Element** | **SSP1** | **SSP2** | **SSP3** | **SSP4*** | **SSP5** |
|---|---|---|---|---|---|
| TFP growth at frontier | Medium high | Medium | Low | Medium | High |
| Speed of convergence | High | Medium | Low | LI: Low; MI: Low; HI: Medium | High |

*In SSP4, the speed of convergence differs across country groupings with different income levels. LI: low income countries, MI: middle income countries, HI: high income countries

*Adapted from:* O'Neill et al., 2015; IIASA, 2015b.

The figure below illustrates the range of some long-term GDP projections that have been developed in the context of climate change research.




All in 2005 billion US$; all except GCAM are PPP, GCAM is MER; linear extrapolation for GCAM.
*Sources:* IIASA, 2015a; JGCRI, 2016.

## Current modeling capabilities

Researchers and policy-makers currently have access to a range of economic models that project economic variables, such as GDP or income, at the national and sub-national level. These models have been developed for a variety of purposes, ranging from theoretical explorations of policy questions to practical applications of the results in a governmental regulatory or programmatic context, or forecasting for business and government purposes. Increasingly, these models have been expanded and drawn into the climate change arena, and used to inform questions about optimal global paths for GHG emissions, the importance of adaptation in reducing impacts, and other questions. In particular, IAMs of global climate change study the interlinkages between human systems and natural systems, and include representations of the economy that range from simple to complex.

Many of the models currently in use are capable of producing economic futures. However, there is significant variation among models in terms of their modeling time horizon, their geographic scope and resolution, the economic variables they output, and the level of sectoral detail. For example, many IAMs project economic and other outputs over the very long term (2100 or further) but offer less sectoral detail and are not set up to generate projections at the sub-national scale. In contrast, the models that economists develop for short-term forecasting or analysis frequently embody more economic and regional detail, but typically extend only 10 to 30 years. Model type and structure can also influence results. For example, how models address structural and technological change, whether models are forward-looking or recursive-dynamic, and how models specify their terminal conditions may have important implications for economic results. The table below summarizes key features for selected models.

## Key Features of Selected Models

| | AMIGA | DIEM | EPPA | GCAM / GCAM-USA | IGEM | Moody's Macro Model | NEMS | REMI PI+ | RTI ADAGE U.S. Regional Model | US REP |
|---|---|---|---|---|---|---|---|---|---|---|
| **Full Name** | All-Modular Integrated Growth Assessment Model | Dynamic Integrated Economy/Energy/ Emissions Model | The MIT Economic Projection and Policy Analysis model | Global Change Assessment Model | Intertemporal General Equilibrium Model | U.S. Macro, State, County, and Metropolitan Statistical Area Forecast Models | National Energy Modeling System | Regional Economic Models, Inc. PI+ | RTI Applied Dynamic Analysis of the Global Economy, U.S. Regional Model | MIT US Regional Energy Policy Model |
| **Home Institution** | Argonne National Laboratory | Duke University (Nicholas Institute for Environmental Policy Solutions) | MIT Joint Program on the Science and Policy of Global Change | Pacific Northwest National Laboratory | Dale Jorgenson Associates | Moody's Analytics | Energy Information Administration | Regional Economic Models, Inc. | RTI International | MIT Joint Program on the Science and Policy of Global Change |
| **Model Type** | CGE *(intertemporally optimizing)* | CGE *(intertemporally optimizing)* and electricity-dispatch linear program | CGE (*recursive dynamic*); IAM | Partial equilibrium (*recursive dynamic*); IAM | CGE *(intertemporally optimizing)* | Structural macro-econometric forecasting model | Partial equilibrium, process-economy | CGE, input-output, econometric | CGE *(intertemporally optimizing)* | CGE (*recursive dynamic*) |
| **Timeframe** | Annual, 2050 | 5 years, 2050 | 5 Years, 2100 | 5 Years, 2100 | Annual, 75 year term | Quarterly, 30 year horizon | Annual, 25 year term | Annual, 2060 | 5 Years, 2050 | 2 or 5 Years, 2050 |
| **Geographical Detail** | U.S. and rest-of-world model; U.S. detail at census division and electricity market regions | U.S. regions (with flexibility to define regions using different aggregations of states) | 18 global regions, including U.S. | 32 global geopolitical regions (including U.S.); 231 water basins; 283 agro-ecological zones; GCAM-USA: energy system at the U.S. state level | U.S. national level | U.S. national, state, county, and metropolitan statistical area levels | U.S. national level and 9 census regions | U.S. national, census region, state, county-levels | U.S. national, U.S. census regions | U.S. national-level, state-level (flexible aggregation to U.S. regions) |

| | AMIGA | DIEM | EPPA | GCAM / GCAM-USA | IGEM | Moody's Macro Model | NEMS | REMI PI+ | RTI ADAGE U.S. Regional Model | US REP |
|---|---|---|---|---|---|---|---|---|---|---|
| **Economic Variables (*not an exhaustive list*)** | Income, GDP, prices, consumption, investment spending, imports/ exports, wages, interest rate | GDP, welfare, household consumption, investment and trade flows, energy production by type, energy demand and prices, GHG emissions and prices | GDP, income, energy, sectoral output, consumption, carbon prices | Energy, agriculture, and land prices and quantities, capital stocks, energy supply, taxes, quantities and prices of pollutant and GHG emissions; trade patterns; technology choice | GDP, consumption, industry output, capital stock, investment, prices, productivity, welfare, inequality and progressivity | Income, output (e.g., GDP), employment, housing, prices | GDP, employment, population, interest rates, energy prices, fuel prices, income, energy consumption, emissions, electric generation mix and capacity | Income, GDP, prices, consumption, investment spending, capital stocks, imports/ exports, and employment | GDP, consumption, industry output, prices, employment, wage rates, investment, trade, energy production and consumption | GDP, income, welfare, taxes, imports, trade, consumption, prices |
| **Sectoral Coverage** | 100 individual sectors with detailed representations of the energy sector and heavy industries | Five non-energy sectors (agriculture, energy-intensive manufacturing, other manufacturing, services, and transportation), which can be further disaggregated within computational limits, and energy industries (fuels and electricity) | 14 sectors (5 are related to energy and electricity) aggregated from GTAP 8; 15 backstop technologies (11 are electricity sector technologies) with cost data drawn from existing reports or studies (from EIA, IEA, etc.) | Three final demand sectors: Buildings, Transportation, and Industry. Detailed energy supply for renewable and non-renewable resources, energy transformation sectors for power, hydrogen, and refined products with different technologies. Detailed land use sector covering agricultural demand, competition between bioenergy and crops, and more | 35 producing sectors, including five energy producing sectors, each with its own production function | More than 1,800 variables represent different sectors and relationships. Manufacturing and service industries are represented at the three-digit and two-digit NAICS level, respectively, at the national, state, country, and metropolitan statistical area levels | Economic output is projected for 66 economic sectors (3 or 4 digit NAICS codes). Employment is projected for 59 industries. Other variables are projected for industrial sectors, and the residential, commercial, and transportation sectors | Up to 160-sectors mapped to NAICS codes | Up to 10 sectors, of which five are broad industrial groups (e.g., agriculture, manufacturing, services) and five are primary energy industries (e.g., fossil fuel, petroleum refining) | 52 sectors with detailed representation of electricity and energy sectors |

*Sources:* For all models except NEMS, modeling teams reviewed the information provided in the table above for accuracy. For NEMS, information is based on public model documentation available at: http://www.eia.gov/forecasts/aeo/nems/overview/pdf/0581(2009).pdf, and http://www.eia.gov/forecasts/aeo/nems/documentation/macroeconomic/pdf/m065(2014).pdf.

## Methods for Developing National-scale, Fine-resolution Projections

Projecting economic change over the long term, at the national scale and with fine spatial resolution, presents challenges. Some variables (well-understood variables such as GDP) might be relatively easier to project at the national and sub-national level, but become more difficult as the geographic unit or scale shrinks. Reconciling estimates for different geographic scales can also be difficult: while statewide economic growth rates, for example, will influence growth rates in many communities, economic growth in local communities will also be governed by many highly local factors such as development patterns and local industries.

**Example of National-scale, Fine-resolution Projections**

For the Third National Climate Assessment, population projections were provided through 2100 in five-year time steps for each county in the conterminous United States (see for example, the dataset for the Northwest region: https://www.epa.gov/iclus/iclus-data-northwest-region). These projections are broadly consistent with peer-reviewed storylines of population growth and economic development that are now widely used by the climate change impacts community.

A variety of methods are available to develop nationwide projections at a fine resolution. These methods can generally be characterized as top-down (or downscaling) and bottom-up approaches, as discussed below, reflecting the entry point for scenario development. In choosing among and applying these methods, however, users often face trade-offs. Top-down approaches can enable stronger consistency with national or global scenarios but are not finely tuned to distinctly local factors, while bottom-up approaches can capture local changes and behavioral components but present challenges in terms of time intensity, consistency across geographical areas, and aggregating up to the national level.

### Downscaling Approaches

Downscaling is often used generally to refer to a family of methods that can be used to produce finer-resolution data or projections from information that is modeled at a coarser scale. Methods for developing climate projections at fine spatial scales have been well studied and documented, and fine-scale projections for temperature and precipitation exist for the United States and other countries. Downscaling approaches have also been applied to socioeconomic variables in a few instances. At this time, however, downscaling methods for producing subnational projections of socioeconomic variables have not been extensively studied, nor are they in widespread use in climate analyses in the United States.

Van Vuuren et al. (2010) offers a typology of approaches for downscaling. These approaches include:

- **Algorithm downscaling**—One technique for quantitative downscaling of global- and national-level information is the use of algorithms, ranging from simple to complex. Some techniques include proportional or linear downscaling, convergence downscaling, and scenario-based downscaling. More complex downscaling algorithms employ statistical relationships based on historical data or models.
- **Conditional modeling**—This approach involves using finer-scale models that are conditional on the results or assumptions at the coarser scale (e.g., the coarser-scale modeling provides boundary conditions for the finer-scale models). Conditional modeling will only be possible if sufficient

information is available to conduct the modeling on the finer scale. Storylines can also be helpful for developing assumptions for finer-scale models that are consistent with coarser-scale results. Finer-scale projections resulting from simulation processes can be benchmarked against coarser-scale projections, or the two can be reconciled using iterative approaches.

- **Fully coupled models**—A more elaborate modeling approach uses interactively coupled models that link different scales. In these coupled models, information at more aggregated levels is downscaled to lower levels, and dynamic modeling processes at the lower levels then influence results at the more aggregated levels. This approach can also employ and combine any of the downscaling techniques discussed above. For example, economic variables could be modeled at the regional (multi-state) level and linked to national models. Then the regional results could be further downscaled using simple algorithms.

## Bottom-up Approaches

A related family of approaches focuses on developing economic scenarios and projections at finer scales (e.g., regional, state, or local) and then aggregating these finer-resolution products, potentially up to a national scale. Methods may include the fine-scale economic models (as are described above in the downscaling section), as well as techniques such as agent-based modeling, participatory scenario development, and micro-simulation. Taking a bottom-up approach may have advantages in some circumstances, particularly when it is important to represent local conditions and circumstances in the scenario, or to capture behavioral differences and responses. Fine-scale modeling and similar approaches, however, can be resource-intensive and therefore difficult to replicate across many jurisdictions. A bottom-up approach also brings the challenge of developing appropriate data sets and aggregation across jurisdictions. Such a bottom-up national projection may also be difficult to reconcile with other (top-down) national projections. Fine-scale modeling may also exacerbate the uncertainty associated with long term projections of socioeconomic variables, as indicated in the text box below.

**The Relationship Between Mean Absolute Percent Error (MAPE) of Population Projections and Time Horizon and Spatial Resolution**

At the USGCRP workshop (held in June 2014), *Towards Scenarios of U.S. Demographic Change*, one presenter illustrated how projection uncertainty increases with the spatial resolution and temporal extent of a projection, using MAPE. In the figure, mean absolute percent errors increase with the length of the time horizon or the spatial resolution; errors increase dramatically when both time frame and spatial resolution increase.

*Source:* Towards Scenarios of U.S. Demographic Change: Workshop Report.
*Note:* MAPE is a common measure of projection error. MAPE tells us how large an error we can expect from the projection on average.

*Mean absolute percent errors of projections, by length of horizon (years) and geographic unit*

| Length of Horizon | States | Counties | Census Tracts |
|---|---|---|---|
| 5 | 3 | 6 | 9 |
| 10 | 6 | 12 | 18 |
| 15 | 9 | 18 | 27 |
| 20 | 12 | 24 | 36 |

# References for the Appendices


Bin, O., Dumas, C., Poulter, B., and J. Whitehead. 2007. Measuring the impacts of climate change on North Carolina coastal resources. National Commission on Energy Policy, Washington, DC.

Bosello, F., Roson, R. and R. S. J. Tol. 2004. Economy-wide estimates of the implications of climate change: Human health. *Ecological Economics,* 58:579-591.

Briggs, A.H., Weinstein, M.C., Fenwick, E.A.L., Karnon, J., Sculpher, M.J., and A. D. Paltiel. 2012. Model parameter estimation and uncertainty: A report of the ISPOR-SMDM Modeling Good Research Practices Task Force-6. *Value in Health* 15: 835-842.

Bureau of Labor Statistics (BLS). 2015. The U.S. Economy to 2024. Retrieved from http://www.bls.gov/emp/ep_table_401.htm (Last Accessed 3/31/16).

Brown, T. C., R. Foti, and J. A. Ramirez. 2013. Projected freshwater withdrawals in the United States under a changing climate. *Water Resources Research*, 49:1259-1276.

Center for Integrative Environmental Research (CIER) at University of Maryland. 2007. The US economic impacts of climate change and the costs of inaction.

Clarke, L.E., Edmonds, J.A., Jacoby, H.D., Pitcher, H.M., Reilly, J.M., Richels, R.G. 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Synthesis And Assessment Product 2.1a. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Retrieved from: http://data.globalchange.gov/assets/f0/98/3830374208a6065f5c3d5186b942/sap2-1a-final-all.pdf

Congressional Budget Office (CBO). 2015. Long-Term Budget Outlook. Retrieved from https://www.cbo.gov/publication/50250 (Last Accessed: 3/31/16).

Congressional Budget Office (CBO). 2009. CBO's Long-Term Model: An Overview. Washington, DC: The Congress of the United States. Retrieved from https://www.cbo.gov/sites/default/files/111th-congress-2009-2010/reports/06-26-cbolt.pdf

Curry, J.A. and P. J. Webster. 2011. Climate science and the uncertainty monster. *Bureau of the American Meteorological Society*, 1667-1682.

Energy Information Administration (EIA). 2015. Annual Energy Outlook. Retrieved from https://www.eia.gov/analysis/projection-data.cfm#annualproj (Last Accessed: 3/31/16).

Electric Power Research Institute (EPRI). 2003. Global climate change and California: Potential implications for ecosystems, health, and the economy. Sacramento: Prepared for California Energy Commission, Public Interest Energy Research Program. Report No. 500-03-058CF.

Gillingham, K., Nordhaus, W., Anthoff, D., Blanford, G., Bosetti, V., Christensen, P., McJeon, H., Reilly, J., and P. Sztorc. 2015. Modeling uncertainty in climate change: A multi-model comparison. Cowles foundation for research in economics, Yale University.

Great Lakes Regional Assessment (GLRA). 2000. Preparing for a changing climate: The potential consequences of climate variability and change: Great Lakes. A summary by the Great Lakes Regional Assessment Group for the U.S. Global Change Research Program.

Hendry, D.F. and N.R. Ericsson. 2001. Understanding Economic Forecasts. MIT Press: Cambridge, MA.

International Institute for Applied Systems Analysis (IIASA). 2015a. SSP Database – Version 1.0. Retrieved from: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=download.

International Institute for Applied Systems Analysis (IIASA). 2015b. Supplementary note for the SSP data sets. Retrieved from: https://secure.iiasa.ac.at/web-apps/ene/SspDb/static/download/ssp_suplementary%20text.pdf

Joint Global Change Research Institute (JGCRI). 2016. GCAM RCP Scenario Results. Retrieved from http://www.globalchange.umd.edu/gcamrcp/.

Kirshen, P., Ruth, M., and M. Anderson. 2006. Climate's long-term impacts on urban infrastructures and services: The case of metro Boston. In M. Ruth, K. Donaghy, and P. Kirshen (eds.). *Regional Climate Change and Variability: Impacts and Responses*. Northampton, MA: Edward Elgar Publishing.

Mansur, E. T., Mendelsohn, R., and W. Morrison. 2005. A discrete-continuous choice model of climate change impacts on energy (Working Paper No. ES-43). Yale School of Management. New Haven, CT.

Martinich, J., Neumann, J., Ludwig, L and L. Jantarasami. 2013. Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change*, 18 (2), 169-185.

McFarland, J., Zhou, Y., Clarke, L., Sullivan, P., Colman, J., Jaglom, W. S., Colley, M., Patel, P., Eom, J., Kim, S.H., Page Kyle, G., Schultz, P., Venkatesh, B., Haydel, J., Mack, C., and J. Creason. 2015. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change,* 131: 111-125.

Mendelsohn, R. and J. E. Neumann (eds). 1999. *The Impact of Climate Change on the United States Economy*. New York: Cambridge University Press.

Mendelsohn, R. (ed). 2001. *Global Warming and the American Economy: A Regional Assessment of Climate Change Impacts.* England: Edward Elgar Publishing, 2001.

Morgan, M.G. and Henrion, M. 1990. Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. New York: Cambridge University Press.

Neumann, J., Hudgens, D., Herter, J., and J. Martinich. 2010. The economics of adaptation along developed coastlines. *Wiley Interdisciplinary Reviews: Climate Change* 2:89–98.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., and Solecki, W. 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* (in press).

O'Neill, B.C., E. Krieglar, K. Riahi, K. Ebi, S. Hallegatte, T. Carter, R. Mathur, and D. van Vuuren. 2014. *Climatic Change* 122: 387-400.

Organization for Economic Co-operation and Development (OECD). 2014. Economic Outlook No. 95 – Long-term baseline projections. Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=EO95_LTB (Last Accessed: 3/31/16).

Paltsev, S., Monier, E., Scott, J., Sokolov, A., Reilly, J. 2015. Integrated economic and climate projections for impact assessment. *Climatic Change* 131: 21-33.

Pendleton, L., King, P., Mohn, C., Webster, D. G., Vaughn, R. K., and P. Adams. 2009. Estimating the potential economic impacts of climate change on Southern California Beaches. Draft paper. California Climate Change Center. Paper No. CEC-500-2009-033-D.

Rosenzweig, C., Solecki, W., DeGaetano, O'Grady, M., Hassol, S., and P. Grabhorn (eds.). 2011. Responding to climate change in New York State: the ClimAID integrated assessment for effective climate change adaptation in New York State. Final Report. NYSERDA Report No. 10851.

Ruth, M., K. Donaghy, and P. Kirshen (eds.). 2006. *Regional Climate Change and Variability: Impacts and Responses*. Northampton, MA: Edward Elgar Publishing.

Smith, J. B. and D. Tirpak (eds.). 1989. The potential effects of global climate change on the United States. Washington, DC: U.S. Environmental Protection Agency.

Smith, J.B. and R. Mendelsohn (eds.). 2006. *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California*. Northampton, MA: Edward Elgar Publishing.

Social Security Administration (SSA). 2015. The 2015 Annual Report of the Board of Trustees of the Federal Old-Age and Survivors Insurance and Federal Disability Insurance Trust Funds. Retrieved from https://www.ssa.gov/oact/tr/2015/ (Last Accessed 4/4/16).

Stanton, E. A., and F. Ackerman. 2007. Florida and climate change: The cost of inaction. Tufts University, Global Development and Environment Institute, Stockholm Environment Institute, US Center.

U.S. Energy Information Agency. 2015. Assumptions to the Annual Energy Outlook 2015. Washington, DC: U.S. Department of Energy. Retrieved from http://www.eia.gov/forecasts/aeo/assumptions/pdf/0554(2015).pdf

USFS (U.S. Forest Service). 2012. Future of America's forest and rangelands: 2010 Resources Planning Act assessment. General Technical Report WO-87. U.S. Department of Agriculture, Washington, D.C.

van Vuuren, D.P., Smith, S.J., and Riahi, K. 2010. Downscaling socioeconomic and emissions scenarios for global environmental change research: A review. *Wiley Interdisciplinary Reviews: Climate Change* 1 (3):393–404.