Stay humble and prepare for surprises: lessons for the energy transition

MIT Energy Initiative
Joseph DeCarolis, Administrator

November 13, 2024 | Cambridge, MA

What does EIA do?

The U.S. Energy Information Administration (EIA) is the statistical and analytical agency within the U.S. Department of Energy.

EIA collects, analyzes, and disseminates independent and impartial energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment. EIA is the nation's premier source of energy information and, by law, its data, analyses, and forecasts are independent of approval by any other officer or employee of the U.S. government.

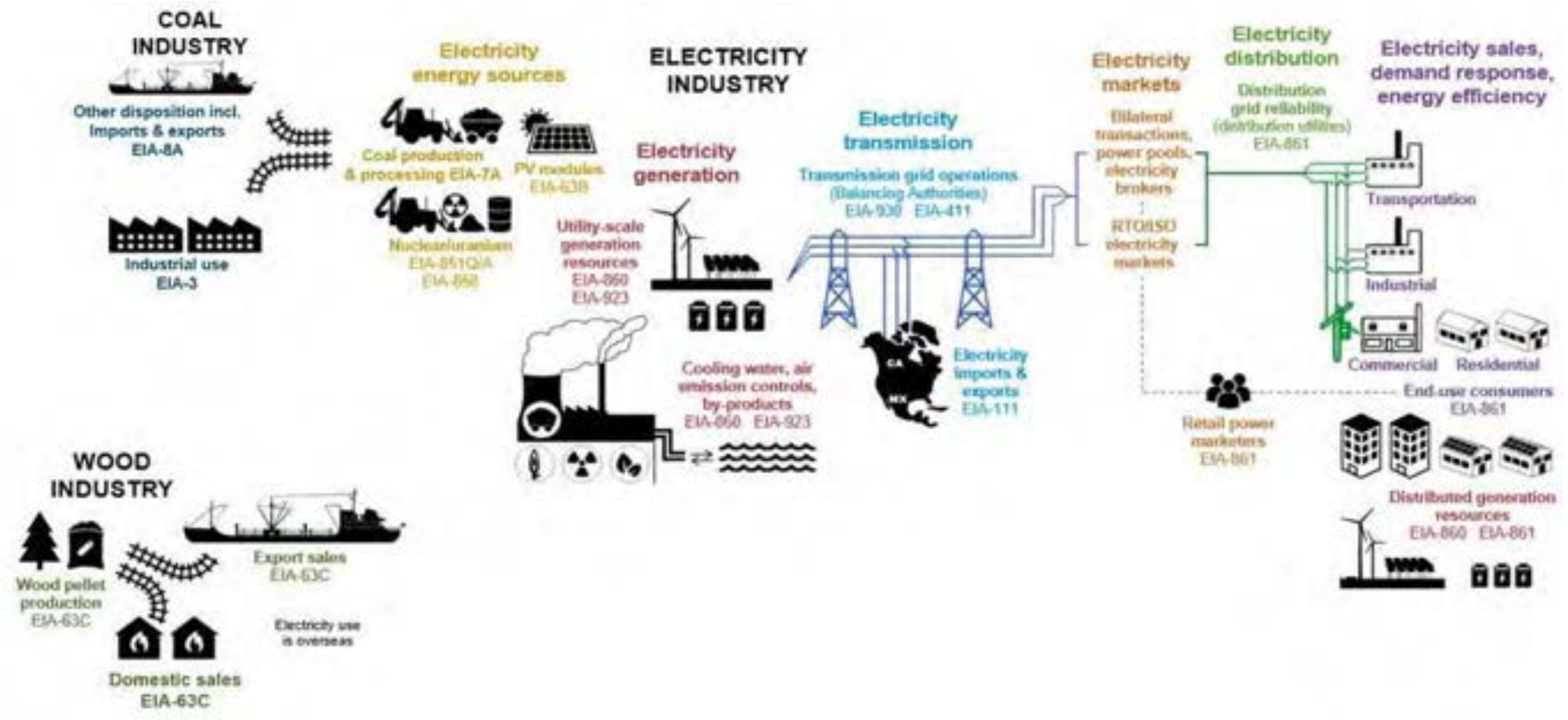
EIA maintains a comprehensive energy statistics program

- EIA's data program is foundational to our mission. Policy makers, energy producers, consumers, investors, traders, and analysts use EIA statistics in their day-to-day activities.

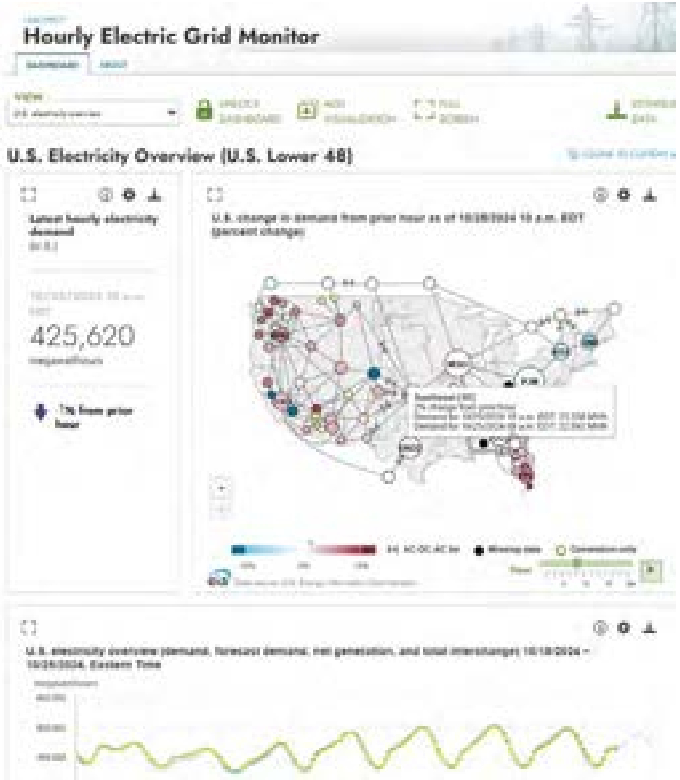
- The energy supply survey program represents EIA's largest operational area; survey data published in more than 300 reports a year across weekly, monthly, quarterly, and annual product lines.

- Three large-scale, multi-year consumption surveys: the *Commercial Buildings Energy Consumption Survey* (CBECS); *Residential Energy Consumption Survey* (RECS); and *Manufacturing Energy Consumption Survey* (MECS).

Electricity Data Collection



EIA Electricity Dashboards

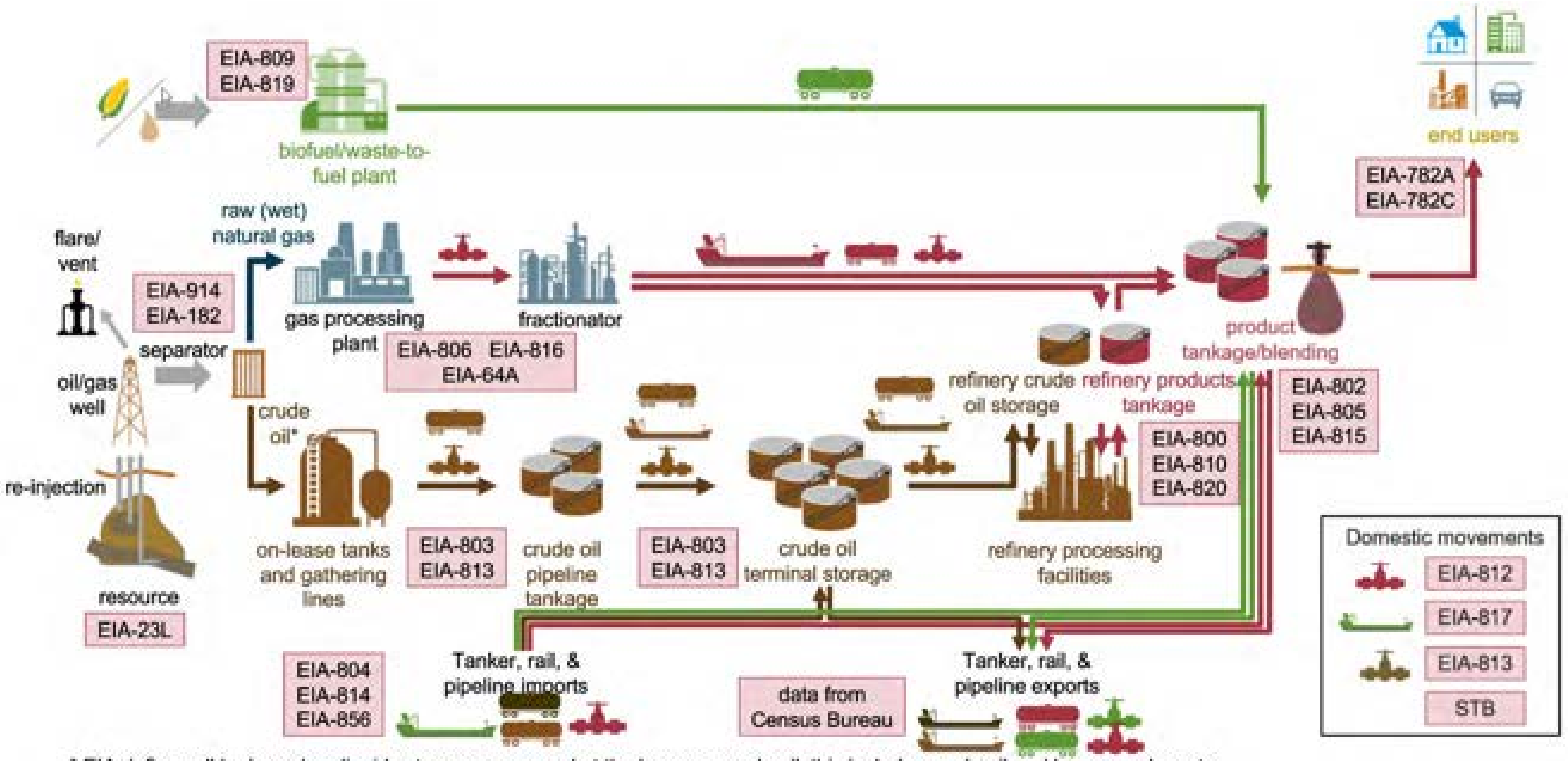


https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48

Wholesale Electricity Market Portal

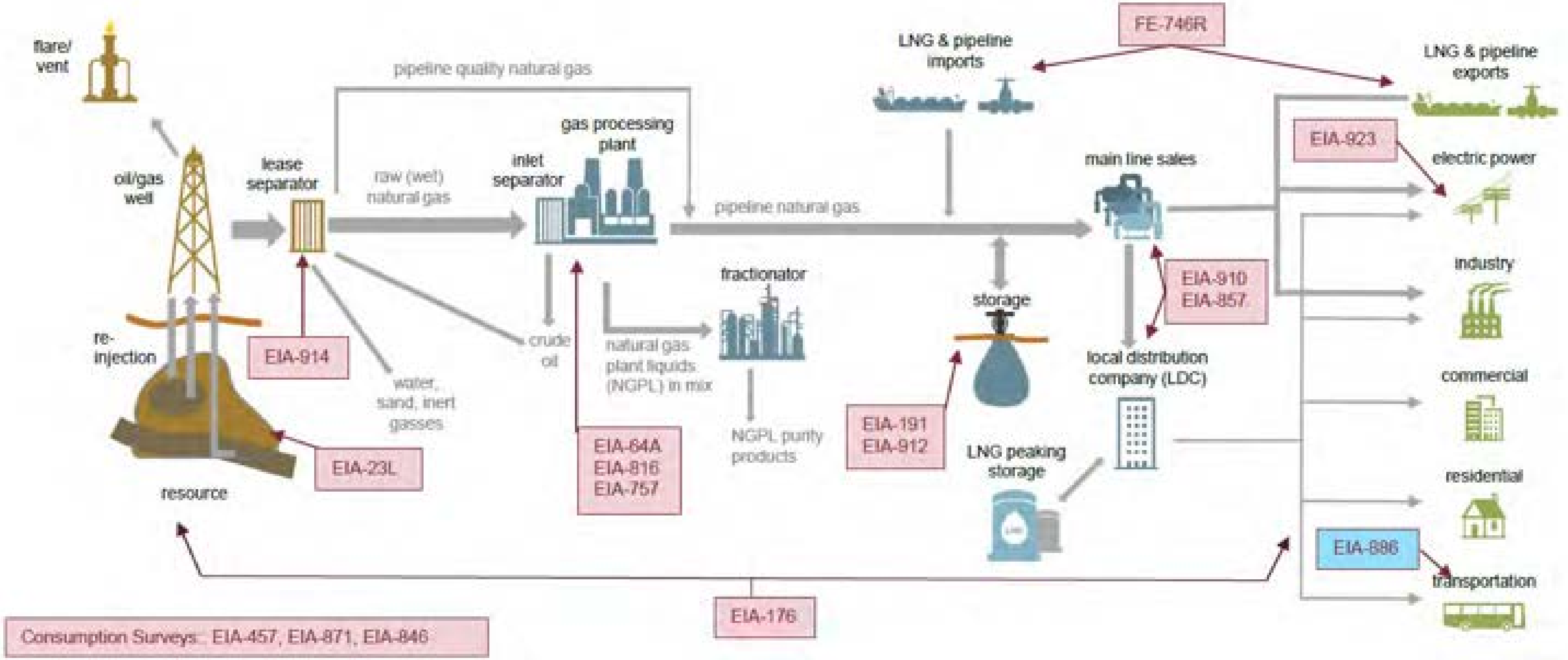
https://www.eia.gov/electricity/wholesalemarkets/

Petroleum Data Collection



* EIA defines all hydrocarbon liquids streams recovered at the lease as crude oil; this includes crude oil and lease condensate.

Natural Gas Data Collection



EIA analyses bring context and meaning to energy data

***Short-Term Energy Outlook* (STEO)**

Monthly forecasts of U.S. and global supply, consumption, trade, stocks, prices, and energy-related carbon dioxide emissions with a horizon of 12 to 24 months

***Annual Energy Outlook* (AEO)**

Projects U.S. energy supply, consumption, and trade over a 30-year period; the AEO is produced using EIA's National Energy Modeling System (NEMS)

***International Energy Outlook* (IEO)**

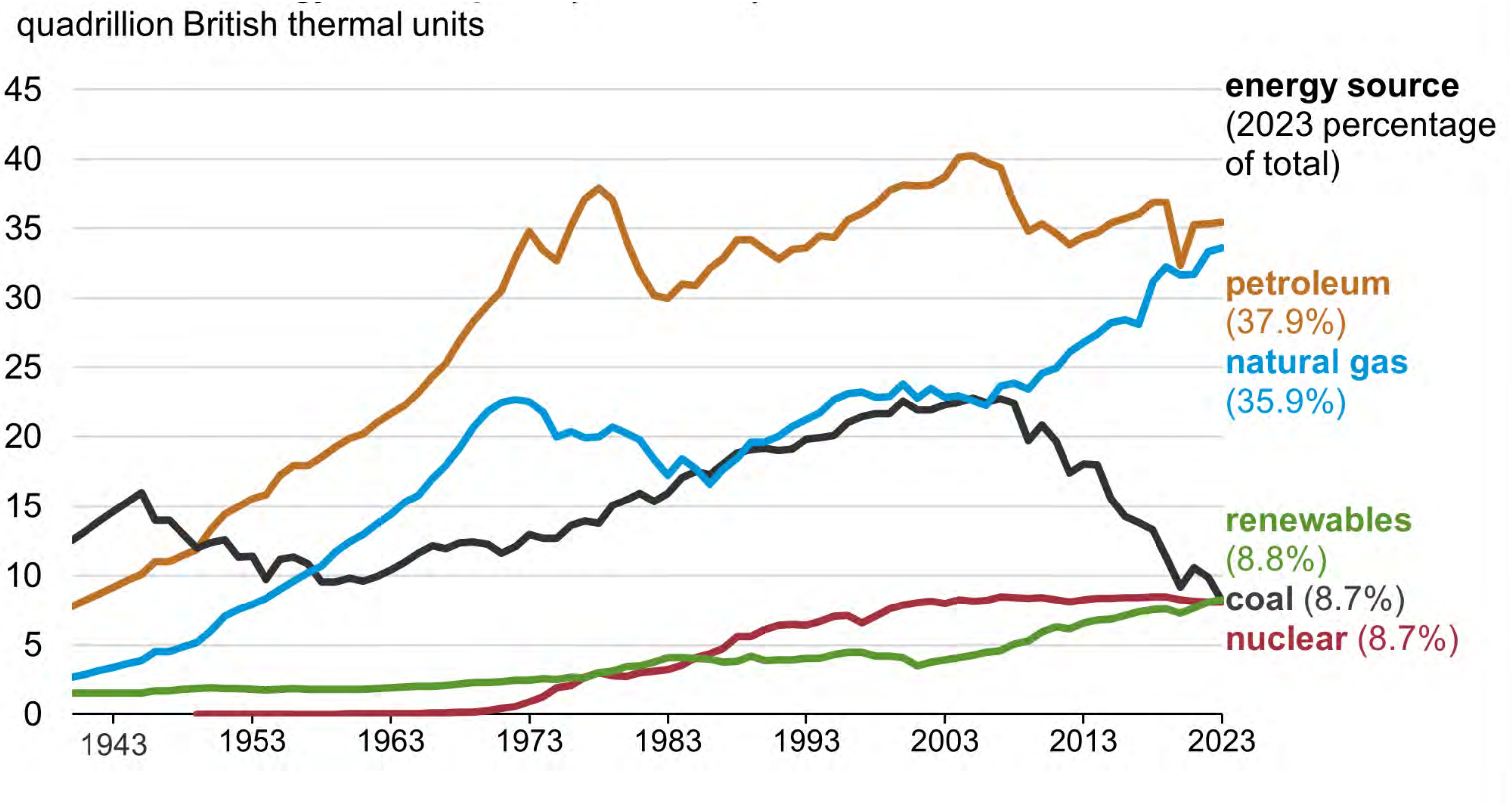
Projects global energy supply, consumption, and trade over a 30-year period; the IEO is produced using EIA's World Energy Projection System (WEPS)

Other Reports and Analyses

- *Today in Energy* summarizes topical energy trends, published daily on the EIA homepage
- Reports for Congress and key stakeholders

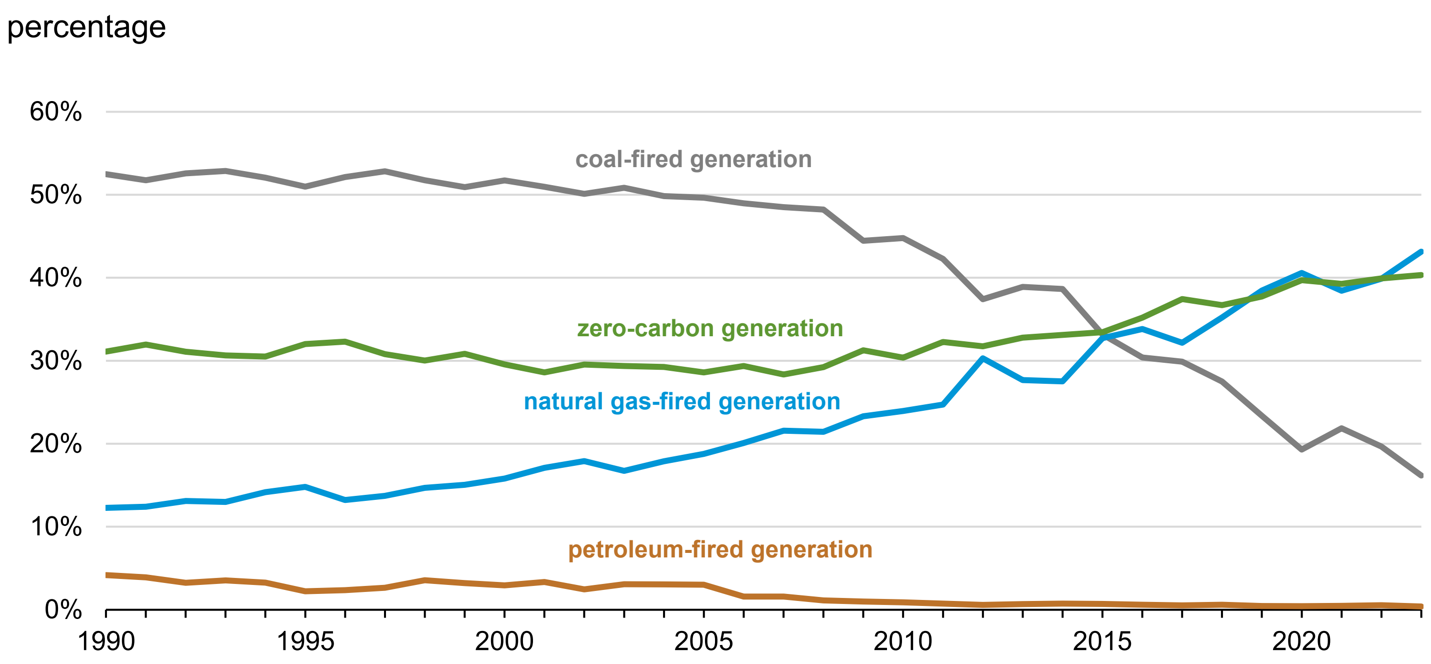
The Energy Transition

Annual U.S. energy consumption, 1940-2023



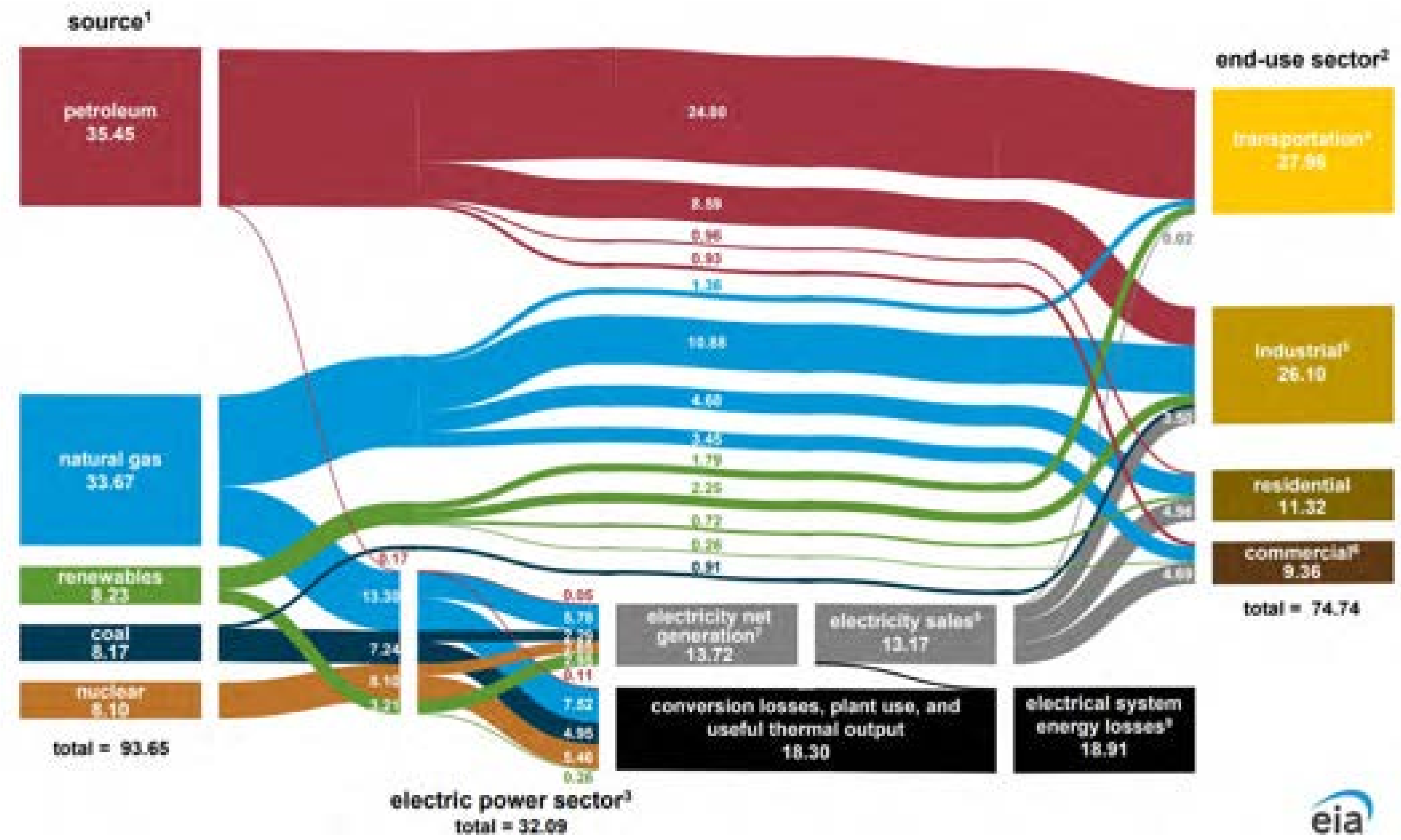
Data source: U.S. Energy Information Administration, https://www.eia.gov/todayinenergy/detail.php?id=62444

Annual percentage of electricity generation by source



Data source: U.S. Energy Information Administration, Monthly Energy Review, March 2024, Table 7.2a Electricity Net Generation Total (All Sectors) and Table 10.6 Solar Electricity Net Generation. Note: Zero-carbon generation excludes small-scale solar generation

U.S. energy consumption by source and sector, 2023



Options:

1. Increase carbon-free electricity and fuels
2. Decrease final energy demands
3. Carbon dioxide removal

Data source: https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy_sankey_2023.pdf

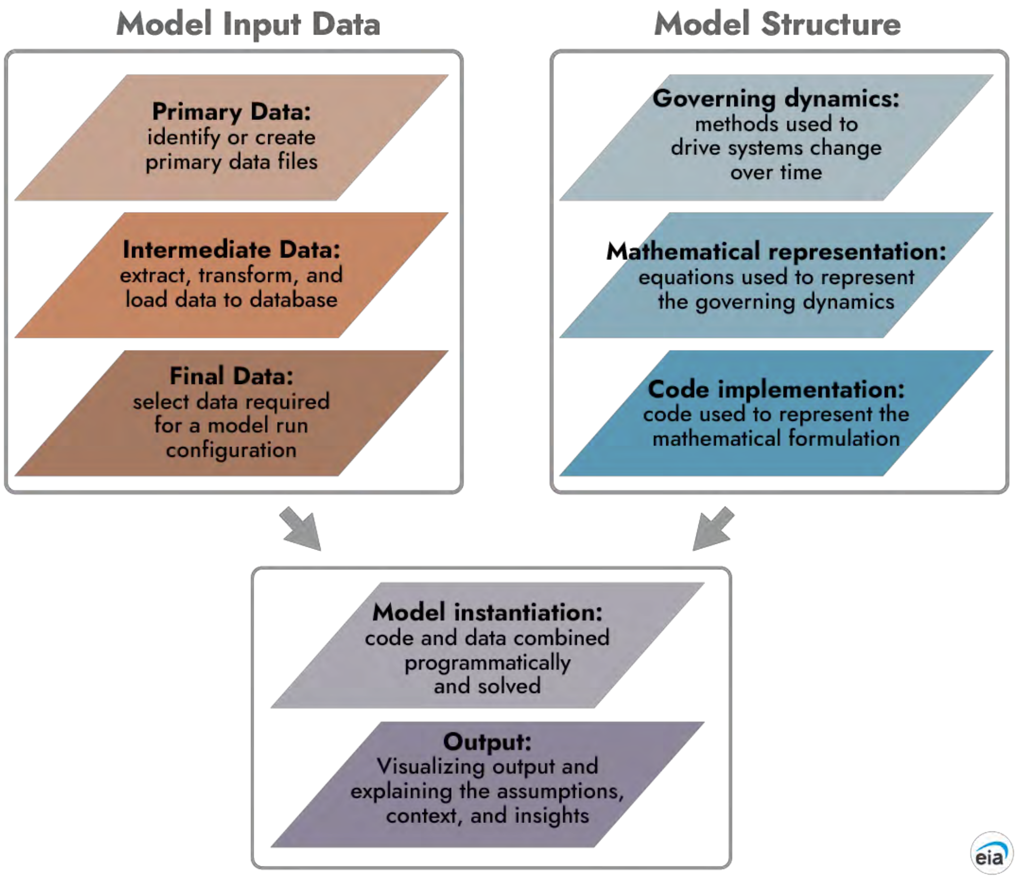
The Role of Models

“Models are an enormously important tool for clarifying your thought. You don’t have to literally believe your model – in fact, you’re a fool if you do – to believe that putting together a simplified but complete account of how things work helps you gain a much more sophisticated understanding of the real situation. People who don’t use models end up relying on slogans… all of which are just wrong some of the time.”

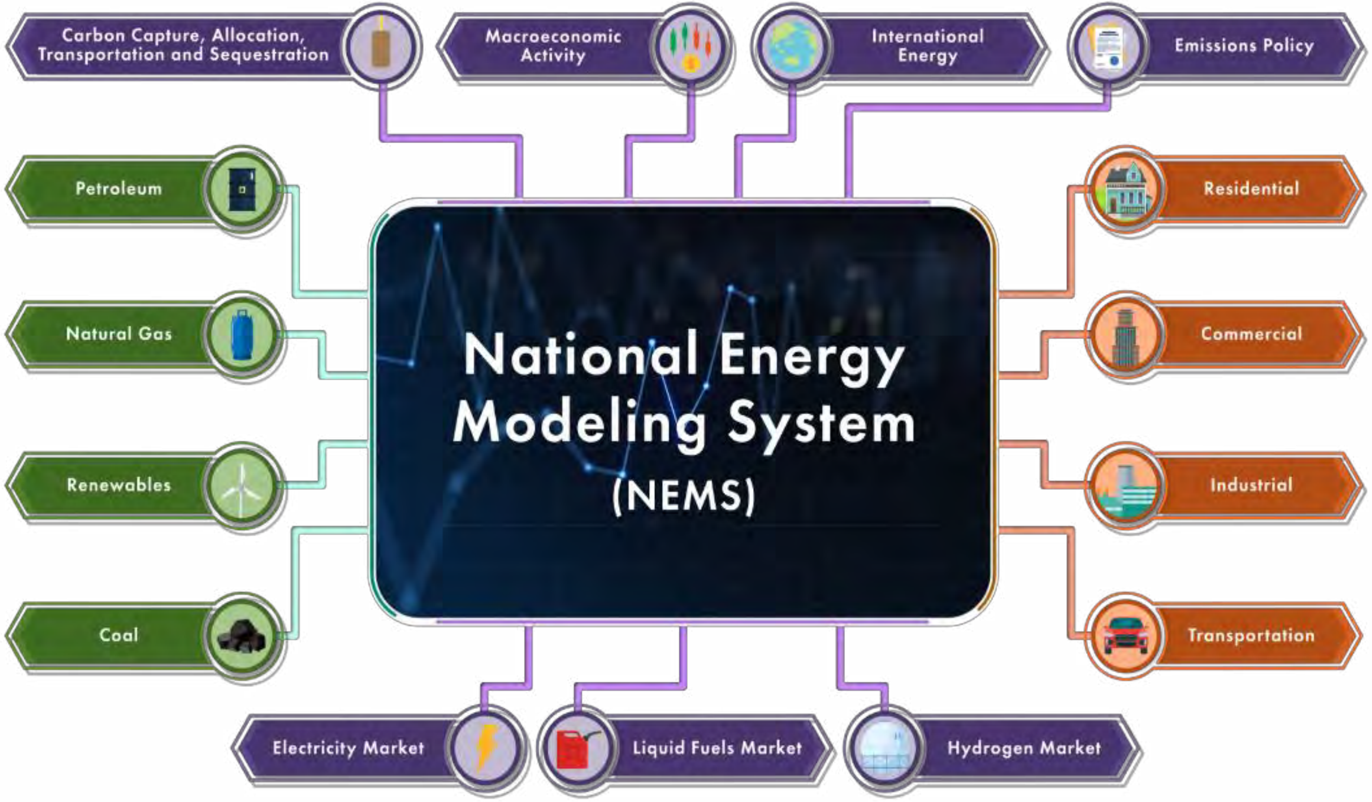
- Paul Krugman, NYT blog, 11/18/2010

The role of models

- Energy systems are too complicated to rely exclusively on our mental models
- Models represent a self-consistent framework that enables systematic exploration of the future decision space



EIA's National Energy Modeling System (NEMS)



Documentation:
https://www.eia.gov/outlooks/aeo/nems/documentation/

Code:
https://github.com/EIAgov/NEMS

Should models be used to forecast?

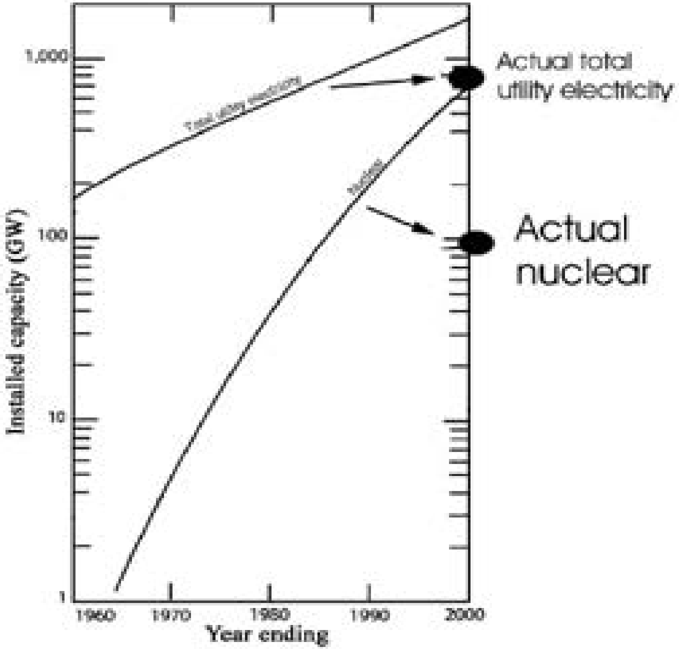
- No. Long-term energy models cannot be validated.

- According to Hodges and Dewar (1992)*, four conditions that determine whether model can be validated:
    1. It must be possible to observe and measure the situation being modeled.
    2. The situation being modeled must exhibit a constancy of structure in time.
    3. The situation being modeled must exhibit constancy across variations in conditions not specified in the model.
    4. It must be possible to collect ample data with which to make predictive tests of the model.

- Validation of long-term trends is not possible
- Little to guide the modeler and reign in efforts that do not improve model performance; leads to greater complexity over time

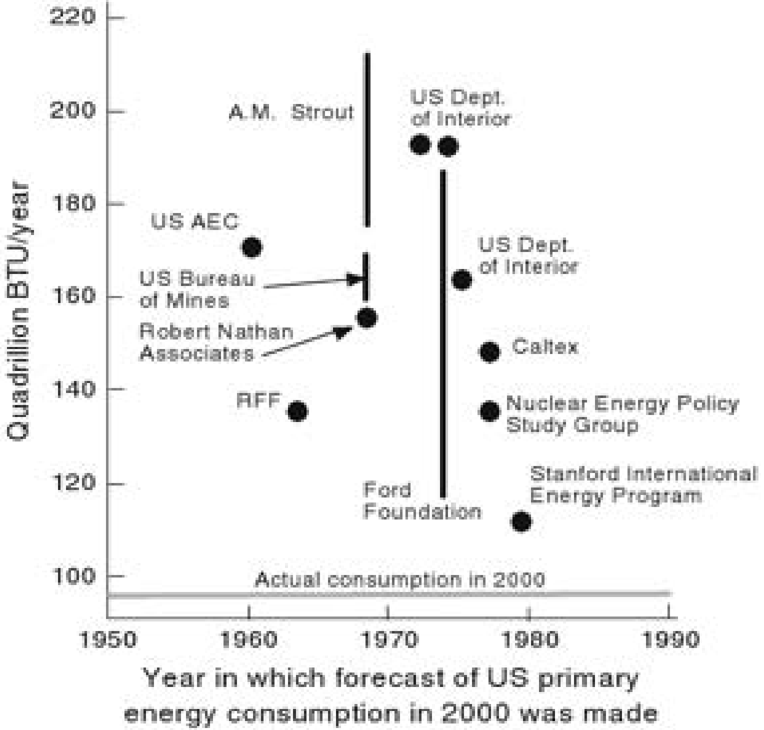
* Hodges, J.S. and Dewar, J.A., 1992. *Is it you or your model talking?: A framework for model validation*, RAND.
Note: Craig et al. (2002) were the first to connect this report to a discussion of energy models.

Energy system point forecasts are generally dismal



U.S. Atomic Energy Commission forecast from 1962

Source: Craig et al. (2002). "What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States." *Ann. Rev. Energy Environ*. 27:83-118.



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

Proper use of energy models

Energy models provide value in the following ways:

- Aid in thinking and hypothesizing
- Create dialogue among stakeholders on complex issues
- Identify key system features and effects, pitfalls, tradeoffs
- Identify key sources of uncertainty and knowledge gaps
- Help inform decision strategies

“It has often been contended that the primary goal of policy modeling should be the insights quantitative models can provide, not the precise-looking projections” – Huntington et al (1982)

“It is not the individual results of a model that are so important; it is the improved user appreciation of the policy problem that is the greatest contribution of modeling." – William Hogan

Past Surprises

AEO Retrospective

- EIA publishes an AEO Retrospective every two years
- Compares Reference case against realized outcomes
- Focused on statistical measures: percent difference, average percent difference, standard deviation
- Hard to interpret; ignores the side cases

Table 1. Comparison of AEO Reference case projections with realized outcomes, 1994–2021

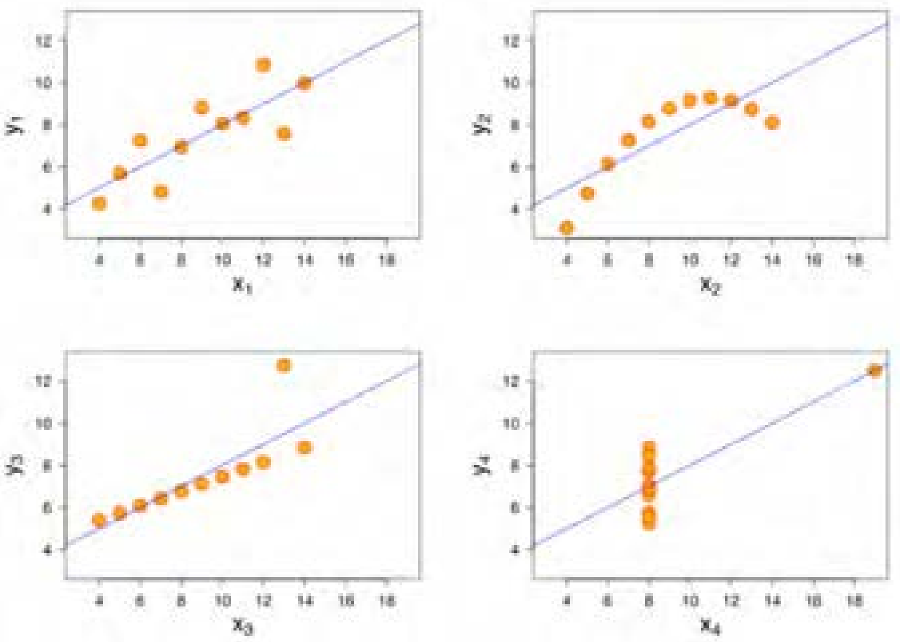
Variable	Average absolute percentage differences (%)	Percentage of projections over-estimated (%)
Gross domestic product		
Real gross domestic product (average cumulative growth) [1] (table 3)	0.8	61.1
Petroleum		
Imported refiner acquisition cost of crude oil (constant dollars) (table 4a)	45.6	32.8
Imported refiner acquisition cost of crude oil (nominal dollars) (table 4b)	41.3	30.1
Total petroleum and other liquids consumption (table 5)	10.5	73.5
Crude oil production (table 6)	19.4	31.6
Petroleum net imports (table 7)	487.5	73.5
Natural gas		
Natural gas price, electric power sector (constant dollars)[2] (table 8a)	46.9	57.8
Natural gas price, electric power sector (nominal dollars)[2] (table 8b)	49.7	59.6
Total natural gas consumption (table 9)	8.9	54.8
Dry natural gas production (table 10)	11.3	39.4
Natural gas net imports (table 11)[3]	284.9	59.6
Coal		
Coal prices to electric generating plants (constant dollars)[4] (table 12a)	20.5	42.2
Coal prices to electric generating plants (nominal dollars)[4] (table 12b)	19.6	45.7
Total coal consumption (table 13)	36	79.8
Coal production excluding waste coal (table 14)	29.5	80.8
Electricity		
Average electricity prices (constant dollars) (table 15a)	9.8	31.6
Average electricity prices (nominal dollars) (table 15b)	9.8	38.9

Data source: https://www.eia.gov/outlooks/aeo/retrospective/

Anscombe's Quartet offers a warning

Anscombe's quartet

I		II		III		IV	
x	*y*	*x*	*y*	*x*	*y*	*x*	*y*
10.0	8.04	10.0	9.14	10.0	7.46	8.0	6.58
8.0	6.95	8.0	8.14	8.0	6.77	8.0	5.76
13.0	7.58	13.0	8.74	13.0	12.74	8.0	7.71
9.0	8.81	9.0	8.77	9.0	7.11	8.0	8.84
11.0	8.33	11.0	9.26	11.0	7.81	8.0	8.47
14.0	9.96	14.0	8.10	14.0	8.84	8.0	7.04
6.0	7.24	6.0	6.13	6.0	6.08	8.0	5.25
4.0	4.26	4.0	3.10	4.0	5.39	19.0	12.50
12.0	10.84	12.0	9.13	12.0	8.15	8.0	5.56
7.0	4.82	7.0	7.26	7.0	6.42	8.0	7.91
5.0	5.68	5.0	4.74	5.0	5.73	8.0	6.89



Same descriptive statistics!

Source: [*https://en.wikipedia.org/wiki/Anscombe%27s_quartet*](https://en.wikipedia.org/wiki/Anscombe%27s_quartet)

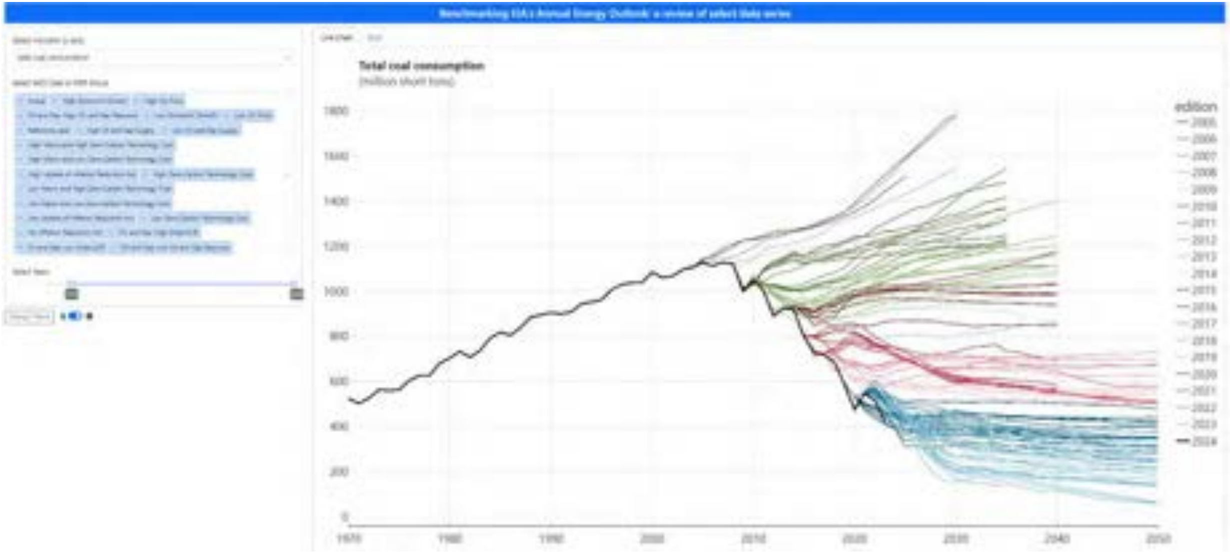
New EIA benchmarking tool

- To address the limitations in the AEO Retrospective, we developed an open-source tool to visualize our projections: https://github.com/EIAgov/dash-benchmark

- Data management practices changed over time, so past AEO projections not available in the same way (further back = more effort)

Notes:

- In the earliest years (2005-2010), we've (so far) extracted the Reference case
- Model time horizon has expanded from 2030 to 2050 over last 20 years



Surprise #1 Shale Oil and Natural Gas

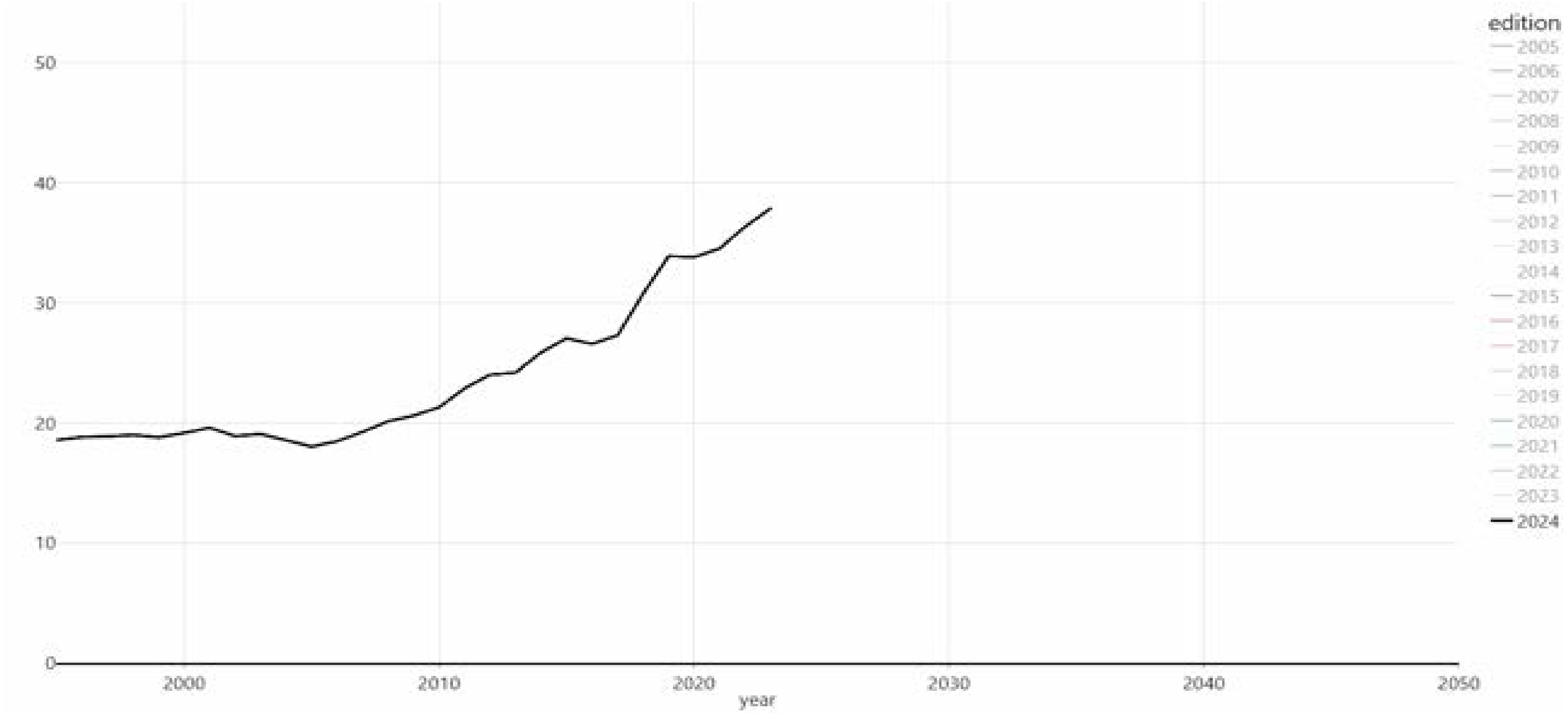
- Horizontal drilling and treatment (i.e., fracking) into source rock (i.e., shale) radically changed oil and natural gas development

- EIA began examining the impacts of shale resources in 2008

- Long-term modeling at EIA was slow to catch up:
  - In early 2010s EIA didn't have sufficient data or modeling capabilities to accurately project exponential growth in production based on a developing technology.
  - By 2013, EIA realized that the traditional relationships between rig count and production were changing; launched the *Drilling Productivity Report*
  - Today we have a large database of tight/shale wells we can analyze to assess how production will develop over the long term

Domestic dry natural gas production

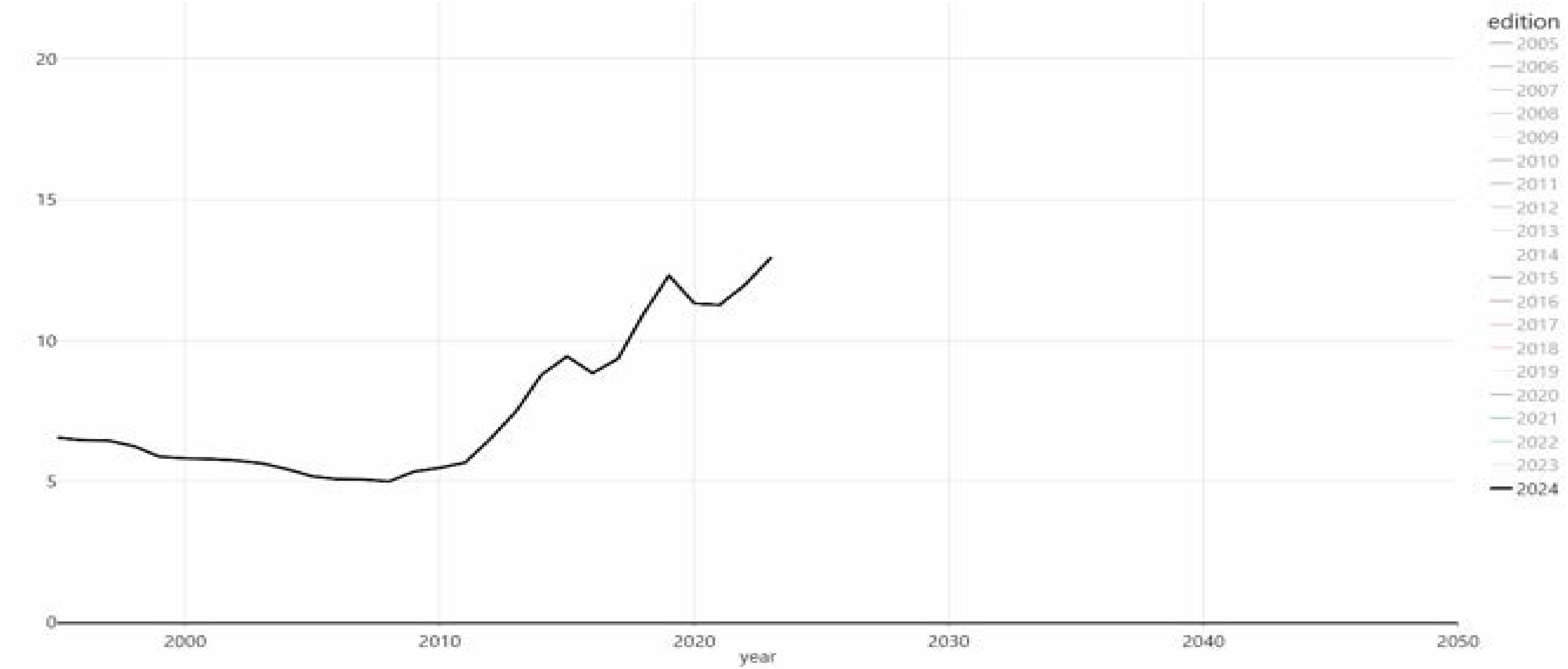
Trillion cubic feet



Data source: U.S. Energy Information Administration, https://github.com/EIAgov/dash-benchmark

Domestic crude oil production

Million barrels / day



Data source: U.S. Energy Information Administration, https://github.com/EIAgov/dash-benchmark

Surprise #2: Rapid wind and solar deployment

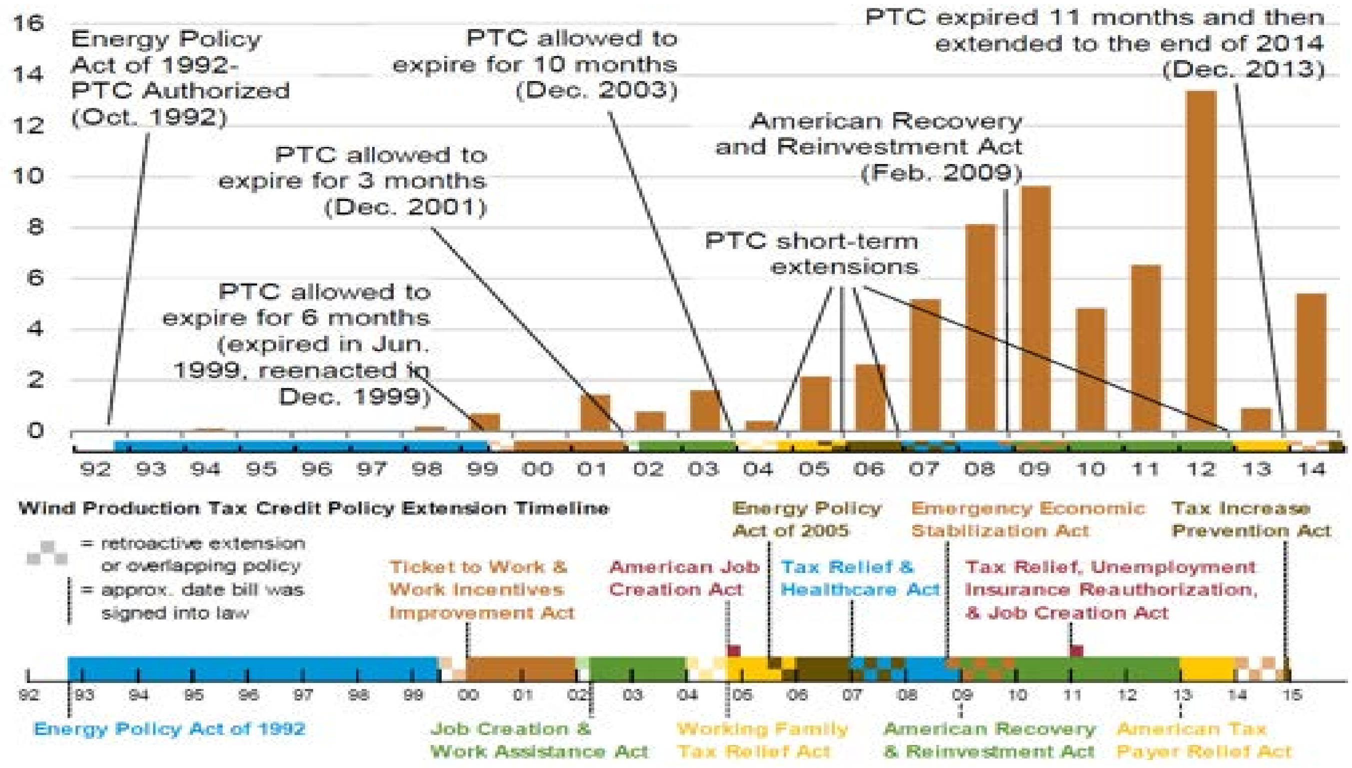
- Capital costs of wind and solar PV began to decline rapidly in 2010s
  - EIA baseline capital cost data did not keep pace with reality
  - Learning rates were not high enough

- EIA focus on “existing laws and regulations” did not account for policy changes over the model time horizon (e.g., investment and production tax credits)

Annual estimated capital costs for wind technologies from various agencies, 2005-2015

Data source: U.S. Energy Information Administration, 2016 "Wind and Solar Data Projections from the U.S. Energy Information Administration: Past Performance and Planned Enhancements" https://www.eia.gov/outlooks/aeo/supplement/renewable/

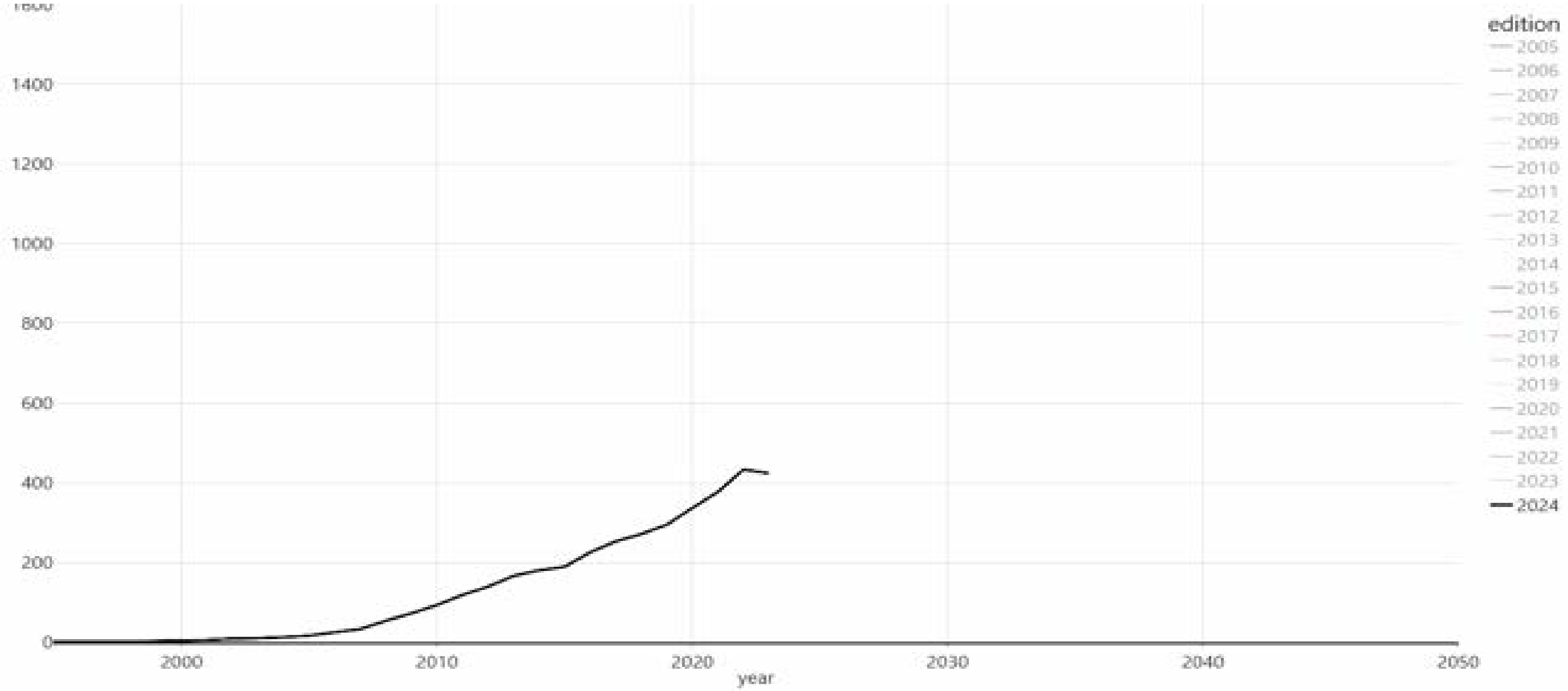
Annual wind capacity additions, 1992-2014



Data source: U.S. Energy Information Administration, 2016 "Wind and Solar Data Projections from the U.S. Energy Information Administration: Past Performance and Planned Enhancements" https://www.eia.gov/outlooks/aeo/supplement/renewable/

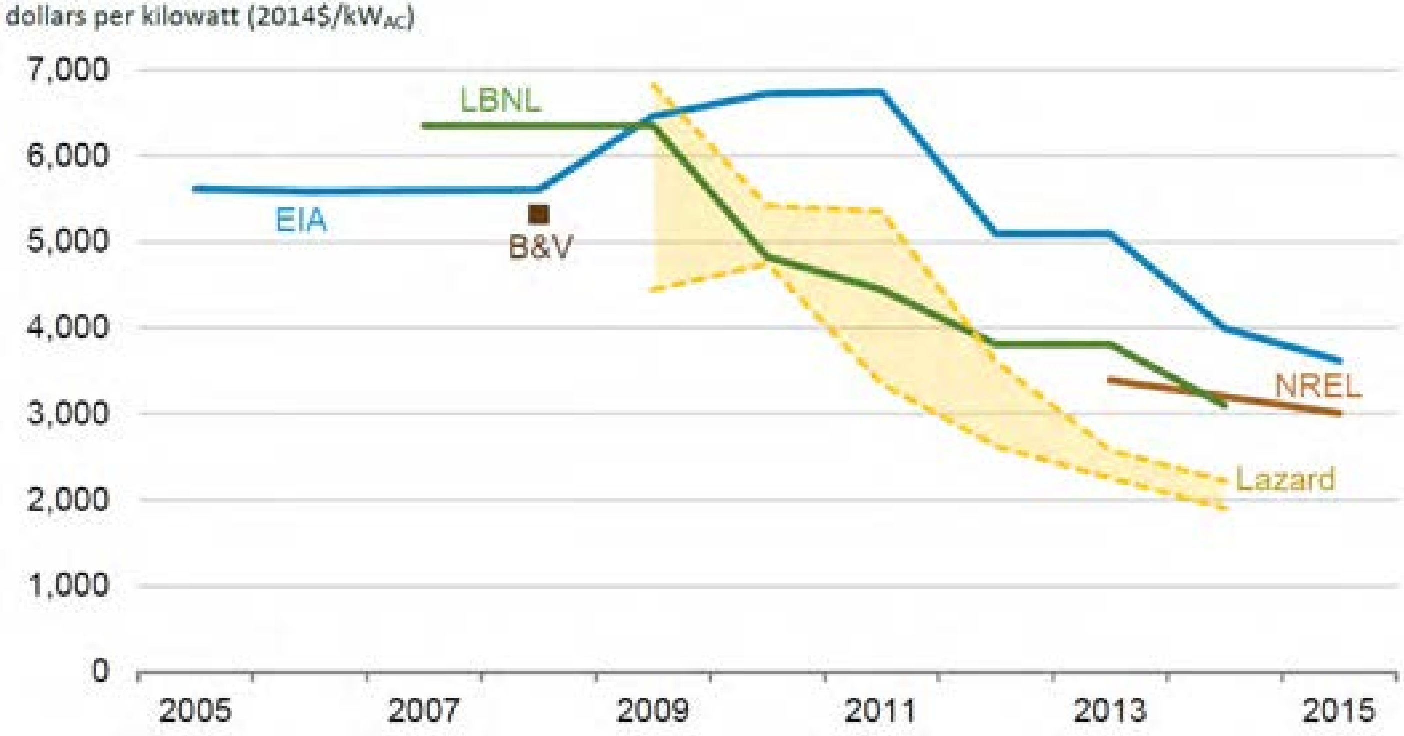
Projected wind generation

Billion kWh



Data source: https://github.com/EIAgov/dash-benchmark

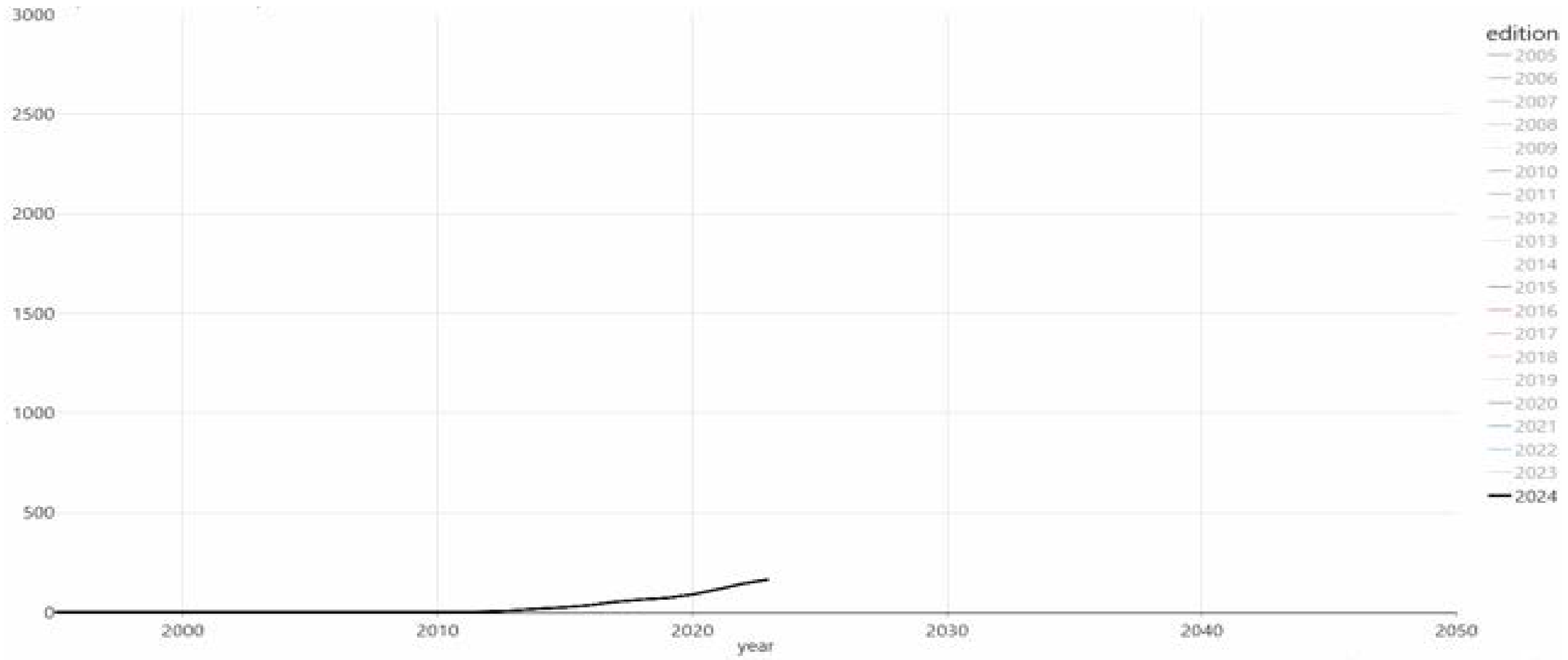
Annual estimated capital costs for utility-scale solar PV from various agencies, 2005-2015



Data source: U.S. Energy Information Administration, 2016 "Wind and Solar Data Projections from the U.S. Energy Information Administration: Past Performance and Planned Enhancements" https://www.eia.gov/outlooks/aeo/supplement/renewable/

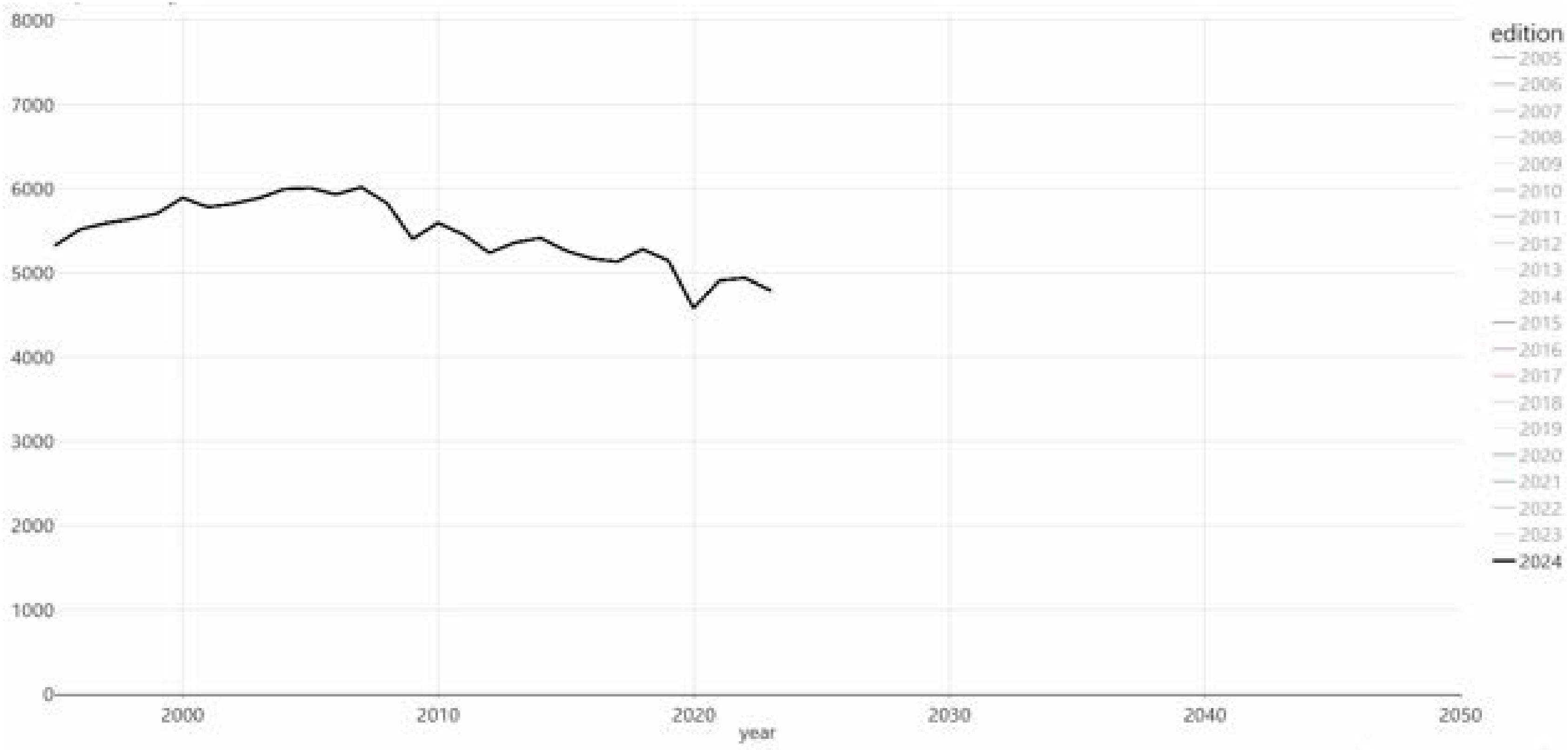
Projected solar generation

Billion kWh



Data source: https://github.com/EIAgov/dash-benchmark

Energy-related CO_2 emissions



Source: https://github.com/EIAgov/dash-benchmark

What’s going on?

- As a statistical agency, our projections are based on rigorously derived historical data
- Takes time to identify new trends in data, BUT Producing 30-year projections every year
- Judgements about model calibration and scenario design affected by **cognitive heuristics***

Heuristics are mental shortcuts that can facilitate problem-solving and probability judgments.

- The “**availability”** heuristic: people assess probabilities of a future event or outcome on the basis of how easily they can remember past examples or how easily they can imagine possible examples.
- **The “anchoring and adjustment**” heuristic: people often start with an initial value or “anchor” and then modify their judgment as they consider factors relevant to the specifics of the issue at hand. **Often this adjustment is insufficient**

Heuristics can be hard to overcome, particularly in an environment where modelers can be judged for errant projections.

* Tversky, A. and Kahneman, D., 1974. Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, *185*(4157), pp.1124-1131.

Capturing Uncertainty

Addressing uncertainty in our long-term models

How do we illuminate and inform future energy pathways given the inherent uncertainty?

Depends on the specific question.

Parametric uncertainty: uncertainty in the model input parameters

- Scenario analysis, parametric sensitivity analysis, Monte Carlo simulation, Method of Morris, stochastic optimization, robust optimization

Structural uncertainty: imperfect and incomplete nature of the model equations describing the system

- Alternative model formulations, modeling-to-generate alternatives, model intercomparison exercises (e.g., Stanford Energy Modeling Forum)

National Research Council (1992)*:

"Uncertainty is inherent in the nature of models and cannot be eliminated. Nor should it be ignored."

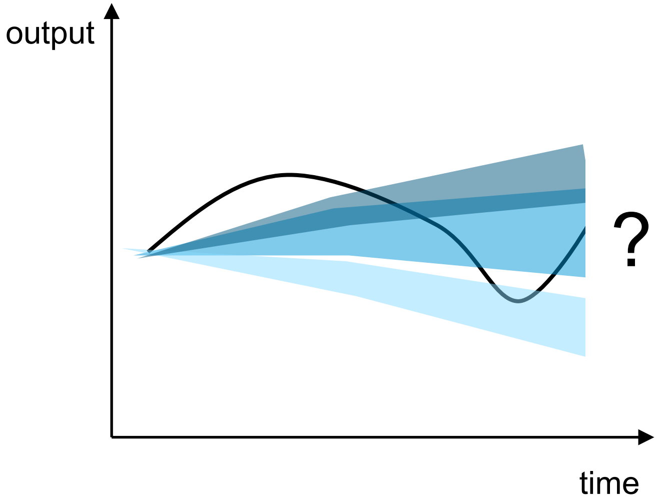
"NEMS should be designed to represent and analyze the effects of uncertainty explicitly."

** National Research Council 1992. The National Energy Modeling System. Washington, DC: The National Academies Press. https://doi.org/10.17226/1997.*

Need to quantify uncertainty

The energy system is in a period of rapid transition, which heightens uncertainty.

- Climate change impacts
- Infrastructure and supply chains
- International trade and security
- Technology innovation
- Novel technologies
- Electricity demand growth
- Policy
- Impacts on *people*
- *Unknown unknowns?*



Uncertainty can no longer be a side bar. Key insights must be conditioned on a consideration of uncertainty.

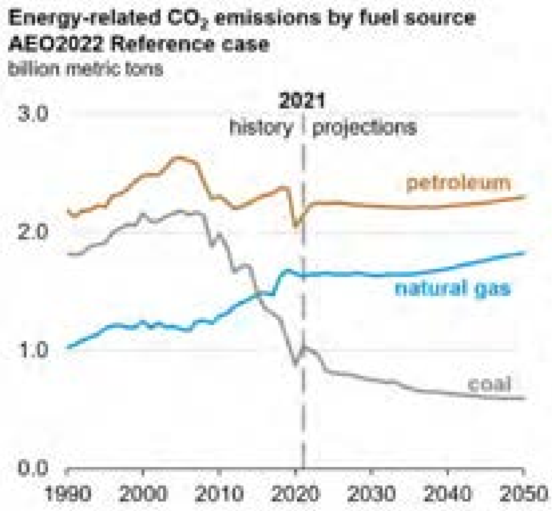
Clarifying the meaning of the Reference Case

From the AEO 2022:

"Projections in the Reference case of our Annual Energy Outlook 2022 (AEO2022) are not predictions of what will happen, but rather, they are modeled projections of what may happen given certain assumptions and methodologies. **The Reference case serves as a baseline for comparison between side cases that explain alternative trends**. By varying Reference case assumptions and methodologies in side cases, AEO2022 can illustrate important factors in future energy production and use in the United States."

However:

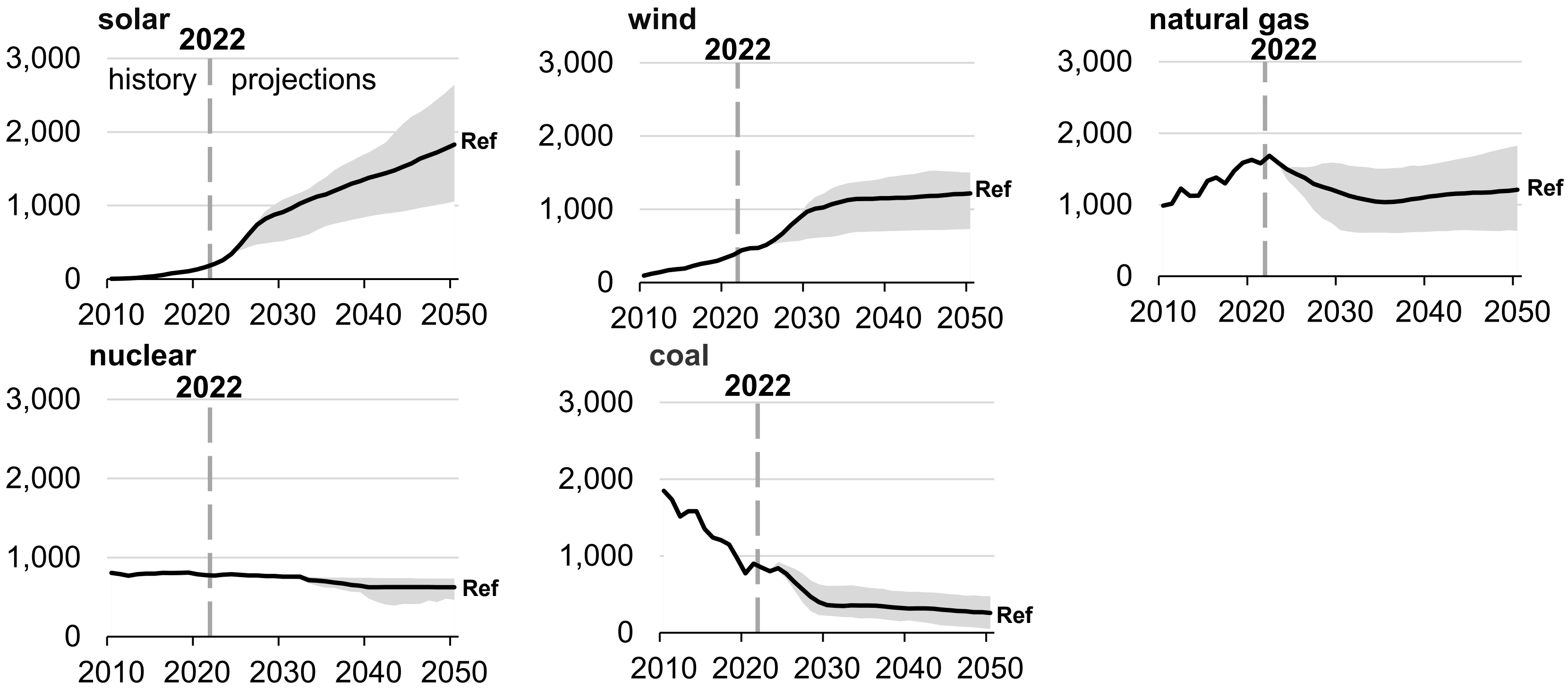
- 70% of AEO Narrative figures focus exclusively on the Reference Case
- AEO Retrospective focuses exclusively on the Reference Case



Even if the Reference Case is our best guess, the **probability** of realizing a single trajectory drawn from a continuous solution space **is zero**.

AEO2023: Emphasizing the range of outcomes across side cases

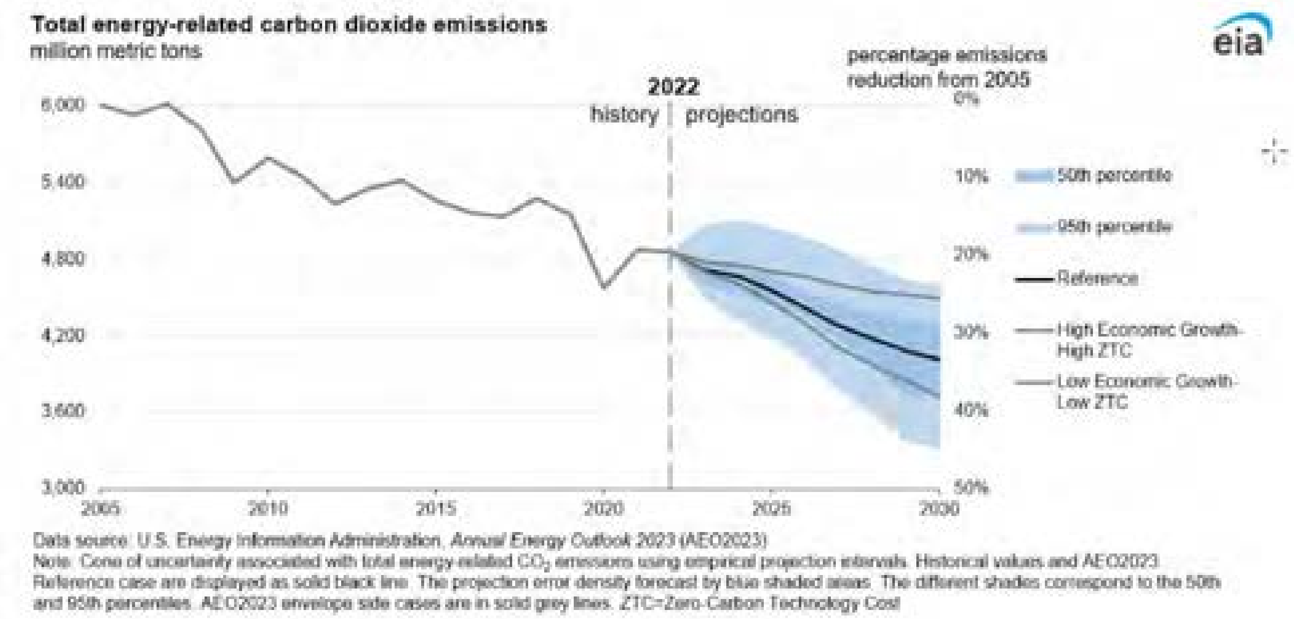
U.S. electricity generation by select technologies for all cases
billion kilowatthours



Data source: U.S. Energy Information Administration, Annual Energy Outlook 2023 (AEO2023)
Note: Shaded regions represent maximum and minimum values for each projection year across the AEO2023 Reference case and side cases. Ref=Reference case.

AEO2023: Emissions cone of uncertainty

- Utilized approach by Kaack et al. (2017)* to develop uncertainty cones
- Quantify the difference between our past Reference case values and observed values
- Non-parametric, median-centered method applied to total energy-related CO_2 emissions
- Past differences account for new policy beyond “current laws and regulations”



- Dark blue cone captures 50% of historical projection errors
- Lighter blue cone captures 95% of historical projection errors

* Kaack, L.H., Apt, J., Morgan, M.G. and McSharry, P (2017). Empirical prediction intervals improve energy forecasting. *Proceedings of the National Academy of Sciences*, *114*(33): 8752-8757.

EIA Long-Term Modeling Plans

Goals for our long-term outlooks

- Capture the key market dynamics that drive energy-related decision making
- Provide a consistent, policy-neutral baseline
- Quantify uncertainty to capture the fullest range of possible outcomes
- Be flexible and nimble: easily incorporate new model features; produce timely analysis
- Make our modeling work transparent and accessible

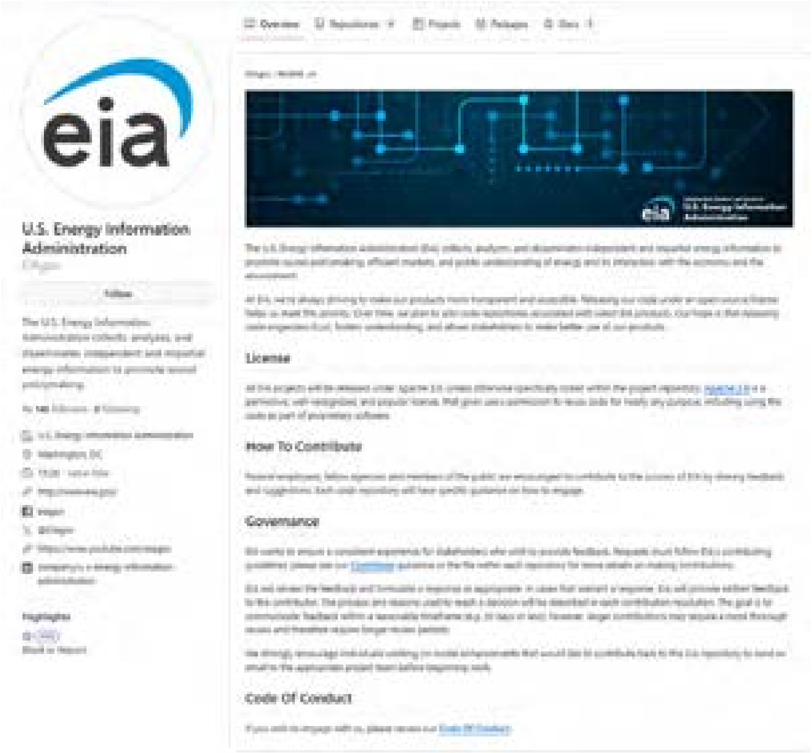
> (14) striving to migrate toward a single, consistent, and open-source modeling platform, and increasing open access to model systems, data, and outcomes, for—

Infrastructure Investment and Jobs Act, 2021. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf

Track 1: Update the National Energy Modeling System (NEMS)

- NEMS is now open source
- Available on GitHub under the Apache 2.0 license
- Apache 2.0 is permissive and clarifies both copyright and patent rights for developers and downstream users.
- Governance plan to process stakeholder feedback in a fair and consistent way.

https://github.com/eiagov



Track 1: Update the National Energy Modeling System (NEMS)

NEMS will feature three new modules in AEO2025:

- The **Hydrogen Market Module**, which will represent hydrogen production and pricing, including the impacts of policy, storage, and logistics
- The **Carbon Capture, Allocation, Transportation, and Sequestration Module**, which will allocate projected supply of captured CO2 across the energy system to utilization or storage
- The **Hydrocarbon Supply Module**, which will improve the representation of upstream oil and natural gas resources, replacing the legacy NEMS Oil and Gas Supply Module

Allows us to more comprehensively address existing laws and regulations in the Reference case, including up-to-date provisions in the Inflation Reduction Act (IRA)

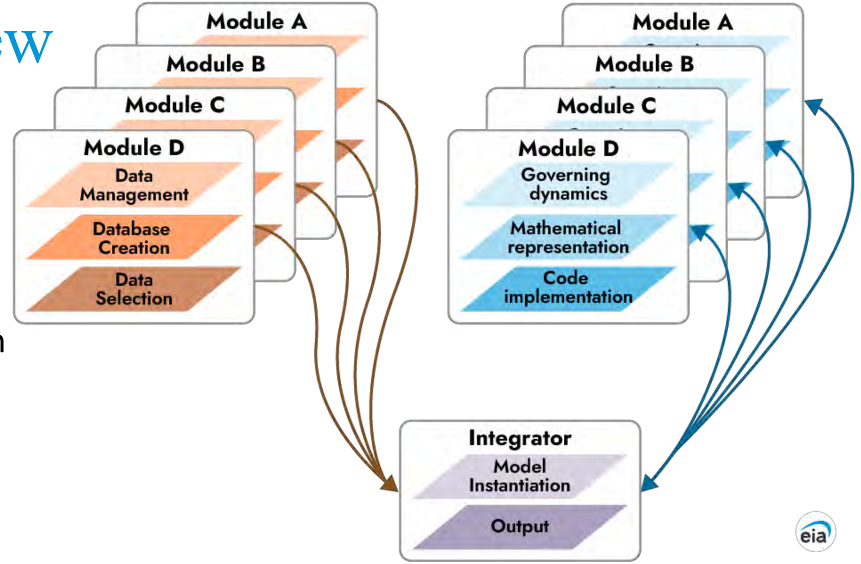
Track 2: Project BlueSky

- The purpose of the BlueSky Project is to develop the next generation model
  - **Modular** – it will allow the governing dynamics to vary across different parts of the energy system represented in each module.
  - **Flexible** – it will be designed so that it can be used to assess new energy and technology pathways, policies, economic conditions, and trade patterns.
  - **Transparent** – it will include model documentation, code, and data that are discoverable and readily understood by other modelers.
  - **Robust** – it will assess how energy systems might realistically change under different assumptions about the future.

- The BlueSky Prototype is the first public release of EIA's long-term efforts in developing this next generation model.

https://www.eia.gov/totalenergy/data/bluesky/

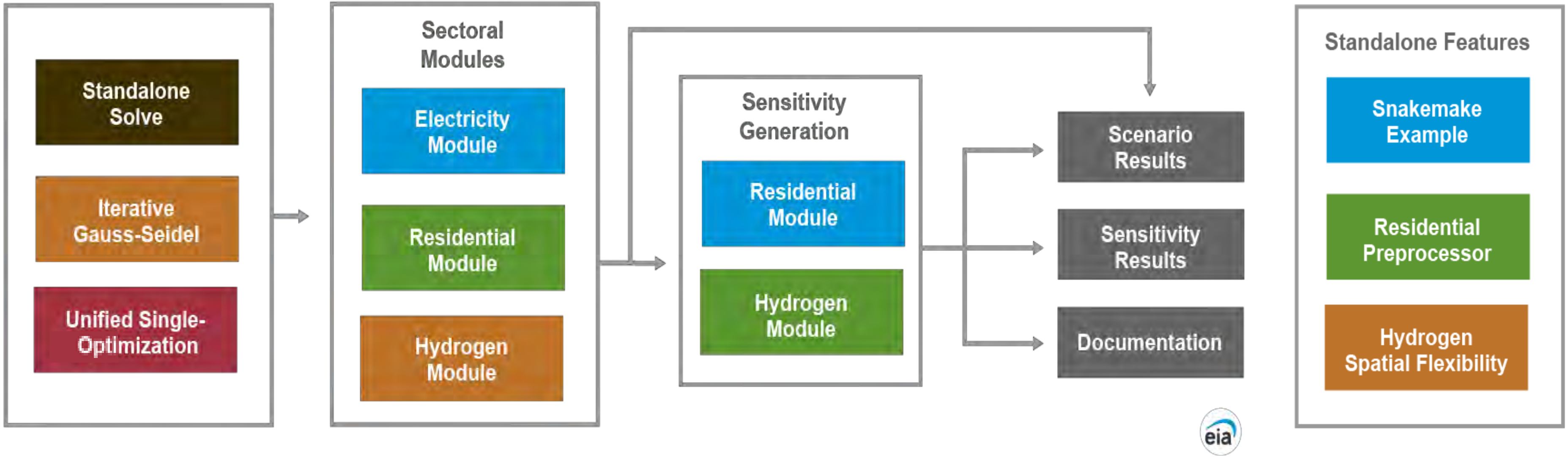
Track 2: BlueSky Prototype Overview



- Maintain a modular structure similar to NEMS
- Allows us to:
  - test different approaches
  - vary the level of complexity by module depending on the question being addressed.
  - isolate analysis to a particular part of the energy system or economy
- Each module can contain its own governing dynamics
- Can be solved as a single mathematical optimization or using iterative methods

For more information: *https://www.eia.gov/beta/working_papers/pdf_files/Next%20Gen%20Model%20Paper%20v9.pdf*

Track 2: BlueSky Prototype Overview



BlueSky GitHub repository: https://github.com/EIAgov/BlueSky

Parting Thoughts

Parting Thoughts

- Energy systems are highly complex, evolving rapidly, and uncertain
- Long-term forecasts – producing point estimates – are a bad idea
- Built-in conservatism in models:
  - Cognitive heuristics
  - Fear of being wrong or an outlier
- Need to explore a wider range of possibilities; insights conditioned on range
- EIA efforts:
  - Retooled AEO to focus on ranges and explanation rather than singular projections
  - Made NEMS open source and are building in new low carbon pathways
  - Developing a next generation, open source, community-based energy modeling framework

Parting Thoughts

- Despite our best efforts, there will be unforeseen surprises
- Working with your own model, it's easy to start believing the numbers
- Modelers must remain humble and intellectually honest about we know about the future

Daniel Kahneman, *Thinking, Fast and Slow* (2011):

"An unbiased appreciation of uncertainty is a cornerstone of rationality – but it is not what people and organizations want. Extreme uncertainty is paralyzing under dangerous circumstances, and the admission that one is merely guessing is especially unacceptable when the stakes are high. Acting on pretended knowledge is often the preferred solution." (p. 263)

"We pay more attention to the content of messages than to information about their reliability, and as a result end up with view of the world around us that is simpler and more coherent than the data justify." (p. 118)