How Energy Modeling Works

The Uses and Limitations of Energy Modeling for Decarbonization Planning

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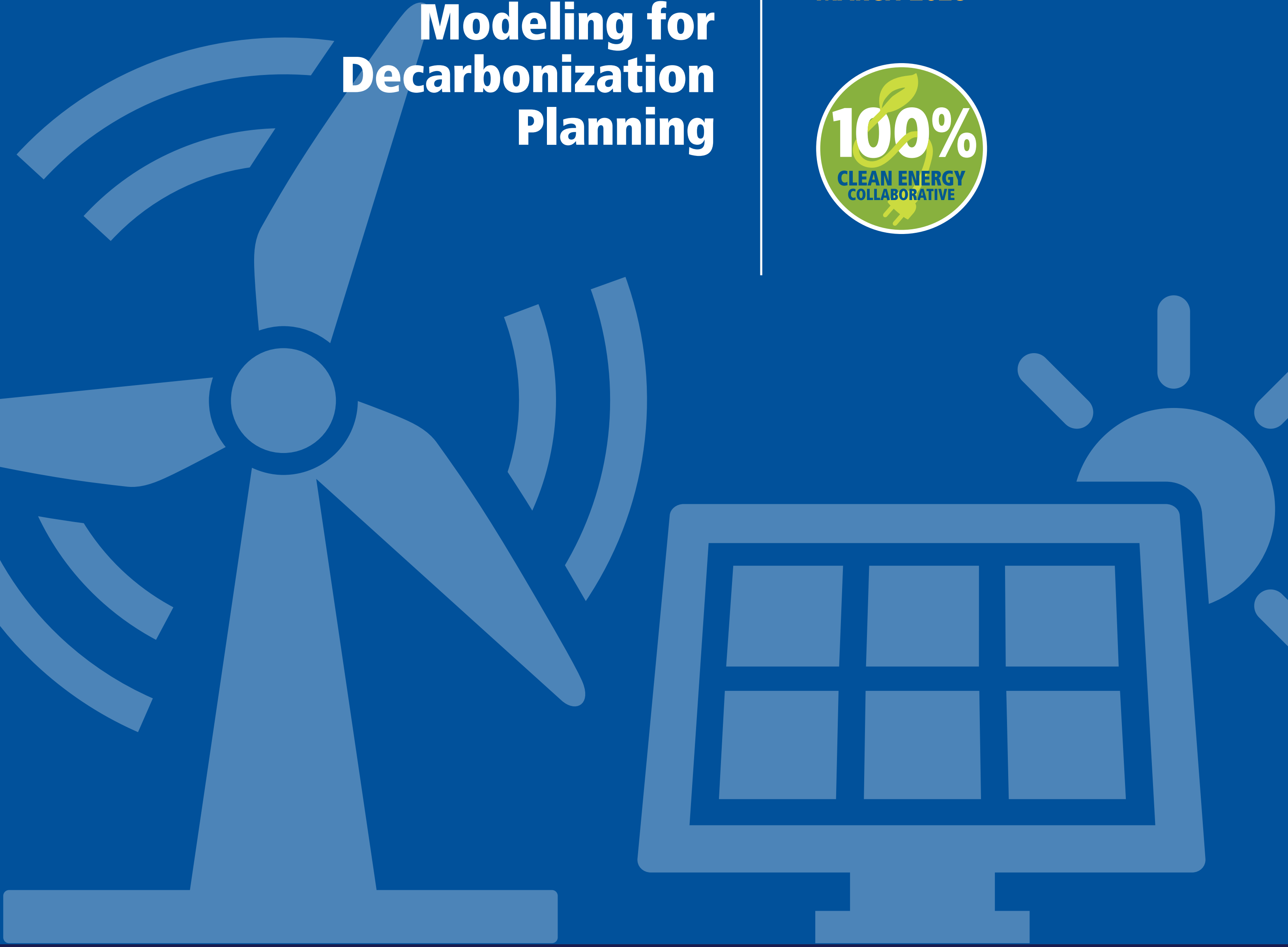

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About the 100% Clean Energy Collaborative

The Clean Energy States Alliance (CESA) created the 100% Clean Energy Collaborative to assist states that have 100% clean energy goals by providing knowledge-sharing activities and analysis so that together they can address program challenges and opportunities. The Collaborative also provides information and technical assistance to states that may consider establishing similar goals. www.cesa.org/100

About the Clean Energy States Alliance

CESA is a leading bipartisan coalition of state energy agencies working together to advance the rapid expansion of clean energy technologies and bring the benefits of clean energy to all. Established in 2002, CESA is a national, member-supported nonprofit that works with its members to develop and implement effective clean energy policies and programs. www.cesa.org

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Disclaimer

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How Energy Modeling Works:

The Uses and Limitations of Energy Modeling for Decarbonization Planning

by Charles Hua and Bentham Paulos for the 100% Clean Energy Collaborative

Introduction

As the impacts of climate change intensify and the solutions for climate mitigation become more robust, states have assumed a leadership role on climate and energy issues. Most Americans now live in a state with a goal of 100% renewable energy or net-zero greenhouse gas emissions.[1]

With a rapidly changing policy, regulatory, and market landscape transforming the energy sector, there is demand and need for robust energy modeling to support policy development and implementation. Solar and wind have become conventional energy technologies, and their characteristics are increasingly well-understood by policymakers, investors, grid managers, and other stakeholders. However, getting all the way to zero emissions raises new questions regarding the grid integration of variable renewable energy, technological capabilities, barriers to deployment, and costs and benefits. Energy modeling can play an important role in addressing these questions and in shaping present and future policy and investment decisions.

Energy modeling—using computer software to simulate the growth and function of energy systems—is not a new endeavor. Indeed, utilities have long used energy models for integrated resource planning (IRP), while academic researchers, national labs, and government agencies have used models for research and forecasting. Because of the acceleration of state leadership on climate and energy issues, state agencies and other stakeholders increasingly use models to inform long-term decarbonization strategies. Advances in data science capabilities have resulted in increasingly sophisticated, flexible, and affordable models, which are now able to address a wider range of problems and capture complex and dynamic interactions between model components. New models are more successful at reflecting newer decarbonization approaches and technologies, which had been undervalued by traditional models.

Energy modeling has revealed valuable insights about the opportunities and barriers stakeholders face in advancing their renewable energy and emissions reduction goals. As modeling has evolved, so have its use cases. Yet, what has remained the same is its potential to provide valuable information to assist the development and implementation of climate and energy policies. As modeling becomes more wide-

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[1] Clean Energy States Alliance, "More than Half of Americans Have a 100% Clean Energy Goal," http://www.icontact-archive.com/archive?c=1164501&f=10013&s=30405&m=541358&t=748b7fb72d1d1237c372cf82d1fccb32f869b3db74aafac66cebcebae55786ef, May 2022.

spread, it is critical that stakeholders, particularly ones with non-technical backgrounds, understand how modeling works, what it can and cannot do, and how to interpret model results.

Good models, used and interpreted properly, can provide understanding of the likely consequences of decisions, thereby leading to better decision-making. But models can also be poorly designed, based on flawed assumptions or low-quality data, or misinterpreted, without a proper awareness and assessment of uncertainties and risks. In other cases, models can be used to mislead, sometimes to promote or protect certain business interests or technologies. As energy systems become increasingly complex, the ability for models to handle conditions requiring increased granularity becomes important, raising the stakes of high-quality modeling.

The costs of bad modeling can be significant, locking in long-term investments in undesirable strategies while overlooking opportunities to pursue desirable ones.

Energy models have informed numerous planning, decision-making, and policy processes towards a clean energy future. For example, utilities have used energy models for decades to develop IRPs for long-term investment planning;[2] states like Rhode Island have used modeling to determine which policies to include in their 100% clean energy plans; and cities like Los Angeles have utilized state-of-the-art energy models to chart a pathway towards meeting its goal of 100% renewable electricity by 2045.[3] Other entities have also relied heavily on energy models: government laboratories like the National Renewable Energy Laboratory (NREL) have analyzed the degree to which renewable energy generation can meet future US energy demand, researchers from Princeton University have outlined pathways to achieving net-zero emissions in the US, and non-governmental agencies like the Union of Concerned Scientists have assessed the feasibility of specific states achieving 100% renewable electricity by 2035 targets, all by utilizing energy models. Appendix A below lists these and other examples.

This report seeks to demystify energy modeling. In particular, it aims to bridge the gap between the technical modeling community and the broader range of stakeholders across the climate landscape who need to know how to interpret and act upon model results. The paper discusses the benefits and challenges of energy modeling and its capabilities and limitations in informing planning efforts for energy transition and decarbonization pathways.

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[2] Advanced Energy Economy, "Understanding IRPs: How Utilities Plan for the Future," https://blog.aee.net/understanding-irps-how-utilities-plan-for-the-future, August 2015 (accessed March 12, 2023).

[3] NREL, "LA100: The Los Angeles 100% Renewable Energy Study," https://www.nrel.gov/analysis/los-angeles-100-percent-renewable-study.html, March 2021.

What is Modeling?

As a saying among modelers goes, “all models are wrong, but some are useful.” At its core, modeling is an attempt to simulate the real world—and its complex systems and conditions—through software programs that incorporate certain inputs and generate certain outputs, often using mathematically and computationally intensive processes. Models are used because the systems they simulate are complex, yet these comparatively simple simulations make it easier to understand how changes in technology, policy, or economics may result in different outcomes.

Simplification means that tradeoffs are deeply present in modeling. Models that perform well for a given dataset may not generalize to a broader set of conditions, and vice versa. Choices of certain model parameters may conflict with other model attributes. The interconnectedness of complex systems—such as the energy system with economic, political, and social systems—introduces additional complexities.

> “All models are wrong, but some are useful.”

Although the mathematical nature of modeling gives it a veneer of objectivity, many components of the modeling process are subjective. Choices surrounding the type of model used, assumptions and parameters, the interpretation of model outputs, and a range of other considerations all entail people making decisions based on reasonable but nonetheless subjective judgments. These limitations do not necessarily invalidate the utility of models; rather, they highlight the complexities of modeling and the importance of careful, principled decisionmaking and interpretation throughout the modeling process.

Indeed, modeling, correctly utilized and interpreted, can be a useful and necessary exercise in the energy sector. It can shed light on the opportunities and barriers posed by certain climate and energy goals or the set of potential pathways towards achieving a particular decarbonization goal. By addressing these high-level questions, modeling can lead to more specific questions, such as the optimization of these pathways to identify a single best path to achieving the goal based on certain priorities and constraints (e.g., cost or equity). Useful models generate results and, subsequently, interpretations, which enable a more structured and disciplined approach to designing and implementing energy policies and programs.

Stakeholders often assume that modeling results are predictions of the future, but this is not necessarily true and can lead to poor decision-making. It is more reasonable to say that models show how certain assumptions or choices result in certain outcomes, depending on the design of the model. Even the best models are imperfect representations of reality, with significant uncertainties. Poor modeling may lead to significantly skewed results that decrease the credibility of modeling outputs. As another modeling saying goes, “garbage in, garbage out.” Treating model results uncritically, based on the prestige of the modeler rather than a review of methods and data sources, can lead to trouble. Modeling can also be misused by providing support for pre-conceived policy positions or business models, while stakeholders can support or reject model results that may align or conflict with their pre-existing preferences or expectations for the future.

The solution to these problems is to be transparent and honest in designing models and reporting their results. A best practice for modeling is to lay out a range of scenarios based on differing assumptions and to indicate the varying degrees of uncertainty associated with the outcomes, as well as the key drivers of this uncertainty. It is naïve to expect near-perfect accuracy and precision in forecasting the future. Keeping in mind what modeling is and is not will ensure more appropriate and nuanced interpretations of what it can and cannot tell us.

How Modeling Works

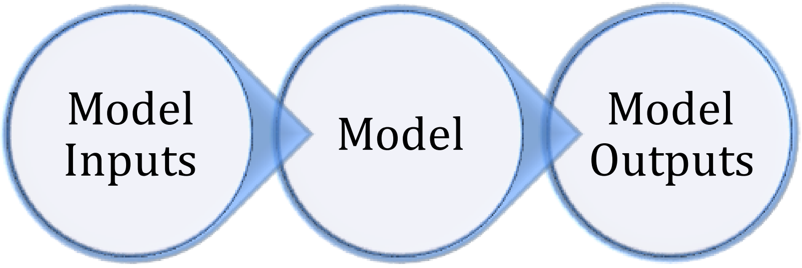
There are two main components of the modeling process: (1) the data inputs and outputs, and (2) the type of model used.

Data Inputs and Outputs

Energy modeling relies on multiple sources of data. There are three main categories of data:

- Existing energy system data
- Projections of future costs, policies, fuel prices, demand, and other data
- Various constraints, such as technological, economic, political, and equity ones

Energy system data often include statistics on current and forecasted fuel availability and prices, electric capacity and generation, energy demand and prices, geospatial renewable energy resource data, and policies. Models can also include various technological, economic, political, and environmental constraints. For example, a modeling process to identify the least-cost pathway to achieve net-zero emissions could incorporate ratepayer impact constraints for low-income residential customers. Models then use these inputs to generate outputs using complex mathematical optimization techniques.



Modelers draw data from a range of public and private sources, each offering its own set of advantages. Public sources can provide a common benchmark across studies. Frequently used public data sources include the US Energy Information Administration (EIA),[4] which has extensive data sets of market information, analysis, and projections; NREL, which provides a well-regarded assessment of current and future costs of energy technologies through the Annual Technology Baseline,[5] and data on solar and wind resources through the National Solar Radiation Database (NSRDB)[6] and the Wind Integration National Dataset Toolkit (WIND)[7]; and the US Environmental Protection Agency (EPA),[8] which provides data on

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[4] EIA, "Electricity data," https://www.eia.gov/electricity/ (accessed March 12, 2023).

[5] NREL, "Annual Technology Baseline," https://atb.nrel.gov/ (accessed March 12, 2023).

[6] NREL, "National Solar Radiation Database (NSRDB)," https://nsrdb.nrel.gov/ (accessed March 12, 2023).

[7] NREL, "Wind Integration National Dataset (WIND) Toolkit," https://www.nrel.gov/grid/wind-toolkit.html (accessed March 12, 2023).

[8] EPA, "Emissions & Generation Resource Integrated Database (eGRID)," https://www.epa.gov/egrid (accessed March 12, 2023).

power plant emissions and operating characteristics through the Emissions & Generation Resource Integrated Database (eGRID). Examples of private data sources include trade associations and consulting firms, such as ABB Velocity Suite and Wood Mackenzie. A more detailed set of data sources and their descriptions is included in Appendix B.

Model Types

> "Garbage in, garbage out."

Electric system modelers use a variety of tools to analyze and interpret data, ranging from simple spreadsheets to complex proprietary software packages. However, two primary types of models are used in practice, each with fundamentally different use cases and applications: the capacity expansion model, which shows how a system can change over time, and the production cost model, which shows how a system will operate.[9] A third type of model can be used to analyze system reliability, including power flow models, which can address engineering and grid planning questions. Examples of capacity expansion models and production cost models are described in detail in Appendix C.

A capacity expansion model describes how a system would change over time due to investments. A production cost model describes how a system operates from day to day. The two are often used in tandem. For example, a capacity expansion model can include a production cost model step at each investment period to prove consistent viability of the modeled system.

Both models can address a range of questions, such as the environmental impacts of decarbonization policies and the value of energy storage and distributed energy resources to energy systems. They also both exhibit tradeoffs between scope and granularity with regards to model performance; for example, broader geographic coverage often leads to less precise results. Their distinct characteristics—which revolve around primary use cases, level of granularity, and spatiotemporal coverage of analysis—are outlined as follows.

A **capacity expansion model** is used to describe how an energy system would change over time as a result of policies, price changes, and technology trends that affect energy investments. Capacity expansion models typically cover time horizons of multiple years to decades, making them valuable for energy planning. Model inputs can include data on future energy demand, fuel prices, technology costs and performance, and policies and regulations. Model outputs include projections of future energy generation, transmission and generation capacity investments and retirements, emissions, energy prices, and credit and allowance prices. Outputs also show the impacts of different policies. Figure 1 (p. 10) depicts a typical output from a capacity expansion model, showing substantial growth in wind (purple bars) and retirement of coal (black bars) over a 40-year period.

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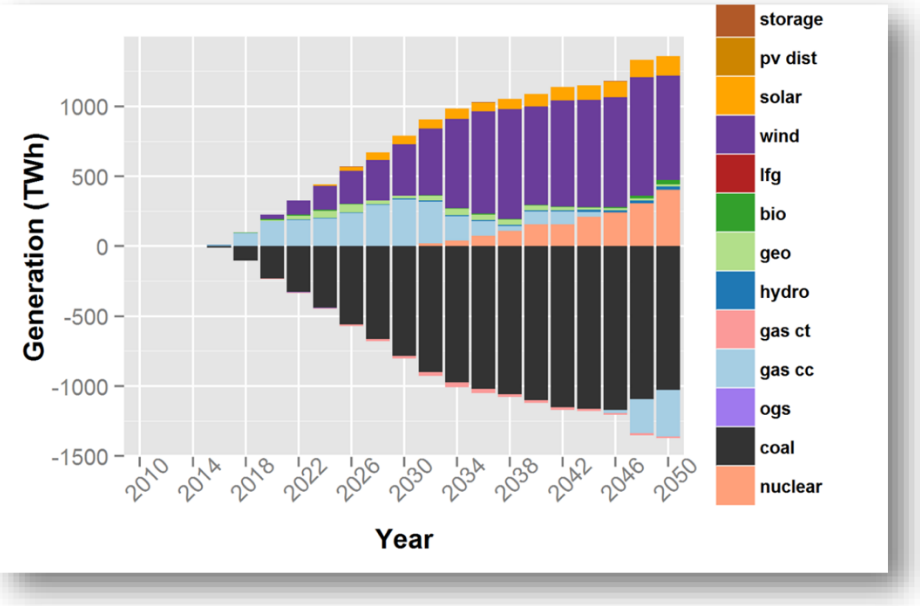
[9] The production cost model is also referred to as the unit commitment and dispatch model.

A good capacity expansion model captures, to some extent, the dispatch and use of certain assets to analyze the life-cycle costs associated with different options. But operational details are limited. A capacity expansion model might use simulated representations of power plants instead of specific ones and may use only approximate locations. And it often lacks the temporal specificity associated with other models (e.g., energy systems data for every hour of every year), as well as the precise representation of transmission and power flow systems. For these reasons, a capacity expansion model is frequently used alongside production cost models to provide a more complete view or to verify results.

Examples of capacity expansion models include the Regional Energy Deployment System (ReEDS)[10] and Integrated Planning Model (IPM)[11] at the national scale, as well as the Resource Planning Model (RPM)[12] and Aurora[13] at the utility scale.

Figure 1 - Capacity Expansion Model. Source: US DOE[14]



A **production cost model**, also known as a unit commitment and dispatch model, is used to describe how a system operates. It is primarily used to simulate the granular operations and performance of energy systems, assess the resource adequacy and reliability impacts of various policies, and analyze how changes to an energy system affect its operations.

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[10] ReEDS was primarily developed and managed by NREL.

[11] IPM was primarily developed and managed by EPA.

[12] RPM was primarily developed and managed by NREL.

[13] Aurora was primarily developed and managed by Energy Exemplar.

[14] Erin Boyd, "Power Sector Modeling 101," US Department of Energy Office of Energy Policy and Systems Analysis, https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf, 2016.

Model inputs are similar to those of capacity expansion models and typically consist of data on the timing and location of power demand, weather impacts, available transmission capacity, generator performance, among other inputs. The model then yields outputs with data on energy generation and consumption, emissions, locational marginal prices, ancillary service prices, and asset curtailments.

Overall, the production cost model is rigorous and detailed in characterizing the granular performance of energy systems. Examples of production cost models include PLEXOS,[15] PROMOD,[16] and GE Multi Area Production Simulation (GE MAPS).[17]

The capacity expansion model and the production cost model are compared in Table 1.

Power flow models are used less frequently in policy studies but are commonly used by utility planners. Also called network reliability models, they simulate transmission and distribution networks to analyze how changes to the energy system impact the system itself. Power flow models focused on the transmission system tend to look at very short time frames, in the seconds or minutes, to gauge impacts on voltage and frequency. These impacts have traditionally been caused by weather events, like lightning strikes, or rapid changes in demand, such as from industrial customers. Models have also increasingly looked at the impact of greater reliance on weather-dependent and inverter-based resources, like wind and solar power. More recently, modeling tools have been developed for the distribution system. The increase in distributed energy resources like solar, storage, and electric vehicle charging can create new issues on the distribution grid around intermittency, multi-direction power flows, and voltage spikes or sags.[18]

There are two primary components of power flow models: analysis of AC power flow (to check operational feasibility in a steady state) and analysis of system dynamics (to check system reliability under certain conditions). The results can be specific to times and places, in order to answer specific questions about equipment and operations. These models are typically run by consultants, utilities, reliability organizations, and independent system operators (ISOs), making them less applicable to a more general audience.

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[15] Energy Exemplar, “PLEXOS,” https://www.energyexemplar.com/plexos (accessed March 12, 2023).

[16] ABB, “PROMOD,” https://www.hitachienergy.com/us/en/offering/product-and-system/energy-planning-trading/market-analysis/promod (accessed March 12, 2023).

[17] GE Energy, “GE MAPS,” https://www.geenergyconsulting.com/practice-area/software-products/maps (accessed March 12, 2023).

[18] Jeremy Wilson, “Limitations of Power-Flow Modeling for Voltage Control on the Modern Distribution Grid,” *Electric Energy T&D Magazine*, https://electricenergyonline.com/energy/magazine/814/article/Limitations-of-Power-Flow-Modeling-for-Voltage-Control-on-the-Modern.htm, September 2014 (accessed March 12, 2023).

Table 1 - Comparison of the Capacity Expansion Model and the Production Cost Model

	Capacity Expansion Model	Production Cost Model
Purpose	Describes how an energy system changes over time.	Describes how a system operates.
Time Horizon	Typically 5-20 years	Typically less than 1 year
Inputs	Data on future electricity demand, fuel prices, technology costs and performance, policies and regulations, the timing and location of power demand, impact of weather, available transmission capacity, the performance of generators, etc.	Data on the timing and location of power demand, impact of weather, available transmission capacity, the performance of generators, etc.
Outputs	Data on energy generation, transmission and generation capacity investment and retirement, impacts of policies, emissions, electricity prices, and credit and allowance prices.	Data on hourly or sub-hourly unit-level energy generation and consumption, emissions, locational marginal prices, ancillary service prices, asset curtailments, and power flows.
Strengths	Particularly beneficial for analyzing the impact of policies and technology trends on the generation and capacity portfolio mix in medium- and long-term scenarios.	Particularly beneficial for assessing operational and environmental impacts of power plant decarbonization policies and the value of energy storage and distributed energy resources to energy systems.[19]
Weaknesses	Relative lack of granularity compared to other models, including use of aggregate model power plants instead of specific plants for dispatch modeling, lack of temporal specificity, and imprecise representation of transmission and power flow systems	• Tradeoff between scope and granularity • Typically requires a regional focus due to inability to simultaneously model the entire US • Less useful for decisions to build or invest in new generation capacity
Use Cases	Evaluate economic, environmental, and equity impacts of policies on generation and capacity	• Simulate the granular operations and performance of energy systems • Assess the resource adequacy and certain reliability impacts of various policies • Analyze how changes to an energy system affects its operations broadly

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[19] Although production cost models often provide an incomplete assessment of the value of energy storage and distributed energy resources since they may not indicate the value of avoided capacity for these resources.

Outputs from the capacity expansion and production cost models can be used to drive other models, such as those tracking economic impacts, jobs, equity, environmental justice, pollution, and health impacts. For example, a capacity expansion model that predicts 1,000 megawatts (MW) of new solar power capacity in a state can be fed into an "input-output" model that simulates a regional economy. This yields an estimate of direct impacts from manufacturing, construction, and operation jobs; tax revenues; and indirect impacts from new funds stimulating the economy. A production cost model can output emissions data, which can inform public health models that assess the medical cost of pollution and shortened lives. When combined with demographic and geographic data, both capacity expansion and production cost models can give guidance on equity and environmental justice impacts.

Ultimately, the decision of which model to use for a given situation depends on the objectives of the modeling effort. State energy agencies and other organizations considering energy modeling should first identify the question they are seeking to answer, then understand how various modeling techniques and approaches fit into the specific question of interest, before identifying and applying a specific modeling tool.

DIY Modeling: Low-Cost Ways to Analyze Energy Futures

One barrier to the planning process is that sophisticated commercial energy models can be expensive and can require serious computing power and modeling experience. As a result, most stakeholders can feel shut out of the process. In the worst cases, bad actors can take advantage of these barriers to deliver modeling results that seem authentic but favor their self-interest and are misaligned with the public interest.

A growing number of free and open-source models and data sets are emerging for energy planning, creating the opportunity for state agencies, advocacy groups, and the general public to conduct their own analyses – and for planning processes to be more open, transparent, and inclusive.

The think tank RMI recently studied how open-source models could have been used to improve an integrated resource plan (IRP) process by Louisville Gas & Electric/Kentucky Utilities in 2021.[20] Although the utility planners used substantive energy models, they short-circuited them to deliver inaccurate results. For example, they used the PLEXOS model to determine generation capacity needed in 2035. But rather than letting the model determine a least-cost portfolio each year through adding and retiring resources, they manually chose amounts of coal, gas, and solar. Their cost estimates did not include any assumptions about the changing cost of technologies and fuels, nor did they attempt to meet their own corporate goal of 70 percent carbon reductions by 2035–or even mention those goals. As another saying goes, "if you torture your models long enough, they'll confess to anything."

RMI replicated the IRP using GenX, a free, open-source, capacity expansion model developed by researchers at MIT and Princeton.[21] RMI supplemented utility-specific data with public data from the US Energy Information Administration (EIA) and the National Renewable Energy Laboratory (NREL). Their study found that a least-cost portfolio would have substantially more and earlier retirement of coal plants, less gas and solar, and more wind power and battery storage than the Louisville Gas & Electric/Kentucky Utilities plan. It also showed the timing additions and retirements to reduce costs and to illustrate how to maintain reliability while making investments over time. Other free, open-source energy models include:

- Engage Energy Modeling Tool from NREL, developed with the specific goal of empowering local and regional stakeholders, built on the open-source Calliope model
- SWITCH, originally developed at UC-Berkeley
- Breakthrough Energy Services, developed at Breakthrough Energy Ventures
- GridPath from Blue Marble Analytics
- Python for Power Systems Analysis (PyPSA)
- PowerSimulations.jl (one of several models and tools available through NREL's Scalable Integrated Infrastructure Planning Initiative)
- Tools for Energy Model Optimization and Analysis (Temoa) from NC State University
- Next Energy Modeling system for Optimization (NEMO) which can be used on its own or as part of Stockholm Environmental Institute's LEAP platform

Some of these can be as complex as models costing thousands of dollars, but a simpler source of substantive and free technical analysis is the Cambium tool from NREL.[22] Cambium is a set of results from national model runs, annually updated, with easy access through a scenario viewer. The data sets contain modeled hourly emission, cost, and operational data for a range of possible futures of the US electricity sector through 2050. The scenario viewer allows the user to select a variety of scenarios for the whole country, regions, or states, and results can be downloaded as data sets and images.

Figure 2 - NREL Cambium Tool Screenshot

Using energy analysis tools and data that are widely available, free, and transparent can increase public input and public support for utility planning decisions. Energy policymakers, regulators, and planners should consider using them when making decisions that have a substantial public interest.

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[20] Aaron Schwartz, Lauren Shwisberg, and Mark Dyson, "Power Planning to the People: How Stakeholder-Driven Modeling Can Help Build a Better Grid," RMI, https://rmi.org/insight/power-planning-to-the-people/, 2022 (accessed March 12, 2023).

[21] 'MIT and Princeton, "GenX," https://energy.mit.edu/genx (accessed March 12, 2023).

[22] NREL, "Cambium," https://www.nrel.gov/analysis/cambium.html (accessed March 12, 2023).

How to Use Models

Advances in Modeling

Models have evolved over time as technical capabilities have improved. The broad availability of low-cost and powerful computers, cloud-based computing, online data sets, and high-speed data transfer have made modeling available to a wider range of stakeholders, including small government agencies, utilities, consulting firms, and academic institutions.

Current models can incorporate a broader set of inputs, consider a wider range of pathways and constraints, and yield a more diverse set of potential outcomes. These models often leverage increased data availability, high performance computing, and advancements in data science. These newer methods use statistical algorithms and models to learn, update, and refine existing assumptions without following explicit instructions from the modeler. In short, they analyze and draw inferences from new information and patterns in data.

Energy modeling has especially benefited from improved treatment of spatial and temporal factors around energy production and consumption. Solar and wind energy generation and heating and cooling energy demand are almost entirely dependent on natural forces such as changing weather, terrain, and time of day. Models like NREL's ReEDS have pioneered the use of historical high-resolution weather data to forecast performance of solar and wind resources. Whereas previous models consisted of relatively simpler assumptions such as constant availability of fuels, near perfect dispatchability of power plants, and peak demand during summer months as a proxy for weather conditions, newer models factor in a wider, more dynamic range of considerations, such as the real-time performance of solar and wind assets in specific locations relative to load. Previous approaches assumed the need for "backup capacity" for renewable investments and poorly defined "integration costs" resulting in a distorted view of grid operations. Using operational details specific to time and place has allowed newer models to generate more realistic outputs. As the quality of data and tools continue to become more advanced, models will achieve a wider range of capabilities.

The Limits of Modeling

Current state-of-the-art models can deliver reasonable representations of reality that yield useful and actionable insights. Yet, all models have limitations, weaknesses, and biases.

There are two primary risks resulting from modeling in the energy sector: errors in modeling and errors in interpretation, both of which are outlined below. Whether models are inadequate due to poor design, poor data, flawed assumptions, or self-interested intent, it is important for stakeholders to recognize the limitations of models and view modeling results through a critical lens.

Errors of Modeling

There are multiple ways in which errors in modeling can cause significant challenges with the interpretation of model outcomes. Those errors include poor model design or data, misaligned incentives, incorrect design choices and scope, wildcard events, and fundamental limits to modeling capabilities.

> "The future is already here; it's just not evenly distributed."

The quality of a model design can depend heavily on the quality of the input data. Renewable energy resources are quite specific in time and location; without a full understanding of the resource, assessments of their performance can be inaccurate. Technology costs have been changing rapidly, rendering projections obsolete. Policies can change, affecting the results substantially.

In some circumstances, models can use skewed assumptions to support pre-existing beliefs and conventional wisdom, while undercutting evidence to the contrary. Electric utilities have long used models that overestimate future load growth. They are incentivized to do so, as they can use the forecasts to support a case to regulators to allow increased investments, which expands their rate base and increases their profits. Research by RMI and Navigant found that load forecasts have routinely exceeded reality, resulting in tens of billions of dollars of unnecessary investment paid for by ratepayers.[23]

In other instances, models can be designed with constraints that affect results. For example, the EIA's Annual Energy Outlook (AEO) presents a reference scenario that is intentionally limited to current government policies. Because many policies expire after a few years, the AEO does not assume they will be in effect for the long term, even if they are typically extended or further policies are adopted, repealed, or reformed.

Some important issues may fall outside of the scope of a particular model. For example, capacity expansion models usually aim to replicate the procurement of new capacity based on wholesale market dynamics, such as capacity and operating expenses, marginal cost and value, and other factors. But such models are not well-suited to address the growth in distributed energy resources (DERs), such as solar and storage owned by consumers, with procurement decisions made by individuals based on their own preferences and goals. While modelers often ignore DERs, newer models, such as the NREL Distributed Generation Market Demand (dGen) model, have begun to leverage research on consumer behavior and incorporate DERs.[24]

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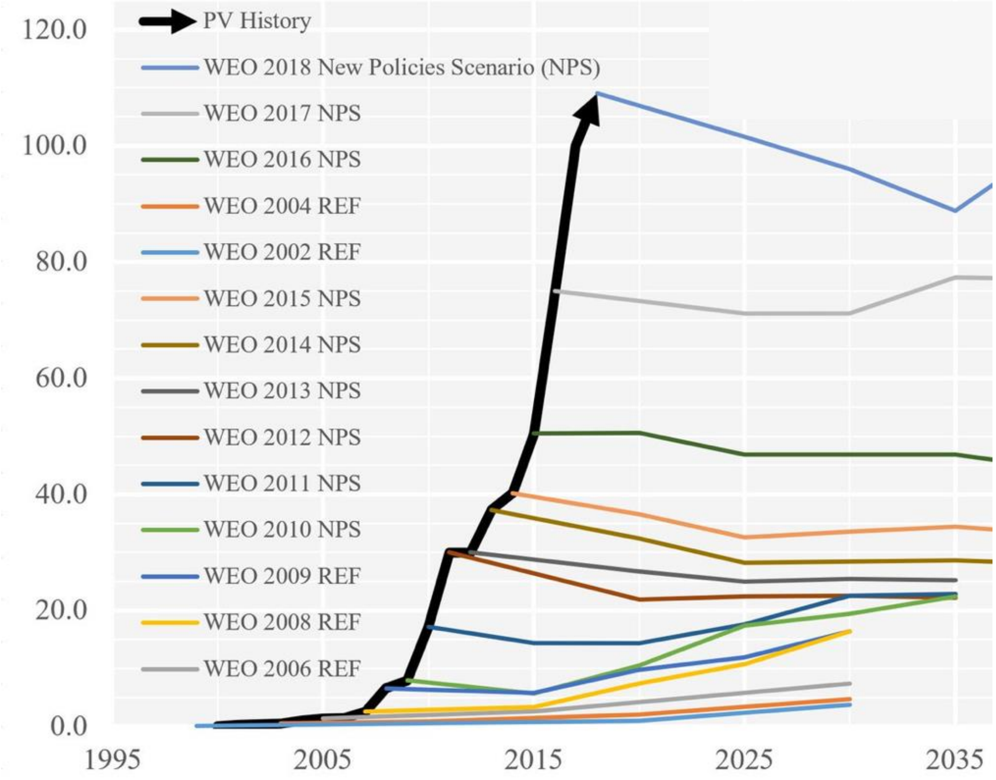
[23] Robert Walton, "As technology upends grid fundamentals, is load forecasting a crapshoot?" Utility Dive, https://www.utilitydive.com/news/as-technology-upends-grid-fundamentals-is-load-forecasting-a-crapshoot/527969/, July 2018 (accessed March 12, 2023).

[24] NREL, "Distributed Generation Market Demand Model, https://www.nrel.gov/analysis/dgen/ (accessed March 12, 2023).

An additional limitation is that some aspects of the energy market are prone to disruptions that are inherently difficult to model. For example, commodities like oil and liquified natural gas are traded globally and subject to uncertain geopolitical dynamics and political disruptions, as highlighted by the impact the 2022 Russian invasion of Ukraine and subsequent sanctions on Russian energy exports have had on global energy markets. Models can attempt to capture a complete range of potential outcomes, even ones that have a theoretically low probability of occurring. However, the inherent volatility and unpredictability of such events creates difficulties in modeling.

Modelers can also simply make mistakes. One common flaw in modeling is the assumption that the future will resemble the past, often referred to as the "straight line" fallacy. Models that fail to adequately account for possible disruptive future cost and performance trends often result in systematically poor treatment of new energy technologies and their impact on energy systems. Many models, including one used by the International Energy Agency (IEA) for their World Energy Outlook, have significantly underestimated the exponential growth potential of renewable energy. Figure 3 shows that IEA vastly underestimated solar growth for over a decade.[25]

Figure 3 - Inaccurate IEA forecasts of annual solar PV growth (in GW of added capacity)



Source: Auke Hoekstra

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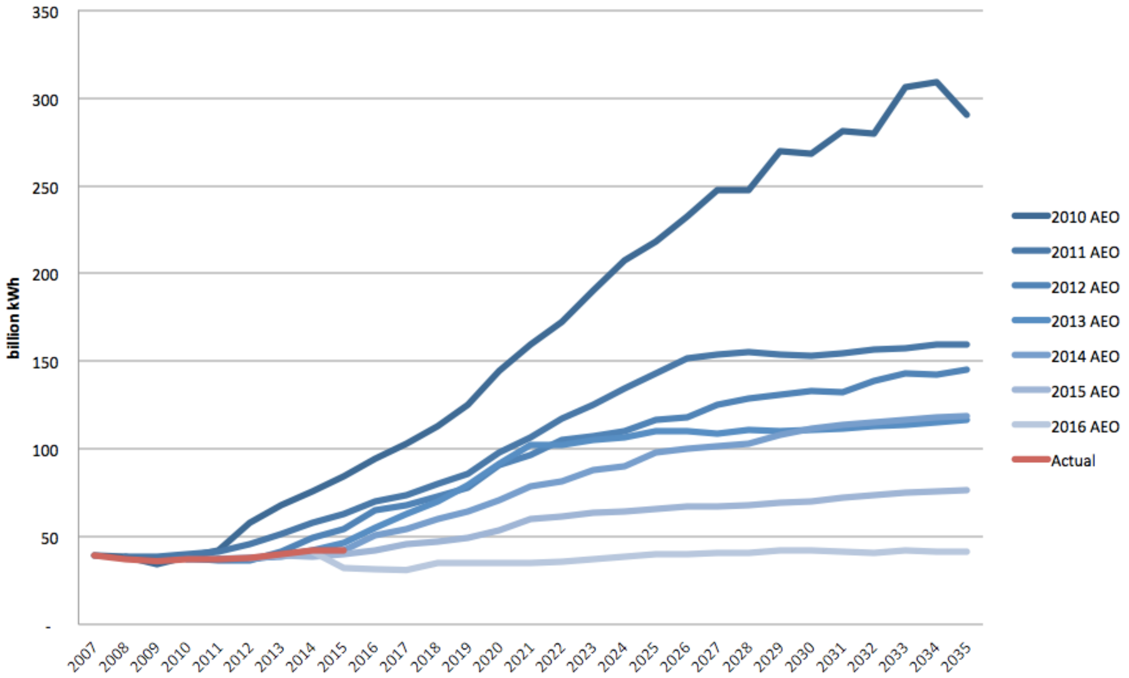
[25] Auke Hoekstra, "Photovoltaic growth: reality versus projections of the International Energy Agency – with 2018 update," Zenmo, https://zenmo.com/en/photovoltaic-growth-reality-versus-projections-of-the-international-energy-agency-with-2018-update-2, January 2019 (accessed March 12, 2023).

In defense of modelers, there have been rapid changes in solar technologies. As the US Energy Information Administration (US EIA) points out, their model "projects technological evolutions rather than technological revolutions" and that "EIA does not attempt to identify disruptive technologies or the timing of their availability and widespread adoption."[26]

On the flip side, models can overpredict performance. For instance, the EIA had anticipated steady growth of biopower production for many years, even as it stayed flat in reality, due to improper model constraints around deployment of solar and wind that led to overestimates in biopower. Eventually, when the EIA improved its treatment of solar and wind growth in its models, biopower expectations plummeted (see Figure 4), aligning with empirical trends over the past decade.[27]

Figure 4 - Inaccurate forecasts of biopower growth by the Energy Information Administration



Source: PaulosAnalysis, using EIA data

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[26] US Energy Information Administration, "EIA's Annual Energy Outlook is a projection, not a prediction," Today in Energy, https://www.eia.gov/todayinenergy/detail.php?id=26272, May 2016 (accessed March 12, 2023).

[27] Bentham Paulos, "On Biofuels, Part 1: Dispelling myths about biopower," Energy Transition, https://energytransition.org/2017/01/on-biofuels-part-1-dispelling-myths-about-biopower, January 2017 (accessed March 12, 2023).

> “If your only tool is a hammer, everything looks like a nail.”

Small errors in model design can quickly accumulate. A recent Lawrence Berkeley National Lab review of EIA’s 2005 Annual Energy Outlook found that the AEO forecasted 2020 power sector carbon dioxide emissions to reach 3,000 million metric tons (MMT), while actual emissions were 1,450 MMT, an over-forecasting by a factor of two.[28] These discrepancies stemmed from significant disparities between certain model assumptions and empirical outcomes: in 2020, electricity demand was 24% lower, the total supply of renewables was 79% higher, and solar and wind generation was 13 times greater in reality than in EIA projections. Meanwhile, the shale gas revolution delivered significant amounts of low-cost natural gas, driving coal out of the market, with coal-based generation falling to a level 70% lower than projected.

At times, modeling has been seen as a crystal ball, the vehicle for answering every question associated with energy planning. Yet, while modeling can function as a useful tool in specific settings, there are risks associated with approaches that do not consider the limitations of modeling. Indeed, “if your only tool is a hammer, everything looks like a nail.” Applying models incorrectly leads to incorrect results.

Errors of Interpretation

Proper interpretation of model results is just as important as a well-designed model. By neglecting to acknowledge the nuances or uncertainties of modeling, stakeholders often fail to appropriately interpret model outcomes.

One of the most common cases of misinterpretation is with the US EIA’s Annual Energy Outlook (AEO). The public and media often regard it as the most definitive and correct vision of the future—the “official” vision of the federal government. But, like all models, it is simply the result of the assumptions built into it. As US EIA takes pains to point out, their Reference Case is “not a prediction of what will happen, but rather a modeled projection of what might happen given certain assumptions and methodologies.”[29]

Often, stakeholders regard AEO’s Reference case as the “most likely” scenario; however, the intent of the Reference case is to assume no new policy adoption, often over a timeframe of decades, which is very unlikely. The US EIA admits that “often these policies have timelines or other attributes that are revised by subsequent legislation or interpreted by executive departments “ and that “some policies can interact in ways that are difficult to foresee.”

Lastly, many models assume perfect markets and planning, where market actors always select the least-cost and best-performing options. They also optimize for system-wide conditions, even though individual

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[28] Ryan H Wiser et al., “Halfway to Zero: Progress towards a Carbon-Free Power Sector,” Berkeley Lab, https://emp.lbl.gov/publications/halfway-zero-progress-towards-carbon, April 2021.

[29] EIA, “EIA’s Annual Energy outlook is a projection, not a prediction,” https://www.eia.gov/todayinenergy/detail.php?id=26272, 2016 (accessed March 12, 2023).

actors make decisions based on their own interests, not for the system as a whole. But individual actors are subject to many common market failures, such as a lack of competition, incomplete information, the "sunk cost fallacy," and skewed incentives. Errors of interpretation can lead to incorrect decisions, just as errors of modeling can.

Managing Errors

To reduce errors of modeling and of interpretation, modeling processes should follow a set of best practices, from the initial design through the dissemination of results.

> "Foresight is not about predicting the future but about minimizing surprise."

First, models should recognize the inherent uncertainties associated with energy planning and explore how future economic and technology trends may impact the electricity system. A range of potential scenarios should be assessed, with a discussion of their relative likelihoods and their respective benefits, costs, opportunities, and risks. These scenarios should illustrate how changes to assumptions and model inputs affect results, a process known as sensitivity analysis. For example, the US EIA's AEO includes eight "side" cases alongside a central "reference" case that consider a range of assumptions regarding economic growth, oil prices, oil and gas supply, and costs of renewables. A sensitivity analysis could, for example, vary fuel prices in a scenario to see how investment choices change.[30] Scenarios could include both evolutionary and revolutionary change cases.

Second, models should demonstrate transparency regarding data and methods, with a clear and complete description of methodologies. Using publicly available models like ReEDS and public data sources is often useful in enhancing the accessibility and replicability of results. A hallmark of science, after all, is to have replicable results.

Third, models should be selected based on what is most appropriate for a given task. There are several key considerations that inform this decision. In dealing with renewable energy and consumer demand, time and place are especially important factors, yet some models are constrained by their ability to cover certain geographies or time periods and time horizons. Furthermore, some models are more effective than others at representing specific, real generation units rather than generic model power plants, as well as other electric assets (e.g., transmission and grid infrastructure). Meanwhile, other models may be more successful at incorporating equity and environmental issues.

Models should be subjected to rigorous review before publication to a broader audience. When evaluating the strength of a given model, it is important to identify the underlying objectives of the modeling effort, the considerations that influenced the design of the model and the degree to which they

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[30] EIA, "Annual Energy Outlook 2022 Case Descriptions," https://www.eia.gov/outlooks/aeo/assumptions/case_descriptions.php (accessed March 12, 2023).

connect with this objective, and the rigorous integration of probabilistic techniques to illustrate the uncertainties associated with model projections. It is particularly important for policymakers, program administrators, and other stakeholders who commission energy modeling efforts to consider the limitations of energy models and leverage the experience and expertise of other stakeholders throughout the modeling process. Ideally, energy models are reviewed twice: when the initial methodology is set and when the results are produced.

Even after quality data sources have been selected and a robust modeling effort has been completed, the modeling process is not complete. The final step is to communicate the results in a clear and compelling way to a range of audiences, from regulators and utility officials, to legislators, the press, and the public. A visually appealing cover design and layout will not, by itself, make a dense report more accessible. Results should be communicated in a range of formats, from a short summary to a medium-length report, with full discussion of details in a technical appendix. Maps and graphics are a must. Interactive data visualizations can let viewers ask their own questions of the data and do their own sensitivity analysis by changing parameters. Data should be available for download in spreadsheets. Presentations should be made to stakeholder groups and the press, and online webinars should be recorded and posted.

Though all these steps require time, money, and expertise, they will increase the likelihood of producing a strong and useful analysis.

Modeling Advice from NREL

In 2013, NREL produced a report, *Re-Assume: A Decision Maker's Guide to Evaluating Energy Scenarios, Modeling, and Assumptions*, containing ten key lessons for policymakers on modeling, which are paraphrased as follows.

1. Do not expect models to predict the future.
2. Match the model to the problem.
3. Make assumptions, frameworks, and methods transparent.
4. Understand the limitations of models, particularly around their representation of human behavior.
5. Utilize a diverse range of tools and methods to address uncertainty in models.
6. Consider how renewable energy systems, in particular, are modeled.
7. Communicate well.
8. Expect and identify bias.
9. Consider all energy scenarios, even ones that were not heavily dependent on modeling.
10. Conduct analyses to retroactively understand the effectiveness of different modeling approaches to identify best practices and avoid common mistakes.

Source: NREL, https://www.osti.gov/biblio/1090954

Conclusion

"Prediction is very difficult, especially about the future."

This report has attempted to describe what energy models do and do not do; their tradeoffs, strengths, and weaknesses; and how to interpret and communicate their outcomes. Models are always imperfect, yet they are a necessary attempt to understand the complex dynamics of the real world and can provide a systematic way to look at the future. Indeed, they often prove influential in guiding behavior.

Despite its quantitative veneer, modeling is not a purely objective and technical process. Getting good results with broad buy-in requires stakeholder engagement throughout the model design and implementation. Understanding and applying the results requires knowing the context and goals of the research, and the biases of the participants.

This report closes with one final maxim: "Prediction is very difficult, especially about the future." For modeling tools to add value to energy planning, decision-making, and implementation efforts, a modeling process should have well-defined and transparent objectives, good data, state-of-the-art models, and honest communications. But it must also be tempered with an awareness of the limits inherent in predicting the unknown. A successful modeling effort can provide insight that leads to good decisions, yielding benefits for years to come.

Suggested Further Reading

The authors highly recommend the US Department of Energy's *Power Sector Modeling 101* presentation[31] and NREL's report on *Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences*.[32]

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[31] Erin Boyd, "Power Sector Modeling 101," US Department of Energy Office of Energy Policy and Systems Analysis, https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf, 2016.

[32] Nate Blair, Ella Zhou, and Dan Getman, "Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences," National Renewable Energy Laboratory and Douglas J. Arent, Joint Institute for Strategic Energy Analysis, https://www.nrel.gov/docs/fy16osti/64831.pdf, October 2015.

Appendix A: Examples of How Models Have Been Applied to Clean Energy Scenarios

NATIONAL STUDIES				
Study	**Year**	**Author(s)**	**Models Used**	**Objective**
100% Wind-Water-Solar and Storage	2022	Mark Jacobson et al.	GATOR-GCMOM (global weather-climate-air pollution model), LOADMATCH (grid integration model)	To evaluate the impacts of 100% renewable energy in the US.
2035 Report	2020	University of California-Berkeley, GridLab, Energy Innovation	ReEDS, PLEXOS	To determine how far the US could transition its power system in 15 years while applying a cost constraint.
Accelerating Decarbonization of the U.S. Energy System	2021	National Academies of Sciences, Engineering, and Medicine	The report does not conduct modeling itself, but relies on existing literature.	To identify near-term actions to advance progress towards a goal of net-zero emissions by 2050 in the US.
LA100: The Los Angeles 100% Renewable Energy Study	2021	NREL, Los Angeles Department of Water & Power	The study used multiple models, including the dGen and RPM models.	To analyze pathways for Los Angeles to achieve its goal of 100% renewable electricity by 2045.
On the Road to 100 Percent Renewables	2022	Union of Concerned Scientists	ReEDS	To assess the feasibility of achieving 100% renewable electricity by 2035 for 24 states.
Princeton Net-ZERO America Project (NZAP)	2020	Princeton University	EnergyPATHWAYS, RIO	To outline pathways to achieving net-zero emissions in the US with specificity.
Renewable Electricity Futures Study (RE Futures)	2012	NREL	ReEDS	To analyze the degree to which renewable energy generation can meet future US energy demand.
Wholesale Electricity Market Design for Rapid Decarbonization	2019	Energy Innovation, Regulatory Assistance Project, Grid Strategies	The report does not conducting itself, but relies on existing literature.	To explore which wholesale market design would be best for decarbonizing the power system based on cost and reliability factors.

STATE AND REGIONAL STUDIES				
Study	Year	Author(s)	Models Used	Objective
Achieving New England's Ambitious 2050 Greenhouse Gas Reduction Goals Will Require Keeping the Foot on the Clean Energy Development Accelerator	2019	The Brattle Group	The report primarily used proprietary models from The Brattle Group, including the Decarbonized Energy Economy Model.	To assess the technology investment needs associated with reducing emissions 80% by 2050 for the New England economy.
Meeting the Challenge of Our Time: Pathways to a Clean Energy Future for the Northwest	2019	Clean Energy Transition Institute	EnergyPATHWAYS, RIO	To explore alternative pathways to achieve deep emissions reductions in the Northwest US and understand interdependencies and tradeoffs between states.
The Road to 100% Renewable Electricity by 2030 in Rhode Island	2020	Rhode Island Office of Energy Resources, The Brattle Group	The report primarily used proprietary models from The Brattle Group, including the Resource Acquisition Cost Model, gridSIM Model, and the Ratepayer Cost Model. NREL's IMPLAN and JEDI models were also used.	To analyze the feasibility and optimal pathways of achieving 100% renewable electricity by 2030 for Rhode Island.
Washington 2021 State Energy Strategy: Transitioning to an Equitable Clean Energy Future	2020	Washington State Department of Commerce	EnergyPATHWAYS, RIO	To analyze the feasibility and optimal pathways of achieving 100% clean energy by 2045 for Washington.

Appendix B: Data Sources

The following data sources are often used in modeling.

PUBLIC SECTOR		
Data Source Name	Data Source Manager	Description
Annual Technology Baseline (ATB)	National Renewable Energy Laboratory (NREL)	ATB is an annually produced database on technology cost and performance data for various energy technologies.
Database of State Incentives for Renewables & Efficiency (DSIRE)	North Carolina Clean Energy Technology Center (NCCETC)	DSIRE is a comprehensive database on energy incentives and policies at the federal, state, local, and utility levels.
Emissions & Generation Resource Integrated Database (eGRID)	US Environmental Protection Agency (EPA)	eGRID is a database that contains data on environmental attributes and performance of electric power generation across the US
Form EIA-860, Form EIA-923, and Other Datasets	US Energy Information Administration (EIA)	EIA has several comprehensive energy datasets for the US, consisting of consumption, generation, emissions, prices, and other data.
National Electric Energy Data System (NEEDS)	US Environmental Protection Agency (EPA)	NEEDS is a database that consists of power generation units used to construct model plants and associated data.
National Solar Radiation Database (NSRDB)	National Renewable Energy Laboratory (NREL)	NSRDB is a collection of hourly and sub-hourly data on solar resources and other meteorological data relevant to solar.
State and Local Planning for Energy (SLOPE)	National Renewable Energy Laboratory (NREL)	SLOPE is a platform that consists of tools that enable scenario comparison and data analysis regarding state and local energy data.
Wind Integration National Dataset (WIND) Toolkit	National Renewable Energy Laboratory (NREL)	WIND is a collection of data on wind resources and other meteorological data relevant to wind.

PRIVATE SECTOR		
Data Source Name	Data Source Manager	Description
ABB Velocity Suite	ABB	ABB Velocity Suite consists of data sets, data analysis tools, and data visualization resources across energy markets.
SNL Energy	S&P Global	SNL Energy is a dataset containing financial data for a range of stakeholders across the US power sector.

Appendix C: Model Examples

This appendix compares and contrasts the two primary models discussed in this report: the capacity expansion model and the production cost model. Because they serve different objectives, they can be—and are often—used in tandem.

NATIONAL SCALE			
	Model Name	**Model Developer**	**Model Description**
Capacity Expansion Model	EnergyPATHWAYS	Evolved Energy Research	An open-source modeling platform used to evaluate long-term, economy-wide decarbonization pathways.
	Integrated Planning Model (IPM)	ICF	A multi-regional model of the US power sector used to evaluate the economic and environmental impacts of power sector policies.
	Regional Energy Deployment System (ReEDS)	NREL	A model of the US power system used to simulate the impacts of power sector decisions and investments.

UTILITY SCALE			
	Model Name	**Model Developer**	**Model Description**
Capacity Expansion Model	Aurora	Energy Exemplar	A software platform for forecasting and analysis of future energy scenarios.
	Resource Planning Model (RPM)	NREL	A model of a regional power system, such as a utility service territory or state.
Production Cost Model	GE Multi Area Production Simulation (GE MAPS)	GE Energy Consulting	A model of power systems used to evaluate the interactions between generation and transmission and other economic impacts.
	PLEXOS	Energy Exemplar	A software platform used for energy systems modeling and forecasting across spatial and temporal factors.
	PROMOD	Hitachi Energy	A model that simulates electricity markets leveraging granular data inputs used for locational marginal price forecasts.

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