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Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences

Nate Blair, Ella Zhou, and Dan Getman
National Renewable Energy Laboratory (NREL)

Douglas J. Arent
Joint Institute for Strategic Energy Analysis

This work is part of the China Grids Program for a Low-Carbon Future, supported by the Children's Investment Fund Foundation.

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-6A20-64831
October 2015

Contract No. DE-AC36-08GO28308

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Preface

China now installs more renewable electricity each year than any other country in the world. Much of this is *variable* renewable electricity, especially wind and solar generation. A growing body of experience exists from around the world on how to plan and operate electricity grids with high penetrations of variable renewable electricity. China is actively contributing to this body of experience given the rapid growth in renewable electricity deployment there, while at the same time digesting experiences from other countries.

This report is part of a series describing technical collaboration between the National Renewable Energy Laboratory (NREL), the China National Renewable Energy Center (CNREC) along with other key research institutes in China, and the Danish Energy Agency. The collaboration focuses on sharing experiences in the planning, deployment and operation of high-penetration renewable electricity grid systems. The Children's Investment Fund Foundation in the United Kingdom has funded this five-year collaboration.

The core element of the collaboration during this first year was a series of expert engagements in China to share technical knowledge and experience on four key topics:

1. Comprehensive energy scenario design and modeling
2. Renewable energy (RE)-friendly grid development
3. Power system flexibility
4. Boosting distributed generation of RE.

These engagements built on and significantly expanded existing collaboration between the Danish Energy Agency and CNREC experts.

This report summarizes some of the issues discussed during the engagement on the first topic listed above. It focuses primarily on NREL's experience with capacity expansion modeling, limiting its discussion to the U.S. context by design. Exploration of whether and how U.S. experiences can inform Chinese energy planning will be part of the continuing project, and will benefit from the knowledge base provided by this report. We believe the initial stage of collaboration represented in this report has successfully started a process of mutual understanding, helping Chinese researchers to begin evaluating how lessons learned in other countries might translate to China's unique geographic, economic, social, and political contexts.

We look forward to continuing the collaboration for the remaining four years and building on these initial successes.

Acknowledgments

The authors would like to thank Lars Møllenbach Bregnbæk and Tao Ye of the Chinese National Renewable Energy Centre for data on the China Renewable Energy Analysis Model—Electricity and District Heating Optimization (CREAM-EDO) model and draft review. For their review and comments, the authors would like to thank the following NREL colleagues: Jeffrey Logan, Trieu Mai, Changgui Dong, Wesley Cole, and John Barnett. This work is a part of the China Grids Program for a Low-Carbon Future, supported by the Children's Investment Fund Foundation.

Acronyms

ATB	Annual Technology Baseline
CNREC	China National Renewable Energy Center
CREAM-EDO	China Renewable Energy Analysis Model—Electricity and District Heating Optimization
CSP	concentrating solar power
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
GW	gigawatt
IPCC	Intergovernmental Panel on Climate Change
kW	kilowatt
LCOE	levelized cost of energy
MARKAL	Market Allocation model
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PV	photovoltaics
RE	renewable energy
ReEDS	Regional Energy Deployment System model
REF	Renewable Electricity Futures study
RMB	Renminbi (Chinese currency)

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Introduction

Mathematical and computational models are widely used for the analysis and design of both physical and financial systems. Modeling the electric grid is of particular importance to China for three reasons. First, power-sector assets are expensive and long-lived, and they are critical to any country's development. China's electric load, transmission, and other energy-related infrastructure are expected to continue to grow rapidly; therefore, it is crucial to understand and help plan for the future in which those assets will operate (NDRC ERI 2015). Second, China has dramatically increased its deployment of renewable energy (RE), and is likely to continue further accelerating such deployment over the coming decades. Careful planning and assessment of the various aspects (technical, economic, social, and political) of integrating a large amount of renewables on the grid is required. Third, companies need the tools to develop a strategy for their own involvement in the power market China is now developing, and to enable a possible transition to an efficient and high RE future.

This report on modeling and scenario analysis is the first in a series on planning and operating high penetration renewable electricity futures in China. The five-year collaboration program—*The China Grids Program for a Low-Carbon Future*—is carried out by the China National Renewable Energy Center (CNREC), the National Renewable Energy Laboratory (NREL), and the Danish Energy Agency. It is supported by the Children's Investment Fund Foundation. The program seeks to assist the implementation of China's energy revolution—a transition from the current fossil fuel-dominated energy system to one that has much higher levels of RE and energy efficiency. Year-one activities fall into four task areas: modeling and scenario analysis, RE-friendly grid development, power system flexibility, and distributed renewable generation. The three partner institutes participated in an intensive one-week set of workshops under each subject area during the first year of the program, and NREL is tasked with producing a series of four technical reports that summarize the experience and best practices in the United States, with consideration of China's key challenges in these areas.

The modeling and scenario analysis task seeks to clarify, using rigorous statistical modeling and analysis, the potential for RE as a viable, economically attractive energy supply, in light of the continued growth in China's total energy consumption and development of fossil fuel generation. Modeling methods and related lessons learned from the U.S. experience expressed in this report are intended as a source of reference for the modelers at CNREC and a broader energy system modeling community. Improvements in their models would serve to build confidence in the role of modeling and scenario analysis and, in turn, in the high penetration renewables futures envisioned for China. The report is also intended for policymakers and other stakeholders who would be assessing the modeling results to gain insights for decision-making purposes.

This report focuses on the experience at NREL, using primarily the Regional Energy Deployment System (ReEDS) model for capacity expansion. There are many other capacity expansion models available for the United States and other countries, as well as the global electricity system. The ReEDS model has been highlighted in this report because NREL's experience with it addresses many of the questions and challenges raised in the Chinese context during the one-week modeling workshop hosted by CNREC in early 2015. The issues discussed in this report are consistently raised when addressing RE development in any model. Other models and scenario reports that are worth investigating include:

- The Annual Energy Outlook (EIA 2015) published by the United States Energy Information Administration (EIA), relying on its capacity expansion model, the National Energy Modeling System (NEMS) (EIA 2009). The NEMS model is economy-wide and includes more sectors than ReEDS. For example, it includes modeling of the natural gas and coal supply markets, and a model of electricity load. The ReEDS model typically extracts the fuel price and load trajectories from the Annual Energy Outlook each year as inputs.
- A recent Intergovernmental Panel on Climate Change (IPCC) report highlights approximately 170 potential capacity expansion scenarios at a global level, summarizes the carbon dioxide and other environmental outcomes, and discusses why different models arrive at different views of the future (Edenhofer et al. 2012).[1]
- MARKAL is another widely used model. Short for MARKet ALlocation, MARKAL is a dynamic optimization model that fosters strategic energy planning. By integrating energy, environmental, and economic factors, the MARKAL model provides energy system solutions to support national planning and policy decisions. Originally sponsored by U.S. Department of Energy (DOE) and the International Energy Agency, the MARKAL model was developed at Brookhaven National Laboratory for energy-system modeling and analysis in the late 1970s. The model now has widespread international acceptance: more than 40 countries use it to analyze a broad range of issues in energy planning and environmental policy formulation. Current applications now include analyzing environmental policies, projecting inventories of greenhouse gas emissions, and estimating the value of regional cooperation. International workshops on its use are offered regularly (ETSAP 2015).

Electric grid modeling is extremely difficult due to the size, complexity, time-scales, and uncertainty of many underlying characteristics. The U.S. Eastern Interconnection alone, for example, has nearly 180,000 miles of transmission lines and 436 gigawatts (GW) of installed generation (Kirsch et al. 2012). Even though China has more installed generation capacity than the United States, the Chinese grid has fewer miles of transmission, but that amount is expected to grow significantly. Therefore, the difficulty in modeling is reducing this complexity to be tractable in models. For example, NREL's ReEDS model (NREL 2015a) performs a cost-minimization for every two-year period from 2006 to 2050, using a reduced network with 134 nodes for the contiguous United States, one in each of the represented balancing areas, and about 300 aggregate lines that connect contiguous balancing areas (Short et al. 2011) in combination with a set of sophisticated statistical calculations to account for load, reserve, and operating reserves. The nonlinearities, discrete decisions, and non-convexities add to the complexity of the modeling task, as do uncertainties in demand, supply, and price.

All models are imperfect representations of the actual grid, load, transmission system, electricity markets, and policies. Each must consider tradeoffs between adding more complexity and getting a slightly better representation of the grid versus creating a tool that takes more and more time to complete a single iteration as more details are added.

[1] See chapter 10 of Edenhofer et al. for a discussion of global RE deployment scenarios.

Additionally, it is important to stress that models, particularly capacity expansion techno-economic models like those discussed in this report, are designed to provide insights on possible pathways, and the influence of technology innovation, transmission expansion, demand changes, and policies of the power system. These models are not typically designed to “predict the future.”

Finally, the process of scenario modeling can be daunting, especially when working on a large system such as CNREC’s. This requires effective stakeholder engagement in several stages, particularly related to scenario design, input assumptions, and model methodologies. Having conducted a number of technology-specific and integrated studies of future scenarios, NREL’s experience indicates that having an effective set of stakeholders and audience members involved throughout the process, including commenting on intermediate results, is critical. The worst case would be to spend several years on a major project only to have it be dismissed by a set of stakeholders due to a single oversight that the modeling team alone did not consider. NREL previously published a report on lessons learned regarding the discussion of modeling results with stakeholders; see Appendix A for the key takeaways from that report.

The goal of this report is to address in detail NREL’s approach to several (but not all) key questions that arise when modeling future capacity expansion within the context of significant levels of variable RE. These questions have been selected for their level of general importance to scenario modeling, but also for their importance specifically to CNREC to inform model and scenario analysis enhancements. These key questions involve topics such as technical costs and performance, modeling of key grid operational issues, scenario modeling including regionality, and visualization.

Issue One: What Analysis Questions are Answered Using Capacity Expansion Models?

Examples of NREL's Use of Capacity Expansion Models

NREL has been directly modeling electric grid capacity expansion since 2001 and the inception of the WinDS model (Blair et al. 2008), which has evolved over time to become the ReEDS model (NREL 2015a). The ReEDS model has been used extensively to examine the future scenarios of the U.S. power system, as well as technology innovation impacts and policy scenarios. In addition to some of the key studies listed below, NREL performs various other, more targeted analyses to answer focused questions. Some key examples of analysis conducted using capacity expansion modeling include:

- *20% Wind Energy by 2030* (EERE 2008): The WinDS model was developed and used to model a scenario in which 20% of electric generation would come from onshore and offshore wind by 2030. WinDS evaluated the best location to site the wind in this case, and evaluated and reported the impacts of this level of wind on the grid.
- *Evaluating a Proposed 20% National Renewable Portfolio Standard* (Logan et al. 2009): This report was developed to investigate the implications of a federal renewable portfolio standard option under consideration at the time. The policy option that was evaluated would have required 20% nationwide electricity from renewable sources, a constraint easily considered by ReEDS. Logan et al. conducted various sensitivity analyses using ReEDS to explore factors that affected impacts from a variety of renewable portfolio standard designs. The types of policy analysis desired are a key component of deciding how to represent the geographic regions within the model.
- *SunShot Vision Study* (DOE 2012): This study evaluated the implications of reaching the goal of $1/watt for utility-scale photovoltaic (PV) power with similar cost reductions for residential and commercial applications, and for concentrating solar power (CSP) technologies. Again, ReEDS was used to evaluate the potential capacity growth and energy contribution mixes under this cost reduction strategy in competition with other renewable and conventional technologies.
- *ReEDS Modeling of the President's 2020 U.S. Renewable Electricity Generation Goal* (Zinaman et al. 2014): This analysis was unique in its near-term nature (between now and 2020). Many of the capacity expansion models focus on trying to get the long-term scenarios correct and don't invest significantly in getting the details of the near-term grid accurately. This analysis, due to the focus out only to 2020, required reexamination of the representation of the current, mostly conventional fleet of generators and their plant-specific characteristics.
- New *Wind Vision Report* (DOE 2015a): This expansive update to the *20% Wind Energy by 2030* (EERE 2008) includes wind technology cost and performance updates, an electric grid update, as well as improved representation within the ReEDS model. In the *20% Wind Energy by 2030* (EERE 2008) report, significant development of wind occurred in the central region of the United States, which would require new transmission lines to send it to the eastern states. In this updated report, new low wind class turbines and enhanced performance of high wind class turbines were accounted for. Results

indicated economic opportunities for wind generation (optimized for low-wind-speed environments) closer to the centers of demand rather than transmitting power from the central states that have better resources, but require additional transmission.

- *2015 Standard Scenarios* (Sullivan et al. 2015): This report describes 19 standard scenarios projecting the evolution of the U.S. electric sector from the present through 2050 and the current model algorithms and assumptions for ReEDS. The central scenario, running ReEDS v. 2015.1 with default settings, has continuous load growth through 2050 and retirement in the electricity fleet starting in 2010. The standard scenarios involve changes in parameters such as fuel prices, rate of demand growth, technology improvement, and the retirement schedule of today's fleet. For each parameter examined in the standard scenarios, a set of two scenarios are analyzed in both directions from the baseline assumption in the central scenario, e.g., high fuel price scenario and low fuel price scenario. In addition, individually defined scenarios are chosen to present its own vision of the future distinct from the central scenario, such as carbon policy.
- *Renewable Electricity Futures Study – Exploration of High-Penetration Renewable Electricity Futures* (REF) (Hand et al. 2012): This study looked at over 30 different scenarios at various levels of RE generation from 20% to 90% and at various levels of anticipated technology improvement through 2050. This complex arrangement of scenarios (represented in Figure 1) allowed the authors to delve more deeply into comparisons of results across scenarios and draw conclusions within this parametric space. For China-focused scenarios, one would envision an even larger emphasis on variations of the demand growth assumptions (low, mid-line, and high growth scenarios) along with more uncertainty around technology improvement due to the dramatic market growth anticipated with the deployment levels required by the size of the future Chinese system.

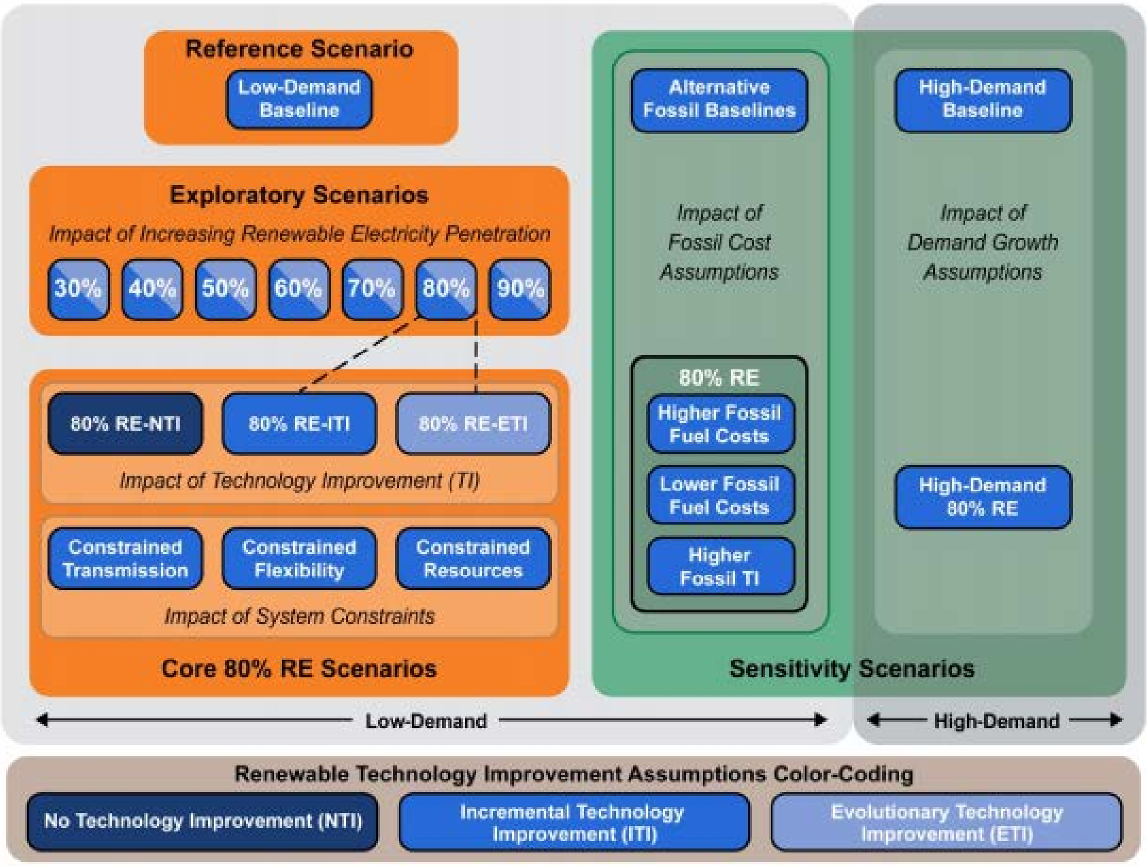
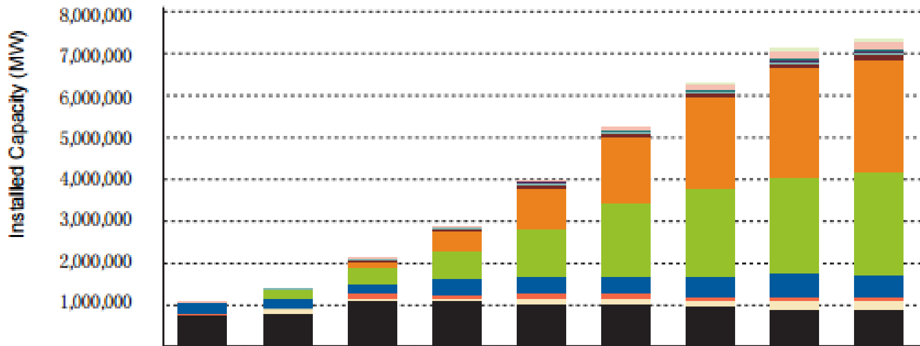


Figure 1. Renewable Electricity Futures (REF) study scenarios

Source: Hand et al. 2012

The other critical and somewhat unique aspect of the REF study was that, once ReEDS generated the 80% scenario for 2050, the resulting capacity was then represented in a production cost model (GridView in this case) and a set of hourly analyses were run in GridView. This activity sought to validate that the grid operations and dispatch would meet load reliability throughout the country at 80% penetration of RE, at the hourly level. Other studies have continued to seek to represent the operational aspects of high penetrations of renewables.

The REF study is a useful reference for the recently released China 2050 High Renewables Study. In April 2015, the Energy Research Institute of the National Development and Reform Commission (China) launched a study of the China 2050 high RE penetration scenario (NDRC ERI 2015). The key graphic from this report representing a high-renewable penetration scenario is shown below in Figure 2.



	2011	2015	2020	2025	2030	2035	2040	2045	2050
Chemical energy storage							47,179	106,061	158,525
Pumped hydro storage	29,608	38,490	50,038	65,049	81,311	93,508	107,534	123,664	142,213
Ocean energy						1,000	1,000	1,000	1,000
Geothermal power						3,750	11,250	11,250	11,250
Wood pellets power		1,100	1,980	3,221	4,955	8,200	12,329	27,465	32,854
Straw and stalk power	3,402	6,738	11,250	15,573	24,431	38,345	50,110	58,084	61,047
Biogas power	382	16,192	39,306	39,304	39,304	39,306	33,730	34,681	39,306
Municipal waste power	2,011	5,040	8,400	12,574	18,899	33,484	54,215	72,544	80,857
Solar power	3,763	42,025	157,025	500,235	1,048,858	1,657,055	2,206,333	2,678,200	2,696,164
Wind power	48,350	114,880	317,088	632,176	1,103,944	1,663,348	2,092,248	2,287,630	2,396,591
Hydropower	230,670	267,099	313,973	402,363	440,752	460,800	471,881	512,000	554,140
Nuclear power	12,570	42,790	50,500	64,000	66,000	69,000	78,000	85,000	100,000
Oil power	1,224	1,166	1,139	1,098	1,012	862	824	824	824
Natural gas power	32,649	94,273	110,355	125,909	130,119	156,818	173,119	191,750	219,834
Coal power	749,062	822,495	1,083,388	1,079,878	1,052,150	1,037,588	972,299	928,534	886,691

Figure 2. Power installed capacity in high penetration scenario

Source: NDRC ERI 2015

Figure 2 shows the results from the China Renewable Energy Analysis Model—Electricity and District Heating Optimization (CREAM-EDO) model. Under a high penetration RE scenario, strong growth in several forms of RE is seen in the Chinese grid. In particular, wind and solar power are both estimated to reach over 2 terawatts of capacity around 2040. The forecasted levels of geothermal, hydropower, ocean energy, and storage are all higher than modeled by ReEDS using typical input assumptions in the U.S. electric grid by 2050. The market expansions for these technologies would impact the global cost of these technologies, potentially making them more viable in other parts of the world.

The robustness of the CREAM-EDO model will likely continue to improve with additional planned efforts to improve assumptions and inputs to strengthen subsequent findings. Even though the Chinese and U.S. electric grids are currently very different and will likely remain unique as both potentially move towards higher levels of renewables, power system modeling principles can be applied in both countries.

The aforementioned NREL projects have led to a number of improvements to the ReEDS model. First, in many cases, new developments within the ReEDS model have been necessary to represent new technologies or greater detail in order to address a specific question of the study. Second, resources, costs, and other performance aspects of the model have also been updated. Finally, the model, analyses, and results have been extensively reviewed by key stakeholders to assure expert validation of key inputs and methodologies. All of these developments make the underlying model stronger with each major study. NREL is currently conducting two major studies that will further improve the model's treatment of additional technologies, including hydropower and geothermal generation.

Issue Two: Critical inputs to capacity expansion modeling and representation of renewables generation.

The capacity expansion models reviewed here (ReEDS from NREL and CREAM-EDO from CNREC) require several thousand inputs. This section will focus primarily on cost and performance data inputs and discuss several lessons learned.

Load Data

The ReEDS model utilizes load trajectories (by region and time period) from the U.S. EIA Annual Energy Outlook report (EIA 2015). However, the load trajectories are not fixed through time: they are adjusted between solves in ReEDS based on deviations between computed and expected electricity prices. After each optimization, a regional electricity price is computed in ReEDS and used to adjust the load growth forecast for subsequent years (Short et al. 2011).

The situation in China regarding load data is different and probably more dynamic than in the United States. Even though electricity demand growth has slowed over the past two years in China, overall load is still expected to grow much more rapidly in China than in the United States or Europe in the next decade due to urbanization. However, China's medium-to-long term load growth trajectory is highly uncertain because of the economic structural transition. Studies from NDRC ERI, International Energy Agency, and Lawrence Berkeley National Laboratory show significantly different energy consumption curves into the future (Zhou et al. 2013; NDRC ERI 2015). This growth uncertainty drives much of the final outputs of the Chinese modeling. The very large amount of wind and solar deployment in Figure 2 would not be required with a flat electricity load from 2015 to 2050. This assumption about load data should be considered very carefully and a range of values needs to be examined via the scenario process.

Renewable Resource Data

Understanding the details of the renewable resource data (solar, wind, geothermal, and hydropower, for example) for a region or country is critical to obtain accurate and detailed results for deployment. The U.S. modelers have the advantage of a public annually-averaged solar data set. Obtaining wind resource data is more difficult, but has been effectively accomplished in the United States. International onshore resource data are a patchwork of various existing data. One of the key problems is that large-scale geographic averaging of the resource often "averages together" the excellent resource locations with those that are more modest, making it difficult to focus on the most economic regions first (see Sullivan et al. 2014). Detailed renewable resource data representations can allow the most cost-effective site locations to be deployed in the model, which can lead to growth in industry and additional cost reductions due to economies of scale. In ReEDS, there are 356 wind/CSP resource regions that are aggregated from U.S. counties. This is the level at which wind and CSP capacity expansion occurs and resource limitations are considered (Short et al. 2011).

The resource data are combined with other land-use data sets to identify non-usable areas (for example, a utility-scale solar power plant cannot be built in the middle of Yellowstone National Park) to obtain the supply curve of solar availability by cost. In China, the Wind and Solar

Resource Center of the China Meteorological Administration (CMA) has two sets of renewable resource data. One set is calculated from satellite data and calibrated with observed data from 96 observatories around the country; the other set is the collected data of the duration of sunshine at over 2,000 meteorological stations around the country combined with the observatory data. The resource data available in China are typically 45 km x 45 km in resolution. In 2014, CMA scaled the wind resource data to a higher resolution (1 km x 1 km) by applying statistical adjustments (CMA 2014).

Transmission

The accurate location of current transmission lines is a key data set in the U.S. analyses that NREL performs. These data are critical to establish the current pathways for electricity to flow and, in an optimized system, to add power from wind, solar, gas, and other forms of generation to the existing transmission system. However, as the scenario looks further into the future, the construction of new transmission lines to connect energy sources and loads is critical (including the price of that transmission). Table 1 includes the major assumptions related to new transmission and interconnection in ReEDS, with additional details available in Short et al. (2011). For wind, CSP, and PV technologies, no additional grid interconnection cost is incurred because their capital cost assumptions include the onside switchyard, a short spur line, and relevant upgrades at the substation (Sullivan et al. 2015).

Table 1. Assumptions for Transmission and Interconnection

Category	Range
Inter-BA line costs ($/MW-mile)	$800–$7,580
Substation costs ($/MW)	$11,800–$28,600
Intertie (AC-DC-AC) costs ($/MW)	$250,000
Intra-BA line costs ($/MW-mile)	$2,400–$10,680
Transmission losses	1% per 100 miles

Because the U.S. electricity load is not expected to grow as dramatically as in the Chinese system, the current U.S. transmission infrastructure will remain mostly unchanged for the next several decades. Conversely, in China, accurate modeling of transmission build out is critically important in evaluating future scenarios because the system is anticipated to grow quickly over the coming decades.

Fuel Prices

As with load forecasts, NREL uses U.S. EIA Annual Energy Outlook (EIA 2015) forecasts for natural gas, coal, and nuclear fuel price trajectories with some built in regional variation and elasticities as options. This reduces the modeling burden but does not provide truly robust feedback from the ReEDS scenario being run to the fuel prices, and can ignore some of the detailed regional distribution issues around natural gas or coal distribution. Dramatic drops in electricity from coal would tend to push downward the price of coal in certain ReEDS scenarios. ReEDS addresses this with coal and gas price elasticities informed by several NEMS-based scenarios. The ReEDS team has also begun work to link the model to more detailed natural gas market models built by other organizations.

With some of the scenarios for China predicting dramatic growth in all forms of energy supply including fossil fuels, the modeling of the supply side of gas and coal warrants attention.

Introduction to Technical Costs

As discussed in the introduction, NREL has engaged in various technology-specific analyses for more than a decade. During that time, the cost and performance of renewable technologies has changed significantly, with lower costs and better and more reliable performance across technologies. As a result, it is important to capture the most current pricing and have a robust process for estimating future cost and performance data. As alluded to above, the cost issue is compounded in China, where the anticipated deployment levels are so much more than in other countries that the Chinese market will likely have its own dynamics, and may significantly influence global market prices of some technologies (e.g., Solar PV [Gan and Li 2015; IEA 2014]). Therefore, economies-of-scale cost reductions are a critical piece of this analysis for China. In the United States, even though the technical costs based on the U.S. market conditions are reflective of the global dynamics, the modeling of economies of scale is not as impactful on the final results because the levels of penetration analyzed typically do not drive the overall global market as much as the deployments in China would in certain scenarios such as those CNREC is modeling.

Annual Technology Baseline

The NREL Annual Technology Baseline (ATB) summarizes cost and performance data, and cost estimates through 2050 (NREL 2015b). The reported data represent an initial effort to provide a consistent set of technology cost and performance data, and to define a conceptual and consistent scenario framework that can be used in future analyses. The long-term objective of this effort is to identify a range of possible futures of the U.S. electricity sector through which specific energy system issues are considered. The ATB (1) defines a set of prospective scenarios that bookend ranges of key technology, market, and policy assumptions and (2) assesses these scenarios in NREL's market models to understand the range of resulting outcomes, including energy technology deployment and production, energy prices, and carbon dioxide (CO_2) emissions. The specific products from the initial effort include the following:

- An ATB workbook documenting detailed cost and performance data (both current and projected) for both renewable and conventional technologies
- An ATB summary presentation in PowerPoint describing each of the technologies and providing additional context for their treatment in the workbook.

The ATB currently includes the following technologies:

- Land-based wind power plants
- Offshore wind power plants
- Utility-scale solar PV power plants
- CSP plants

- Geothermal power plants: flash and binary organic rankine cycle
- Hydropower plants: upgrades to existing facilities, powering non-powered dams, and new stream-reach development
- Conventional power plants: coal (several configurations), natural gas turbines, natural gas combined cycle, biopower, nuclear, and several with carbon capture and sequestration options.

As can be seen from this list, NREL is not including several of the technologies that CNREC and others are including in their modeling for China, such as ocean technologies. NREL currently does not have adequate data or research into these costs to effectively represent them within the ATB construct. In addition, both geothermal technologies and hydropower technologies do not include future projections of costs at this time—although other ongoing efforts are planned to result in future projections.

For each technology, the capital cost, operations and maintenance (O&M), and performance are represented both for the present and future. These data are captured into a spreadsheet, such as shown in Figure 3. From a visualization standpoint, this spreadsheet has been designed to be accessible, transparent, and easily navigable.

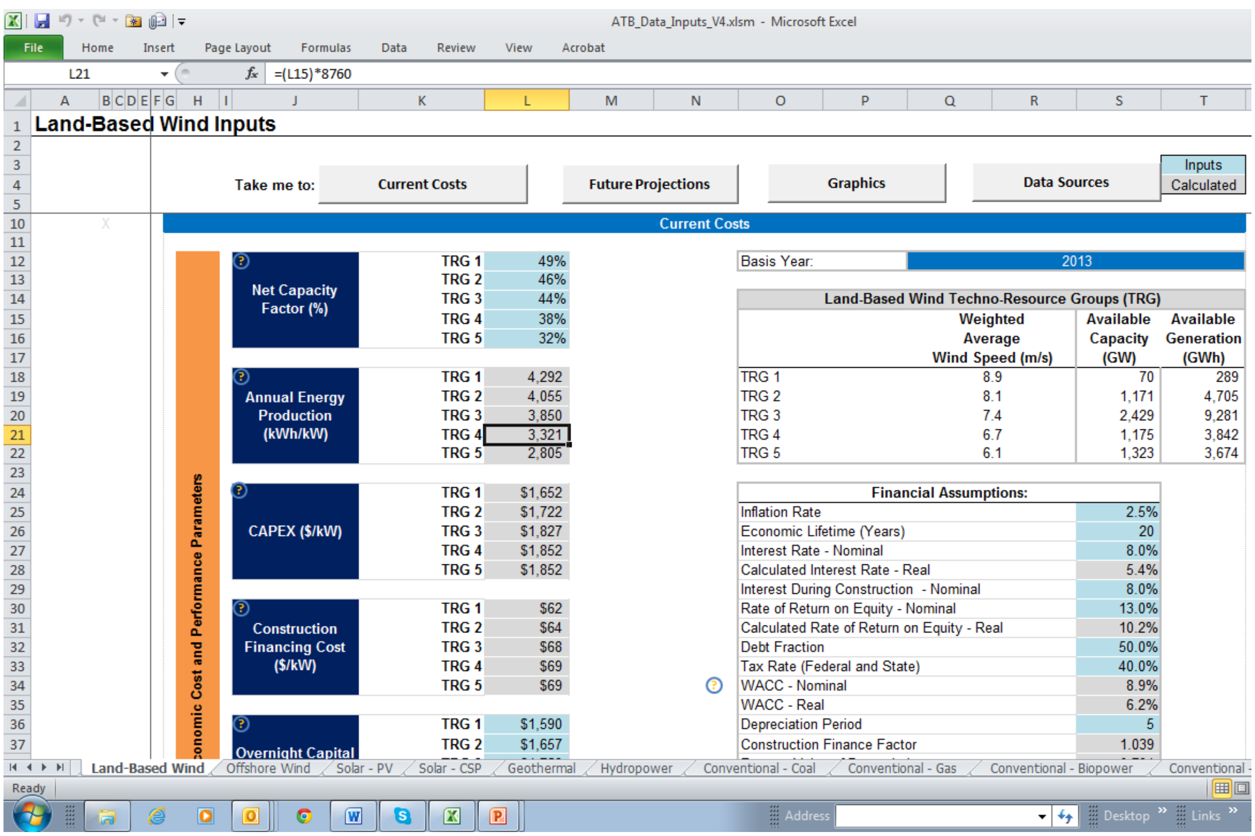


Figure 3. Screenshot of ATB data inputs sheet

A comparison between 2014 technology cost data adopted by NREL in ReEDS and by CNREC in CREAM-EDO shows quite significant divergence in capital cost and some fixed annual O&M costs (See Table 2). The ATB data represent the technology cost in the United States in 2014 in current values, and are adopted in ReEDS with a cost trajectory into the future; the CREAM-EDO data are representative of the cost of technologies projected to be installed in China between 2010 and 2019 in 2011 Chinese renminbi (RMB), converted in the table to U.S. dollars with the average RMB/U.S. dollar exchange rate in 2014. Because cost changes over time are yet to be implemented in CREAM-EDO, this table effectively compares the technology data used in the simulations of year 2014 in the two models. As Table 2 shows, U.S. capital cost numbers are, in general, much higher than those in China. This is not only a result of the cost differences of the same technologies in each country—including civil and structural costs, mechanical equipment supply and installation, electrical instrumentation and control, project indirect costs, etc.—but it also indicates that, due to different policy environments for a given type of generation, different technologies might be used in China versus in the United States. For example, the coal plants in China have much lower capital cost than a new coal power plant in the United States because the Chinese coal plants have long achieved cost breakthroughs due to advanced technology and less reliance on environmental controls, among other factors.

Table 2. Technology Cost Comparison Between ATB and CREAM-EDO

Type	CAPEX ($/kW)		Fixed Annual O&M ($/kW)		Variable O&M ($/MWh)	
	ATB	EDO	ATB	EDO	ATB	EDO
Wind – Onshore	1,827.00	1,381.94	51.00	10.88	0.00	0.00
Wind – Offshore	6,340.00	2,343.29	132.00	17.41	0.00	0.00
Solar – PV	2,647.00	1,299.12	18.00	26.79	0.00	0.00
Gas – CC	1,021.00	3,57.26	14.00	7.37	3.00	0.06
Coal – new	3,446.00	1,266.65	32.00	29.36	5.00	3.70
Biomass	4,278.00	1,688.86	107.00	29.94	5.00	2.68
Nuclear	6,482.00	2,101.33	95.00	133.16	2.00	4.71

Through the ATB, the costs and performance for these technologies can be compared via a simple levelized cost of energy (LCOE) calculation.[2] The following three graphs indicate the current and future LCOE calculations for onshore wind, solar PV, and CSP.

[2] See Hand et al. (2012) for more on LCOE calculation methodology. ReEDS does not directly rely on LCOEs in its capacity expansion decision-making; the LCOEs shown in Figure 4 through 6 are illustrative only.

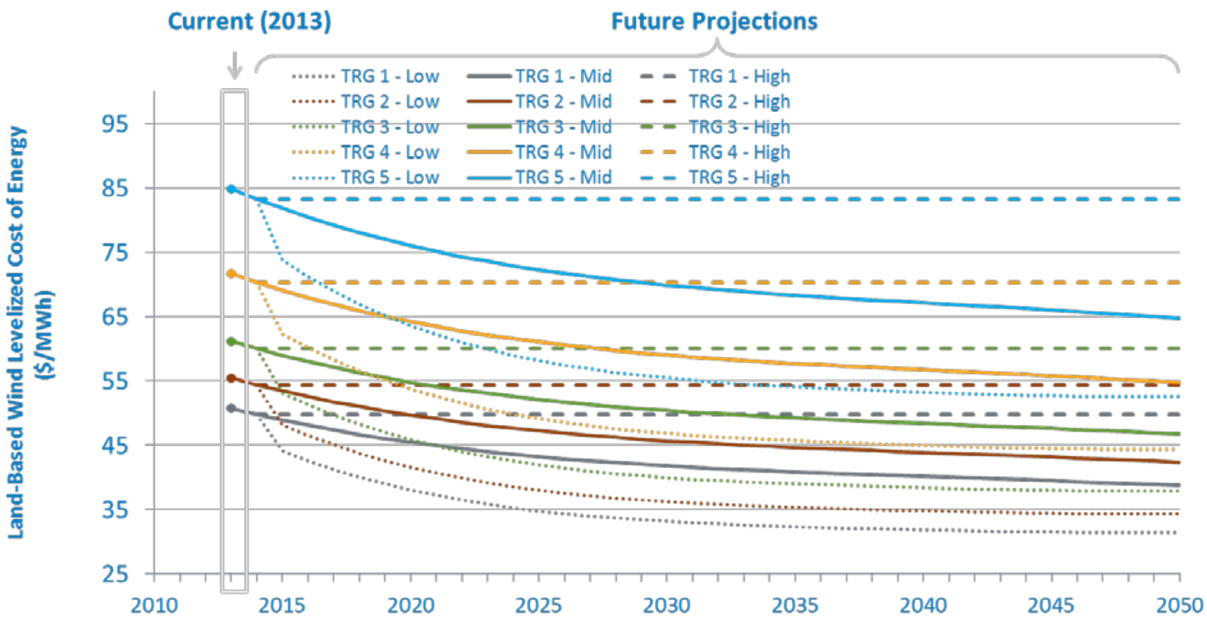


Figure 4. Current and future LCOE for onshore wind (ATB)[3]

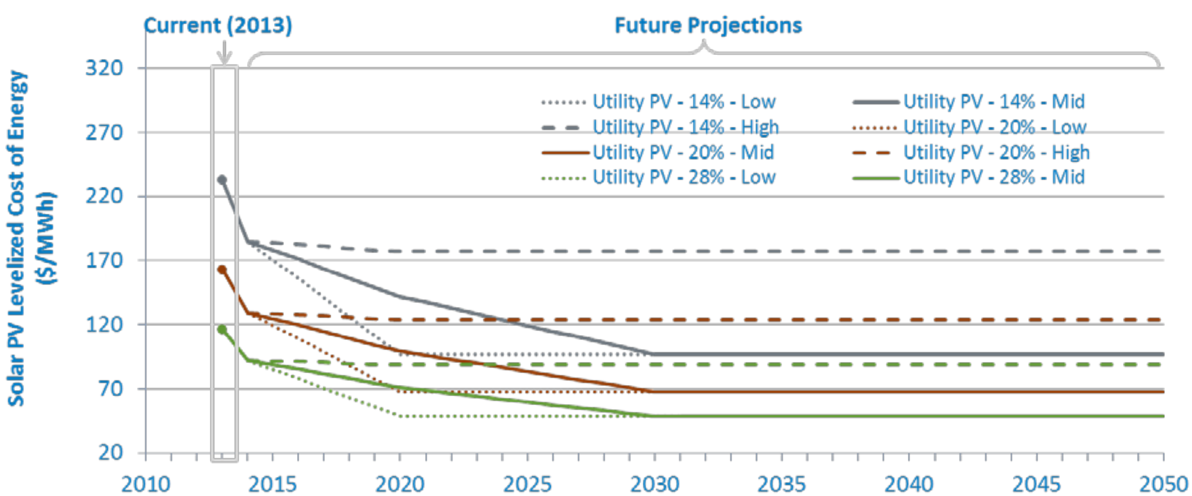


Figure 5. Current and future LCOE for solar PV (ATB)

[3] TRGs ("technology resource groups") from 1 to 5 indicate the best wind resource classes (1) to less ideal wind resource class (5).

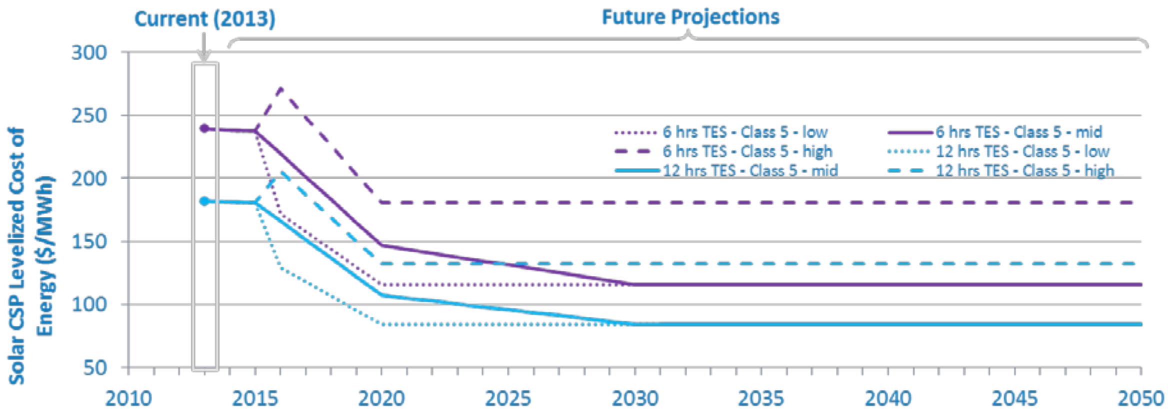


Figure 6. Current and future LCOE for CSP (ATB)[4]

Several key conclusions can be made from these graphs that are relevant to China. First, the LCOE of a specific plant is a function of the local resource, cost of capital, O&M, fuel, and performance (e.g., capacity factor). Therefore, the resource available at a specific cost is a critical input. The resource data are a function of the geographic dispersion of the resource, so a higher level of resolution of the resource is desirable to make sure high-resource pockets are not missed. Second, the expectation is that costs will continue to decrease for all three of these key technologies in the next few decades.

The NREL Transparent Cost Database (NREL 2015c) shown in Figure 7 contains a broad spectrum of cost and performance data estimates for each technology from dozens of reports (including the ATB), which are supported by DOE and outside data sources.

[4] TES stands for thermal energy storage. This graph shows the cost trajectories for CSP plants of the same resource class, with different storage (6 hours and 12 hours) in low, medium, and high cost reduction cases.

Figure 7. The Transparent Cost Database presents hundreds of cost and performance data points in an interactive viewer and allows the user to explore each specific data point

Lessons Learned in Technical Costs and Performance Data

First, the sourcing of data is critical to achieve the outcome desired. Figure 8 shows the LCOE value comparison among different technologies within the ATB. The cost of each renewable technology is shown as a range, indicative of different resource areas across the United States; some locations have better solar or wind resources than others. Hydropower has a wide range of specific sites where it can be deployed as well. Conventional technologies, on the other hand, have very minimal variation in cost around the country, resulting in a representation by a single point for each technology. There are variations in fuel prices and installation costs around the country but those are minimal compared to the capital cost and the national average fuel price.

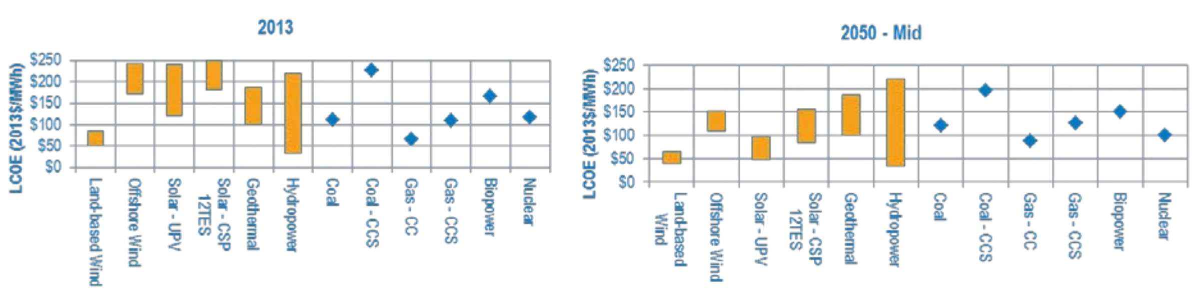


Figure 8. Comparison of LCOE projections through 2050 for the mid-line case in the NREL ATB

Second, it is not obvious which technology is least expensive in any region of the country; cost is dependent on the site and assumed pathways of technological improvement. Further, uncertainty in 2050 values or any future value has always been very high. For example, estimates of nuclear penetration in the United States from 1970s were significantly higher than actual penetrations today, and wind capacity growth has consistently been underestimated in EIA reference scenarios (Semenov et al. 1989; EIA 2005). To assess possible future configurations, it is therefore important to use a range of inputs within the complex scenario modeling tool such as ReEDS or CREAM-EDO. Understanding the methodology and assumptions behind each technology cost and performance data set combination is critical: any systematic bias for a particular technology could significantly alter the scenario results inappropriately. If, for example, the geothermal future projections were deemed to be only 30% likely to occur while the wind future projections were more than 90% likely to be achieved, those trajectories should not be treated with equal weight. Furthermore, even the definitions of terms such as "overnight capital costs" can differ (i.e., what items are included or not in the definition) between studies and the algorithms that are used to calculate the LCOE or other metrics.

Because of the differences in methodology and assumptions, certain organizations try to source all of the technology cost and performance data from the same entity so that these cost estimates use a consistent methodology. NREL had previously subcontracted to consulting firms to provide a consistent set of cost and performance data across all technologies. Some stakeholders of these major reports found these data to be valid, but not completely transparent because the firms needed to protect some of the original, confidential source data. Therefore, NREL and the DOE electric sector programs have moved towards a more technology-by-technology methodology. The ATB and other related efforts attempt to confirm that (1) the definitions of terms are specific and consistent, and (2) the calculation of metrics, such as the LCOE, is consistently applied. These efforts are supported by teams of technology experts, where the team that deeply understands wind technologies would estimate the current and future costs of wind, and separately the solar, biomass, and hydropower technology experts would conduct a similar exercise for their respective technology areas of expertise.

Issue Three: Representation of Grid Operation Physics and Rules within ReEDS

Technical Constraints in ReEDS

The ReEDS model provides a variety of constraints as the model seeks the lowest cost solution. Some of these are physical (i.e., the load constraint), some are representative of the operation of the grid today (i.e., reserve margins), and some are driven by policy (i.e., renewable portfolio standard constraints on the state level). This section lists some of the key constraints represented in the ReEDS model.

- Load Constraint: This constraint requires that generation matches load at all times. The load constraint also requires that enough electricity is being produced in each timeslice and used locally or available via transmission. In ReEDS, there are four timeslices in each of four representative days per season (e.g., winter morning) for a total of 16 timeslices, plus an additional "superpeak" timeslice.
- Reserve Margin: This constraint means that the available capacity (within a balancing area or via trade across boundaries) is able to meet the peak load with a margin of excess. In practice, legislation requires a service provider to have access to firm capacity in excess of the expected peak load by some percentage, known as the "reserve margin." In the United States, the reserve margin requirement is typically 15%.
- Operating Reserves: ReEDS requires daily operating reserve requirements to be met. The flexibility of generators and storage technologies depends on the ability of the plant to change its output and the time scales necessary to do so. Given start-up times and ramp rates, different technologies are classified to be able to offer varying amounts of spinning or quick-start reserves. Spinning reserves can be provided by generation and storage technologies operating below maximum capacity. The amount of capacity that may be counted toward the requirements depends on the amount that can be ramped up quickly. Quick-start reserves can be provided by technologies that can start generating power quickly (e.g., in less than 10 minutes) from a cold state. For example, natural gas combustion turbines can provide quick-start reserves. In addition, demand-side interruptible load can also contribute to reserve requirements. All operating reserve requirements must be satisfied in each reserve-sharing group in all timeslices. The following operating reserve requirements are considered in ReEDS:
    - Contingency reserve requirements: These requirements ensure that an unanticipated change to the operational status of generators or transmission lines due to unforeseen outages, for example, will not cause an extended disruption to electricity end users. In ReEDS, the contingency reserve requirement is set at 6% of demand in each timeslice. At least half of this requirement must be met with spinning reserves or interruptible load; the other half can be met with quick-start units.
    - Frequency regulation reserve requirements: These requirements ensure that sub-minute deviations between demand and generation can be minimized. Due to the short time scales involved, only spinning reserves can satisfy the frequency

regulation requirements. In ReEDS, this requirement is set at 1.5% of average demand in each timeslice.

- Variable RE forecast error reserve requirements: These requirements ensure stability of the system despite uncertainties in forecasting for wind and solar PV. Generally, forecast error reserve requirements increase as wind and PV penetration grows.

While each of these constraints is based on the physical need to provide reliability, the actual level at which they are set is decided based on reliability versus cost. To date in the United States, costs have been absorbed to maintain a very high level of reliability. While ReEDS has a limited approach to dispatch based on 17 timeslices for the entire year (and no sub-hourly assessment of detailed ramp rate interactions, etc.), the REF study ran the same situation in GridView to validate that the ReEDS generation mix with 80% renewable power can meet requirements at an hourly level, and work is ongoing with another production cost model, PLEXOS, to examine the operational impacts of high levels of renewables. To date, in REF reports, the presence of significant renewable generation typically requires more transmission, larger control areas for electricity operations, and potentially some curtailment of renewables in low demand times with high renewable resource. For example, sunny spring days that are not very warm (low cooling load requirements) and are also windy would typically lead to excess solar and wind generation. Combined with minimum ramping levels and operating hours of conventional plants, this could lead to curtailing the renewable generation.

To provide additional examples of these reserves as requested by CNREC, Appendix B presents three sets of values from the central scenario of the recent Standard Scenarios study. This scenario reaches roughly 45% renewable electricity generation (including hydropower) in the U.S. power sector by 2050. The three data sets are the reserve margin data (Table B-1), the quick-start and spinning reserves by technology (Table B-2), and the forecast error for wind and solar (for the 2015 Central Standard Scenario) (Figure B-1).

Regionality

The regionality of a capacity expansion model typically indicates one of several spatial levels of disaggregation. Ideally, the most accurate answer is derived from modeling at the smallest possible geographic scale, combined with the appropriate scale for policy and regulatory decisions. This gives the best representation of the RE resource, the policymaking decisions, and the cost decisions, as well as various other factors including demographics. However, the potentially enormous amount of data associated with fine spatial resolution would require (1) significant computing resources to manage the data and solve the model, and (2) considerable effort to analyze the outputs, maintain the model, check for errors, and gather and maintain the data. This tension requires that the modeler be mindful of the necessary level of spatial resolution needed to answer the set of questions being asked. In 2007, NREL wrote a report on spatial resolution, comparing several models and discussing thoroughly the issues related to spatial resolution. Some of the concepts discussed below are abstracted from that report (Short 2007).

The necessity for a particular level of spatial resolution in a model (or a particular analysis with a general model) is driven by a variety of factors. The primary factor is the research question to be answered by the modeling effort. Deciding if the questions are national in nature or regionally specific will typically drive the geographic level at which the modeling should be performed.

Several other key factors include regional market differences, interregional energy transport and trade, and appropriate representation of the renewable resource. For example, global models are often limited by their averaging of wind and solar resource data: especially attractive locations may be obscured when their data are averaged out.

An advantage of having a large number of regions in a linear optimization model is to allow for a more natural market response rather than a "knife-edge" type of reaction. With a single national region for example, once a technology (e.g., land-based wind) becomes cost-effective, it is built in large amounts throughout the country. However, in reality, the technology would become cost-effective sooner in certain regions and later in others, resulting in some early adoption before the technology becomes more widely cost-effective.

China has several geographic characteristics similar to those in the United States. At a high level, the best wind and solar resources are geographically separated from the highest concentration of population in the coastal areas of the countries. Therefore, as China and the United States work to understand the best strategies to reach a high level of renewable penetration, tradeoffs between better resource, more transmission, and dispersion of the variable generation capacity to reduce transmission needs are key areas of interest. These analysis questions call for an in-depth review of the regionality in any capacity expansion model and recognition that the model must properly represent the issues of transmission and deployment capacity from west to east. In the ReEDS model, thought was given to separating the load pockets from the areas with the best wind and solar resource so that the model could be used to determine where the capacity will be built separately from where it is shipped to be used.

Issue Four: Effective Visualization of the Model Results

Visualization from NREL Studies

Detailed power system analysis as described in this report is of considerable interest to a broad array of stakeholders, many of whom are not power engineers, economists, or analysts. The question arises: How does one effectively communicate the results of detailed simulations to non-modelers in an intelligible way that doesn't involve excessive "false precision?" The user would ideally understand the key results and be able to examine some of the most significant additional data presented, but also not draw his or her own conclusions that the model's uncertainty would not support. For example, the visualization of the state-level results for the recent 2015 *Wind Vision Report* (screenshot shown in Figure 9) can be browsed by time period (DOE 2015b). However, the user shouldn't then assume that precisely 2.19 GW of wind will be built in Arizona by 2050, but rather that the study indicates that significant wind will be deployed in Texas and several Midwestern states. Note that this is a post-processing visualization.

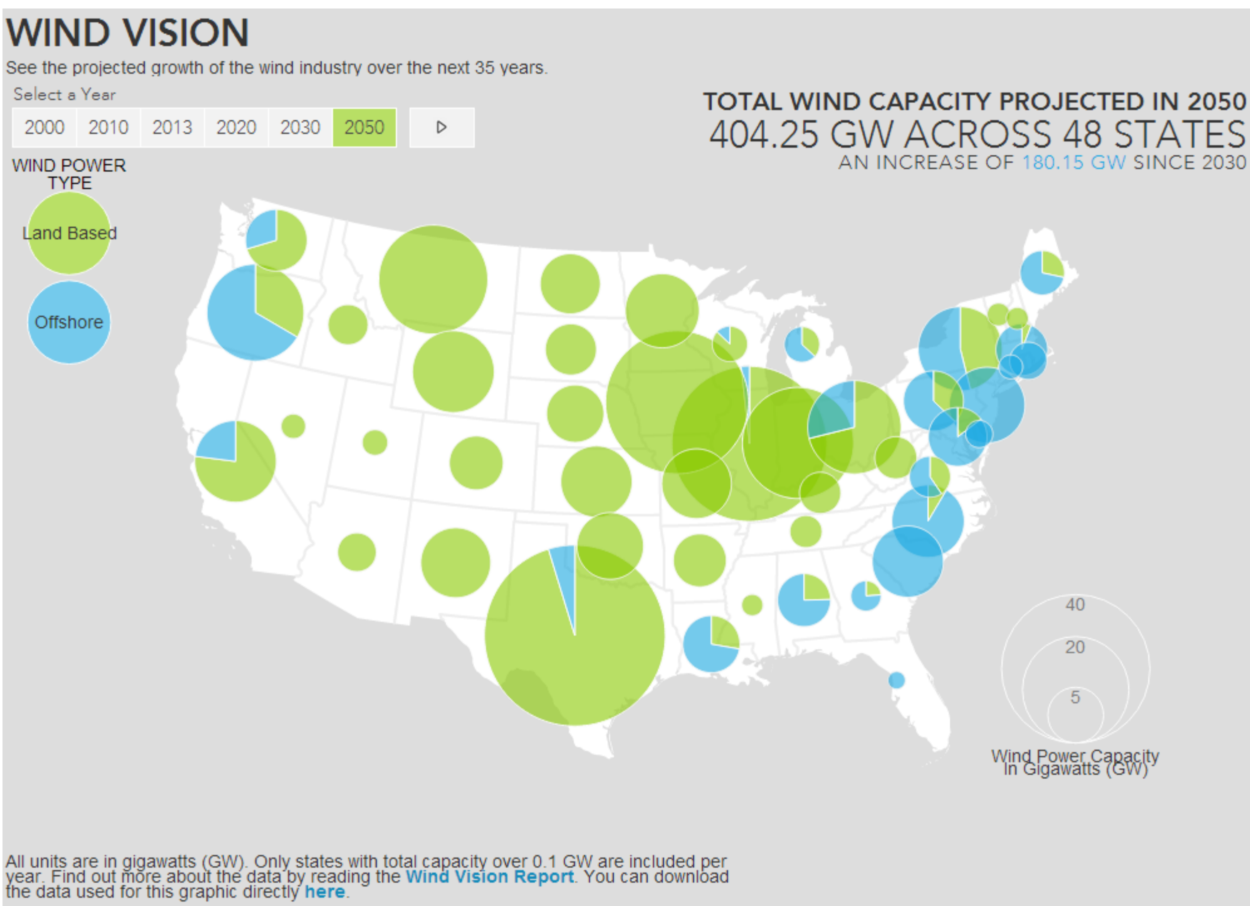


Figure 9. Projected growth of the wind industry for 2050 from the *Wind Vision Report*, 2015

There are a few other instructive examples of dynamic visualizations that have proven to be effective communication tools and allow for user exploration to answer individual lines of inquiry. With the REF study, several groundbreaking visualization techniques were employed.[5] The key visualization for capacity expansion purposes (screenshot shown in Figure 10) displays overall national capacity growth in a graph (at the bottom right corner) as well as the mapped locations of capacity growths around the country over time. The original interactive visualization allowed the users to select technologies of interest to them. We have found that stakeholders are often only focused on one particular technology (wind, solar, etc.).

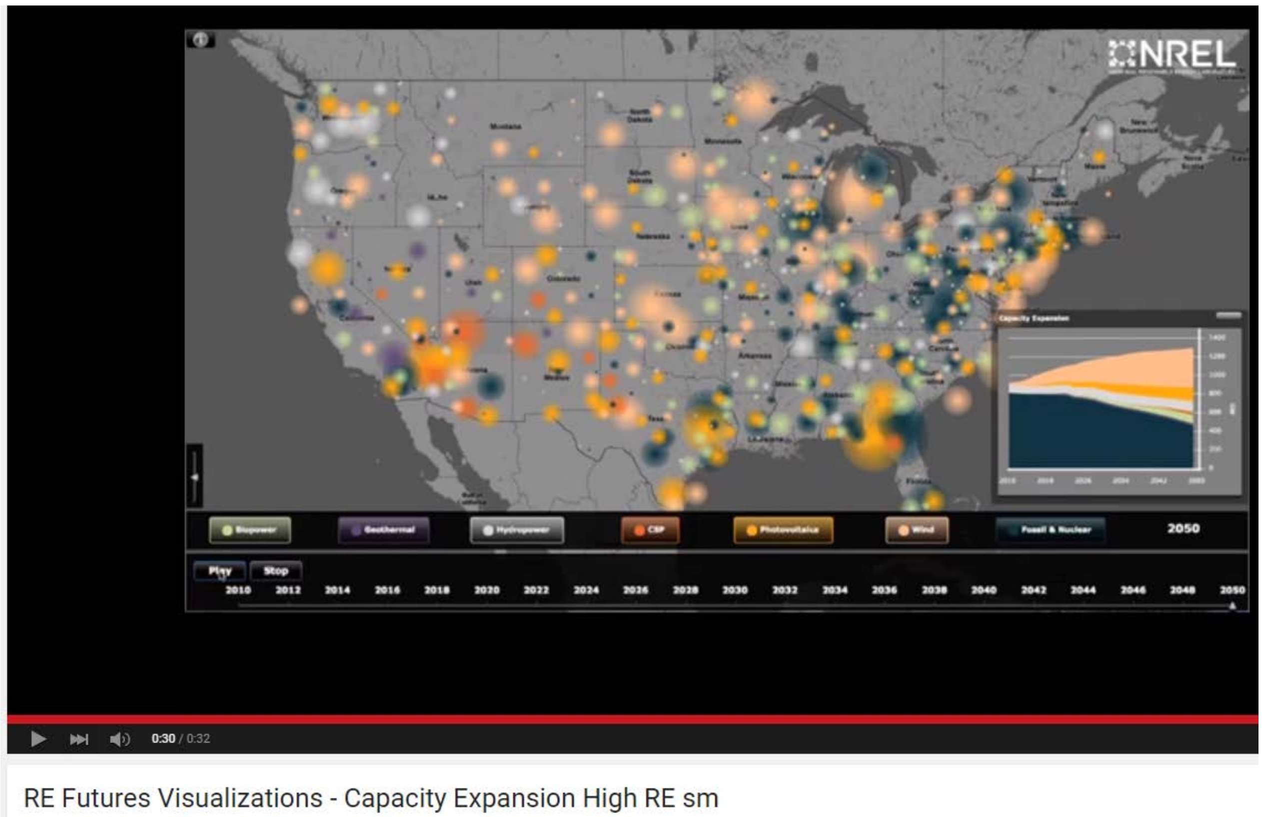


Figure 10. Screenshot of REF visualization video

There is a new set of visualization capabilities in this same vein for the REF study, but it allows for even more interaction with the user. It is the REF Scenario Viewer, hosted on the NREL website (www.nrel.gov), the initial page of which is shown in Figure 11 (NREL 2015d). This visualization technology can be easily adapted to any future scenario results for the United States. Results can be easily added to the suite of scenarios currently represented in the Viewer. (The making of the REF Scenario Viewer is described in Appendix C.) As shown in Figure 11, state-by-state data are shown on the map, and results by technology through time are shown to the right. The price and emissions data are independent of the technology chosen, shown at the bottom. The user can select a scenario at the top, mouse over the individual states to get specific

[5] See YouTube. "RE Futures Visualizations - Capacity Expansion High RE sm." https://www.youtube.com/watch?v=j2oDtcSkV38; "RE Futures Visualizations - Dispatch Aug sm2." https://www.youtube.com/watch?v=fQl7PS243Dg; "RE Futures Visualizations - Transmission Flow Aug sm." https://www.youtube.com/watch?v=79JAg3lbBeQ. Accessed July 16, 2015.

values for these states, and slide the year control back and forth to look at various points in the future.

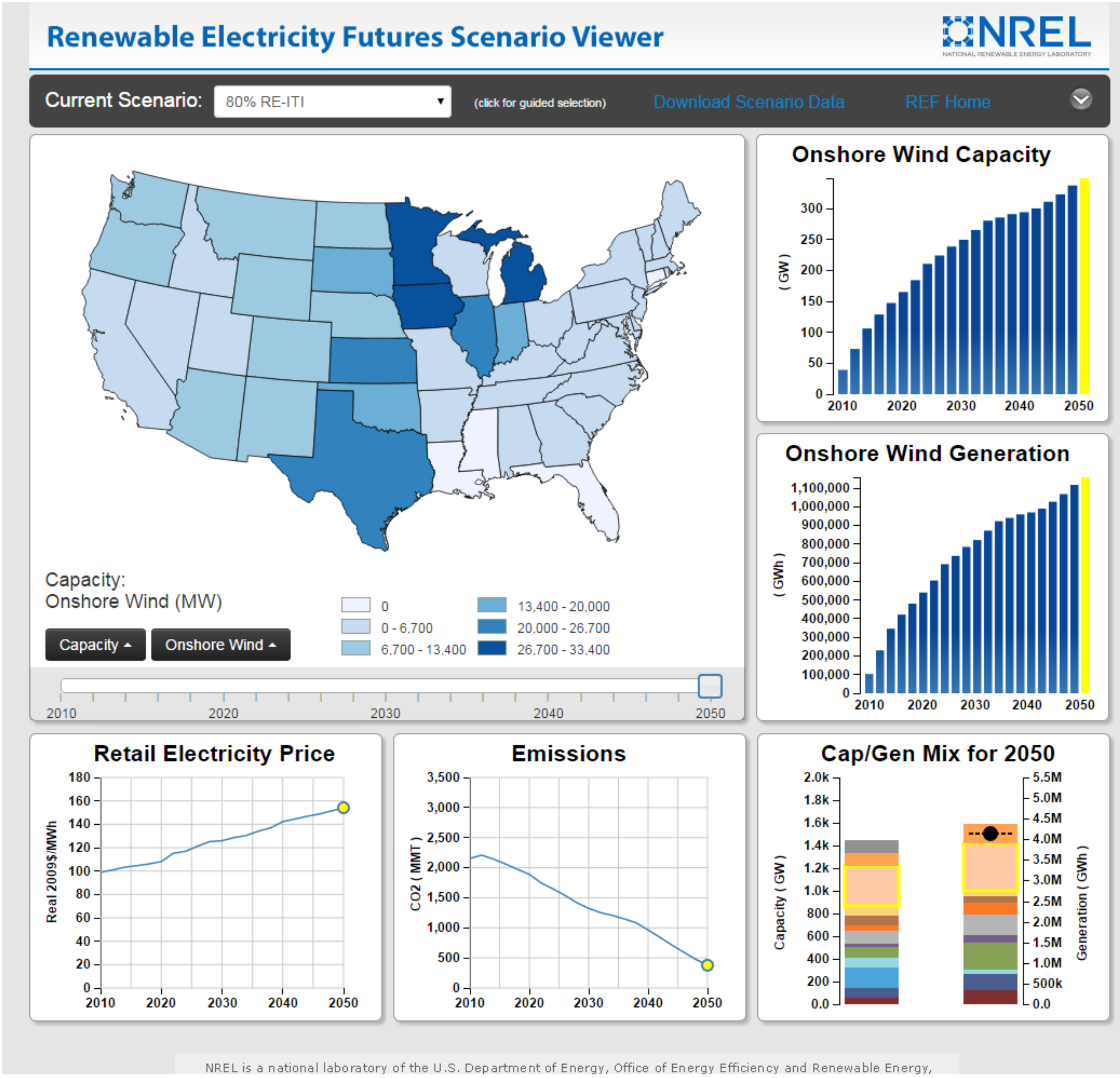


Figure 11. Screenshot of REF Scenario Viewer, initial page

Figure 12 shows a different view of the REF Scenario Viewer. This time, utility PV has been selected as well as a different scenario. The state-by-state data are different and imply that a great deal of utility-scale PV will be built in the southern and eastern United States for this scenario. The mouse is hovering over Colorado specifically to display that information. The scenario uses advanced technology improvements, and utility-scale PV reaches over 400 GW across the entire country.

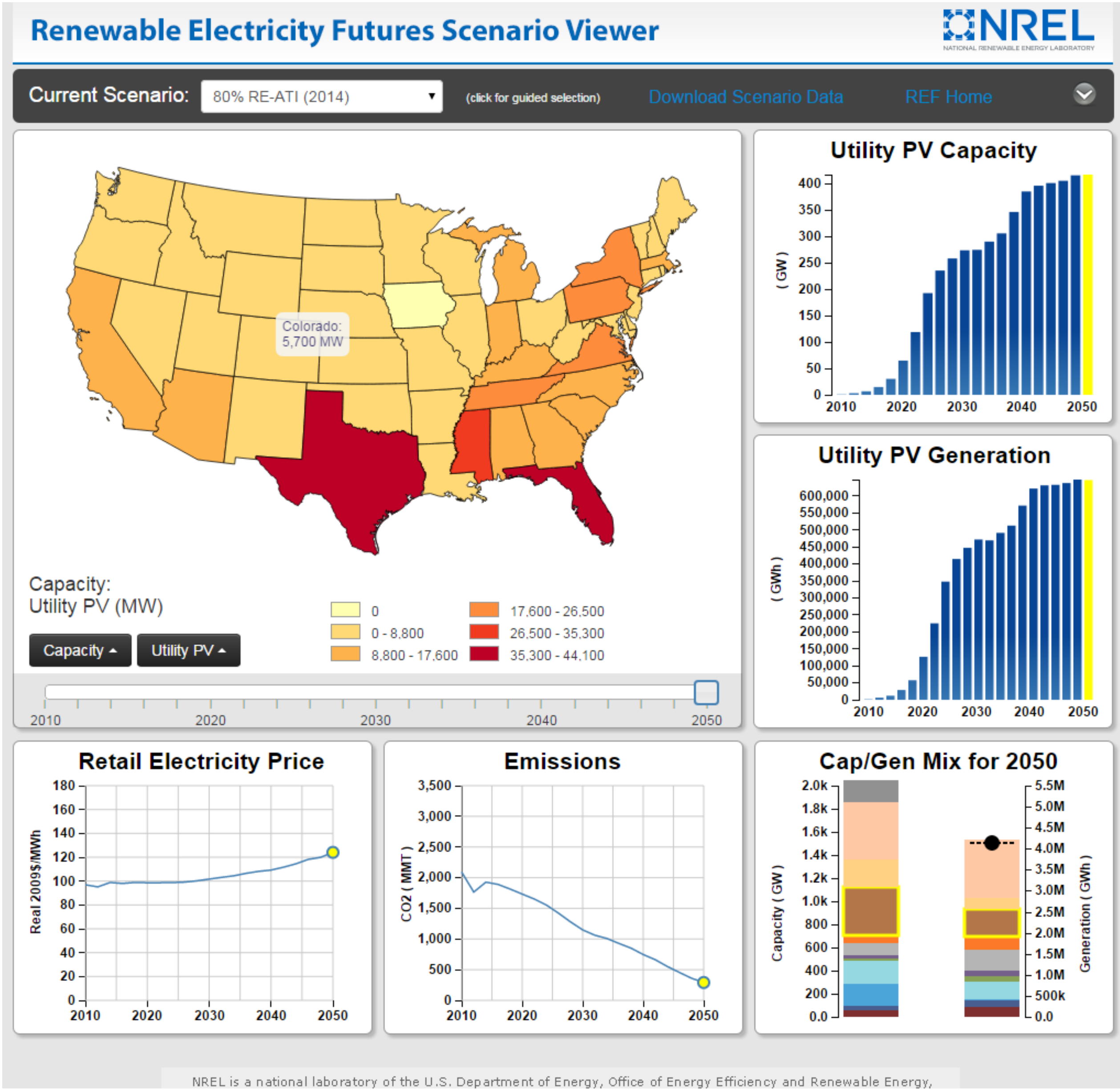


Figure 12. Screenshot of REF Scenario Viewer, 80% renewables with advanced technical improvements scenario

For internal review and validation, the ReEDS team uses a set of R scripts that automatically generate graphs and tables that can be reviewed for all simulations.[6] In fact, the team works to ensure that a broad set of results is reviewed instead of just perhaps the small data point of interest (emissions, for example) to make sure that the bulk of scenario results are appropriate for the assumptions and that the model has not resulted in erroneous outputs somewhere else (no renewable generation being built, for example). This is standard quality assurance practice for modeling.

[6] R is a language and environment for statistical analysis. Read more at https://www.r-project.org/.

Conclusions

Developing and improving an electric grid techno-economic model is a long-term, continuous process. Power system modeling has proven to be useful in informing crucial decisions on policy, investment, and planning, as evidenced by several of NREL's major U.S. electric grid modeling projects that illustrate the type of questions that can be answered through electricity capacity expansion modeling. Technology costs and performance data used by NREL were analyzed and compared with those used by CNREC in CREAM-EDO. More importantly, the key lessons in data sourcing and dealing with uncertainties in future costs were also discussed. On scenario modeling, inclusion of key technical constraints and appropriate geospatial and temporal resolution has proven valuable to enhance the fidelity of the analysis and provide evidence of robustness of the modeling. The advantages and disadvantages of implementing higher spatial resolution in a capacity expansion model are factors to be considered in relation to available data, model processing, robustness of the results, and stakeholder interests. Several examples of results visualization were described, in which user interests can be met through compelling, interactive, and informative web-based interfaces.

Through NREL's experience in electricity capacity expansion modeling, several key attributes of an effective modeling effort include:

1. Start the modeling process with a specific question. Based on the question, the appropriate model, the appropriate spatial and time resolution, and the suitable constraints can be determined. Lacking a clear question, countless scenarios can be constructed without resulting in robust conclusions.
2. The only certainty is uncertainty. For example, many unexpected transitions in the energy sector and power system (e.g., the rapid expansion of U.S. shale gas production and low natural gas prices) are very difficult to foresee or model. Yet, through comparing scenarios and sensitivity analysis, models can provide valuable insights on many questions in the electric power sector.
3. The input data are critical to the outcome. The data need to be consistently sourced, with attention paid to consistent classification of technologies and consistent calculation of metrics such as the capital cost and performance data. In the China context, specific attention should be given to data representing the reduction of technology cost due to economies of scale.
4. Regionality issues should be closely reviewed in a capacity expansion model. For example, in countries where the RE resource area is far away from load centers, it is worth considering separating the high-resource pockets from the load.
5. The presentation of the results needs to consider the audience, finding a balance between communicating nuanced information and uncertainties, and making conclusions easily accessible to a non-technical audience.

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Appendix A. Top Ten Lessons on Scenarios and Modeling for Policymakers

NREL produced a report for the International Energy Agency Renewable Energy Technology Deployment in 2013 to summarize guidance on how to conduct and interpret scenario modeling (Mai et al. 2013). The top ten key conclusions are:

1. Do not expect a model or energy scenario to predict the future. The further an energy scenario looks into the future, the more uncertainty is introduced. Single scenarios are rarely helpful, but must be combined with, and compared against, diverse alternatives as part of a larger strategic exercise.
2. Match the model to the problem. There are almost as many types of energy models as there are questions about our energy future. Make sure the question you want to answer is well-formed, and then pick the right type of model to best address it.
3. Make assumptions and accounting frameworks transparent. Models require thousands, and often millions, of pieces of input data. The meaning of these data needs to be clearly understood by all.
4. Understand the limitations of how human behavior is represented. A typical energy model finds a solution based on the overall system's equilibrium (matching of supply and demand) or least-cost point. However, real-world producers and consumers often find themselves out of equilibrium, and agreement on a system-wide optimal point is rare.
5. Use diverse tools and approaches to address uncertainty. Uncertainty about the future comes in different forms. Some is “characterizable” while others are not (known unknowns and unknown unknowns).
6. Consider how unique traits of RE are modeled. Higher resolution is required to model the site-specificity, variable, and uncertain nature of many renewables. Constrained by computational limits, modelers are forced into trade-offs between decreasing their geographic and time resolution, or simplifying other aspects of the energy economy.
7. Communicate effectively and appropriately. Energy modeling is a highly specialized endeavor. What modelers consider “results” and what decision makers deem useful information may not overlap.
8. Expect bias and learn to identify its traits. All modeling approaches incorporate bias, either accidentally or purposefully. Consumers of energy scenarios can learn to identify scenario, data, and model subjectivity, and take steps to ensure appropriate interpretation.
9. Consider energy scenarios with limited or no modeling. Commissioners of energy scenarios should consider broad stakeholder engagements that focus on “upstream” discussion of assumptions and desired outcomes as a first step before modeling.
10. Conduct retrospective analysis to better understand energy scenario misses and hits. Too often, energy stakeholders do not go back to revisit why certain energy scenarios were so far off the mark or why they provided unexpectedly valuable information.

Appendix B. Reserves in Standard Scenarios

To provide additional examples of these reserves as requested by CNREC, this Appendix includes three sets of values from the recent Standard Scenarios central scenario. This scenario reaches roughly 45% renewable electricity generation (including hydropower) penetration in the U.S. power sector by 2050. The three data sets are the reserve margin data (Table B-1), the quick start and spinning reserves by technology (Table B-2) and the necessary forecast error for wind and solar (for the 2015 Central Standard Scenario) (Figure B-1). The forecast error reserve requirements ensure stability of the system despite uncertainties in forecasting for wind and PV. Generally, forecast error reserve requirements increase as wind and PV penetration grows. The forecast error reserve requirements for wind and PV in ReEDS are assumed to be two standard deviations (Zavadil et al. 2004) of their respective aggregate forecast errors in each reserve-sharing group. The reserve requirements are held constant throughout the year.

Table B-1. Reserve Margin Requirements that are Imposed on ReEDS Throughout a Scenario Timeframe

NERC Reliability Region	Reserve Margin
NORW	17.2%
BASN	12.6%
ROCK	12.5%
CALN	14.2%
CALS	14.9%
MEXW	11.9%
DSW	13.5%
ERCOT	13.8%
MAPP	15.0%
SPP	13.6%
MISO-US	15.0%
SERC-W	15.0%
SERC-SE	15.0%
FRCC	15.0%
SERC-E	15.0%
SERC-N	15.0%
PJM	15.0%
NYISO	15.5%
ISO-NE	15.0%
BC	12.3%
AESO	12.3%
SaskPower	13.0%
Manitoba Hydro	12.0%
IESO	21.3%
Quebec	9.7%
Maritimes	20.0%

Source: NERC 2011

Table B-2. Spinning Reserve and Quick Start Fractions by Technology - a ReEDS Input

Technology	Spinning Reserve Fraction	Quick Start Fraction
Hydropower	0.5	0.50
Gas-Combustion Turbines	0.833	1.00
Gas-Combined Cycle	0.5	0.35
Gas-Combined Cycle with Carbon Capture and Sequestration	0.5	0.35
Old Coal Plants (some with biomass co-fire)	0.2	0.00
New Coal Plants	0.2	0.00
Coal-Integrated Gasified Combined Cycle	0.5	0.00
New Coal with Carbon Capture and Sequestration	0.5	0.00
Oil-Gas-Steam	0.15	0.00
Nuclear	0.1	0.00
Geothermal	0.15	0.00
Biopower	0.063	0.00

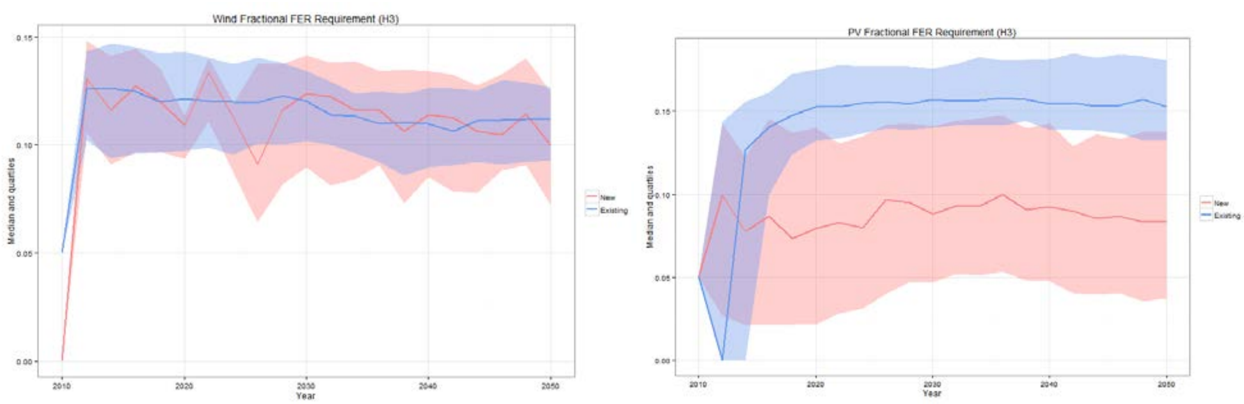

Figure B-1. Mean and quintile graphical representation of regional Wind and PV fractional forecast error requirement

Note that wind is typically between 0.10 and 0.15 for both new and existing wind capacity while PV is typically less than 0.10 for new capacity and over 0.15 for existing capacity.

Appendix C. The Making of the REF Viewer

The visualization or presentation of geospatial data on the web is quite common. There are numerous examples of applications that allow users to explore spatial data sets, query the data, and download data sets from the web. Such tools are commonly used at NREL (and elsewhere) for these purposes. Providing access to data becomes a bit more complicated, and the existing tools begin to be less useful, when the datasets are exceptionally large or complex.

The proliferation of technologies to support data visualization on the web has made development of tools as described above possible; however, the complexity of the data that resulted from this study precluded the use of a preexisting tool. The REF study results include 33 scenarios representing capacity and generation for 14 technologies over 40 years for 48 states. These data could be used to generate over 36,000 individual maps, not to mention associated charts and other visualizations. As this required the development of a specialized application, and other studies produced data similar in format, the REF Viewer was built as a starting point for developing a framework to support spatial-temporal data visualization.

The technology used in creating this visualization is intentionally straightforward and the application itself is designed to be customized for other uses/datasets. The application is completely client-controlled; there are no web services or server-side code, and it was designed with commonly available, open source JavaScript libraries. The libraries include D3 (used for the map and the charts), Backbone (used for data management in the application), and jQuery (used to support the interactive nature of the interface). By employing commonly available libraries, we reduce the need for highly specialized developers to support the framework.

The code behind the REF Viewer is currently being enhanced to reach the goal of a framework that can support other datasets similar in structure to the results of the REF study. This framework is currently being employed to support the Wind Vision study, for which a preliminary viewer is already available at http://en.openei.org/apps/wv_viewer/. This visualization will be enhanced in the coming months to support comparison of scenarios.

In developing this capability, it is clear that there is a balance between providing a lot of tools for manipulating the interface and supporting a variety of users who might access the tool. If the interface is too complex, it alienates users without significant domain experience. If the tool is too simple, experienced analysts will have no use for it. In the end, the REF Viewer attempts to find a middle ground where experienced analysts can use it to generate views of the data they want to use in communicating about the study and less experienced users can still explore the data to better understand the results of the study.