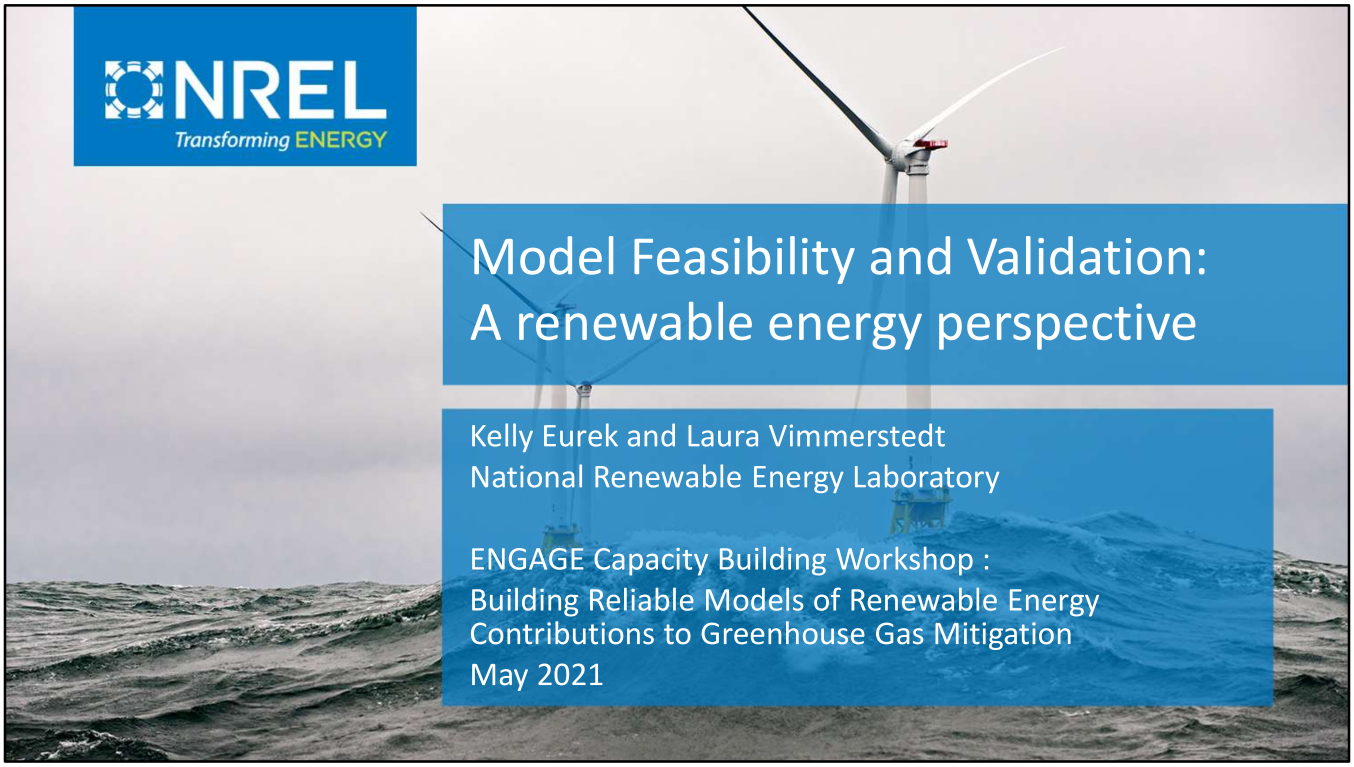

Model Feasibility and Validation: A renewable energy perspective

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ENGAGE Capacity Building Workshop :
Building Reliable Models of Renewable Energy Contributions to Greenhouse Gas Mitigation
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Overview

- The following slides are designed to inspire energy system modelers in thinking about model feasibility and validation.
  - **Feasibility**: is a model outcome achievable in reality?
  - **Validation**: is a model working correctly?

- We showcase examples of how researchers at the National Renewable Energy Laboratory (NREL) approach model feasibility and validation from the perspective of renewable energy in the United States.

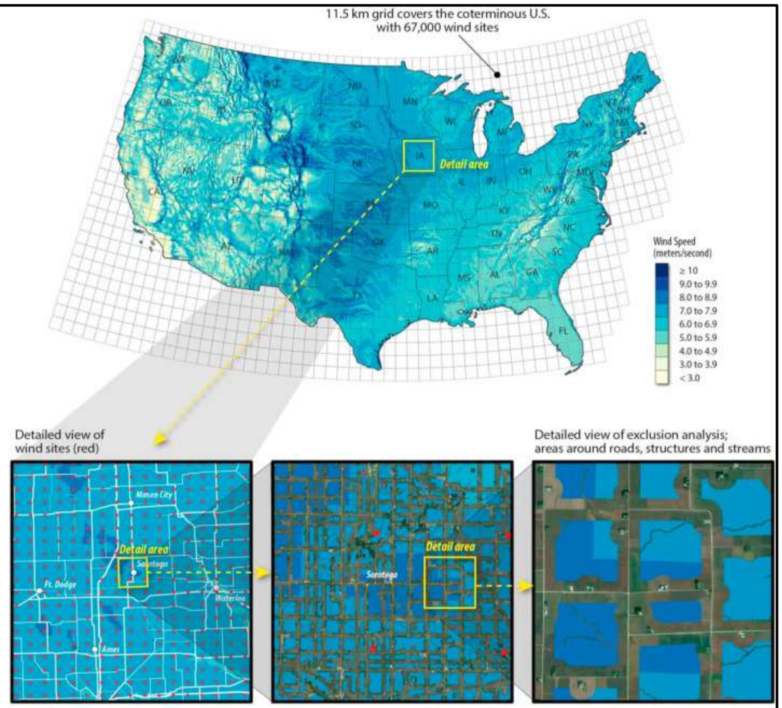
- Although these examples are neither comprehensive nor applicable for every modeling analysis, they can help researchers think about best practices.

Feasibility of Renewable Energy Technology Deployment in Models: Three Examples

1. Site availability: challenges of siting wind in a low-carbon future
2. Interdependence of technology adoption and supporting infrastructure
3. Renewable energy manufacturing capacity

Site Availability:
What are the challenges of siting wind farms in a low-carbon future?

Detailed geospatial analysis determines if availability of land for wind development might affect deployment of wind turbine.



https://www.nrel.gov/news/program/2021/beyond-technical-potential-nrel-explores-the-challenges-of-siting-wind-in-a-low-carbon-future.html NREL | 4

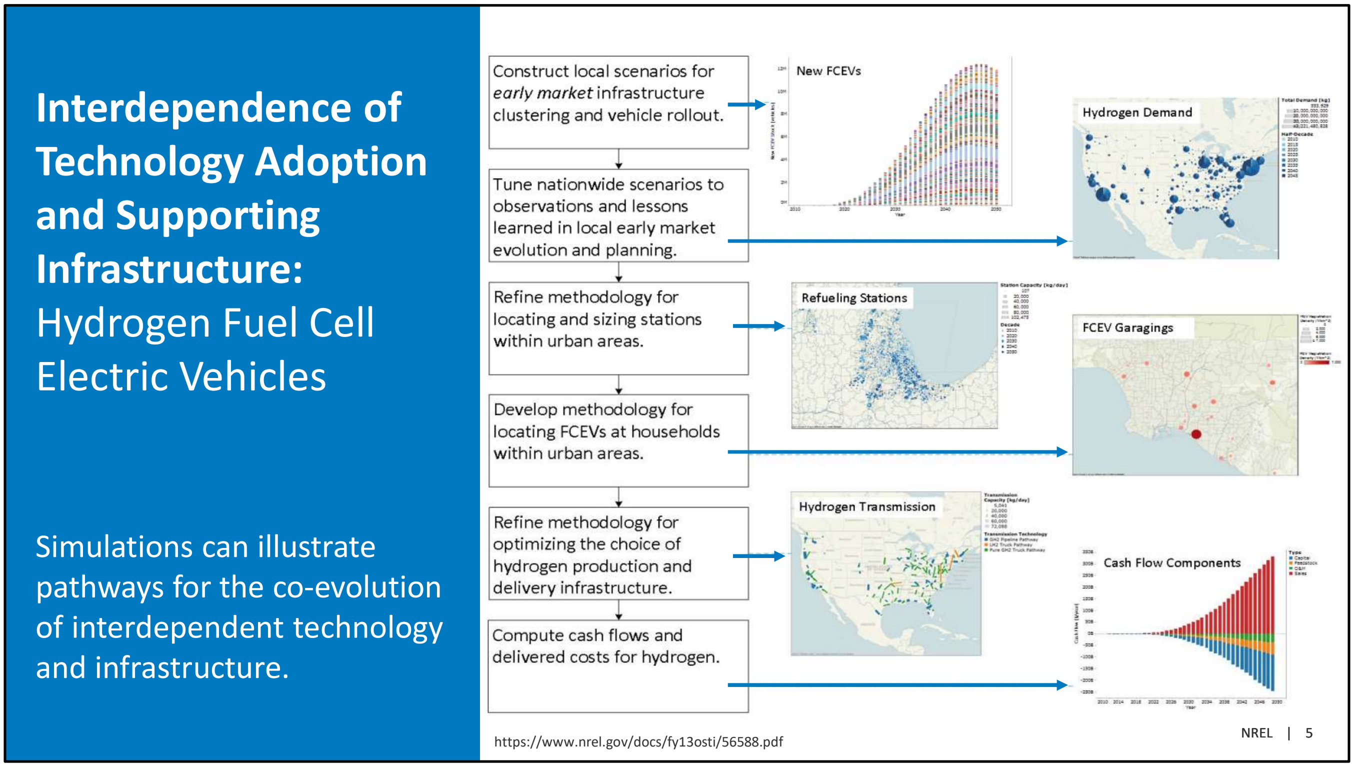
Feasibility Example #1: Demand for wind energy in the power sector under a a low-carbon future may create challenges of siting wind farms.

- What are the regional siting constraints for wind turbines?
- Technology advancements may require larger setbacks from buildings and infrastructure.

Report: *Land use and turbine technology influences on wind potential in the United States*
https://www.nrel.gov/news/program/2021/beyond-technical-potential-nrel-explores-the-challenges-of-siting-wind-in-a-low-carbon-future.html

Summary: "*As clean energy ambitions have expanded, critically evaluating renewable energy supply has become increasingly important to the energy research community and stakeholders. This study examines the onshore wind resource potential for the conterminous United States and its sensitivity to siting constraints and turbine technology innovation. We compile localized regulatory information and use high-resolution data to present multiple siting regimes covering relatively constrained to unconstrained potentials. Our efforts reveal high sensitivity to these variables and sizable uncertainty in the overall wind energy resource potential. Specifically, we find that siting constraints may shift the total capacity available to commercial wind energy by 2.3–15.1 TW. Furthermore, our results illustrate that technology advancement could require larger setbacks from buildings and infrastructure, reducing the total available capacity potential by 20% relative to estimates using current technology, but that this reduction is largely offset by increased generation such that the net effect on generation is 1%. The observed sensitivity to and uncertainty resulting from the variables we analyze suggest there is value in continued study and development of increasingly sophisticated approaches to characterizing wind resource potential.*"

Reference: Lopez, Anthony, Trieu Mai, Eric Lantz, Dylan Harrison-Atlas, Travis Williams, and Galen Maclaurin. "Land use and turbine technology influences on wind potential in the United States." *Energy* 223 (2021): 120044.



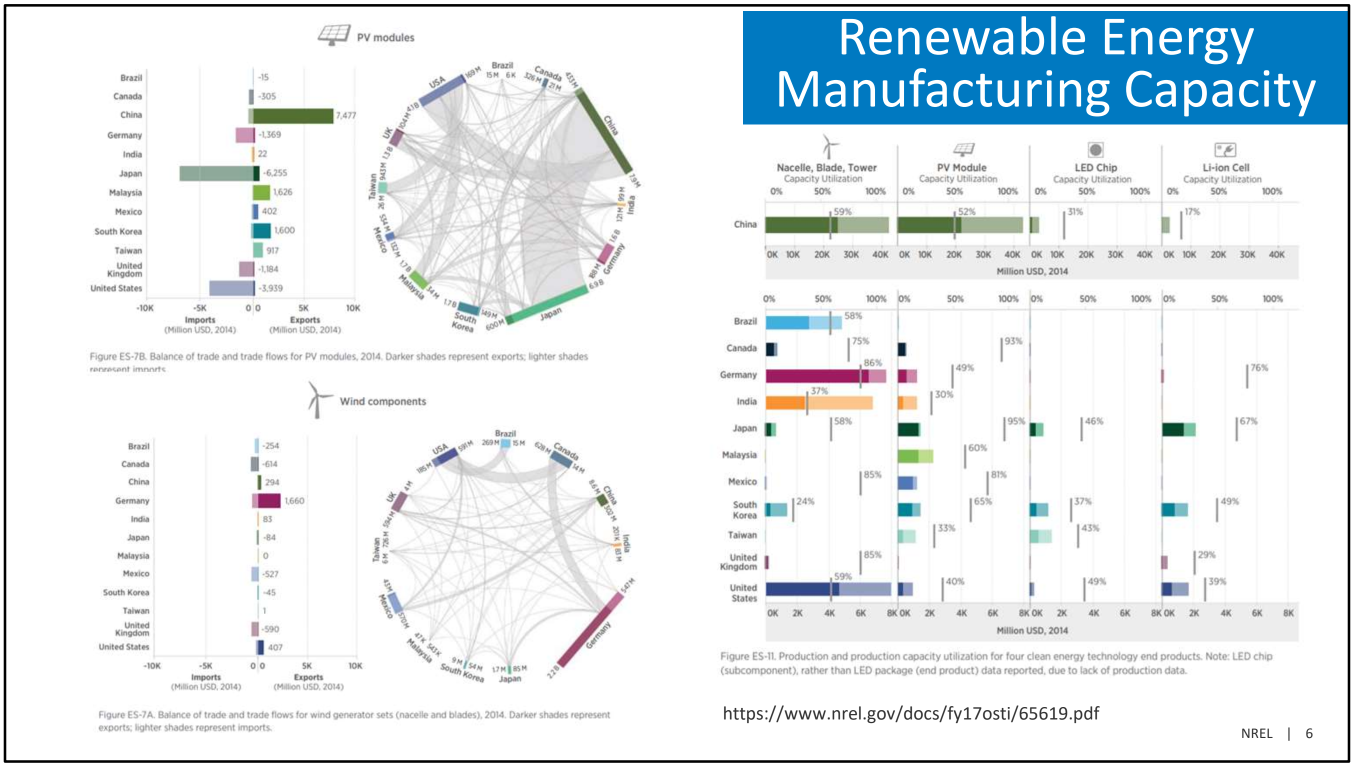
Feasibility Example #2: If hydrogen fuel cell electric vehicle adoption increases, fueling infrastructure must also be expanded.

- There must be fuel infrastructure to incentivize consumer adoption of vehicles.
- There must be demand for hydrogen to incentivize the construction of fueling infrastructure.

Report: *SERA scenarios of early market fuel cell electric vehicle introductions: modeling framework, regional markets, and station clustering*
https://www.nrel.gov/docs/fy13osti/56588.pdf

Summary: "*The availability of fueling infrastructure has become a major barrier to the early market success of hydrogen fuel cell electric vehicles (FCEVs). Various models have addressed infrastructure development during the early transition phase, but few long-term models have captured development dynamics in a manner that is consistent with real-world planning activities. This report describes the development and analysis of detailed temporal and spatial scenarios for early market infrastructure clustering and vehicle rollout using the Scenario Evaluation, Regionalization and Analysis (SERA) model. The capability to focus on dynamics within particular regions and to articulate detailed station placement strategies within urban areas adds realism and a planning perspective to these national scenario results.*"

Reference: Bush, Brian, Marc Melaina, M. Penev, and W. Daniel. *SERA scenarios of early market fuel cell electric vehicle introductions: modeling framework, regional markets, and station clustering*. No. NREL/TP-5400-56588. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.



Feasibility Example #3: The rapid and sustained deployment of renewable energy may require expansion of the renewable energy manufacturing sector.

- How might existing manufacturing capacities limit near-term deployment of renewable energy technologies into the power grid?
- How will manufacturing evolve under a high renewable energy future?
- Can multiple countries deploy large amounts of renewable energy at the same time?

Report*: Benchmarks of Global Clean Energy Manufacturing*
https://www.nrel.gov/news/program/2021/cemac-releases-global-clean-energy-manufacturing-data-and-insights.html

Summary: "*This report assesses technologies in terms of common points of reference, or benchmarks, including market characteristics, global trade flows, and manufacturing value added. Although many organizations have analyzed market aspects of clean energy manufacturing, trade and value added are unique to this report. These benchmarks provide insight into the shifting clean energy manufacturing landscape between 2014 and 2016 to help guide research agendas, highlight trade impacts, and identify manufacturing opportunities by location and technology.*"

References:

Sandor, Debra, Donald Chung, David Keyser, Margaret Mann, and Jill Engel-Cox. *Benchmarks of Global Clean Energy Manufacturing*. No. NREL/TP-6A50-65619. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2017. https://www.nrel.gov/docs/fy17osti/65619.pdf

Sandor, Debbie, David Keyser, Samantha Reese, Ahmad Mayyas, Ashwin Ramdas, Tian Tian, and James McCall. *Benchmarks of Global Clean Energy Manufacturing, 2014-2016.* No. NREL/TP-6A50-78037. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2021. https://www.nrel.gov/docs/fy21osti/78037.pdf

Six Strategies for Validation of Renewable Energy Models

1. Intuition
2. Higher-resolution testing
3. Expert and stakeholder review
4. Multi-model scenario comparison
5. Historical calibration
6. Advanced visualization

Key questions for model validation:

- How do we know if the models is working correctly?
- Which outputs should we inspect and how do we identify if/when there are modeling errors?
- What are some techniques we can use to validate our models?

This list of strategies is not comprehensive, but it can serve as a menu of options that can be employed by researchers.

Does the model behave intuitively?

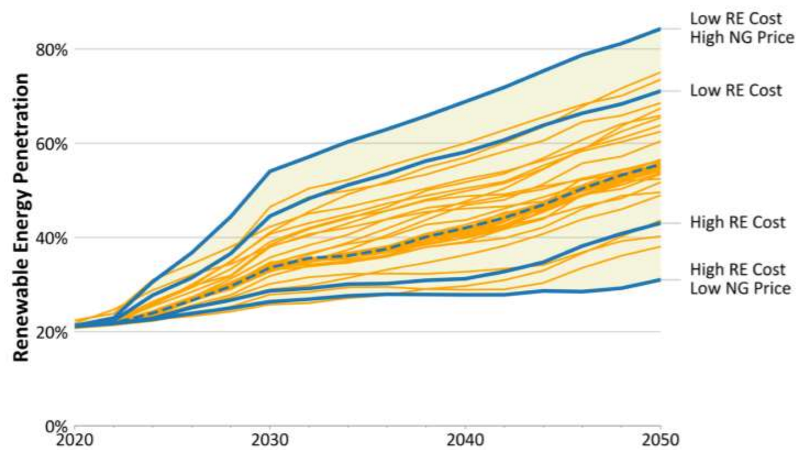


Figure 12. Renewable energy penetration over time across the Standard Scenarios. The highest and lowest renewable energy penetration scenarios in 2050 are labeled, along with the Low RE and High RE Cost scenarios. Renewable energy penetration is defined as renewable energy generation divided by total generation.

https://www.nrel.gov/analysis/standard-scenarios.html

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Validation Strategy #1: Examine the model outcomes in the context of the model inputs and the algorithms to see if the results are intuitive.

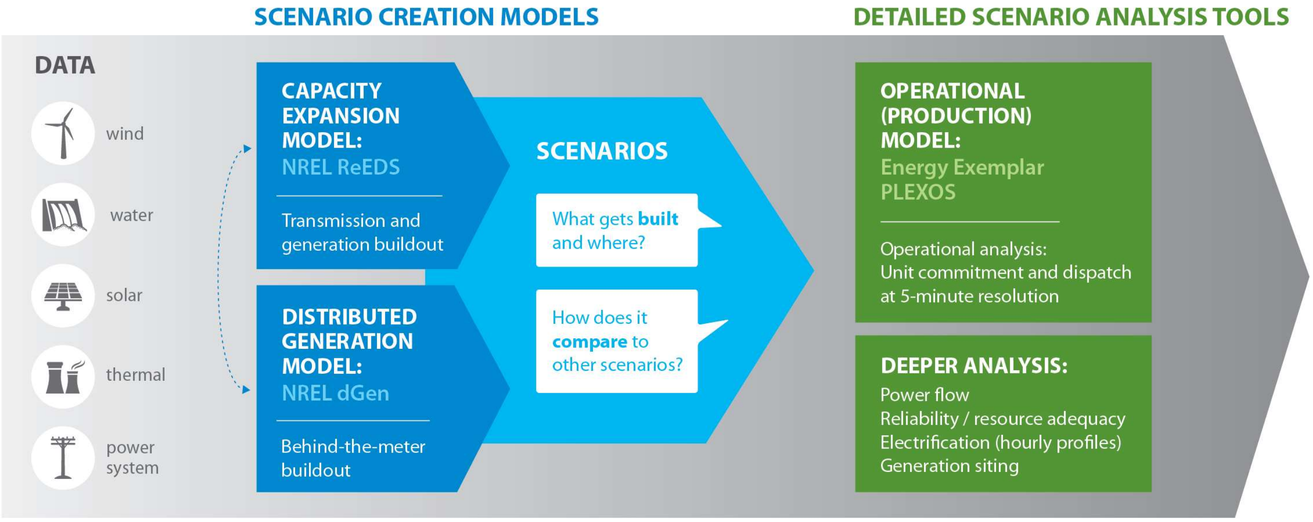
Limitations:

- Intuition may not be relevant in attempts to model novel situations.
- Intuition may be incorrect. Reliance on intuition can embed modelers' biases into models.

NREL Example: NREL Standard Scenarios https://www.nrel.gov/analysis/standard-scenarios.html
"This report summarizes the results of 45 forward-looking scenarios of the U.S. power sector…that incorporate sensitivities such as fuel prices, demand growth, retirements, technology and financing costs, and transmission and resource restrictions, resulting in a wide range of possible generation mixes."

Reference: Cole, Wesley J., Sean Corcoran, Nathaniel Gates, Trieu T. Mai, and Paritosh Das. *2020 Standard Scenarios Report: A US Electric Sector Outlook*. No. NREL/PR-6A20-77442. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

Pass model outcomes into higher-resolution models for deeper analysis



https://www.nrel.gov/analysis/naris.html

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Validation Strategy #2: Pass model outcomes to a higher resolution model.
Some examples of how this could be used, include:

- Model individual countries at higher spatial resolution
- Model hourly operations
- Model a single component of a larger system

Limitations:

- Linkages between models may not exist or may be difficult to establish

NREL Example: North American Renewable Integration Study https://www.nrel.gov/analysis/naris.html
Investment decisions from a capacity expansion model of are passed to a detailed operational model for deeper analysis.

Reference: North American Renewable Integration Study https://www.nrel.gov/analysis/naris.html

Solicit review from a group of subject matter experts and stakeholders

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Validation Strategy #3: Solicit opinions from subject matter experts and stakeholders and make appropriate revisions to the modeling.

Limitations:
- Assembling a group of experts can be expensive.
- Experts may not reach consensus or may lack knowledge of relevant considerations.
- Groups of experts may be subject to "group think," or the tendency to focus on a limited set of accepted ideas.

NREL Example: The Los Angeles 100% Renewable Energy Study.“https://maps.nrel.gov/la100/#
“The City of Los Angeles has set ambitious goals to transform its energy supply—so the Los Angeles Department of Water and Power (LADWP) partnered with the National Renewable Energy Laboratory (NREL) on the Los Angeles 100% Renewable Energy Study (LA100), a first-of-its-kind objective, highly detailed, rigorous, and science-based study to analyze potential pathways the community can take to achieve a 100% clean energy future.”

Reference:
"The Los Angeles 100% Renewable Energy Study; National Renewable Energy Laboratory: Golden, CO, USA, 2020.“https://maps.nrel.gov/la100/#

Compare and contrast outcomes of a scenario ensemble across various models

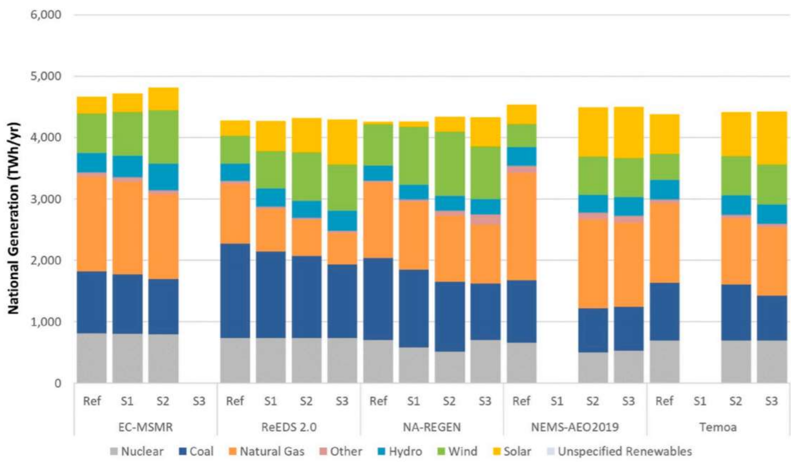

Fig. 13. 2030 generation (TWh/yr) in the U.S. by technology, model, and scenario.

Table 1
Scenario list and assumptions.

Policy Scenario	Description
Reference	The reference scenario assumes a current policies trend estimate with all on-the-books federal and state/provincial policies, including existing renewable mandates and subsidies.
Scenario 1: Full Coordination	Constrains power sector renewables share across North America to be at least 30% in 2020, 40% in 2030, 50% in 2040, and 60% in 2050. Countries and regions can exchange tradeable permits to comply with the renewable mandate.
Scenario 2: No International Coordination	Requires the same renewable targets as Scenario 1, but the requirement is applied to all countries individually without the ability to coordinate across international boundaries.
Scenario 3: No Interregional Coordination	Requires the same renewable targets applied to each model's subnational regions.

https://www.sciencedirect.com/science/article/pii/S0301421520304341

Validation Strategy #4: Execute a scenario ensemble across a suite of models and compare outcomes.

- This is a common practice for IAM studies (ADVANCE, AMPERE, CD-LINKS, ENGAGE, NAVIGATE, etc.).
- This approach encourages cross-organization knowledge exchange.

Limitations:

- Each model has strengths and weaknesses, but no model is correct.
- Researchers must understand these limitations when analyzing the behavior of one model versus another.

NREL Example: Electric sector impacts of renewable policy coordination: A multi-model study of the North American energy system
https://www.sciencedirect.com/science/article/pii/S0301421520304341
"This paper assesses the impacts of regional and international renewable policy coordination on economic, environmental, and planning outcomes in the North American power sector. Using a multi-model comparison with eight energy-economic models, the analysis demonstrates how prospective renewable mandate trade formulations impact power sector outcomes like capacity planning decisions, costs, emissions, trade, and infrastructure investments."

Reference: Bistline, John ET, Maxwell Brown, Sauleh A. Siddiqui, and Kathleen Vaillancourt. "Electric sector impacts of renewable policy coordination: A multi-model study of the North American energy system." *Energy Policy* 145 (2020): 111707.

Use the model to recreate historical decision-making

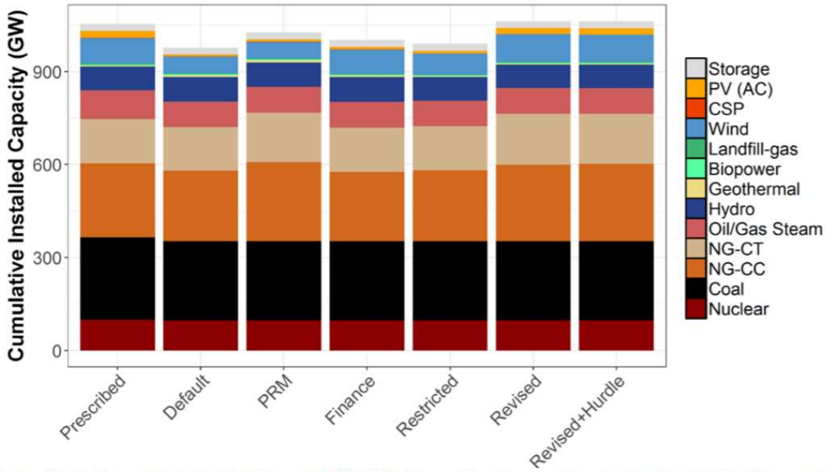

Figure ES-1. Capacity installed from 2010-2016. "Prescribed" uses historical builds, "Default" uses the ReEDS version 2017 default inputs, "PRM" adjusts the reserve margins to more closely match historical levels, "Finance" adjusts the financing inputs to better match historical levels, "Restricted" disallows new hydropower, geothermal, and compressed air energy storage, "Revised" combines the PRM, Finance, and Restricted changes, and "Revised+Hurdle" adds a hurdle rate to the Revised scenario. Additional details are in Section 3.

https://www.nrel.gov/docs/fy19osti/71916.pdf

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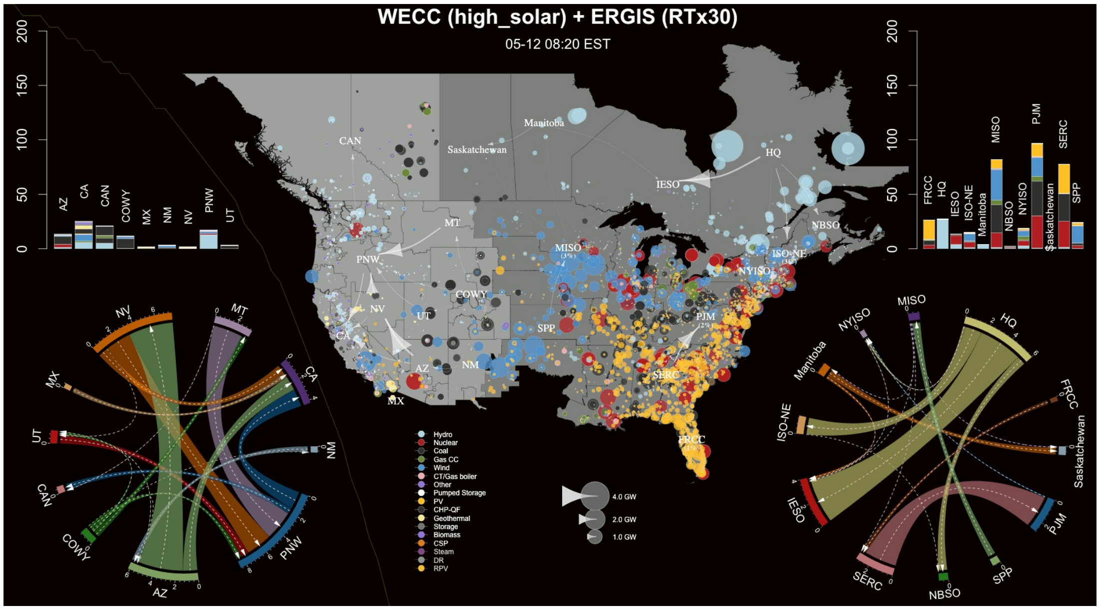
Validation Strategy #5: Use the model to recreate historical decision making.

Limitations:
- Matching historical data can be difficult due to non-economic behavior.
- Historical regimes do not necessarily reflect future decision making, and modelers should be careful not to over calibrate a model.

NREL Example: Historical Comparison of Capacity Build Decisions from the Regional Energy Deployment System (ReEDS) Model. https://www.nrel.gov/docs/fy19osti/71916.pdf
"In this work, we perform a model validation exercise, comparing capacity expansion decision from ReEDS for 2010-2016 against the actual buildout of the electricity sector. We find that with three key adjustments ReEDS is able to reproduce national-level results with reasonably high accuracy (see Figure ES-1). Those three adjustments are to use historical average planning reserve margins instead of the NERC-recommended reserve margin levels, using actual financing costs rather than long-term average financing costs, and disallowing the lowest-cost hydropower upgrades, geothermal sites, and compress-air energy storage sites. We also compare the ReEDS results at a state-level and find that state-level results can be better represented by including a hurdle rate (cost penalty) for transferring power between regions. The improved results with that hurdle rate indicate that the ReEDS transmission representation is likely not sufficiently stringent and should be improved. Overall, these results show that with the improvements described above, ReEDS can effectively reproduce historical capacity additions, which increases our confidence in using the model in making forward-looking projections."

Reference: Cole, Wesley J., and Nina M. Vincent. *Historical Comparison of Capacity Build Decisions from the Regional Energy Deployment System (ReEDS) Model*. No. NREL/TP-6A20-71916. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2019.

Use advanced, multidimensional visualizations to review model outcomes



https://www.nrel.gov/grid/ergis.html

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Validation Strategy #6: Models are multi-dimensional (space, time, technology, sectors, etc). Therefore, we should examine model outcomes using multidimensional visualization tools.

Limitations:

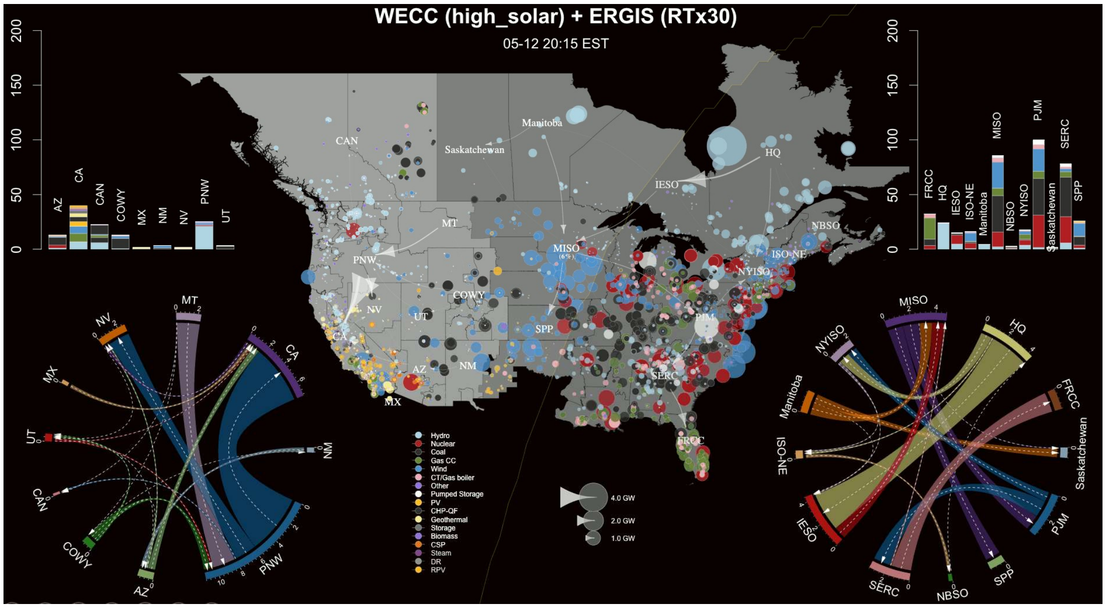
- Developing advanced visualizations can be expensive and time consuming to develop
- Advanced visualizations can

NREL Example: Eastern Renewable Generation Integration Study https://www.nrel.gov/grid/ergis.html
"Using high-performance computing capabilities and innovative visualization tools, NREL shows the power grid of the Eastern United States—one of the largest power systems in the world—can accommodate upwards of 30% wind and solar/photovoltaic (PV) power."

The visualization on this slide demonstrates a snapshot of modeled generator output, transmission flows, and solar resource across the Western and Eastern United States and Canada.

Reference:
Eastern Renewable Generation Integration Study https://www.nrel.gov/grid/ergis.html

Use advanced, multidimensional visualizations to review model outcomes



https://www.nrel.gov/grid/ergis.html

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See previous slide.

Thank You

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