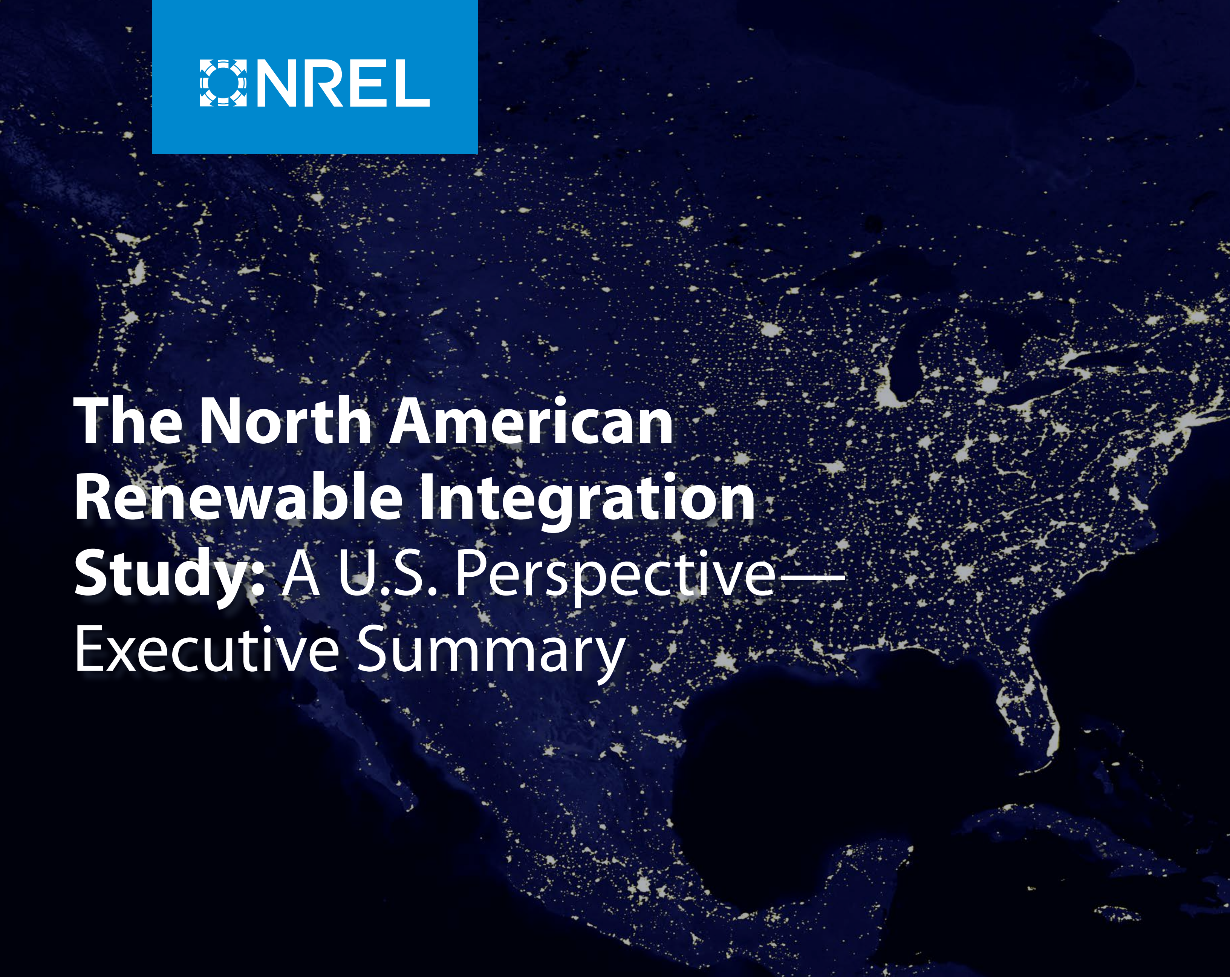

The North American Renewable Integration Study: A U.S. Perspective—Executive Summary

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Authors

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The North American electric power system is undergoing significant change, with renewable resources now contributing more generation than ever before. This transformation is poised to continue given decreasing technology costs and ambitious decarbonization goals at the federal, state, local, corporate, and consumer levels. The North American Renewable Integration Study (NARIS) aims to inform grid planners, utilities, industry, policymakers, and other stakeholders about challenges and opportunities for continental system integration of large amounts of wind, solar, and hydropower to support a low-carbon future grid.

The National Renewable Energy Laboratory (NREL) conducted a detailed, continent-wide analysis with planning scenarios of transmission, generation, and demand to reach up to 80% carbon reductions from the U.S. electric power system, and similar reductions continent-wide. We used a suite of models to study future scenarios and gain insights, including potential impacts on costs, emissions, system adequacy, and the specific technologies that help enable the transition to a low-carbon grid. Our analysis had a particular focus on the potential role of cooperation among the three North American countries and between regions within each country, and how transmission can support sharing of supply and demand diversity.

The NARIS project began in 2016. This summary and a separate full report describe a U.S. perspective in coordination with the U.S. Department of Energy, and a companion report describes a Canadian perspective in coordination with Natural Resources Canada. NARIS was an extension of a previous body of work, including the Western Wind and Solar Integration Study, the Eastern Renewable Generation Integration Study, Interconnections Seam Study, and the Pan Canadian Wind Integration Study. NARIS analyzed the entire continent in detail while studying higher renewable generation than previous studies. The scenarios in NARIS were informed by the goals in the Mid-Century Strategies for the Paris Agreement in each country.

With input from the NARIS Technical Review Committee, NREL developed and evaluated a set of four core scenarios (see Table 1, page 2) to understand the impacts of renewable technology cost trajectories, emission constraints, and demand growth levels on the key outcomes. We also assessed 38 additional sensitivity scenarios to help understand the value of transmission and cooperation between regions and countries, the impact of technology cost assumptions for storage and distributed generation, and the impacts of natural gas prices and generator retirements. We also performed analysis to understand the potential benefits of hydropower flexibility in the future grid. The scenario assumptions were finalized at the end of 2018, using cost trajectories from the NREL Annual Technology Baseline and existing mandatory state and federal policies enacted as of that time. The scenarios are discussed in in the full *The North American Renewable Integration Study (NARIS): A U.S. Perspective* report.

Compared to the updated 2020 Annual Technology Baseline cost trajectories, the NARIS Business as Usual scenario represents the Conservative trajectory and Low-Cost Variable Generation represents a trajectory between Advanced and Moderate. The resulting infrastructure and operational patterns for each scenario are the result of cost-minimizing optimizations. Existing and evolving market structures may or may not support these development and operational patterns. The NARIS analysis provides insights into the feasibility of possible pathways, and the technologies and strategies that can minimize the costs.

Table 1. Description of the Core Scenarios

Scenario	Key Assumptions	Renewable Contribution[a]
Business as Usual (BAU)	The North American grid continues to evolve with expected trajectories for all technology costs, and there are no major changes to carbon legislation across the continent. The scenario includes only state-based requirements as of October 2018 in the United States.	50% (57% total carbon-free)
Low-Cost Variable Generation (Low-Cost VG)	VG, including wind and solar, follows a low-cost trajectory based on NREL's 2018 Annual Technology Baseline (ATB). Otherwise, the scenario is the same as the BAU scenario.	70% (78% total carbon-free)
Carbon Constrained (CO_2 Constrained)	Carbon emissions from the electricity sector are reduced throughout North America, including an 80% reduction from 2005 levels in the United States and Mexico and a 92% reduction in Canada, also from 2005 levels. Otherwise, the scenario is the same as the BAU scenario.	71% (78% total carbon-free)
Electrification	New end-use energy demands, including heating and transportation are electrified. And 2050 loads are nearly double the 2020 loads. Otherwise, the scenario is the same as Carbon Constrained scenario.	79% (84% total carbon-free)

[a] Renewable Contribution is the modeled share of annual generation in 2050 from all renewable technologies. Renewable contribution in the Electrification scenario is higher than the Carbon Constrained because it is subject to the same carbon constraint (80% reduction), but with much higher loads. This requires more zero-carbon generation, both in absolute terms and relative to total load.

Figure 1 shows the modeled generation by fuel type in 2050 for the core scenarios (compared to the near-term 2024 model year). Annual renewable energy contributions in the scenarios studied vary from 50% (BAU) to 79% (Electrification), and the Low-Cost VG and Carbon Constrained scenarios both reach approximately 70%. The thermal generation is mostly gas and nuclear generation in all scenarios, with significant coal contributions only in the BAU. Although most solar capacity in 2050 is utility-scale, distributed rooftop solar photovoltaic (PV) adoption is significant (over 60 GW DC in the BAU, and over 160 GW in the Low-Cost VG).

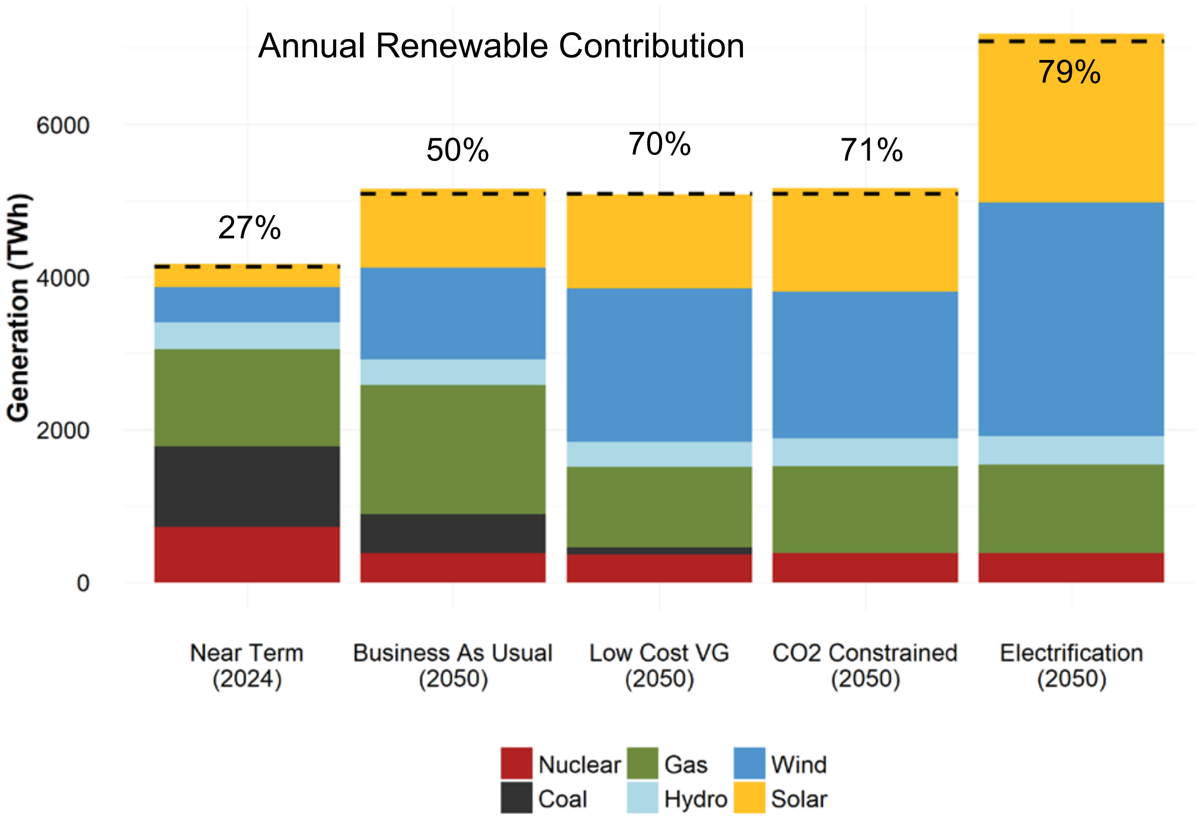

Figure 1. Projected U.S. generation in 2024 and 2050 in the NARIS core scenarios

Total U.S. demand is represented with the dashed line. These results are from the NREL Regional Energy Deployment System (ReEDS) model. The 2024 Near Term is nearly identical for all scenarios.

Table 2. Installed Capacity in the Core Scenarios (GW)

Type	Near-Term (2024)	BAU (2050)	Low-Cost VG (2050)	Carbon Constrained (2050)	Electrification (2050)
Coal	190	80	20	0	0
Gas	470	670	610	620	740
Hydro	90	90	90	90	90
Nuclear	50	50	50	50	50
Solar	140	510	700	710	1,230
Storage	20	30	30	60	130
Wind	140	280	490	480	840

The scenarios were evaluated using a variety of models (see Figure 2). All scenarios were designed using a utility-scale co-optimization of generation and transmission (NREL Regional Energy Deployment System [ReEDS] model), minimizing the total system cost for utility-scale generation and transmission. The behind-the-meter solar PV market was projected with an agent-based model (NREL Distributed Generation Market Demand [dGen]) to simulate customer adoption. Several scenarios were evaluated for resource adequacy (NREL Probabilistic Resource Adequacy Suite) and simulation of 5-minute operations with nodal transmission resolution (Energy Exemplar PLEXOS model) in 2050. All modeling was performed using consistent data sets through the NREL Renewable Energy Potential (reV) model, National Solar Radiation Database, and the Wind Integration National Dataset Toolkit. The range of conditions studied includes wind, load, and solar profiles based on 2007–2013 meteorology, and hydrological conditions that include typical, wet, dry, and inflexible (representing typical hydrology with inflexible operational rules).

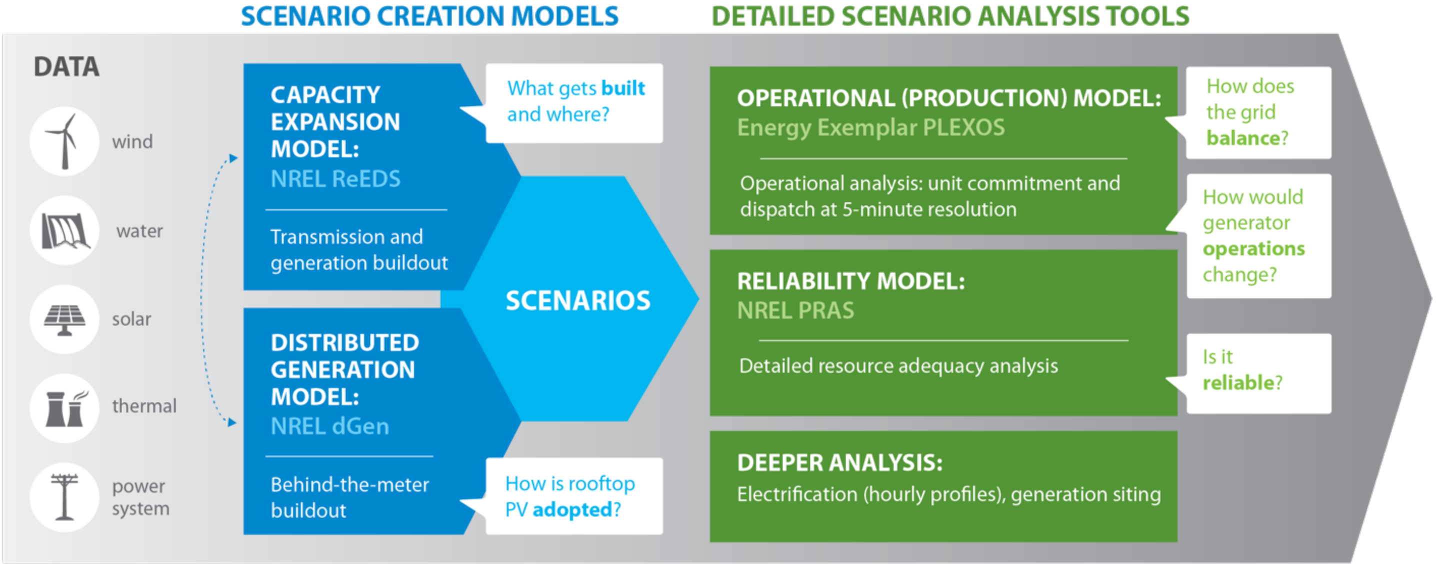

Figure 2. Overview of the different models used in NARIS, including key questions each model can help answer

This Executive Summary provides high-level insights from a U.S. perspective of the NARIS analysis, which is presented in full in *The North American Renewable Integration Study (NARIS): A U.S. Perspective*.

Multiple pathways can lead to 80% carbon reduction by 2050.

Steeper cost reduction of wind and solar technologies can lead to a faster and less costly transition, and carbon targets can still be achieved with conservative wind and solar cost assumptions.

NARIS shows that carbon emissions from the grid can be reduced significantly (more than 80% continent-wide) while maintaining the ability to balance supply and demand in a variety of scenarios. Figure 3 shows the emissions trajectory of the scenarios through 2050 as modeled in the core scenarios. The Low-Cost VG scenario maintains a trajectory that is lower in emissions than the constrained scenarios until the year 2050, when emissions are very similar in Low-Cost VG and Carbon Constrained.

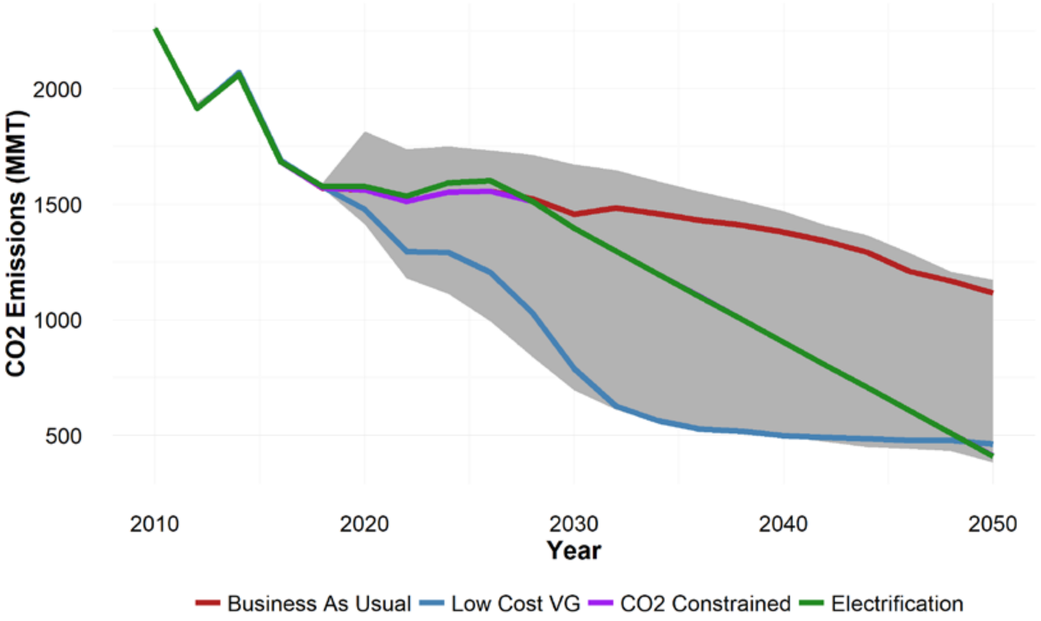

Figure 3. Projected U.S. power sector annual CO_2 emissions trajectory through 2050 in the core scenarios

The emissions reductions resulting from the electrification of energy end uses (e.g., transportation and heating) in the Electrification scenario are not considered in this power sector analysis. The CO_2 Constrained and Electrification scenarios follow an identical trajectory after 2028 because of the binding carbon constraints. All carbon quantification in NARIS is direct emissions only and does not consider life-cycle emissions.

Assuming conservative technology cost assumptions for wind and solar, the Carbon Constrained scenario has total system costs that are 6% higher than the BAU to achieve an 80% CO_2 reduction in the United States. Wind and solar cost trajectories have a more significant impact on costs than the carbon policy assumptions. The Low-Cost VG scenario is very similar to the Carbon Constrained scenario in 2050 build-out and emissions, but the total costs are 16% lower than in the BAU (with the lower-cost trajectories, the carbon reductions come at no additional cost to the system). In the Electrification scenario, the electric system costs are $2 trillion higher, but there are nonelectricity energy cost reductions that are not considered in the analysis.

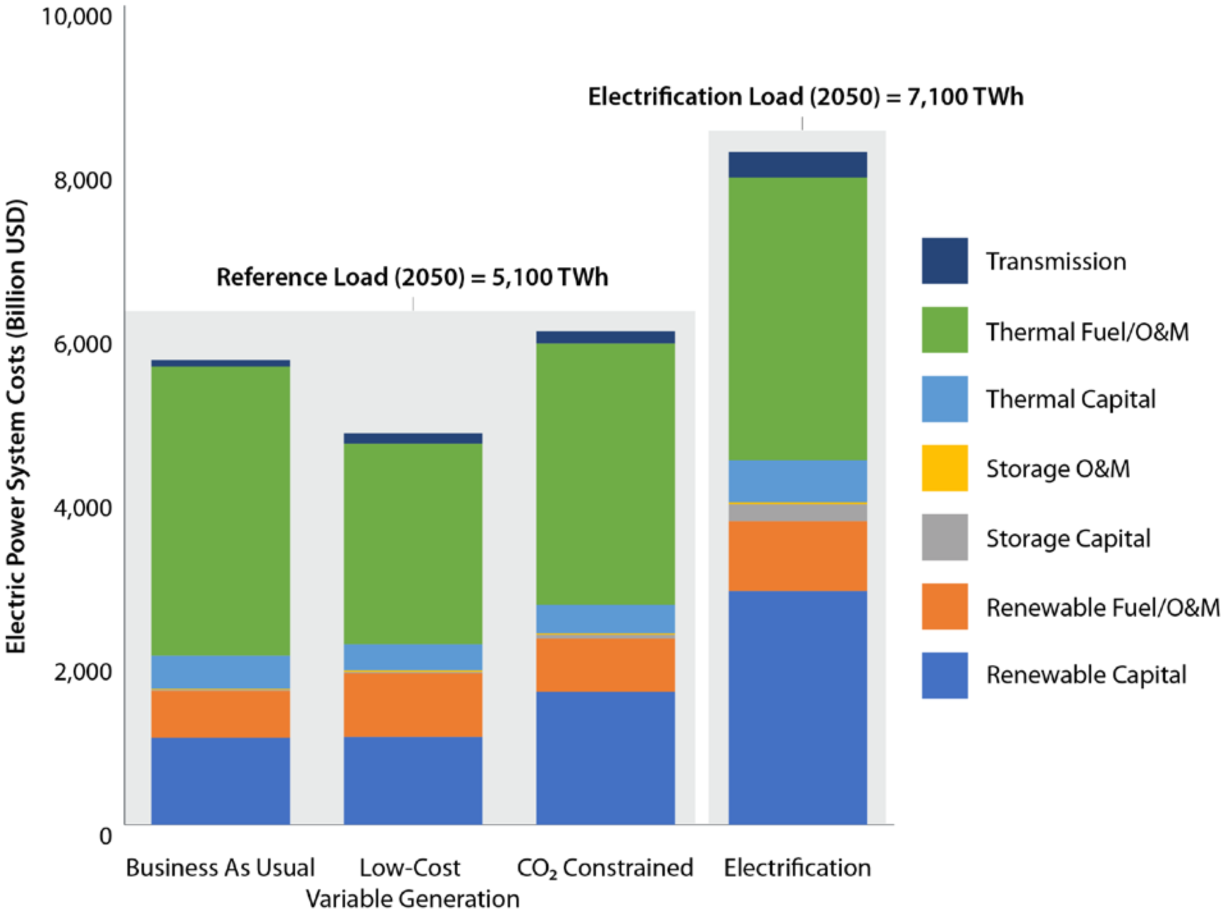

Figure 4. Projected total 2020–2050 U.S. system costs for the core scenarios (2018$)

The Electrification scenario costs include only electric sector costs and represent a large difference in 2050 demand (2050 demand is noted on figure); this does not consider the savings from reducing energy use in other sectors.

The future low-carbon system can balance supply and demand in a wide range of future conditions, with all technologies contributing to resource adequacy.

Between 1,200 and 2,000 GW of renewable energy can be deployed to produce 70%–80% of U.S. electricity by 2050 while meeting planning reserve requirements.

Using 7 years of meteorological information (2007–2013) to represent wind, solar, and load profiles and 10,000 random draws of generator outages, we estimated loss-of-load hours, which measures the regional expected number of hours where supply cannot meet demand in a year, and expected unserved energy, which measures the expected amount of energy demand that cannot be met due to reasonably foreseeable outages. The expected unserved energy and loss-of-load hours both compare favorably with the North American Energy Reliability Corporation *2020 Long-Term Reliability Assessment*.

Thermal generation (nuclear, gas, and coal) contributes significantly to adequacy in all scenarios, even as most of the energy generation comes from wind and solar. Storage can also help provide capacity to the system. Figure 5 shows the planning reserve requirement and contribution by resource type through time for three scenarios. Even though thermal resources provide less than half of annual energy across the range of scenarios (30% in the Low-Cost VG), the bulk of the planning reserves (between the color lines and the dashed line) are provided by thermal units. In the Low-Cost VG scenario, additional planning reserve requirements between 2020 and 2050 (due to increased load) are met by the increase in renewable contributions to adequacy. In the Low-Cost VG + Storage scenario (which is a sensitivity analysis that assumes more advanced technology innovation in wind, solar, and storage cost trajectories), over 200 GW of storage displaces some of the need for those thermal generators to provide adequacy. The scenario analysis shows a wide range of potential storage adoption in future scenarios, from almost no adoption in the BAU up to close to 500 GW in the Electrification scenario with low-cost storage trajectories.

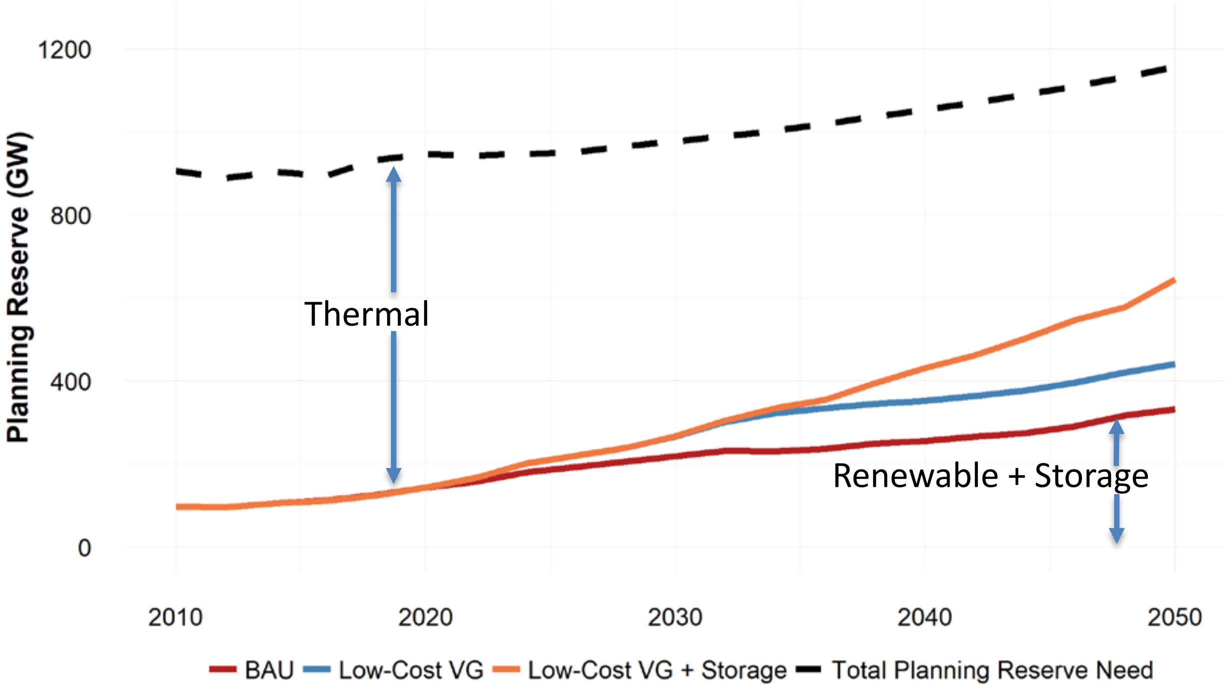

Figure 5. Planning reserve contribution of renewables plus storage in three scenarios

The dashed line shows the planning reserve need for the United States. The solid lines show the contribution of renewables plus storage in three scenarios. These results are from the ReEDS model.

Regional and international cooperation can provide significant net system benefits through 2050.

Increasing electricity trade between countries can provide $10 billion–$30 billion of net value to the system. Interregional transmission expansion achieves up to $180 billion in net benefits.

Figure 6 shows the net system benefits of expanding transmission in the future scenarios. The net values are estimated by comparing the total system cost in each core scenario in model runs with and without allowing additional transmission expansion (either interregional or international). Allowing international transmission expansion provides $10 billion–$30 billion (2018 USD) of net value to the continental system in total between 2020 and 2050 in all the scenarios except BAU; this demonstrates some of the potential benefits of international collaboration. Interregional transmission expansion provides $60 billion–$180 billion in net system benefits as modeled; this is true for a predesigned, high-voltage direct current, macrogrid overlay or model-optimized interregional transmission lines. Although the net system value of the macrogrid is slightly less than the value of the model-optimized transmission build, some benefits of the macrogrid overlay are not quantified in the model (including self-contingency and controllability). These findings are consistent with the NREL Interconnections Seam Study.

Although these values are less than 4% of the total $5 trillion–$8 trillion total system costs (which include all capital and operating generation and transmission system costs), transmission plays an important role in minimizing costs. Transmission expansion benefits are higher with more electrification and higher wind and solar contribution, a trend that could continue in lower-carbon scenarios or longer-term futures. Transmission can also provide reliability benefits and enable exchanging load and renewable generation diversity between regions, both under normal conditions and in extreme events.

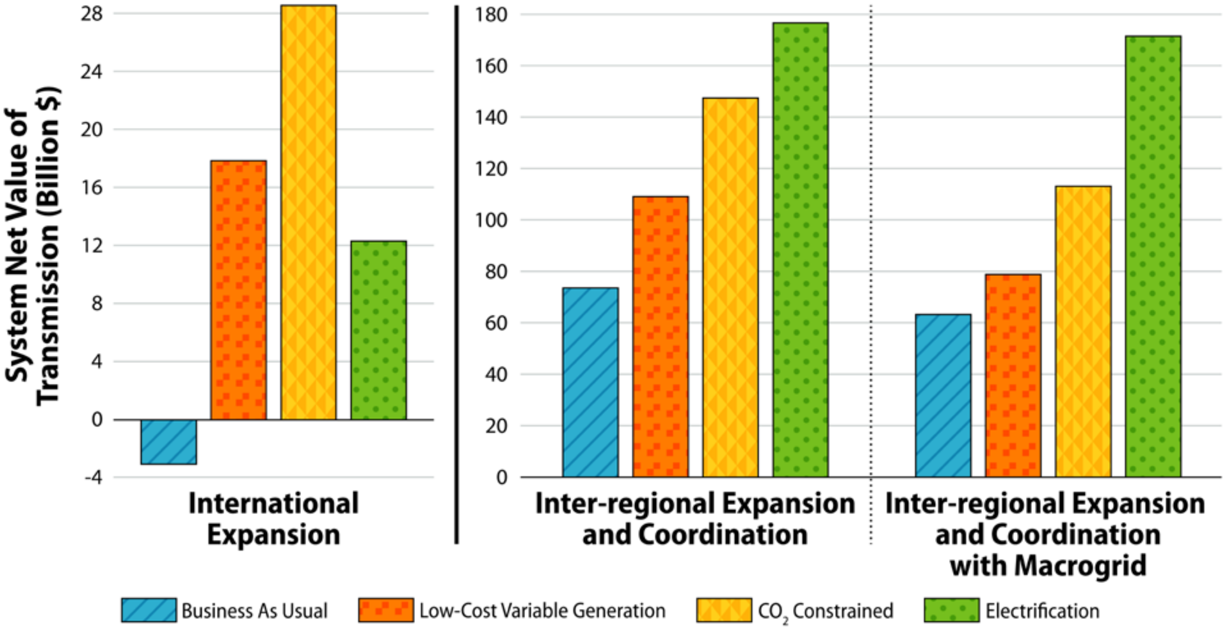

Figure 6. Net value of transmission in the core scenarios

Each net value estimate is calculated by comparing a scenario that allows transmission builds to a version of the scenario with restricted transmission builds. These results are from the ReEDS model.

Operational flexibility comes from transmission, electricity storage, and flexible operation of all generator types, including hydropower, wind, solar, and thermal generation.

For the Low-Cost VG scenarios with 2050 infrastructure, we analyzed nodal unit commitment and dispatch modeling (using PLEXOS) at 5-minute time resolution for a single year of meteorological data. This dispatch exhibits many sources of flexibility. Figure 7 shows the 5-minute nationwide dispatch during the last week of June. This chart shows many different forms of flexibility, including flexible operation of natural gas and hydropower (both peaking at sunset each day), curtailment (occurring mid-day on the lower-load days), storage (mostly pumped-storage hydropower dispatching from sunset until sunrise). International imports (the gap between the black demand line and the supply stack), enabled by transmission build-outs, do help the U.S. grid balance from sunset to sunrise.

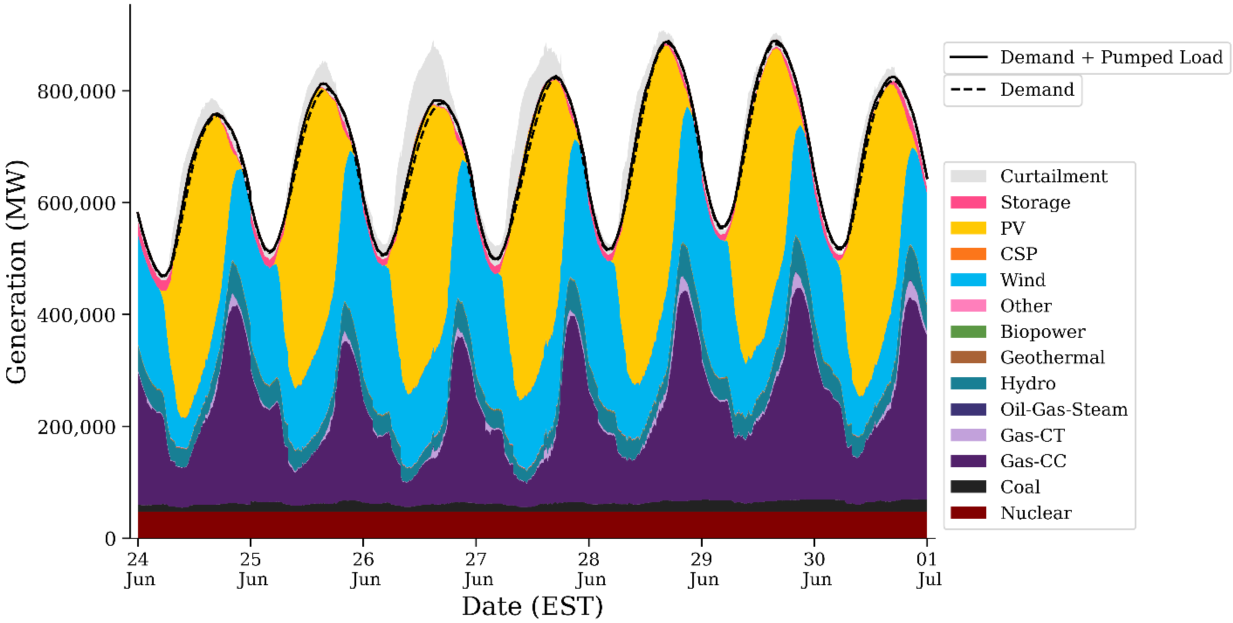

Figure 7. U.S.-wide 5-minute dispatch stack for late June

These results are from the PLEXOS model, using load, wind, and solar data from 2012 meteorological patterns.

Hydropower provides a zero-carbon source of energy, capacity, and flexibility to the grid. To understand the benefits of hydropower flexibility in the future grid, we modeled the operations in the Low-Cost VG 2050 scenario assuming no ability to adjust power output from hydropower generators and compared this to results with a level of flexibility intended to represent that of today. Table 3 shows the results, which indicate annual system costs are $2.3 billion higher without this flexibility.

Table 3. Benefits of Hydropower Flexibility as Modeled in 2050

Metric	Impact
Cost	Today’s level of hydropower flexibility reduced annual operating costs by $2.3 billion, representing 3.0% of the system production costs.
Curtailment	The flexibility of hydropower to turn down during periods of curtailment and generate more during periods of need reduced curtailment from 9.9% to 9.2%.
Emissions	Increased flexibility reduced carbon emissions in this scenario by 1.3%.

These values are based on a comparison of the 5-minute dispatch model runs from the Low-Cost VG scenario with runs from an identical scenario with all hydropower flexibility disabled (dispatchable hydropower generators are assumed to have flat output levels for each month). U.S. and Canadian hydropower resources were included in the sensitivity, so the presented results are aggregated for the continent.

Future Work

In addition to highlighting several opportunities for a coordinated, continental low-carbon grid, NARIS created open-source data and methods on which future studies can build. Next steps for future work include (but are not limited to):

- **Reliability:** NARIS addressed the adequacy portion of reliability in detail, but the stability element of reliability was not studied. Future studies could continue to study wider ranges of meteorological conditions and extreme events, and also address frequency and voltage stability for high-renewable scenarios, building on existing work (e.g., the Western Wind and Solar Integration Study).
- **Evolving Technologies and Goals:** Government and private-sector CO_2 emission reduction goals, as well as technology costs (especially storage), have changed since the NARIS assumptions were finalized at the end of 2018. Studying scenarios requiring additional emission reductions could increase the importance of some of the findings or illuminate new findings. These scenarios provide a useful basis for studying impacts of technologies and operating practices (including wind and solar providing essential reliability services beyond reserve), but they are not a projection of the expected future.
- **Markets:** The NARIS scenarios were created by co-optimization of generation and transmission. Current market structures may or may not support the transmission infrastructures and generation fleets projected in the study; future work could help us understand potential implications for U.S. wholesale markets and retail rate impacts.
- **Demand:** The uncertainty of electricity demand patterns in the long-term future is significant because of climate change and electrification of other sectors. Building on recent work (e.g., the Electrification Futures Study), electrification-focused studies could also help refine and quantify the benefits of electrification to other sectors and could help us understand the potential flexibility of new demands.

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