NATIONAL RENEWABLE ENERGY LABORATORY

Volume 1 of 4

Renewable Electricity Futures Study

Exploration of High-Penetration Renewable Electricity Futures

Volume 1 PDF

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Volume 4 PDF

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Renewable Electricity Futures Study

Volume 1: Exploration of High-Penetration Renewable Electricity Futures [ABRIDGED]

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Please Note:
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List of Acronyms and Abbreviations

AC	alternating current
AEO	Annual Energy Outlook
AWEA	American Wind Energy Association
BA	balancing area
Btu	British Thermal Unit(s)
CAES	compressed air energy storage
CC	combined cycle
CCS	carbon capture and storage
CO_2	carbon dioxide
CO_2e, CO_2eq	carbon dioxide equivalent
CSP	concentrating solar power
CT	combustion turbine
DC	direct current
DOE	U.S. Department of Energy
EEPS	energy efficiency portfolio standard
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EREC	European Renewable Energy Council
FERC	Federal Energy Regulatory Commission
Fossil-HTI	Fossil Energy – Higher Technology Improvement
gal	gallons
GHG	greenhouse gases
GT	gigatonnes
GW	gigawatt(s)
GWEC	Global Wind Energy Council
GWh	gigawatt-hour(s)
hrs	hours
HVDC	high-voltage, direct current
IGCC	integrated gasification combined cycle
INL	Idaho National Laboratory

IPCC	Intergovernmental Panel on Climate Change
IWG	Interagency Working Group
km^2	square kilometers
kV	kilovolt(s)
kW	kilowatt(s)
kW-yr	kilowatt-year
LBNL	Lawrence Berkeley National Laboratory
LCA	life cycle assessment
LMPs	locational marginal prices (LMPs)
m	meter(s)
Mgal	million gallons
MIT	Massachusetts Institute of Technology
MJ	megajoules
MMBtu	million British thermal units
mpg	miles per gallon
MW	megawatt(s)
MWh	megawatt-hour(s)
NCEP	National Centers for Environmental Prediction
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NO_x	oxides of nitrogen
NRC	National Research Council
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
ORNL	Oak Ridge National Laboratory
PEV	plug-in hybrid or electric vehicle
PNNL	Pacific Northwest National Laboratory
PSH	pumped-storage hydropower
ppm	parts per million
PV	photovoltaic
RE	renewable electricity
RE Futures	Renewable Electricity Futures Study
ReEDS	Regional Energy Deployment System

RE-ETI	Renewable Electricity—Evolutionary Technology Improvement
RE-ITI	Renewable Electricity—Incremental Technology Improvement
RE-NTI	Renewable Electricity—No Technology Improvement
RPS	renewable portfolio standard
SEIA	Solar Energy Industries Association
SNL	Sandia National Laboratories
SO_2	sulfur dioxide
SO_x	oxides of sulfur
SolarDS	Solar Deployment System
tCO_2	metric ton carbon dioxide
TW	terawatt(s)
TWh	terawatt-hour(s)
USGS	U.S. Geological Survey
yr	year

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Executive Summary

The Renewable Electricity Futures Study (RE Futures) is an initial investigation of the extent to which renewable energy supply can meet the electricity demands of the contiguous United States[1] over the next several decades. This study includes geographic and electric system operation resolution that is unprecedented for long-term studies of the U.S. electric sector. The analysis examines the implications and challenges of renewable electricity generation levels—from 30% up to 90%, with a focus on 80%, of all U.S. electricity generation from renewable technologies—in 2050. At such high levels of renewable electricity penetration, the unique characteristics of some renewable resources, specifically geographical distribution and variability and uncertainty in output, pose challenges to the operability of the U.S. electric system. The study focuses on some key technical implications of this environment, exploring whether the U.S. power system can supply electricity to meet customer demand with high levels of renewable electricity, including variable wind and solar generation. The study also begins to address the potential economic, environmental, and social implications of deploying and integrating high levels of renewable electricity in the United States.

RE Futures was framed with a few important questions:

- The United States has diverse and abundant renewable energy resources that are available to contribute higher levels of electricity generation over the next decades. Future renewable electricity generation will be driven in part by federal incentives and renewable portfolio standards mandated in many states.[2] Practically, how much can renewable energy technologies, in aggregate, contribute to future U.S. electricity supply?

- In recent years, variable renewable electricity generation capacity in the United States has increased considerably. Wind capacity, for example, has increased from 2.6 GW in 2000 to 40 GW in 2010, while solar capacity has also begun to grow rapidly. Can the U.S. electric power system accommodate higher levels of variable generation from wind or solar photovoltaics (PV)?

- Overall, renewable energy contributed about 10% of total power-sector U.S. electricity supply in 2010 (6.4% from hydropower, 2.4% from wind energy, 0.7% from biopower, 0.4% from geothermal energy, and 0.05% from solar energy).[3] Are there synergies that can be realized through combining these diverse sources, and to what extent can aggregating their output over larger areas help enable their integration into the power system?

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[1] Alaska, Hawaii, and the U.S. Territories were not included in this study because they rely on electric grid systems that are not connected to the contiguous United States. However, both states and the territories have abundant renewable resources, and they have efforts are underway to substantially increase renewable electricity generation (see Volume 1, Text Box Introduction-1).

[2] Some states have targets of a 20%–30% share of total electricity generation (see http://www.dsireusa.org/ for information on specific state standards) and are making progress toward meeting these goals.

[3] These data reflect estimates for the electric power sector only, and they exclude the end use sectors (i.e., on-site electric power supply that directly meets customer demands). If the end-use and electric power sectors are considered together, the percentage contribution from biomass would increase from 0.7% to 1.4%, and the contribution from solar would increase from 0.05% to 0.12%.

Multiple international studies[4] have explored the possibility of achieving high levels of renewable electricity penetration, primarily as a greenhouse gas (GHG) mitigation measure. RE Futures presents systematic analysis of a broad range of potential renewable electricity futures for the contiguous United States based on unprecedented consideration of geographic, temporal, and electric system operation aspects.[5]

RE Futures explores a number of scenarios using a range of assumptions for generation technology improvement, electric system operational constraints, and electricity demand to project the mix of renewable technologies—including wind, PV, concentrating solar power (CSP), hydropower, geothermal, and biomass—that meet various prescribed levels of renewable generation, from 30% to 90%. Additional sensitivity cases are focused on an 80%-by-2050 scenario. At this 80% renewable generation level, variable generation from wind and solar technologies accounts for almost 50% of the total generation.

Within the limits of the tools used and scenarios assessed, hourly simulation analysis indicates that estimated U.S. electricity demand in 2050 could be met with 80% of generation from renewable electricity technologies with varying degrees of dispatchability, together with a mix of flexible conventional generation and grid storage, additions of transmission, more responsive loads, and changes in power system operations.[6] Further, these results were consistent for a wide range of assumed conditions that constrained transmission expansion, grid flexibility, and renewable resource availability. The analysis also finds that the abundance and diversity of U.S. renewable energy resources can support multiple combinations of renewable technologies that result in deep reductions in electric sector greenhouse gas emissions and water use. Further, the study finds that the incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Of the sensitivities examined, improvement in the cost and performance of renewable technologies is the most impactful level for reducing this incremental cost.

While this analysis suggests such a high renewable generation future is possible, a transformation of the electricity system would need to occur to make this future a reality. This transformation, involving every element of the grid, from system planning through operation, would need to ensure adequate planning and operating reserves, increased flexibility of the electric system, and expanded multi-state transmission infrastructure, and would likely rely on the development and adoption of technology advances, new operating procedures, evolved business models, and new market rules.

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[4] As examples, recent detailed studies include those prepared for Europe (ECF 2010) and Germany (SRU 2010), as well as a review of 164 global energy scenarios by the Intergovernmental Panel on Climate Change (IPCC 2011). Cochran et al. (2012) also describes several case studies of countries successfully managing high levels of variable renewable energy on their electric grids.

[5] Previous, more conceptual or more-limited analyses of high penetrations of renewable energy in the United States and globally include (but are not limited to) Pacala and Socolow (2004); ACORE (2007); Kutscher (2007); Greenblatt (2009); GWEC/GPI (2008); Fthenakis et al. (2009); Jacobson and Delucchi (2009); Sawin and Moomaw (2009); EREC/GPI (2008); and Lovins (2011).

[6] The study did not conduct a full reliability analysis, which would include sub-hourly, stability, and AC power flow analysis.

Key results of this study include the following:

- Deployment of Renewable Energy Technologies
    - Renewable energy resources, accessed with commercially available generation technologies, could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level.
    - All regions of the United States could contribute substantial renewable electricity supply in 2050, consistent with their local renewable resource base.
    - Multiple technology pathways exist to achieve a high renewable electricity future. Assumed constraints that limit power transmission infrastructure, grid flexibility, or the use of particular types of resources can be compensated for through the use of other resources, technologies, and approaches.
    - Annual renewable capacity additions that enable high renewable generation are consistent with current global production capacities but are significantly higher than recent U.S. annual capacity additions for the technologies considered. No insurmountable long-term constraints to renewable electricity technology manufacturing capacity, materials supply, or labor availability were identified.
- Grid Operability and Hourly Resource Adequacy
    - Electricity supply and demand can be balanced in every hour of the year in each region with nearly 80% electricity from renewable resources, including nearly 50% from variable renewable generation, according to simulations of 2050 power system operations.
    - Additional challenges to power system planning and operation would arise in a high renewable electricity future, including management of low-demand periods and curtailment of excess electricity generation.
    - Electric sector modeling shows that a more flexible system is needed to accommodate increasing levels of renewable generation. System flexibility can be increased using a broad portfolio of supply- and demand-side options, and will likely require technology advances, new operating procedures, evolved business models, and new market rules.
- Transmission Expansion
    - As renewable electricity generation increases, additional transmission infrastructure is required to deliver generation from cost-effective remote renewable resources to load centers, enable reserve sharing over greater distances, and smooth output profiles of variable resources by enabling greater geospatial diversity.
- Cost and Environmental Implications of High Renewable Electricity Futures
    - High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use.
    - The direct incremental cost associated with high renewable generation is comparable to published cost estimates of other clean energy scenarios. Improvement in the cost

and performance of renewable technologies is the most impactful lever for reducing this incremental cost.

- Effects of Demand Growth
  - With higher demand growth, high levels of renewable generation present increased resource and grid integration challenges.

This report presents the analysis of some of the technical challenges and opportunities associated with high levels of renewable generation in the U.S. electric system. However, the analysis presented in this report represents only an initial set of inquiries on a national scale. Additional studies are required to more fully assess the technical, operational, reliability, economic, environmental, social, and institutional implications of high levels of renewable electricity generation, and further explore the nature of the electricity system transformation required to enable such a future.

Renewable Resources Characterization

The United States has diverse and abundant renewable resources, including biomass, geothermal, hydropower, ocean, solar, and wind resources. Solar and wind are the most abundant of these resources. These renewable resources are geographically constrained but widespread—most are distributed across all or most of the contiguous states (Figure ES-2). Within these broad resource types, a variety of commercially available renewable electricity generation technologies have been deployed in the United States and other countries, including stand-alone biopower, co-fired

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biopower (in coal plants), hydrothermal geothermal, hydropower, distributed PV, utility-scale PV, CSP,[19] onshore wind, and fixed-bottom offshore wind.

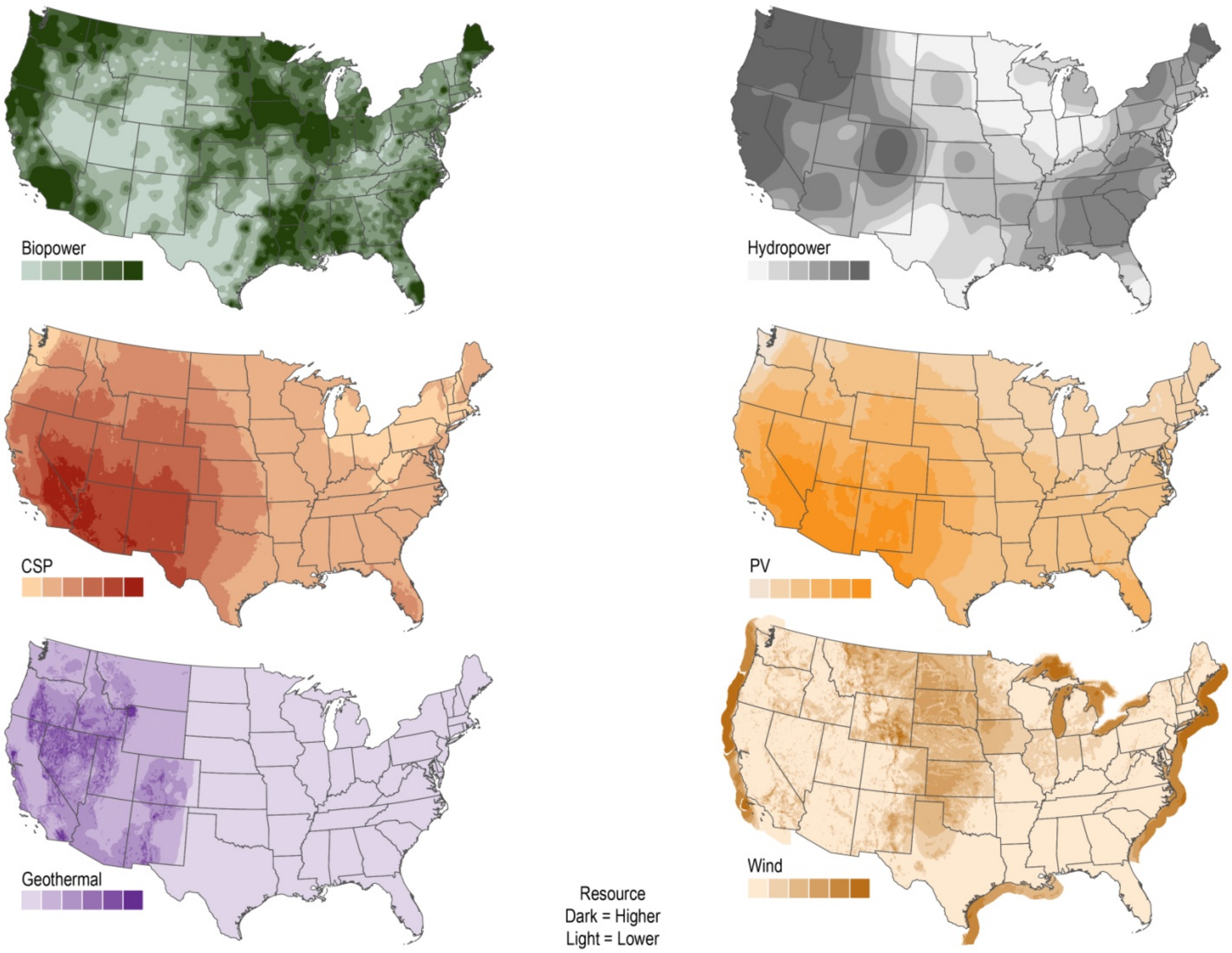

Figure ES-2. Geographic distribution of renewable resources in the contiguous United States

The United States has potential ocean energy and enhanced geothermal resources; however, these technologies were not modeled and therefore the resource potential is not included in this figure.

While only commercially available biomass, geothermal, hydropower, solar PV, CSP, and wind-powered systems were considered in the modeling analysis—only incremental and evolutionary advances in renewable technologies were assumed—the study describes a broad range of commercial and emerging renewable energy technologies in Volume 2, including the following[20]:

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[19] In this report, CSP refers to concentrating solar thermal power. Concentrating photovoltaic technologies were not considered in the modeling analysis.

[20] The renewable resource characterizations described below and used in the models are based on historical climatic average resource patterns and have standard land area exclusions applied. After accounting for these standard exclusions, the aggregate renewable generation resource is many times greater than current electricity demand.

- **Biomass power** (Chapter 6, Volume 2) is generated by collecting and combusting plant matter and using the heat to drive a steam turbine. Biomass resources from agricultural and forest residues, although concentrated primarily in the Midwest and Southeast, are available throughout the United States. While biomass supply is currently limited, increased supply is possible in the future from increased production from energy crops and advanced harvesting technologies. DOE (2011) provides an estimate of 696–1,184 million annual dry tonnes of biomass inventory potential (of which 52%–61% represents dedicated biomass crops) in 2030.[21] The estimated biomass feedstocks correspond to roughly 100 GW of dedicated biopower capacity. Biopower can be generated from stand-alone plants, or biomass can be co-fired in traditional pulverized coal plants.
- **Geothermal power** (Chapter 7, Volume 2) is generated by water that is heated by hot underground rocks to drive a steam turbine. Geothermal resources are generally concentrated in the western United States, and they are relatively limited for hydrothermal technologies (36 GW of new technical resource potential), which rely on natural hot water or steam reservoirs with appropriate flow characteristics. Only commercially available hydrothermal technologies were included in the modeling analysis. Although not modeled, emerging technologies, including enhanced geothermal systems, engineered hydrothermal reservoirs, geopressured resources, low temperature resources, or co-production from oil and gas wells, could expand the geothermal resource potential in the United States by more than 500 GW.
- **Hydropower** (Chapter 8, Volume 2) is generated by using water—from a reservoir or run-of-river—to drive a hydropower turbine. Run-of-river technology could produce electricity without creating large inundated areas, and many existing dams could be equipped to generate electricity. The future technical potential of run-of-river hydropower from within the contiguous United States is estimated at 152–228 GW. Only new run-of-river hydropower capacity was considered in RE Futures modeling, and existing hydropower plants were assumed to continue operation. Other hydropower technologies, such as new generation at non-powered dams and constructed waterways, have the potential to contribute to future electricity supply, but they were not modeled in this study.
- **Ocean technologies** (Chapter 9, Volume 2) are not broadly commercially available at this time, and therefore were not modeled in this study, but both U.S. and international research and development programs are working to reduce the cost of the technologies. Ocean current resources are best on the U.S. Gulf and South Atlantic Coasts; wave energy resources are strongest on the West Coast. All resources are uncertain; preliminary estimates indicate that the U.S. wave energy technical potential is on the order of 2,500 TWh/yr. Other ocean technologies, including ocean thermal energy conversion technologies and tidal technologies, may also contribute to future electricity supply.

[21] To be conservative, for each modeled year, the analysis used feedstock estimates from Walsh et al. (2000) and Milbrandt et al. (2005), which are consistent with the low end of the DOE (2011) estimate for 2030, and did not assume any increase in resource over time; on the other hand, the analysis also did not include potential future growth in demand for biomass from the fuel sector. Maximum biopower capacity deployment was assumed to be roughly 100 GW in this study, with 27% from dedicated biomass crops.

- **Solar resources** (Chapter 10, Volume 2) are the most abundant renewable resources. They extend across the entire United States, with the highest quality resources concentrated in the Southwest. The technical potential of utility-scale PV and CSP technologies is estimated to be approximately 80,000 GW and 37,000 GW, respectively, in the United States. Distributed rooftop PV technologies are more limited, with approximately 700 GW available. PV technologies convert sunlight directly to electricity while CSP technologies collect high temperature heat to drive a steam turbine.
- **Wind resources** (Chapter 11, Volume 2) on land are abundant, extending throughout the United States, and offshore resources provide additional options for coastal and Great Lakes regions. Onshore and fixed-bottom offshore technologies are currently commercially available.[22] Floating platform offshore wind technologies that could access high-quality wind resources in deeper waters are less mature and were not considered in the modeling. Wind technical resource estimates exceed 10,000 GW in the contiguous United States.

Renewable resource supply varies by location and, in most cases, by the time of day and season. The electricity output characteristics of some renewable energy technologies also vary substantially, potentially introducing electric system operation challenges. A key performance characteristic of generators in general is their degree of dispatchability, specifically the ability of operators to control power plant output over a range of specified output generation levels. Conventional fossil plants are considered dispatchable, to varying degrees. Several renewable generator types, including biopower, geothermal, and hydropower plants with reservoir storage, are also considered dispatchable technologies in that system operators have some ability to specify generator output, if needed. Concentrating solar power with thermal storage can similarly be considered a dispatchable technology but is limited by the amount of storage. The output from run-of-river hydropower is generally constant over short time periods (minutes to hours) but varies over longer periods (days to seasons). Several emerging ocean technologies, such as ocean-current, may also provide fairly constant output and, in some cases, may be able to offer some level of dispatchability.

Wind and solar PV have little dispatchability—the output from these sources can be reduced, but not increased on demand. An additional challenge is the variability and uncertainty in the output profile of these resources, with wind and solar having limited predictability over various time scales. High levels of deployment of these generation types can therefore introduce new challenges to the task of ensuring reliable grid operation. However, it deserves note that the requirement for balanced supply and demand must be met on an *aggregate* basis—the variability and uncertainty of any individual plant or load entity does not ultimately define the integration challenge associated with high levels of variable renewable generation.

The analysis presented here focuses on electricity generation technology deployment, system operational challenges, and implications associated with specified levels of renewable generation, which represent the total annual renewable electricity generation from commercially available biomass, geothermal, hydropower, solar, and wind electricity generating technologies.

[22] Although there are no offshore wind power plants operating in the United States, a number of projects have been proposed. In addition, offshore wind is widely deployed in Europe.

3.1 Meeting 80%-by-2050 Renewable Electricity Penetration Would Require Renewable Energy Capacity Additions of 20–45 GW Per Year

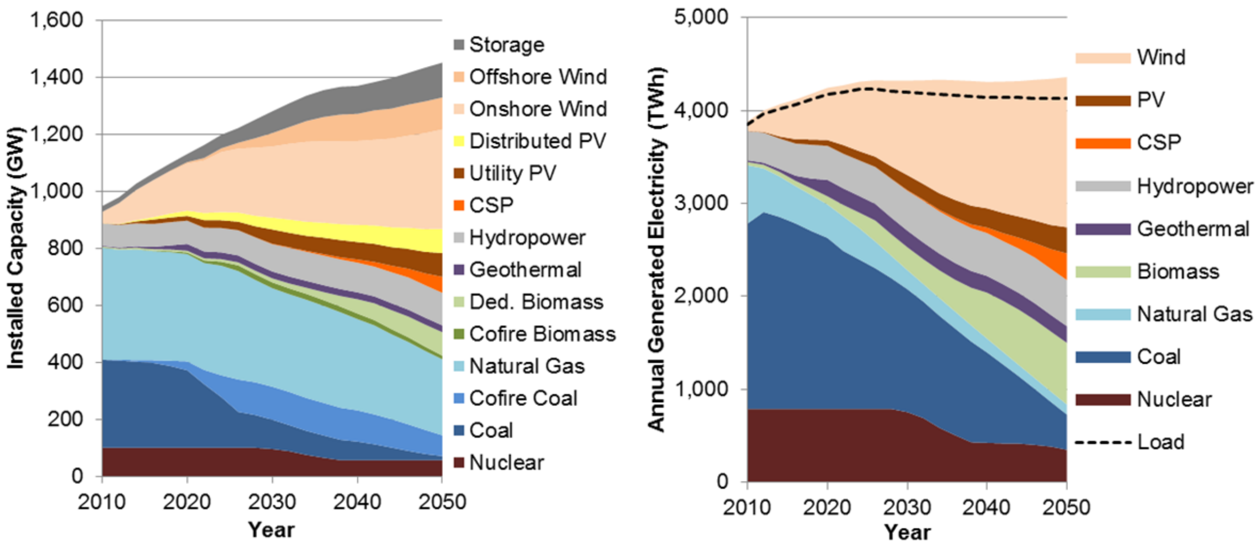
Meeting an 80%-by-2050 renewable electricity future would require a significant increase in renewable capacity and energy supply. Because the selection of renewable technology type, quantity, timing, and location depend on a large number of unknown and uncertain factors, an accurate projection of renewable technology deployment is not possible. Growth in capacity and supply of each renewable technology considered in the analysis was found to occur in all 80%-by-2050 RE scenarios. General trends observed across the scenarios, are discussed in the following sections using the 80% RE-ITI scenario as an example.

Focusing on the 80% RE-ITI scenario, Figure 3-2 presents estimated cumulative installed capacity and energy supply during the study period. Figure 3-3 depicts annual additions for the renewable energy technologies alone. A diverse mix of renewable energy technologies was projected to be employed in the 80% RE-ITI scenario. Wind energy deployed rapidly beginning in 2010, initially dominated by onshore wind technology but with a growing proportion of offshore wind over time. The growth in solar energy was slower in early years, but PV and then CSP began to deploy rapidly in the later years of the forecast horizon. Both dedicated and co-fired biomass were found to contribute significantly to the renewable energy mix, with growth continuing throughout the forecast period, initially focused on co-fired plants and then on dedicated biomass facilities. New hydropower and geothermal[128] were found to contribute proportionately less than the other renewable energy technologies; even within these two technologies, however, capacity expansion was substantial, especially in the early (geothermal) to middle (hydropower) portion of the 2010–2050 time period.

In aggregate, approximately 20 GW of renewable energy capacity would need to be added each year during the first half of the study period and up to 45 GW per year thereafter to reach an 80% renewable electricity future by 2050, compared to approximately 7 GW added in 2010, and 11 GW added in 2009. These annual additions (Figure 3-3) include new renewable generation capacity and the replacement of retired capacity.[129] Total renewable energy capacity would expand from 130 GW at the end of 2010 to 540 GW by 2030 and 920 GW by 2050. This expansion and required growth rate could pose challenges to the renewable energy industries, as highlighted in Section 3.7.

[128] The available hydrothermal resource used in the ReEDS model was limited to approximately 30 GW, and most of this capacity deployed in nearly every 80%-by-2050 RE scenario. Discovery of new resources or widespread application of enhanced geothermal technology could increase the contribution of geothermal resources.

[129] In ReEDS, renewable capacity is automatically replaced at the end of the assumed physical lifetimes (see Appendix A). The annual additions shown in Figure 3-3 include the replacement capacity (repowering). For this reason, annual builds for certain technologies (e.g., geothermal) show a repeating pattern.



(a) Capacity expansion, 2010–2050 (b) Generation expansion, 2010–2050

Figure 3-2. Capacity and generation expansion in the 80% RE-ITI scenario, 2010–2050

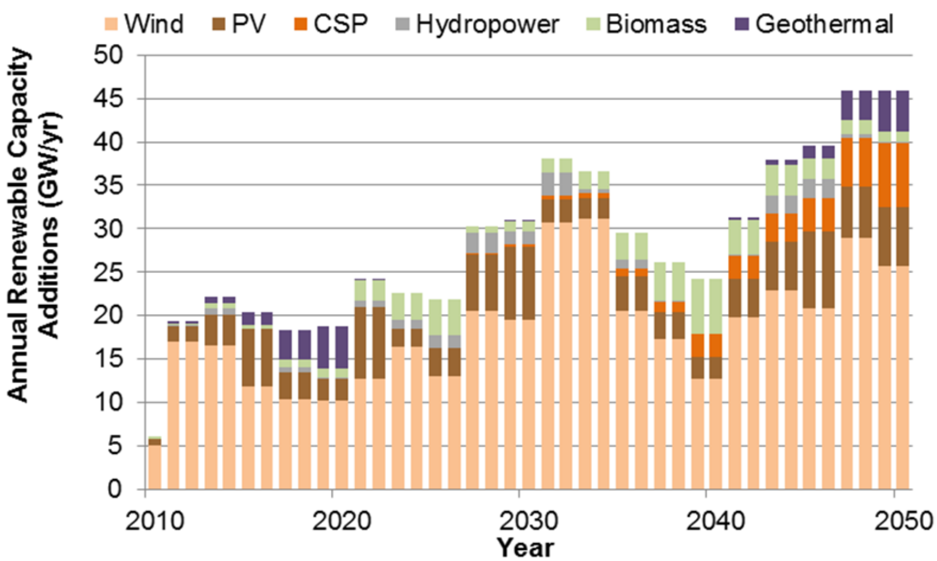


Figure 3-3. Renewable capacity expansion in 80% RE-ITI scenario

This figure includes new installations and the replacement of renewable power plants at the end of their assumed physical lifetimes.

As renewable energy supply increases during the study period, conventional fossil and nuclear generation decreases through plant retirements and reductions in capacity factors. Dedicated coal plant capacity and supply, in particular, drop rapidly, although coal generation from co-fired plants continued throughout the period. Natural gas capacity, meanwhile, remains largely constant in order to meet overall reliability needs, as discussed in Section 2.5.1, but the generation of electricity from those plants declines steadily and significantly with time as renewable electricity generation increases.

3.2 Substantial Renewable Resource Penetrations Would be Required in Every Region

Focusing again on the 80% RE-ITI scenario, Figure 3-4 presents the generated electricity and installed capacity in 2050 by region and technology, and compares total regional generation in 2050 to regional electricity demand in the same year.[130]

As shown in Figure 3-4, several regions are forecast to be net exporters of electricity by 2050, with total electricity supply exceeding regional electricity demand. Most prominently, these include the Great Plains, Northwest, and Southwest regions. Several other regions are found to be net importers of electricity generation, including the Southeast, Florida, and Texas. As described in Section 3.4, new transmission would be required to support these inter-regional electricity transfers.

In the 80% RE-ITI scenario, wind energy supply was significant in most regions, but was most prominent in the Great Plains, Great Lakes, Central, Northwest, and Mid-Atlantic regions (with a large fraction of wind generation coming from offshore resources in the Northeast and Mid-Atlantic regions). Solar energy was found to deploy most substantially in the Southwest (dominated by CSP), followed by California and Texas (CSP and PV), and then by Florida and the Southeast regions (dominated by PV). Biomass supply was most significant in the Great Plains, Great Lakes, Central, and Southeast regions. The significant biomass supply required a large quantity of feedstock from diverse sources, including 14% from urban waste, 18% from mill waste, 11% from forest residue, 30% from agricultural residue, and 27% from dedicated crops. Additional information on biomass feedstock availability and use can be found in RE Futures Chapter 6 (Volume 2). Hydropower supply was most significant in the Northwest, but hydropower was also a sizable contributor in California, the Northeast, and the Southeast. Geothermal was found to deploy primarily in California and the Southwest.

Similar to Figure 3-4, in which the regional breakdown is based on the 11specified regions, Figure 3-5 shows the 2050 regional deployment of generation technologies for the 80% RE-ITI scenario, except the regions shown are generally based on NERC regional boundaries.[131]

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[130] The 11 regions shown in Figure 3-4 were designed arbitrarily and not based on transmission or other electric-grid boundaries.

[131] The regions depicted in Figure 3-5 are based on NERC regions in the Eastern Interconnection and NERC subregions in the Western Electricity Coordinating Council (see http://www.nerc.com/ for a description of NERC regions and subregions).

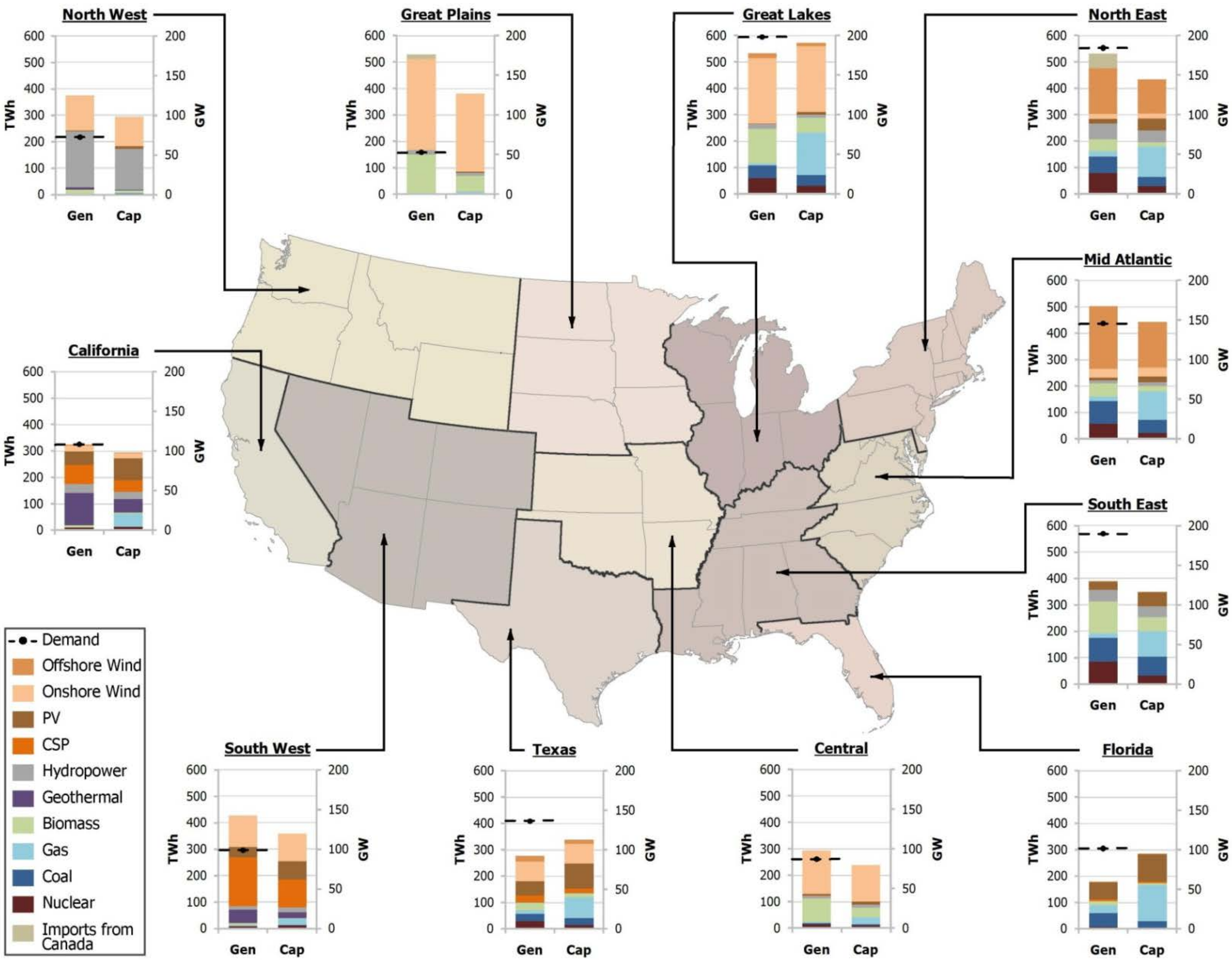


Figure 3-4. Renewable generation and capacity in 2050 in 80% RE-ITI scenario, by region

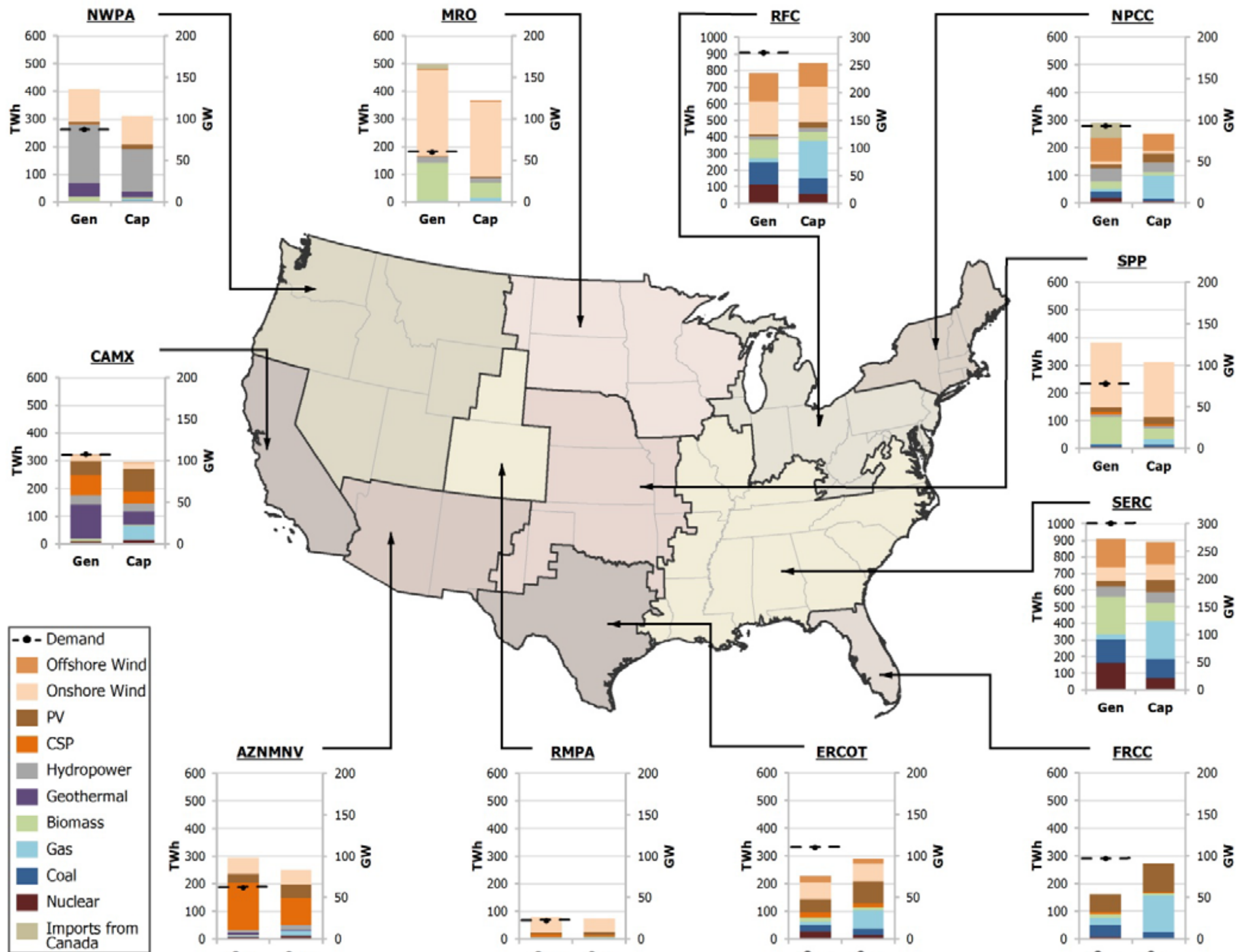


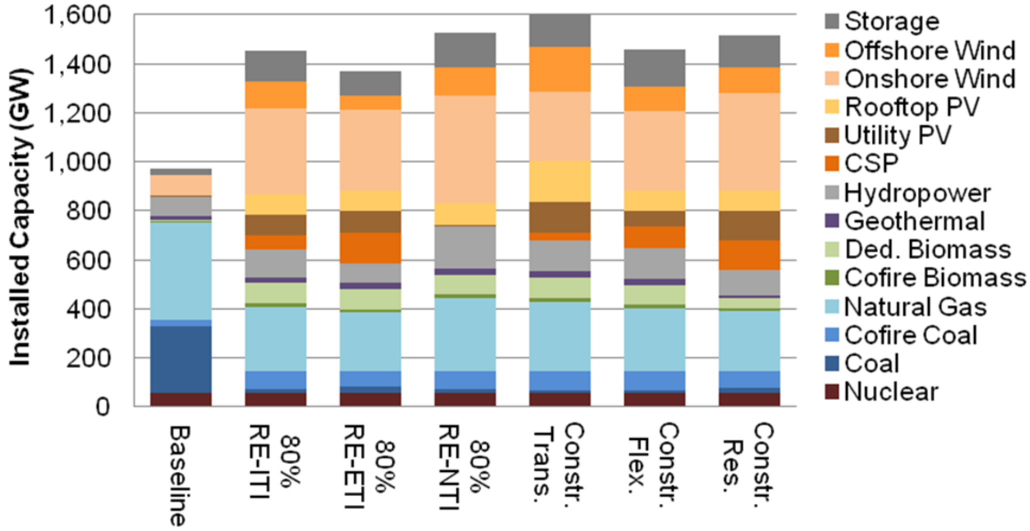
Figure 3-5. Renewable generation and capacity in 2050 in 80% RE-ITI scenario, by North American Electric Reliability Corporation region

AZNMNV = New Mexico Nevada
CAMX = California Mexico
ERCOT = Electric Reliability Council of Texas
FRCC = Florida Reliability Coordinating Council
MRO = Midwest Reliability Organization
NPCC = Northeast Power Coordinating Council
NWPA = Northwest Power Area
RFC = Reliability First Corporation
RMPA = Rocky Mountain Power Area
SERC = SERC Reliability Corporation
SPP = Southwest Power Pool

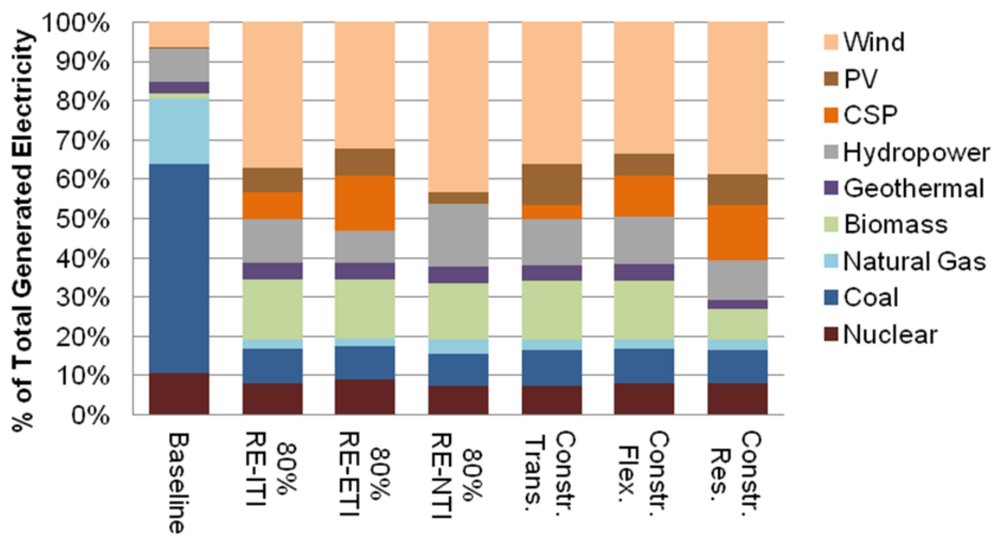
3.3 The Mix of Renewable Generation Technologies Changes to Accommodate Differences in System Conditions and Estimated Technology Improvements

While growth in capacity and supply of each renewable technology considered in the analysis was found to occur in all 80%-by-2050 renewable electricity scenarios, the specific mix of those technologies varied among the six core 80% RE scenarios. Because of the relatively low capacity factor and capacity value of some renewable energy technologies, the 80%-by-2050 renewable electricity scenarios required approximately 1,300 GW–1,500 GW of total electric generation capacity by 2050, compared to 950 GW in the Low-Demand Baseline scenario. Approximately 70% of total generation capacity was found to come from renewable technologies across all of the 80%-by-2050 renewable electricity scenarios, with the relative contribution of different renewable technologies varying by scenario (see Figure 3-6, Figure 3-7, and Table 3-1).

Wind energy was found to contribute 32%–43% of overall electricity generation by 2050 (of which offshore wind contributed 6%–16%), depending on the scenario. Solar energy contributed 3%–22%, depending on the scenario. The growth of CSP was found to be particularly sensitive to scenario design. The sensitivity in the contribution of solar energy was driven by the specific characteristics of solar; for example, CSP is transmission-dependent, PV is variable, and both technologies have high but uncertain cost reduction potential and extensive resource potential. Biomass was found to supply 8%–15% of total electricity generation by 2050, while hydropower's contribution was 8%–16%. Geothermal energy's contribution was 2%–4% because only commercial hydrothermal technologies were considered; geothermal supply could increase if advances in enhanced geothermal systems or other geothermal technologies are realized.



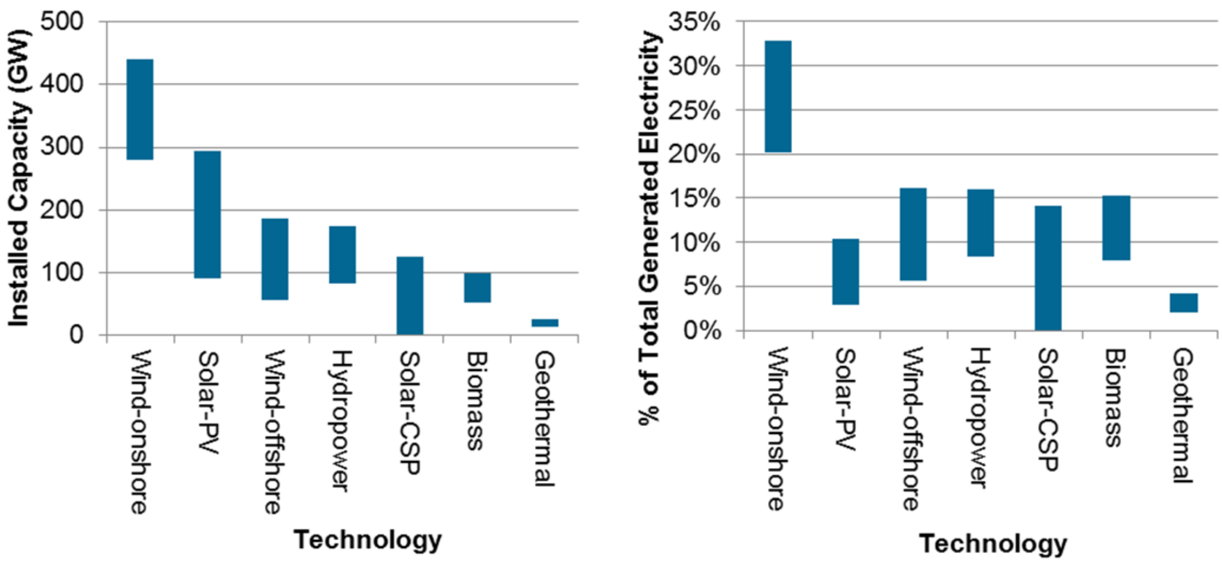
(a) Capacity mix in 2050



(b) Generation mix in 2050

Figure 3-6. Capacity and generation in 2050 in the Low-Demand Baseline and core 80% RE scenarios

Figure 3-7 and Table 3-1 show the range in 2050 capacity and generation by technology among the six low-demand core 80% RE scenarios. Although all of the scenarios meet the same 80% renewable electricity by 2050 penetration level, *the fraction of variable generation (wind and PV) ranges from 39% to 47%*. In Table 3-1, the "low" and "high" columns refer to the lowest and highest deployment levels observed across all low-demand core 80% RE scenarios, and thereby summarize the overall deployment range for each technology across the scenarios presented in this section.



(a) 2050 installed capacity by technology

(b) 2050 contribution to total generated electricity

Figure 3-7. Range of 2050 installed capacity and annual generation by technology for the core 80% RE scenarios