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REPORT REVIEW

# Decision-making for High Renewable Electricity Futures in the United States

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ABSTRACT

**Our research suggests that in 2050, 80% of total U.S. electricity demand could be supplied by renewable electricity technologies that are commercially available today at a cost similar to or lower than published estimates for other clean energy scenarios. In order to achieve this goal, the U.S. power system will need to evolve toward increased efficiency and system flexibility – in part enabled by grid expansion and new operating procedures. Adjustments in business models, market rules, and regulatory regimes may also be needed to handle these high levels of renewables with their different financial and operating characteristics. This short Report Review highlights aspects of policy, regulation, finance, markets and operations that can help enable high penetration renewable energy electricity generation futures. It uses analytical results from the NREL Renewable Electricity Futures (REF) Study [1] as a basis for discussion. As technical issues have been shown not to be key impediments for this pathway at the hourly level for the bulk system, we focus on other aspects of public and private decision-making. We conclude by describing how the REF might inform future research and development by the scientific community.**



## 1. Introduction

As deployment of renewable sources of electricity (RE) gain traction, technical, economic, social, and environmental questions arise as to their role and integration in power systems and the wider energy sector. Multiple international studies[1] have explored the possibility of achieving high levels of RE penetration, primarily from the perspective of greenhouse gas (GHG) mitigation. The NREL Renewable Electricity Futures Study (REF) [1] presents a systematic analysis of a broad range of potential renewable electricity futures for the contiguous United States based on the most detailed consideration to date of geographic, temporal, and electric system operational aspects. It finds that renewable energy resources, accessed with today's commercially available renewable generation technologies, could supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level. Fig. 1 presents the resultant estimated generation capacity in 2050 by technology, for a suite of exploratory scenarios with renewable penetration levels ranging from 20% (Baseline) to 90%.

Fig. 2 shows nationwide dispatch by generator type during the annual peak coincident load in 2050. The operational simulations did not project any hours of unserved load during the peak load hour, lowest coincident load hour, or any other hour of the year [1].

## 2. Beyond technology: how to get there?

Multiple technology pathways exist to achieve a high renewable electricity future. Several countries now have penetration levels of variable generation (wind and solar) in excess of 15% of their overall power generation mix; and many jurisdictions (e.g., Spain, Portugal, Ireland, Germany,[2] Denmark, and the U.S. state of Colorado) have experienced instantaneous penetration levels of over 50% variable generation.[3] With

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[1] As examples, recent detailed studies include those prepared for Europe [2] and Germany [3], as well as a review of 164 global energy scenarios by the Intergovernmental Panel on Climate Change [4].

[2] See e.g., http://www.greentechmedia.com/articles/read/Germany-Hits-59-Renewable-Peak-Grid-Does-Not-Explode.

[3] Renewable energy technologies can be (i) variable with limited predictability, (ii) variable and predictable, (iii) constant, or (iv) controllable [4]. Technologies that are variable with limited predictability are the most challenging for system operators; such sources include wind, solar, and ocean energy.

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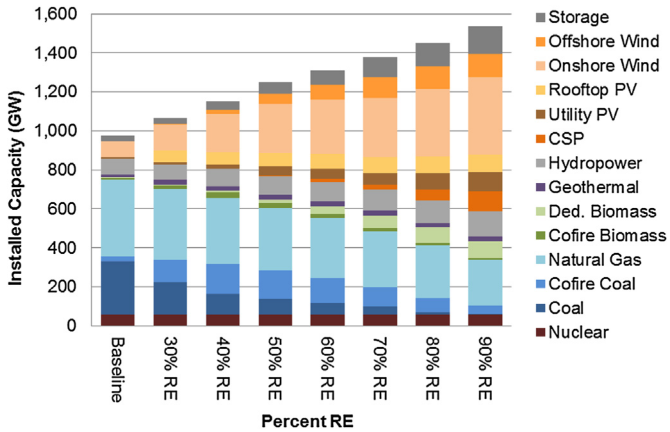


**Fig. 1.** Scenarios of installed capacity in 2050 [1].

these higher penetration levels of variable RE, jurisdictions have begun modifying practices that evolved in an era of large, dispatchable, central-station conventional power plants. These jurisdictions demonstrate that: (i) higher penetration levels of variable RE have implications for grid operations, wholesale and retail power markets, and infrastructure needs, and (ii) constraints that limit transmission infrastructure, grid flexibility, or the use of particular types of resources can be compensated for through the use of other technologies, policies, markets and operational approaches. International experience suggests that a new generation of power sector policies are critical to ensure an effective, efficient high RE power system [5] coupled with appropriate financial mechanisms and market design [6].

We highlight illustrative issues that arise in meeting the types of RE pathways in terms of three categories, namely: policies and regulation, markets and operations, and research and development. Of course, there are not distinct boundaries between these areas, rather there are complex interactions among them. We present the information in this way primarily as a means of emphasizing areas for future discussion in the scientific and policy communities in the near- and mid-term.

### 2.1. Policy and regulation

Policy and regulatory implications of such a transformation of the power sector are significant, and will be important in procuring new RE generation, extending and improving electricity grids, and promoting greater energy efficiency and responsive demand, among others.

Policies to secure new RE generation should be responsive to changing market conditions and market pricing in order to encourage continued growth in RE capacity at reasonable cost. A key research question includes how to most efficiently incentivize sustained additions of the most appropriate and cost effective capacity for the particular service requirements. Options used or considered range from existing policies such as production and investment tax credits to alternatives such as real estate investment trusts (REITs), feed-in tariffs (FiTs), master limited partnerships (MLPs), securitization [7], renewable portfolio standards (RPSs), carbon policies including Clean Energy Standards [8], cap and trade, economy-wide carbon intensity targets, and/or carbon taxes [9].

Grid extension will likely be a key enabler in a high RE future in the U.S. Streamlining siting and permitting [10] both for generation as well as transmission and distribution (T&D) would address some key market barriers [5].

Finally, policies and emerging technologies to promote more efficient and responsive demand will accelerate the energy transformation, both by reducing the scale of the requisite capacity additions, but also by reducing the scale of reserve generation capacity needed to balance variable RE. Regulatory approaches to incentivize both efficient and responsive demand have been demonstrated in the U.S. and abroad, and may include rate decoupling, real-time energy pricing, and cost recovery for EE additions.[4]

### 2.2. Markets and operations

Both electricity market design and power system operations will impact the power system transformation in power plant economics, power system flexibility, and generation adequacy, among others. Market and operational issues are broad, ranging from physics and fundamental power engineering, to portfolio approaches to hedge risk, to new ways of improving resource mapping and forecasting.

As an example, rules governing curtailment, energy imbalances, gate closures, ramping and scheduling could have a substantial impact on both RE and conventional generation project economics and revenue streams [11]. As penetrations of RE grow, regulators will need to examine these rules carefully to balance the competing concerns of consumers, industry, and other stakeholders, while ensuring a viable value proposition for key power system businesses.

Improving system flexibility through technology choice (e.g., fast ramp combined cycle gas plants), operations, and market function will also be a critical factor for integrating high penetrations of variable RE technologies [11]. Market design elements such as fast gate closure, widespread locational pricing, and demand-side bidding, are already in place in most energy markets in the US, and provide the foundation to incentivize flexible capability, but may be insufficient to ensure financial return for all actors.

Finally, RE futures are likely to adversely impact the project economics of many conventional thermal generators, which raises questions about appropriate mechanisms to ensure capacity adequacy under high-RE futures. Fortunately, various ISOs in the US [12]

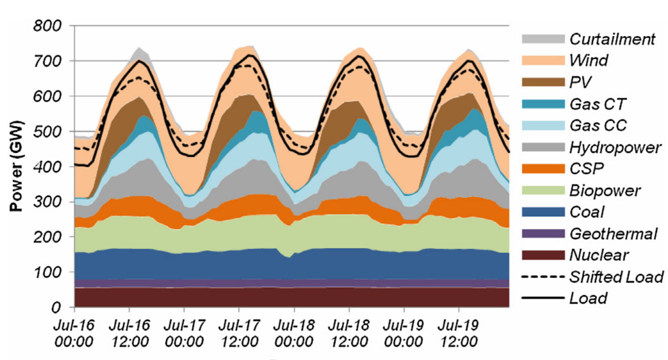


**Fig. 2.** U.S. nationwide dispatch by generator type during the annual peak coincident load in 2050 [1].

[4] See e.g., http://www.nrel.gov/docs/fy10osti/46606.pdf.

and abroad (including Alberta, Australia, the European Commission, and the UK [13]) are experimenting with solutions to the capacity adequacy question. Candidate solutions range from strategic reserve requirements to capacity payments to more market-based approaches such as capacity markets [14].

Across the spectrum of regulatory paradigms, significant changes are already underway. Some vertically-integrated systems are considering greater moves toward market-based mechanisms to support greater RE growth (i.e., Japan), while some highly deregulated systems are considering modifications to liberalized market structures to better coordinate planning for low-carbon systems (i.e., the UK). Thus, it would be inaccurate to presume that the pathway to achieving low-carbon power systems is *determined* by regulatory frameworks. Rather, they are dynamically evolving together [15]. Fundamentally, utility business models will similarly need to evolve.

### *2.3. Research and development*

The REF [1] notes, "… advancements in renewable technologies, reflected by cost and performance improvement assumptions, had the greatest impact on reducing the incremental cost of high renewable generation scenarios." Advancing our understanding and capabilities for system level integration, forecasting and operations, as well as "traditional" research and development (R&D) focus areas of improving technologies, will be important elements of realizing a high RE future. R&D in other emerging areas of energy include tight coupling with IT systems, cyber security, and links to other sectors such as transport, fuels and chemical sectors, and improved life-cycle emissions analysis [16]. R&D is also required on better models for system planning and improved operations. Likewise links to fundamental R&D such as atmospheric science will be required to help improve forecasting and resource modeling. Other possible areas for R&D include:

- Detailed technical analyses of power system reliability and resiliency.
- Comprehensive cost-benefit analyses to better understand the economic and environmental implications of high renewable electricity futures relative to the water sector [17].
- Improved understanding of the institutional and societal challenges associated with the integration of high levels of renewable electricity [18].
- Deeper understanding of supply and demand-side flexibility, including thermal generators, and flexible and controllable loads, in conjunction with sophisticated understanding of customer expectations and adaptability.

## 3. Conclusions

The Renewable Electricity Futures Study [1] demonstrates the resource adequacy of a largely renewable energy-based power system to meet 80% of all loads at the hourly level in the contiguous United States in the coming three to four decades. Creating an enabling environment that is effective, efficient, and adaptive to achieve such a sustainable energy future for the United States will likely require collaboration between policymakers and scientists.

Much of the required innovation spans numerous domains. Such cross-cutting innovation is not always aligned with current institutional structures. New ways of looking at multi-disciplinary research under headings such as energy systems integration may be one useful way to meet the needs of this changing landscape — both in terms of conducting research and training new researchers.

One item we did not highlight is the need for a national discourse on the interactions between the new abundance of natural gas — primarily from shale — and RE systems. How these two areas are considered will have major impacts for both in the power sector [19]. Ultimately, systems approaches will be the key to providing the best information for decision-making.

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## References

[1] National Renewable Energy Laboratory, in: M.M. Hand, S. Baldwin, E. DeMeo, J.M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, D. Sandor (Eds.), Renewable Electricity Futures Study, vol. 4, National Renewable Energy Laboratory, Golden, CO, 2012. NREL/TP-6A20-52409, http://www.nrel.gov/analysis/refutures/.

[2] ECF (European Climate Foundation), Roadmap 2050: a Practical Guide to a Prosperous, Low-carbon Europe, European Climate Foundation, The Hague, Netherlands, 2010. http://www.roadmap2050.eu/ (accessed 06.01.12).

[3] SRU (German Advisory Council on the Environment), Climate-friendly, Reliable, Affordable: 100% Renewable Electricity Supply by 2050, German Advisory Council on the Environment, Berlin, 2010.

[4] IPCC, in: O. Edenhofer, R. Pichs Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds.), Special Report on Renewable Energy Sources and Climate Change Mitigation: Final Release, Cambridge University Press, Cambridge, UK, and New York, 2011. http://srren.ipcc-wg3.de/report/IPCC_SRREN_Full_Report.pdf (accessed 28.01.12).

[5] J. Cochran, L. Bird, J. Heeter, D.A. Arent, Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience, Summary for Policymakers, National Renewable Energy Laboratory, Golden, CO, 2012. NREL/TP-6A20—53730, 20 pp.

[6] M. Bazilian, F. Roques (Eds.), Analytical Methods for Energy Diversity and Security: a Tribute to Shimon Awerbuch, Elsevier Global Energy Policy and Economics Series, Elsevier, Oxford, UK, and Amsterdam, 2008.

[7] M. Mendelsohn, D. Feldman, Financing U.S. Renewable Energy Projects through Public Capital Vehicles: Qualitative and Quantitative Benefits, National Renewable Energy Laboratory, Golden, CO, April 2013. TP-6A20-58315, 38 pp.

[8] EIA, Analysis of impacts of a clean energy standard as requested by Chairman Hall, Anal. Proj. (2011). http://www.eia.gov/analysis/requests/ces_hall/.

[9] L. Kitzing, C. Mitchell, P.E. Morthorst, Renewable energy policies in Europe: converging or diverging? Energy Policy 51 (2012) 192—201.

[10] P. Denholm, R.M. Margolis, Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States, Energy Policy 36 (9) (2008) 3531—3543.

[11] E. Ela, B. Kirby, E. Lannoye, M. Milligan, B. Zavadil, M. O'Malley, Evolution of operating reserve determination in wind power integration studies, in: Proceedings of IEEE Power and Energy Society General Meeting, Minneapolis, Minnesota, July, 2010.

[12] J. Pfiefenberger, Resource Adequacy and Capacity Markets: Overview, Trends and Policy Questions, The Brattle Group, Boston, MA, 2012.

[13] M. Miller, L. Bird, J. Cochran, M. Milligan, M. Bazilian, E. Denny, J. Dillon, J. Bialek, M. O'Malley, K. Neuhoff, RES-E-NEXT: Next Generation of RES-E Policy Instruments, International Energy Agency, Renewable Energy Technology Deployment, Paris, 2013.

[14] J. de Joode, P. Koutstaal, Ö. Özdemir, Financing Investment in New Electricity Generation Capacity in Northwest Europe, ECN-O-13-022, ECN, Petten, The Netherlands, 2013.

[15] FERC (Federal Energy Regulatory Commission), A National Assessment of Demand Response Potential, FERC, Washington, DC, 2009. http://www.ferc.gov/legal/staff-reports/06-09-demand-response.pdf (accessed 27.01.12).

[16] S.L. Dolan, G.A. Heath, life cycle greenhouse gas emissions of utility-scale wind power: Systematic review and harmonization, J. Ind. Ecol 16 (Suppl. 1) (April 2012) S136—S154, NREL Report No. JA-6A20-50213, http://dx.doi.org/10.1111/j.1530-9290.2012.00464.x.

[17] J. Macknick, R. Newmark, G. Heath, K.C. Hallet, A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, NREL/TP-6A20-50900, National Renewable Energy Laboratory, Golden, CO, 2011.

[18] E. Martinot, C. Dienst, L. Weiliang, C. Qimin, Renewable energy futures: targets, scenarios, and pathways, Annu. Rev. Environ. Resour. 32 (2007) 205—239.

[19] J. Logan, A. Lopez, T. Mai, C. Davidson, M. Bazilian, D. Arent, Natural gas scenarios in the U.S. power sector, Energy Econ. 40 (November 2013) 183—195.

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