Deep Decarbonization of the Electric Power Sector: Insights from the Recent Literature

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Introduction

- The electric power sector is expected to be the linchpin of efforts to reduce GHG emissions
- Many recent studies have explored pathways to "deep decarbonization" of the power sector, defined as 80-100% reduction in CO_2 emissions
- This review takes stock of several insights emerging from this recent literature

Approach

- Review and distill insights from 36 deep decarbonization studies all published since 2014
- Half depend exclusively on renewable energy sources to reach low carbon goals; other half harness additional technologies such as nuclear and CCS
- A subset of 15 multi-sector or economy-wide studies included in review

Studies Reviewed: Renewable Energy Only

Amorim, F. et al. **Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling**. Energy 69, 104–112 (2014).

Becker, S. et al. **Features of a fully renewable US electricity system: Optimized mixes of wind and solar PV and transmission grid extensions**. Energy 72, 443–458 (2014).

Cochran, J., Mai, T. & Bazilian, M. **Meta-analysis of high penetration renewable energy scenarios**. Renew. Sustain. Energy Rev. 29, 246–253 (2014).

Connolly, D. & Mathiesen, B. V. **A technical and economic analysis of one potential pathway to a 100% renewable energy system**. Int. J. Sustain. Energy Plan. Manag. 1, 7–28 (2014).

Connolly, D., Lund, H. & Mathiesen, B. V. **Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union**. Renew. Sustain. Energy Rev. 60, 1634–1653 (2016).

Fernandes, L. & Ferreira, P. **Renewable energy scenarios in the Portuguese electricity system**. Energy 69, 51–57 (2014).

Heal, G. **What would it take to reduce US greenhouse gas emissions 80% by 2050?** (2016).

Jacobson, M. . Z. et al. **A roadmap for repowering California for all purposes with wind, water, and sunlight**. Energy 73, 875–889 (2014).

Jacobson, M. Z. et al. **100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States**. Energy Environ. Sci. 8, (2015).

Jacobson, M. Z., Delucchi, M. A., Cameron, M. A. & Frew, B. A. **Low-cost solution to the grid reliability problem with 100 % penetration of intermittent wind , water , and solar for all purposes**. Proc. Natl. Acad. Sci. 112, 15060–15065 (2015).

Knorr, K. et al. **Kombikraftwerk 2**. (2014).

Lenzen, M. et al. **Simulating low-carbon electricity supply for Australia**. Appl. Energy 179, 553–564 (2016).

MacDonald, A. E. et al. **Future cost-competitive electricity systems and their impact on US CO2 emissions**. Nat. Clim. Chang. 6, 526–531 (2016).

Mai, T. et al. **Renewable Electricity Futures for the United States**. IEEE Trans. Sustain. Energy 5, 372–378 (2014).

Mai, T., Mulcahy, D., Hand, M. M. & Baldwin, S. F. **Envisioning a renewable electricity future for the United States**. Energy 65, 374–386 (2014).

Mathiesen, B. V. et al. **IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark**. (2015).

Pleßmann, G. & Blechinger, P. **How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050**. Energy Strateg. Rev. 15, 19–32 (2017).

Riesz, J., Vithayasrichareon, P. & MacGill, I. **Assessing 'gas transition' pathways to low carbon electricity – An Australian case study**. Appl. Energy 154, 794–804 (2015).

Studies Reviewed: Broader Set of Technologies

Akashi, O., Hanaoka, T., Masui, T. & Kainuma, M. **Halving global GHG emissions by 2050 without depending on nuclear and CCS**. Clim. Change 123, 611–622 (2014).
Bibas, R. & Méjean, A. **Potential and limitations of bioenergy for low carbon transitions**. Clim. Change 123, 731–761 (2014).
Boston, A. & Thomas, H. **Managing Flexibility Whilst Decarbonising the GB Electricity System** The Energy Research Partnership. (2015).
Brick, S. & Thernstrom, S. **Renewables and decarbonization: Studies of California, Wisconsin and Germany**. Electr. J. 29, 6–12 (2016).
de Sisternes, F. J., Jenkins, J. D. & Botterud, A. **The value of energy storage in decarbonizing the electricity sector**. Appl. Energy 175, 368–379 (2016).
Després, J. et al. **Storage as a flexibility option in power systems with high shares of variable renewable energy sources: A POLES-based analysis**. Energy Econ. (In press), (2016).
Elliston, B., MacGill, I. & Diesendorf, M. **Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market**. Renew. Energy 66, 196–204 (2014).
Frew, B. A., Becker, S., Dvorak, M. J., Andresen, G. B. & Jacobson, M. Z. **Flexibility mechanisms and pathways to a highly renewable US electricity future**. Energy 101, 65–78 (2016).
Kim, S. H., Wada, K., Kurosawa, A. & Roberts, M. **Nuclear energy response in the EMF27 study**. Clim. Change 123, 443–460 (2014).
Koelbl, B. S., van den Broek, M. a., Faaij, A. P. C. & van Vuuren, D. P. **Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise**. Clim. Change 123, 461–476 (2014).
Krey, V., Luderer, G., Clarke, L. & Kriegler, E. **Getting from here to there – energy technology transformation pathways in the EMF27 scenarios**. Clim. Change 123, 369–382 (2014).
Kriegler, E. et al. **The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies**. Clim. Change 123, 353–367 (2014).
Mileva, A., Johnston, J., Nelson, J. H. & Kammen, D. M. **Power system balancing for deep decarbonization of the electricity sector**. Appl. Energy 162, 1001–1009 (2016).
Morrison, G. M. et al. **Comparison of low-carbon pathways for California**. Clim. Change 131, 545–557 (2015).
Safaei, H. & Keith, D. W. **How much bulk energy storage is needed to decarbonize electricity?** Energy Environ. Sci. 8, 3409–3417 (2015).
Sithole, H. et al. **Developing an optimal electricity generation mix for the UK 2050 future**. Energy 100, 363–373 (2016).
White House. **United States Mid-Century Strategy for Deep Decarbonization**. (2016).
Williams, J. H. et al. **Pathways to deep decarbonization in the United States**. (2015).

Insights

1. The power sector must cut CO_2 first and furthest while expanding to electrify other sectors

- Economy-wide studies all envision electricity supplying greater shares of heating, industry, and transportation energy demand by 2050
- Achieved either by direct electrification of end-uses or by producing electrolytic hydrogen or synthetic natural gas
- Finding affordable and feasible routes to decarbonize the power sector thus has outsized importance in global climate mitigation

Insights

2. Deep decarbonization is more difficult, and requires a different technology mix, than more modest CO_2 reductions

- Reducing power sector CO_2 emissions by one-half to two-thirds can be readily achieved, while reaching zero emissions necessitates rapid expansions of zero-carbon resources
- Lowest-cost portfolio suited to moderate emissions reductions may differ from portfolio suited to deep decarbonization
- If power generation resources are built without considering long-term objectives, costly "lock-in" of a sub-optimal portfolio is possible

Insights

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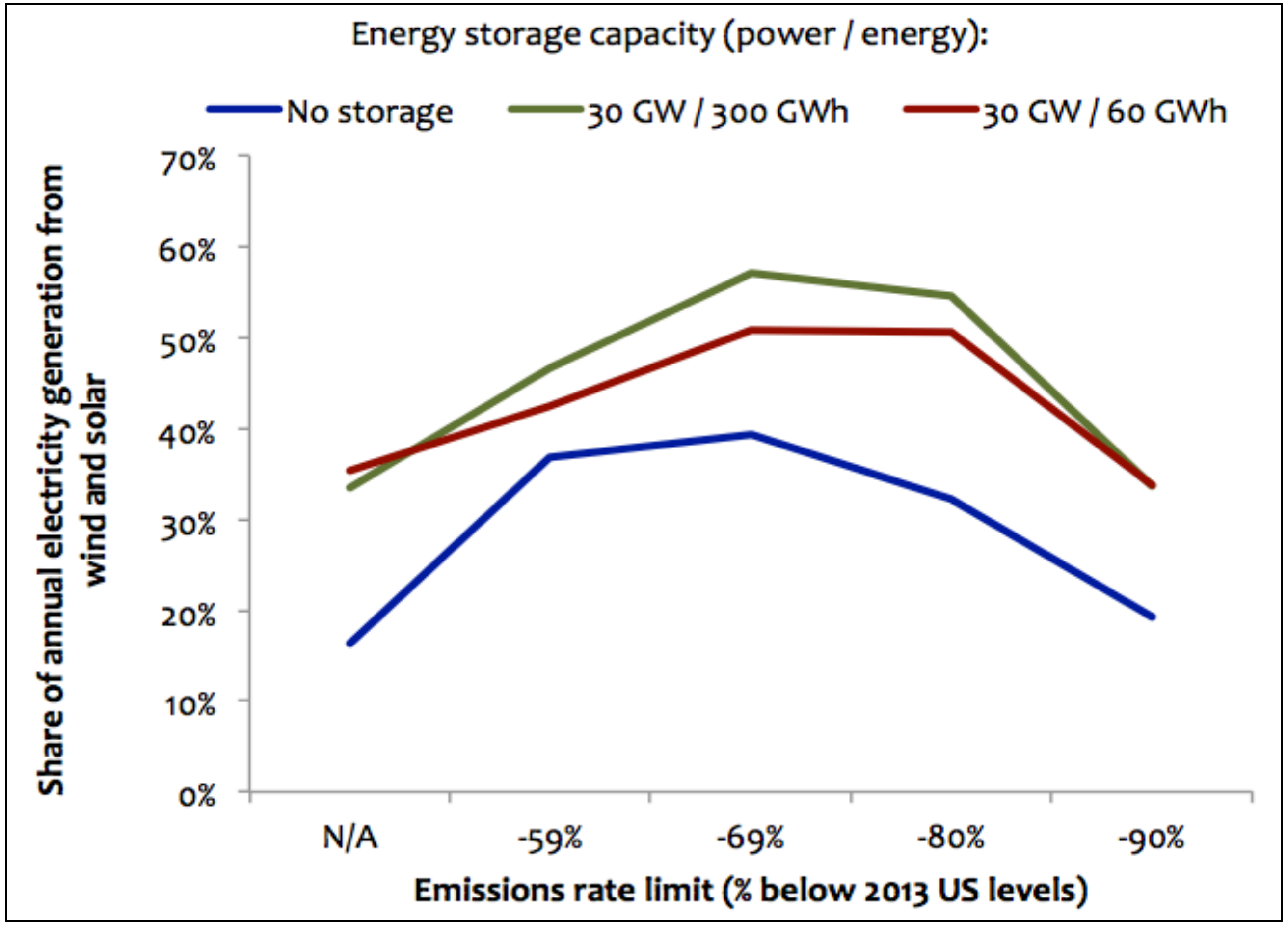

Data from de Sisternes et al. (2016)

Insights

3. Deep decarbonization is possible with RE alone, but challenges rise steeply as RE penetration approaches 100%

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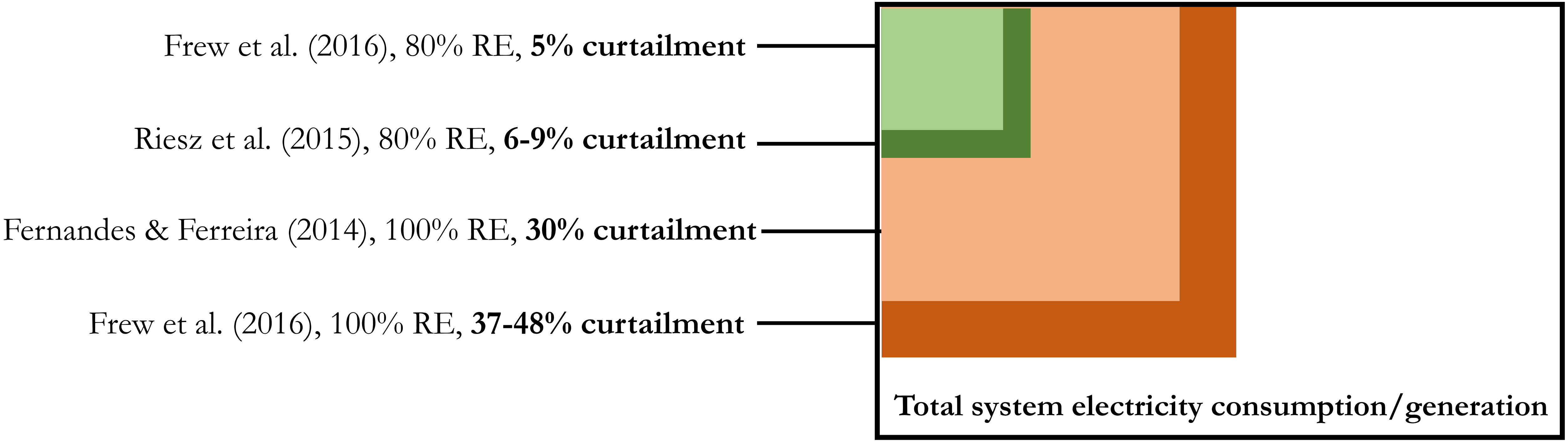
- Very high shares of wind and solar entail significant curtailment of excess renewable energy—even with energy storage, transmission, or demand response



Insights

3. Deep decarbonization is possible with RE alone, but challenges rise steeply as RE penetration approaches 100%

- Most wind and solar-heavy power systems include “shadow systems” of dispatchable power capacity to ensure demand can be met at all times
- Scenarios that do not rely upon such “shadow systems” must instead rely on long-duration seasonal energy storage (not battery storage)

Insights

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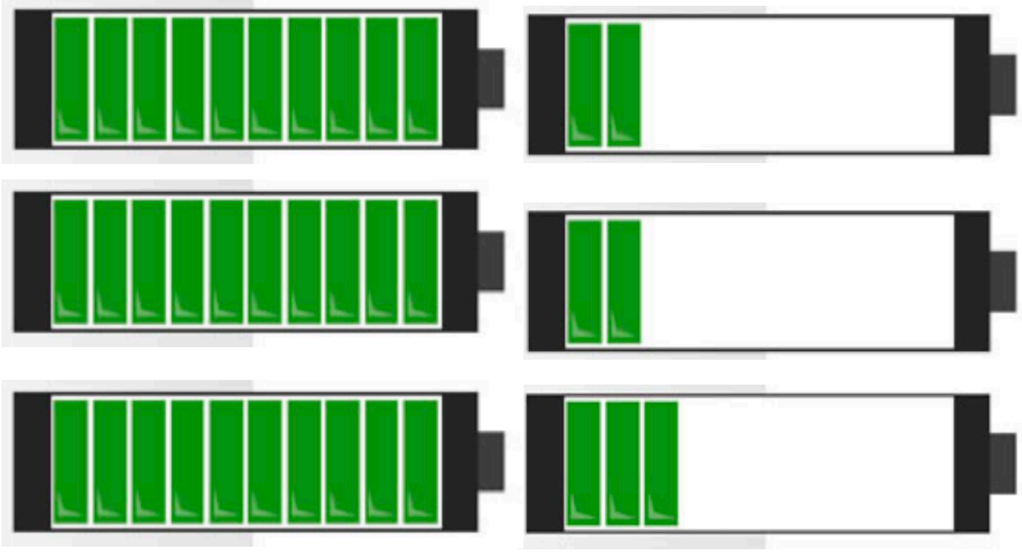
One week's worth of U.S. electricity consumption (for reference)

Eight weeks' worth of U.S. electricity consumption (Becker et al. 2014, low end)



12 weeks' worth of U.S. electricity consumption (Becker et al. 2014, high end)

12 weeks' worth of U.S. electricity consumption (Jacobson et al. 2015, low end)

13 weeks' worth of U.S. electricity consumption (Jacobson et al. 2015, high end)

Insights

3. Deep decarbonization is possible with RE alone, but challenges rise steeply as RE penetration approaches 100%

- High renewable energy scenarios also envision a significant expansion of long-distance transmission
  - ❖ Mai et al. (2014): 56-105% increase in U.S. long-distance transmission capacity
  - ❖ MacDonald et al. (2016): 20,000 miles of new HVDC transmission in U.S.
  - ❖ Pleßmann & Blechinger (2017): 4.5-fold increase in transmission interconnection between E.U. regions
  - ❖ Knorr et al. (2014): 27,500 kilometers of HVDC transmission in Germany

Insights

4. A diversified portfolio of low-carbon resources offers the best chance of affordably decarbonizing the power system

- Costs of systems utilizing only RE rise steeply as RE approaches 100%
- Decarbonization scenarios that harness more diverse portfolios are less costly
  - ❖ Brick and Thernstrom (2016): Portfolios including RE, nuclear, and CCS cost 68-75% less than renewables-centric systems in Wisconsin, California, and Germany
  - ❖ Williams (2015): High-RE pathway for deep decarbonization of the U.S. costs 1.6 times more than a diversified low-carbon portfolio
  - ❖ Mileva et al. (2016) and de Sisternes et al. (2016): Scenarios including dispatchable low-carbon resources reach deep decarbonization goals at lower cost than those relying primarily on wind and solar

Summary

- Despite a wide variety of analytical methods, goals, and scopes, there is strong agreement that a diversified mix of low-carbon resources offers the best chance of affordably decarbonizing the power system
- Dispatchable low-carbon resources appear to be a virtually indispensable part of the most affordable pathways to zero or near-zero CO_2 emissions