Designing future research for sustainable energy systems

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Jill Engel-Cox, Ph.D.

Senior Research Advisor, NREL

and WPI Visiting Professor, Kyushu University

Photo by Jill Engel-Cox

Contents

Metrics for sustainable energy

Global Energy Metrics

Sustainable Development Goal (SDG) 7: Ensure access for all to energy that is:

- affordable — *unit cost related to income*
- reliable — *hours accessible*
- modern — *% population with electricity & clean fuels*
- sustainable — *renewable? clean? advanced? net-zero?* *economy? society? environment?*

Source: Engel-Cox, J. and A. Chapman. (2023), Accomplishments and challenges of metrics for sustainable energy, population, and economics as illustrated through three countries. Frontiers in Sustainable Energy Policy, Volume 2. https://doi.org/10.3389/fsuep.2023.1203520

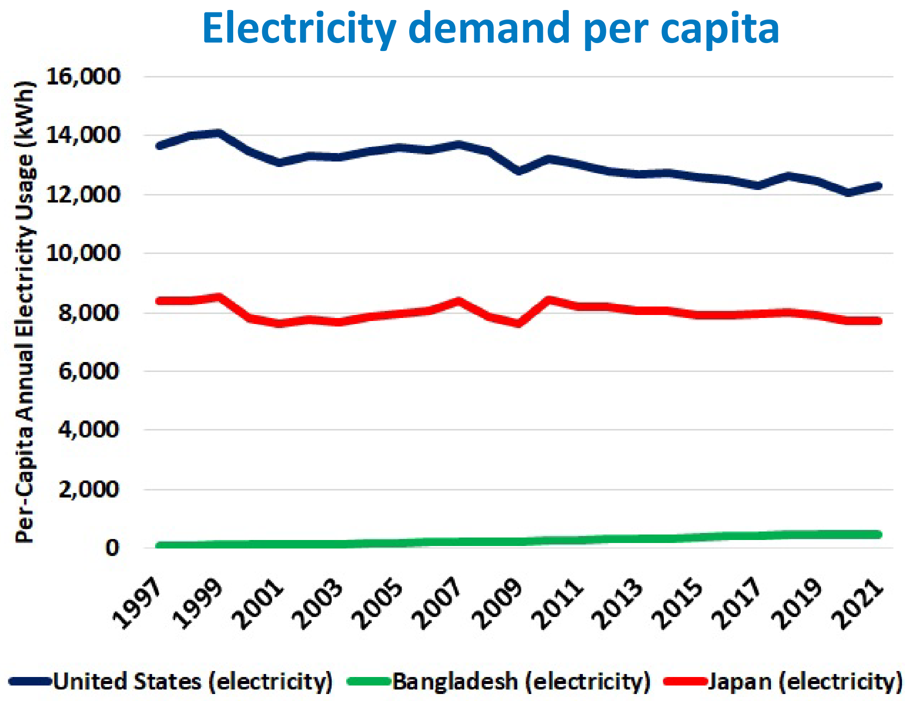
Definitions and metrics are not agreed upon

- **Renewable energy**:
  - Energy sources that do not deplete within the timeframe of human civilizations
  - Solar, wind, geothermal, and usually biomass and hydropower
  - Goals defined by production levels (e.g., MWh) and not GHG emissions
- **Zero GHG (carbon-free) energy**:
  - Produced from sources that do not significantly generate CO_2 and other GHG
  - All renewable energy + nuclear energy
  - Goals measured by emissions from power generation and sometimes upstream/downstream life-cycle
- **Net-zero energy**:
  - Zero GHG energy and allows offsetting GHG emissions by other methods
  - Renewable + nuclear + combustion of fuels with carbon capture
  - Also direct air capture + nature-based carbon sinks, such as reforestation or regenerative agriculture
- **Clean energy :**
  - Implies low levels of all types of pollution, GHG, water use, other negative environmental impacts
  - Usually some combination of renewable energy + net-zero GHG energy

None of these fully measure sustainability for the environment, economics, and society

Source: Engel-Cox, J.A. and Geocaris, M. (2023), Future Low-Carbon Technology Options for a 100 Percent Decarbonized Power Sector. Climate and Energy, 39: 1-10. https://doi.org/10.1002/gas.22333

Illustrate challenge through three countries



- **United States**: flat to declining energy consumption and high energy access with a slightly increasing population and moderate economic growth rate
- **Japan**: declining energy consumption and high energy access with declining population and low economic growth rate
- **Bangladesh**: increasing energy consumption and low energy access with a growing population and high economic growth rate

Source: Engel-Cox, J. and A. Chapman. (2023), Accomplishments and challenges of metrics for sustainable energy, population, and economics as illustrated through three countries. Frontiers in Sustainable Energy Policy, Volume 2. https://doi.org/10.3389/fsuep.2023.1203520

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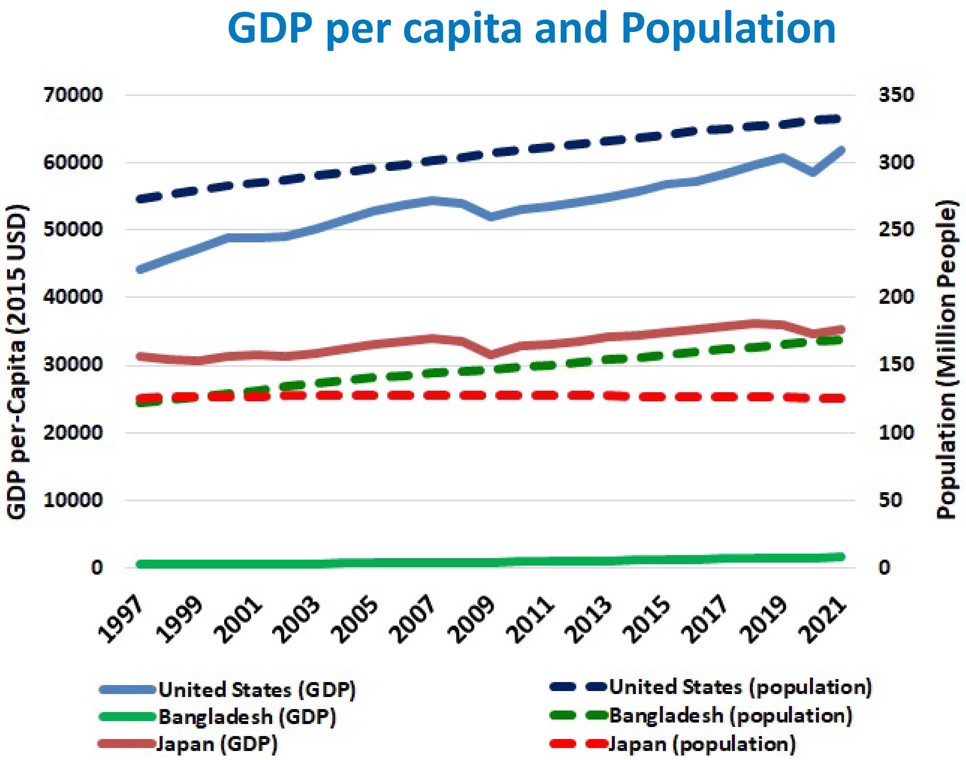

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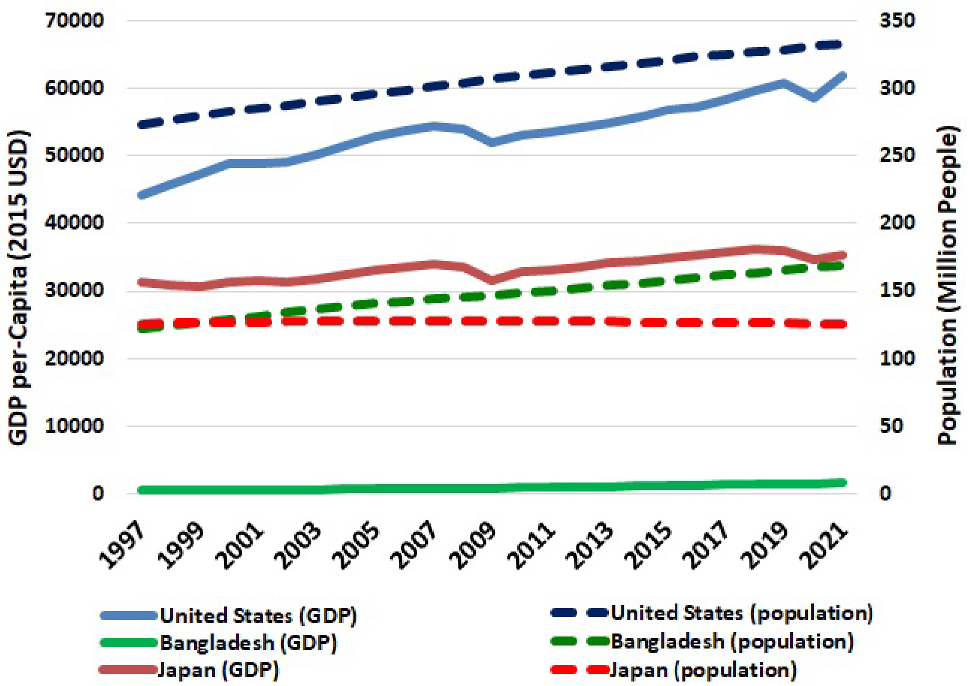
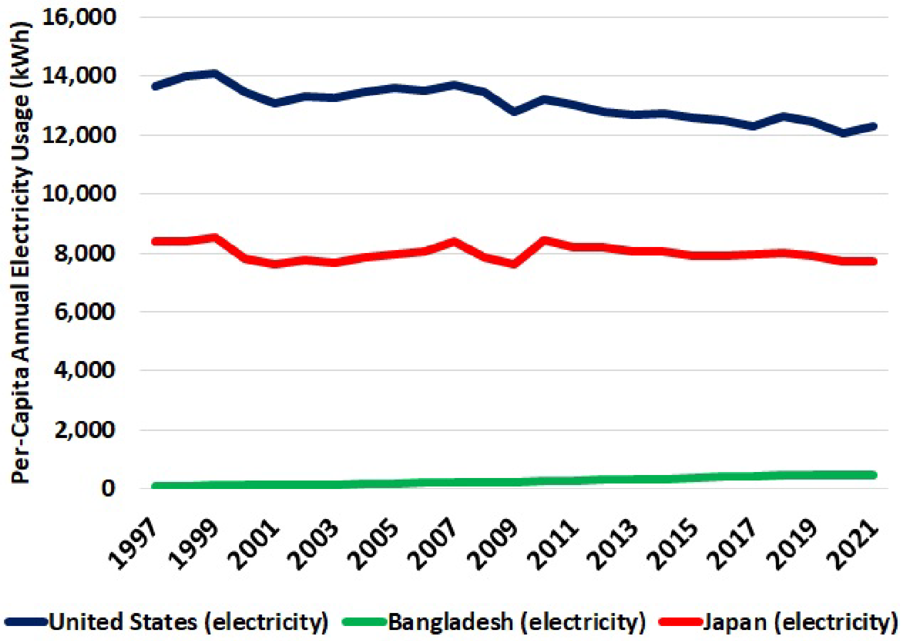
Which country is more “sustainable”?





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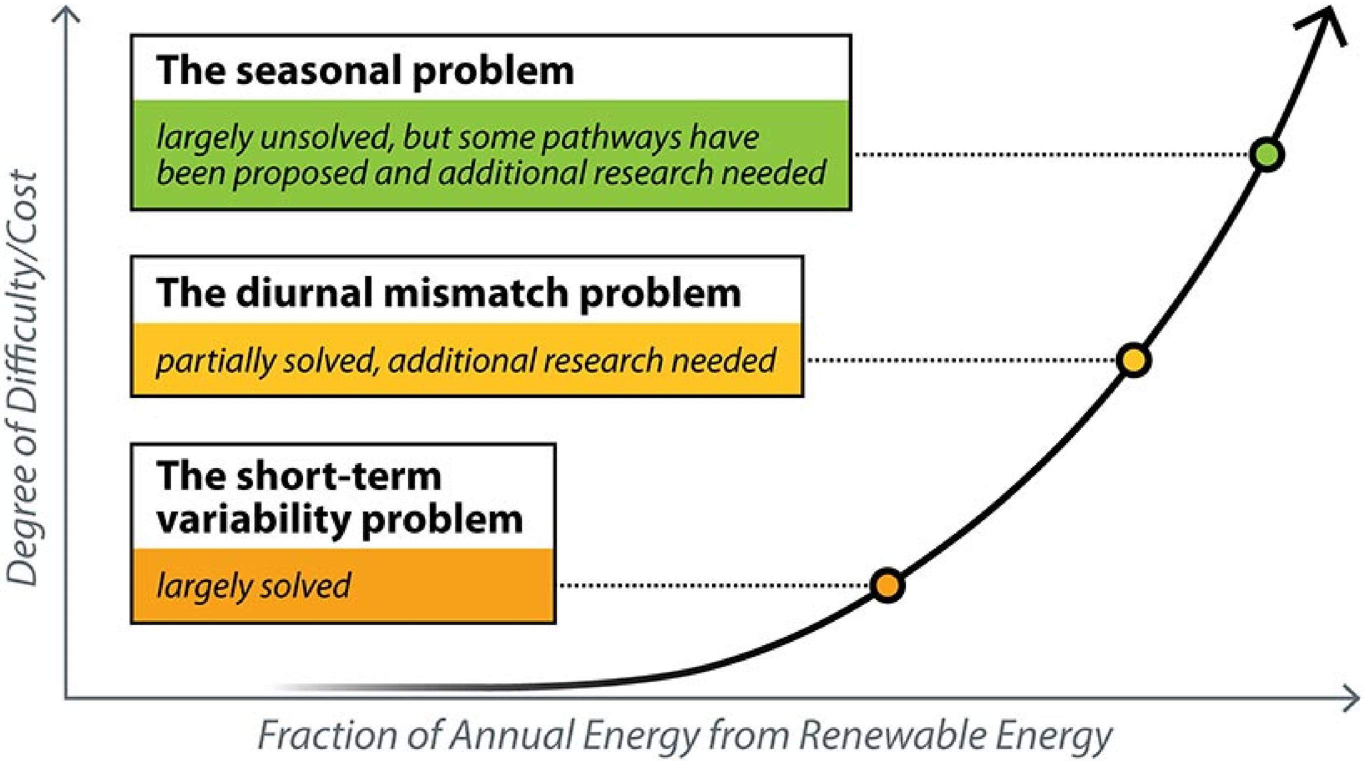
Sustainable energy metrics research questions

- **Energy per capita by country**: What is the optimal level of energy use per capita for each country for a decent quality of life?
- **Sustainable global energy demand**: What is the absolute global human energy demand that is sustainable for the planet?
- **Energy with population decline**: How can societies manage an energy transition with a stable or declining population?
- **General approaches from diverse countries:** What generalizable approaches for sustainable energy could be used across cultures?

Source: Engel-Cox, J. and A. Chapman. (2023), Accomplishments and challenges of metrics for sustainable energy, population, and economics as illustrated through three countries. Frontiers in Sustainable Energy Policy, Volume 2. https://doi.org/10.3389/fsuep.2023.1203520

Research for 100% decarbonized energy systems

Seasonal demand and supply variability challenging as systems approach 100% inverter-based renewables



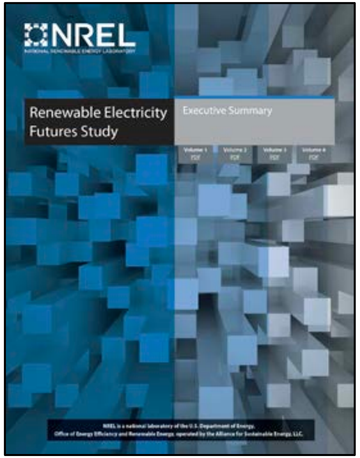
~6 countries have reached 100% renewable electricity primarily through geothermal and hydropower

More difficult (cost, technically) to reach that last 10% with variable inverter-based power such as solar and wind

Total energy an even greater challenge

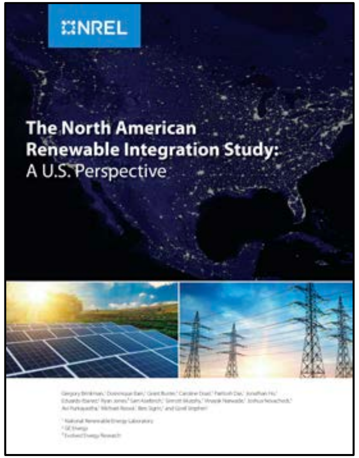
Source: Engel-Cox, J.A. and Geocaris, M. (2023), Future Low-Carbon Technology Options for a 100 Percent Decarbonized Power Sector. Climate and Energy, 39: 1-10. https://doi.org/10.1002/gas.22333

Many studies; focus on example of 100% by 2035



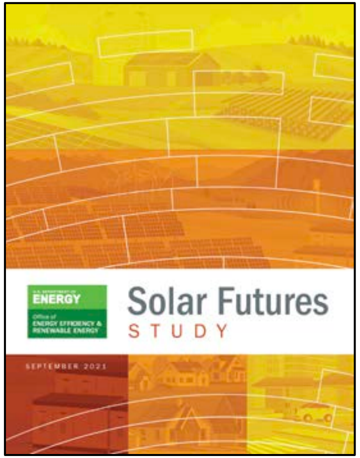
Renewable Electricity Futures Study (2012)

80% RE by 2050



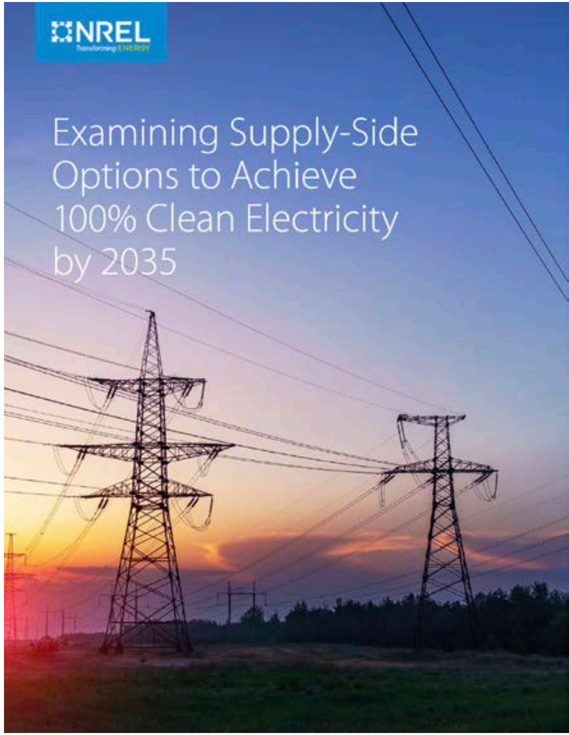
North American Renewable Integration Study (2021)

80% decarbonized by 2050



Solar Futures Study (2021)

100% decarbonized by 2050

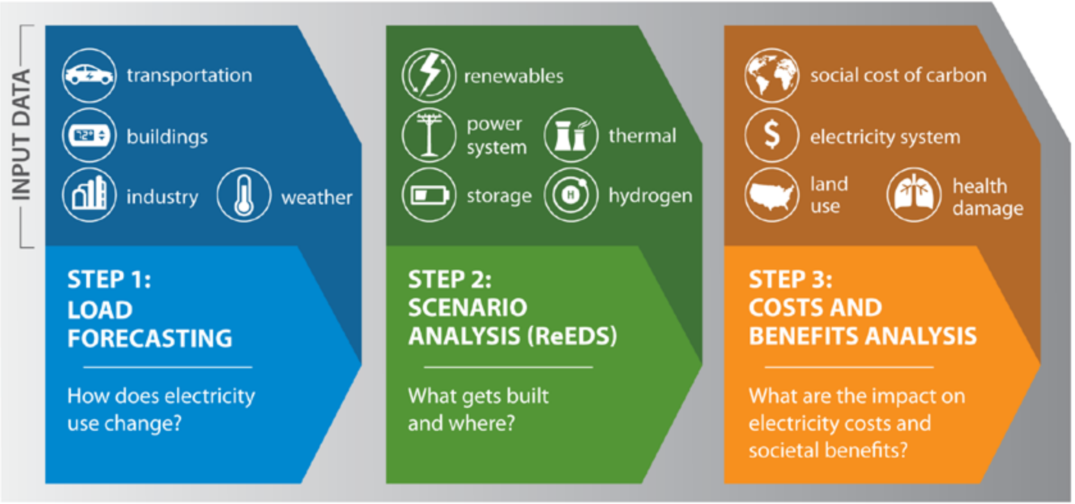


100% decarbonized by 2035

+ electrification trajectory consistent with net zero economy-wide by 2050

Credit for slides in this section to Paul Denholm, Trieu Mai, and colleagues. Access full report, data files, results infographics: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

100% clean energy requires modeling multiple systems



Regional **E**nergy **D**eployment **S**ystem Model

ReEDS

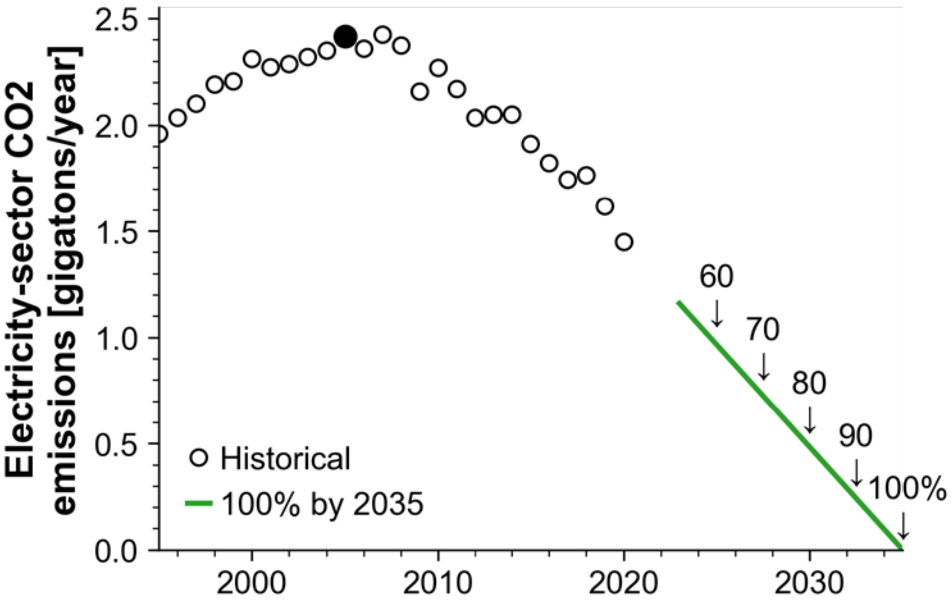
https://www.nrel.gov/analysis/reeds/

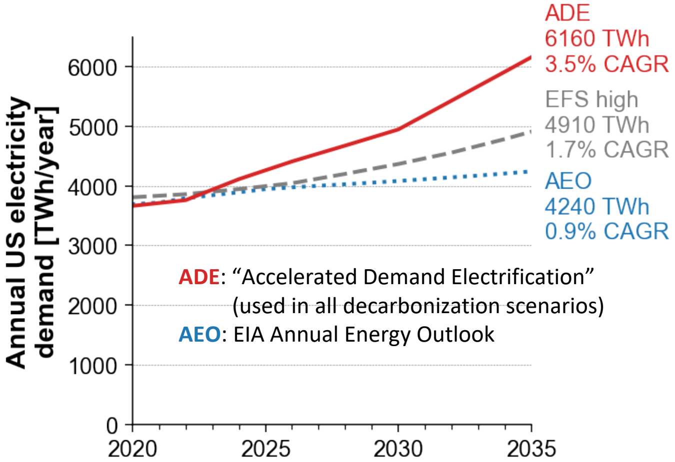
	All options	Infrastructure	Constrained	No CCS
RE siting	Reference	Reference	**Limited**	Reference
CCS	Ref **+ DAC**	Ref (CCS/BECCS)	Ref (CCS/BECCS)	**No CCS**
Transmission	Reference	**+ HVDC macrogrid**	**No interregional; 5× cost**	Reference
Other	Reference	**Lower** H_2, CO_2, bio transport & storage adders	**Higher** H_2, CO_2, bio transport & storage adders	Reference

+ many sensitivities (146 total scenarios)

Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

Finding 1. The challenge is to fully decarbonize the electricity system while meeting new and changing demand from electrified loads

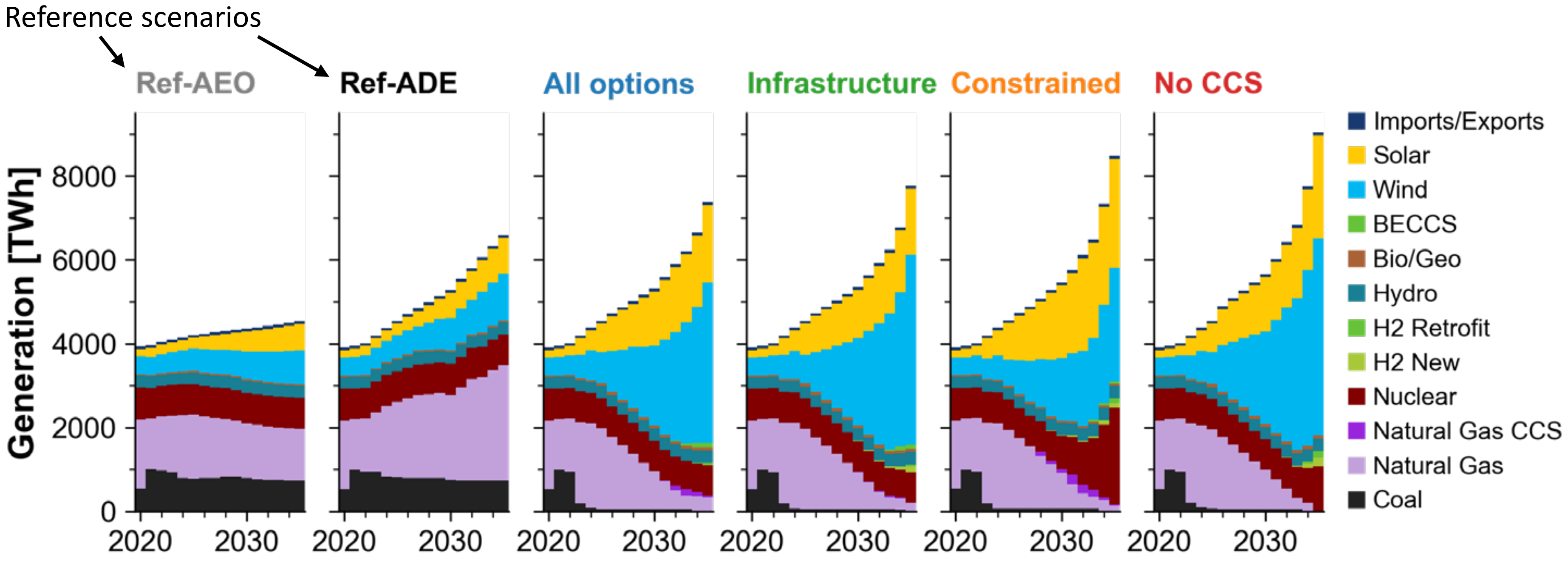




% Reduction from 2005	Electricity Emissions	Energy Emissions
2020 Historical	40%	24%
2035 Ref-AEO	52%	24%
2035 Ref-ADE	31%	37%
2035 Target	100%	65%

Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

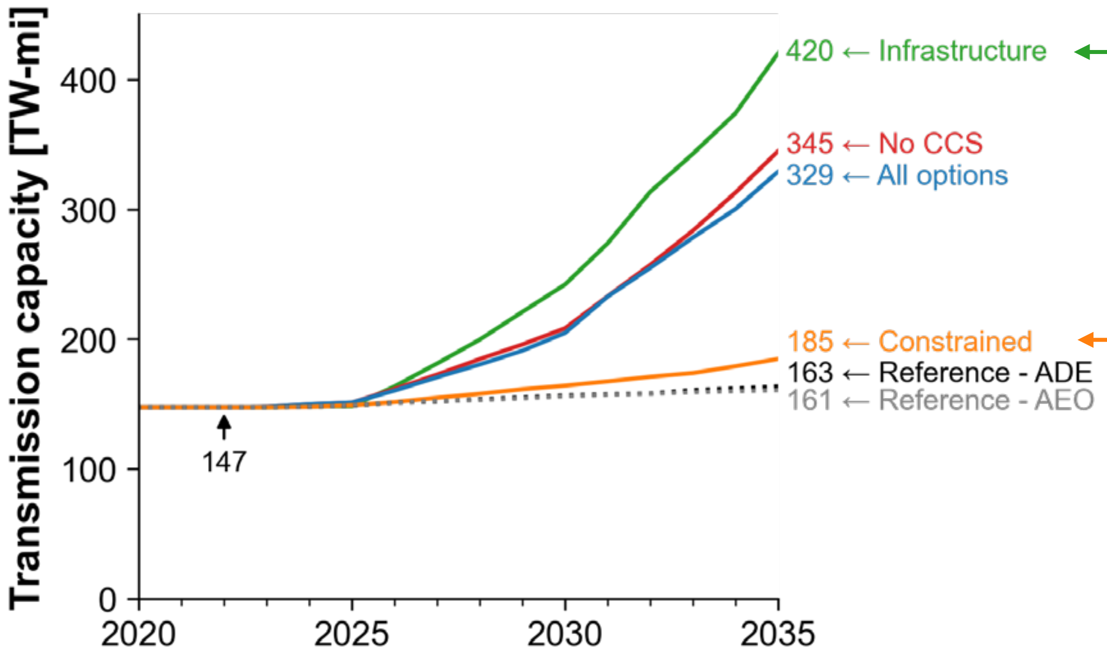
Finding 2. Decarbonizing the grid while setting the economy on the path to net-zero emissions will require massive development of clean energy resources—particularly wind and solar



Requires 4-5X annual deployment of wind and 3X solar (compared to 2020)

Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

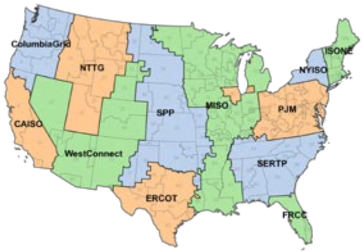
Finding 3. Transmission expansion (mainly for wind) and growth in energy storage (mainly for solar) are important enablers for a low-carbon grid



High-voltage inter-zonal transmission only

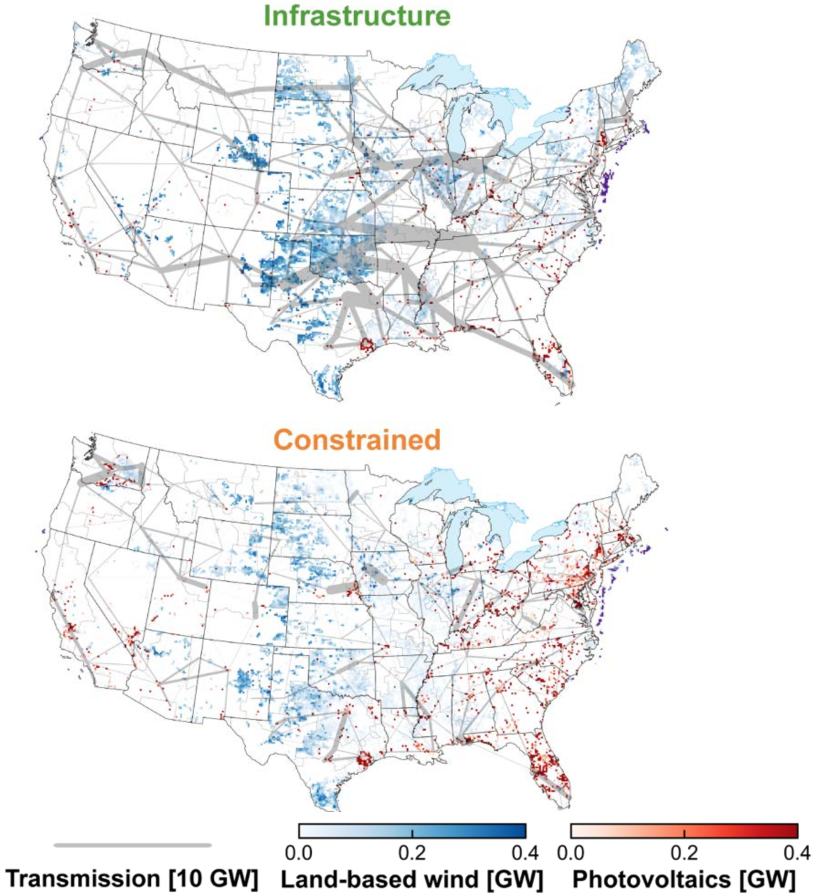
Multi-terminal HVDC macrogrid

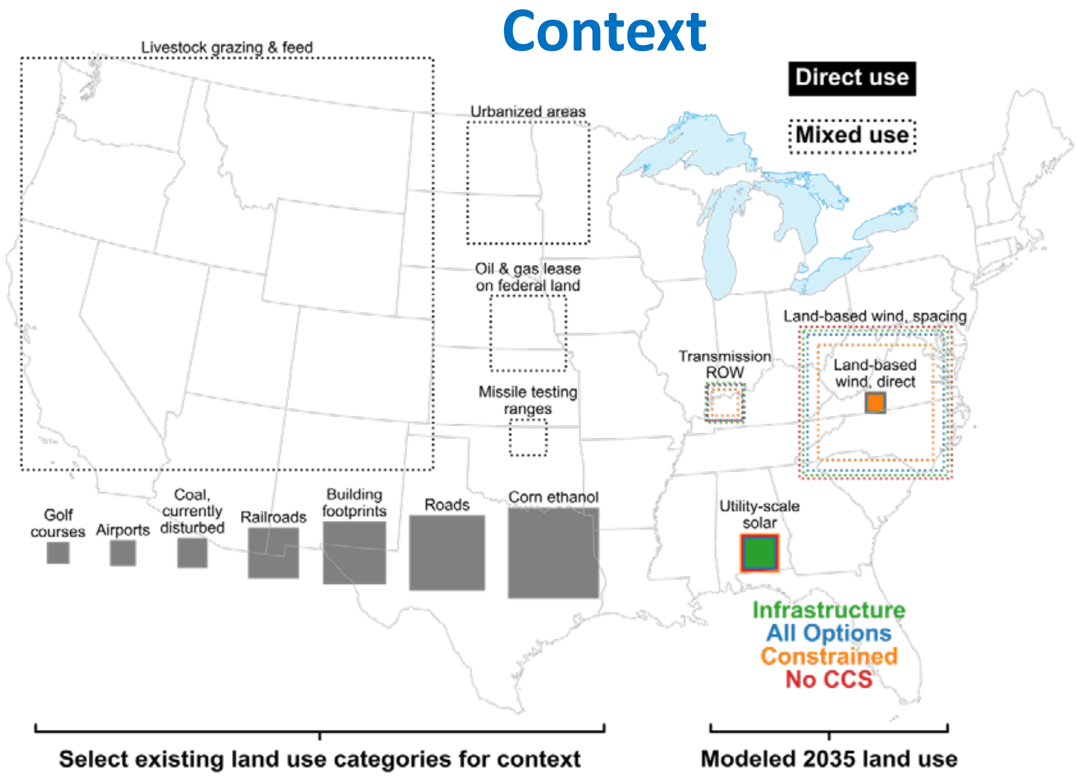
5× transmission cost, No interregional (defined by FERC Order 1000 regions)



Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

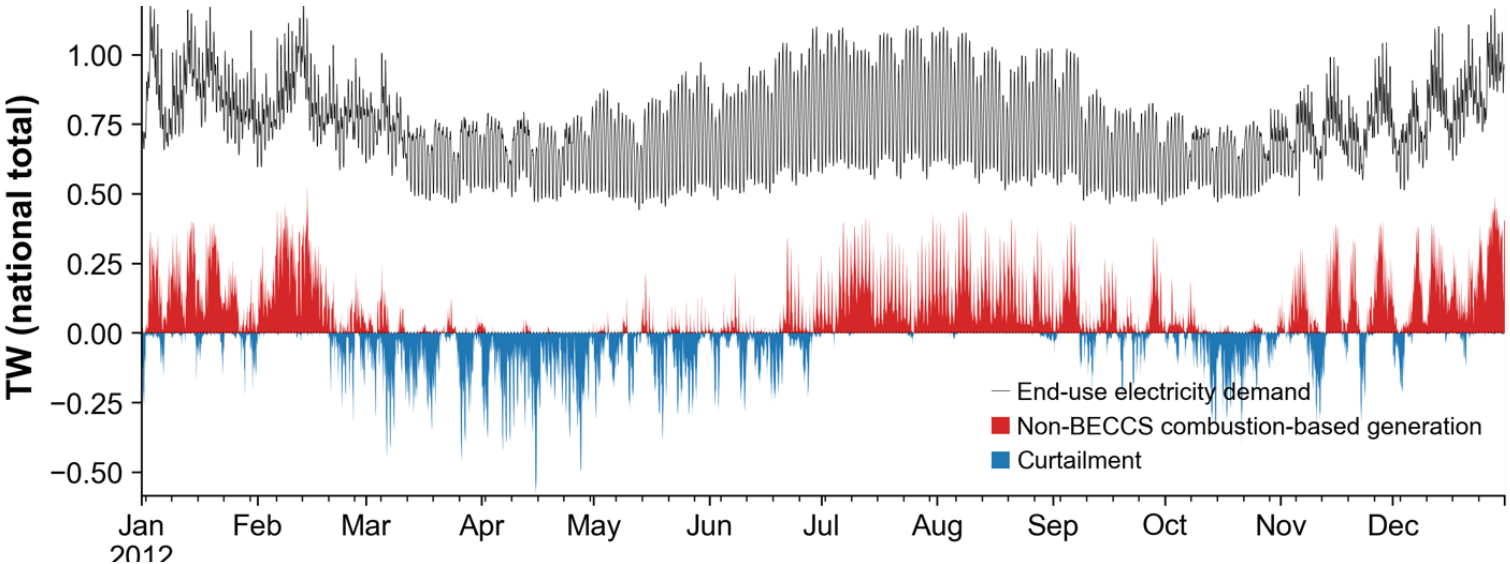
Finding 4. Achieving the clean energy deployment levels to reach 100% requires special attention to land use, siting, and other local factors





Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

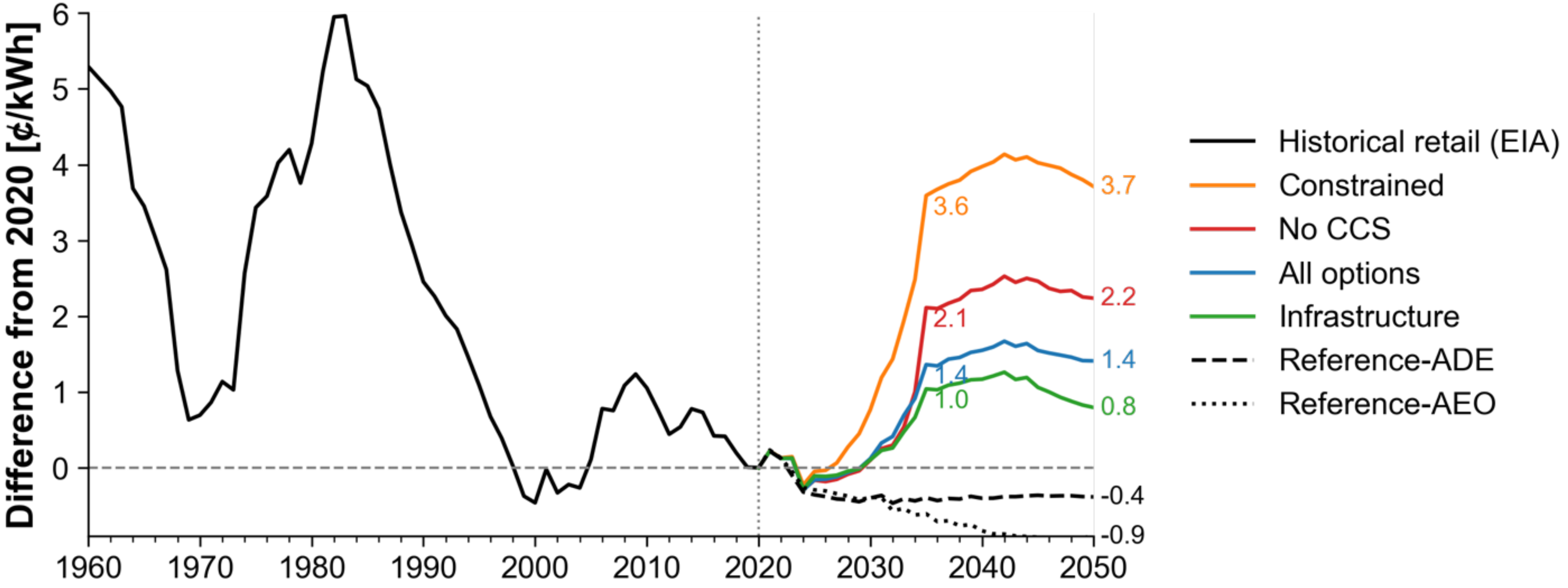
Finding 5. Getting to 100% requires overcoming the seasonal imbalance challenge, but we don't yet know the optimal technology pathway



The seasonal supply/demand balance for the contiguous United States in the All Options scenario (ADE demand case) in 2035 shows the seasonal mismatch challenge.
Demand met by fossil- and hydrogen-fueled resources (red) occurs largely during periods of relatively low wind and solar output, or periods of very high electricity demand. The supply of wind and solar generally exceeds demand resulting in curtailment (blue) in the spring and fall, often for continuous periods.

Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

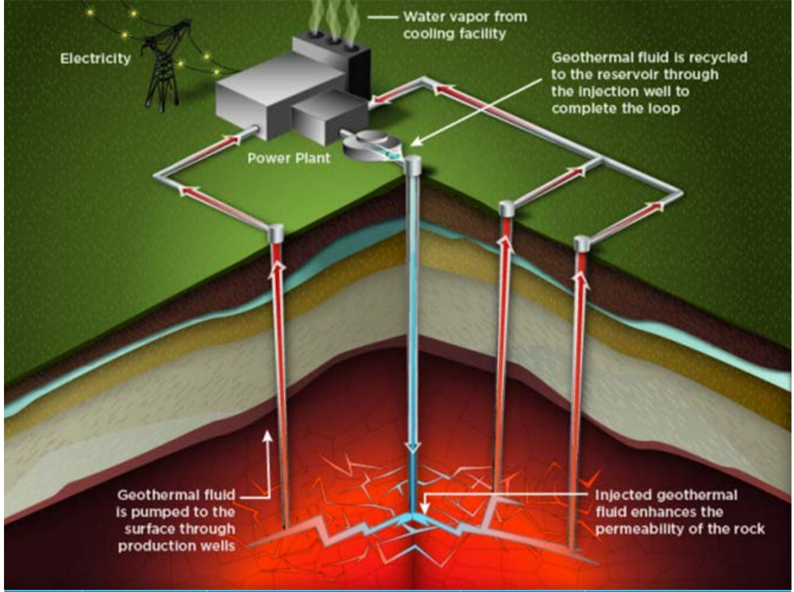
Finding 6. Direct electricity system costs increase in the 100% scenarios, but these increases are well within the range of historical retail price fluctuations

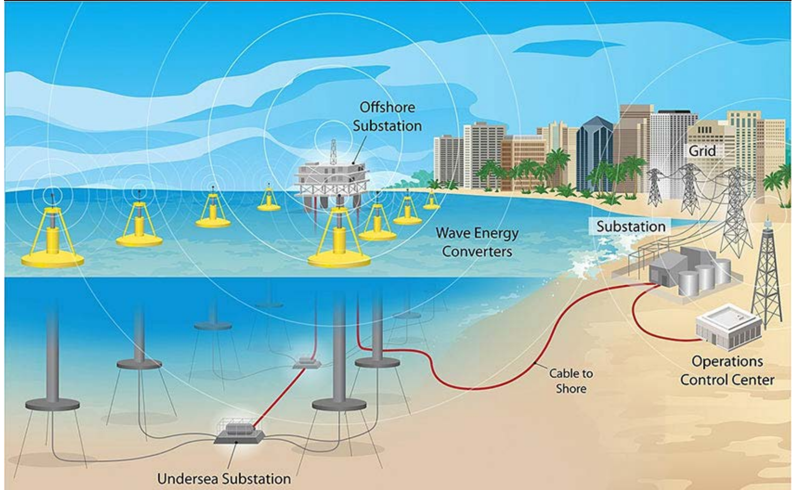


Source: https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.

Technology research needs: Renewable energy technologies with less variability + Storage

- Enhanced/Advanced Geothermal Systems
  - Dry hot rock + injected/piped fluid for heat and electricity
- Subsurface storage
  - Compressed air or gas storage
  - Heat storage
- Water energy
  - Ocean energy (wave and tidal)
  - Powering of retention dams
- Green hydrogen and other fuels
- High capacity batteries

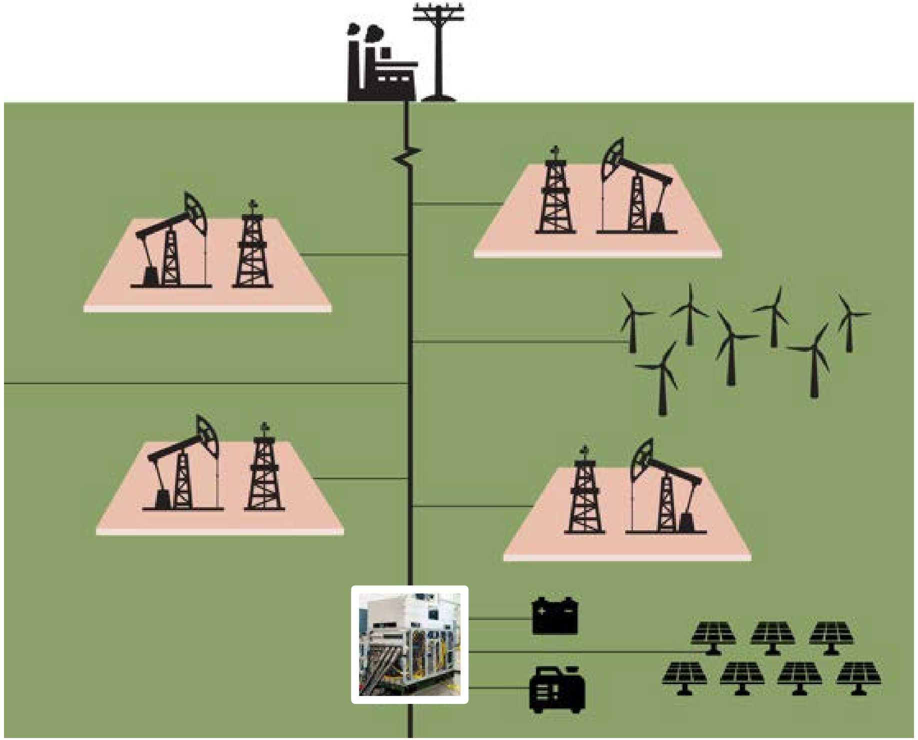




Source: NREL, https://www.nrel.gov/geothermal/sedimentary-egs.html ;
A. Hicks, https://www.nrel.gov/water/wave-array.html

Technology research needs: Dynamic two-way distributed energy resources (DERs) and Virtual Power Plants (VPPs)

- Distributed energy
  - Multiple inter-connected energy generators near demand
  - Increased resiliency and cost savings
  - Community, campus, and industry scales
- Virtual power plants
  - Bundling and coordinated operation of small private energy generation and storage sources
  - Co-benefits to consumer, utility, and coordinator



Source: https://www.nrel.gov/docs/fy19osti/72842.pdf

Deployment research needs: Improved landuse for wind/PV with co-benefits

"Agrivoltaics"

"Floatovoltaics"

Source: NREL, https://images.nrel.gov/

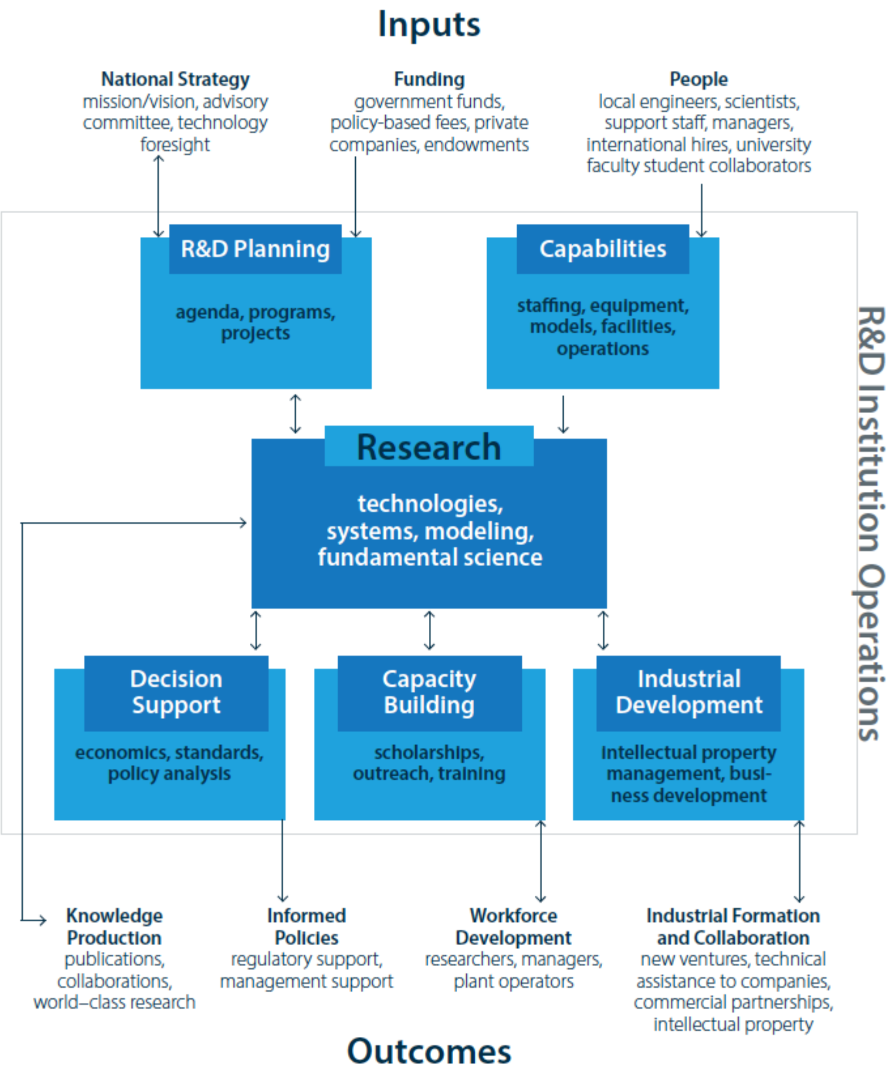
Sustainable energy analysis and technology research topics

- **Modeling and analysis:** For 100% renewable/clean power, need to address…
  - Costs increase as approach 100%
  - Possible significant growth in demand from electrification
  - Expected increase in weather and climate variability
  - Generation mismatch at various timescales (hourly, seasonally)
  - Social and land-use constraints in technology acceptance, transmission, and trade
  - Definitional issues, such as inclusion of nuclear, large hydropower, and carbon capture
- **Technology Solutions**: Achieving 100% clean/renewable energy will involve a combination of technologies, existing and new, so on-going research needed
- **Anticipate and Mitigate:** All energy transitions have positive and negative effects so important to look for potential downsides and find proactive solutions.
- **Community Acceptance**: Siting and social acceptance of large-scale deployment of energy technologies and their supporting grid infrastructure must be addressed
- **Multiple Scenarios**: Solution to reach 100% <goal> energy systems will be based on state/national infrastructure, resources, and social acceptance (no one solution for all)

Principles for new research institutions

Designing a new research program

Operational inputs and outcomes



Source: Engel-Cox, J.. (2024), Creating the National Renewable Energy Laboratory: Implications for New National Energy Research Institutes, NREL/BK-5C00-87774. https://www.nrel.gov/docs/fy24osti/87774.pdf

Designing a new research program

Key principles

- Start with a clear and enduring mission, then build a research agenda to meet that mission
- Learn from other organizations and adapt to local context
- Expect decades of development time to reach objectives
- Plan for flexibility and resilience in the mission, research, and operations
- Achieve sustained commitment from primary sponsors and stakeholders
- Develop highly talented and diverse human capital

Source: Engel-Cox, J.. (2024), Creating the National Renewable Energy Laboratory: Implications for New National Energy Research Institutes, NREL/BK-5C00-87774. https://www.nrel.gov/docs/fy24osti/87774.pdf

Summary and Conclusions

- **Metrics:** Research needed into better sustainability metrics for…
  - Energy per capita by country
  - Sustainable global energy demand
  - Energy with population decline
  - General approaches from diverse countries
- **Technologies:** For 100% renewable/clean power, research and analysis needs to address…
  - Systems with a combination of technologies and multiple scenarios
  - Unknown growth from demand from electrification, efficiency, and population changes
  - Technology and community acceptance
  - Definitional issues, such as inclusion of nuclear, large hydropower, and carbon capture
- **Research Institutions:** New research programs thrive with…
  - Clear mission
  - Collaboration
  - Flexibility
  - Talented diverse researchers and staff

Photo by Jill Engel-Cox

Thank you! Questions?

You are welcome to connect with me on LinkedIn!
Email: jill.engelcox@nrel.gov

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