Electrification Futures Study: Power Systems Operation with Newly Electrified and Flexible Loads

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Study sponsored by U.S. DOE-EERE Strategic Analysis

NREL-led collaboration, multi-year study

NATIONAL RENEWABLE ENERGY LABORATORY

EVOLVED ENERGY RESEARCH

NORTHERN ARIZONA UNIVERSITY

OAK RIDGE National Laboratory

U.S. DEPARTMENT OF ENERGY

- Technology cost and performance (December 2017)
- Demand-side adoption scenarios (June 2018)
- dsgrid model documentation (August 2018)
- Methodological approaches (July 2020)
- Supply-side evolution scenarios (January 2021)
- Electricity system operations (May 2021)

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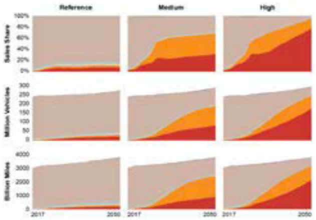
EFS Scenario Analysis Phases

End-Use Technology Adoption:

Demand-Side Scenarios

- EnergyPATHWAYS stock turnover and energy accounting model
- ADOPT vehicle choice model



2016 – 2050 demand

Power System Evolution:

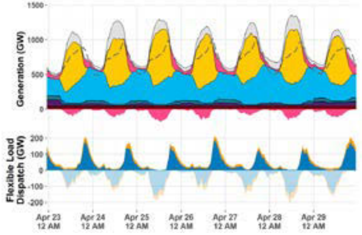
Supply-Side Scenarios

- ReEDS capacity expansion model
- dGen rooftop photovoltaic adoption model

2050 capacity

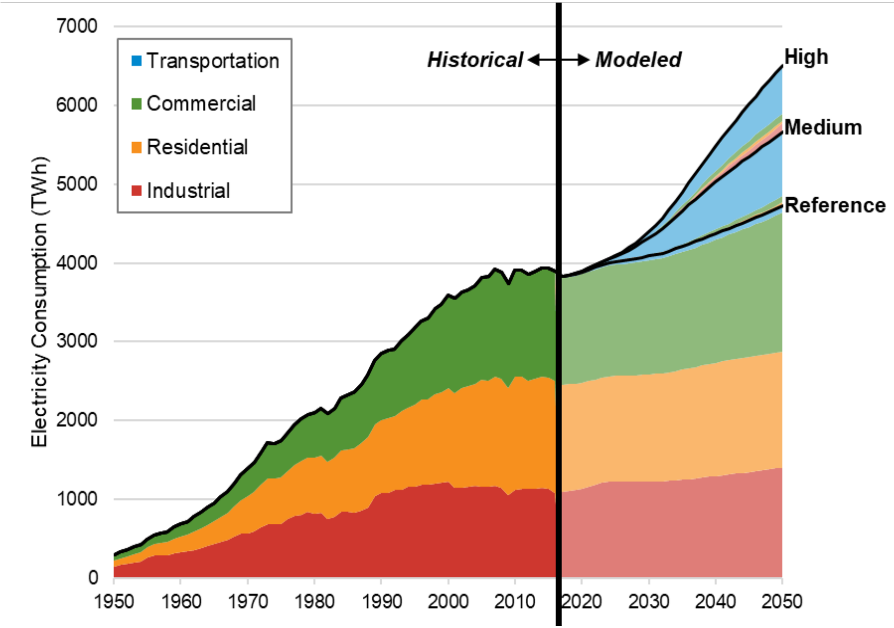
2050 Grid Operation Analysis

- PLEXOS production cost model

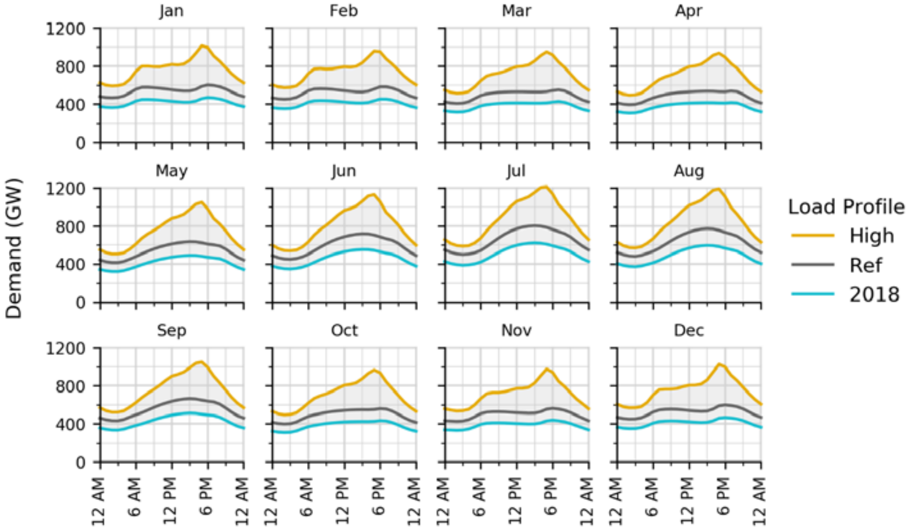


View reports at www.nrel.gov/efs

Vehicle electrification dominates incremental growth in annual electricity demand



Greater electricity consumption

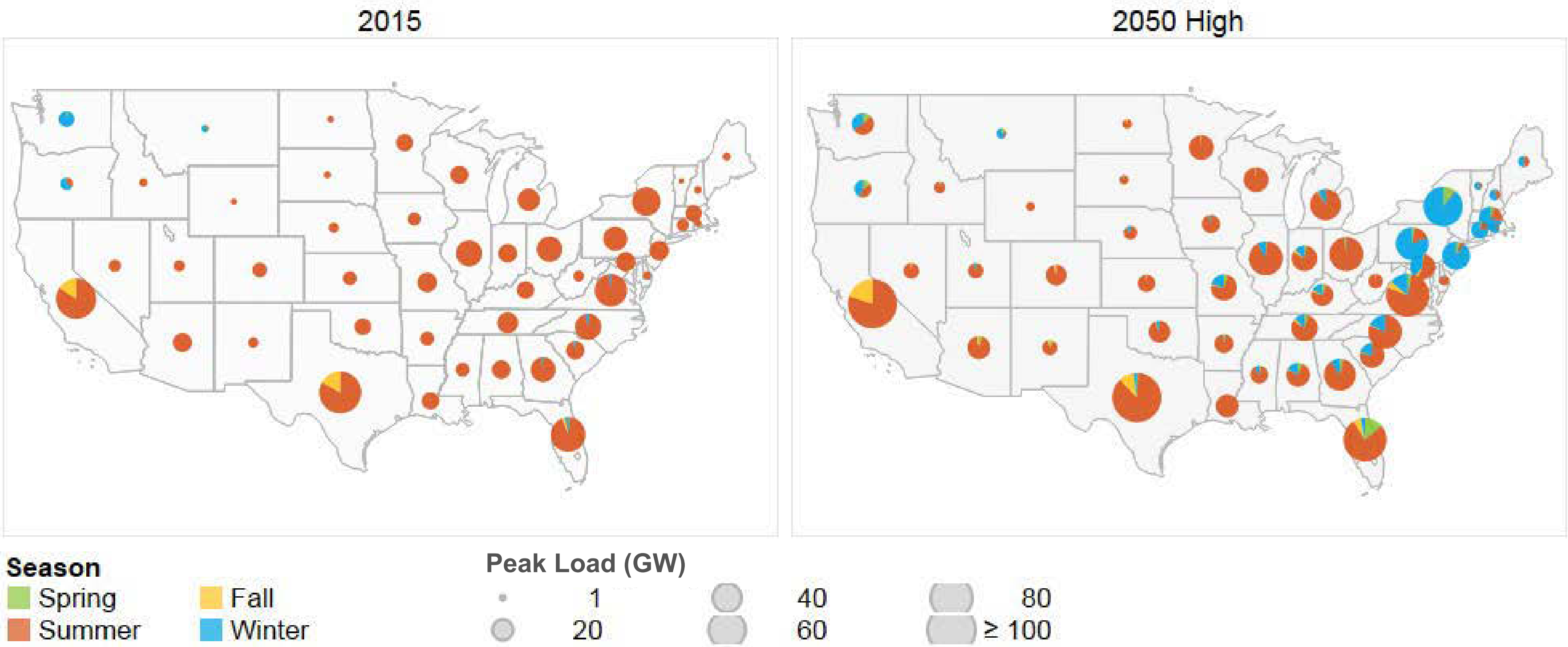


Possibly higher, sharper, and more frequent peaks in 2050

(in the absence of demand flexibility)

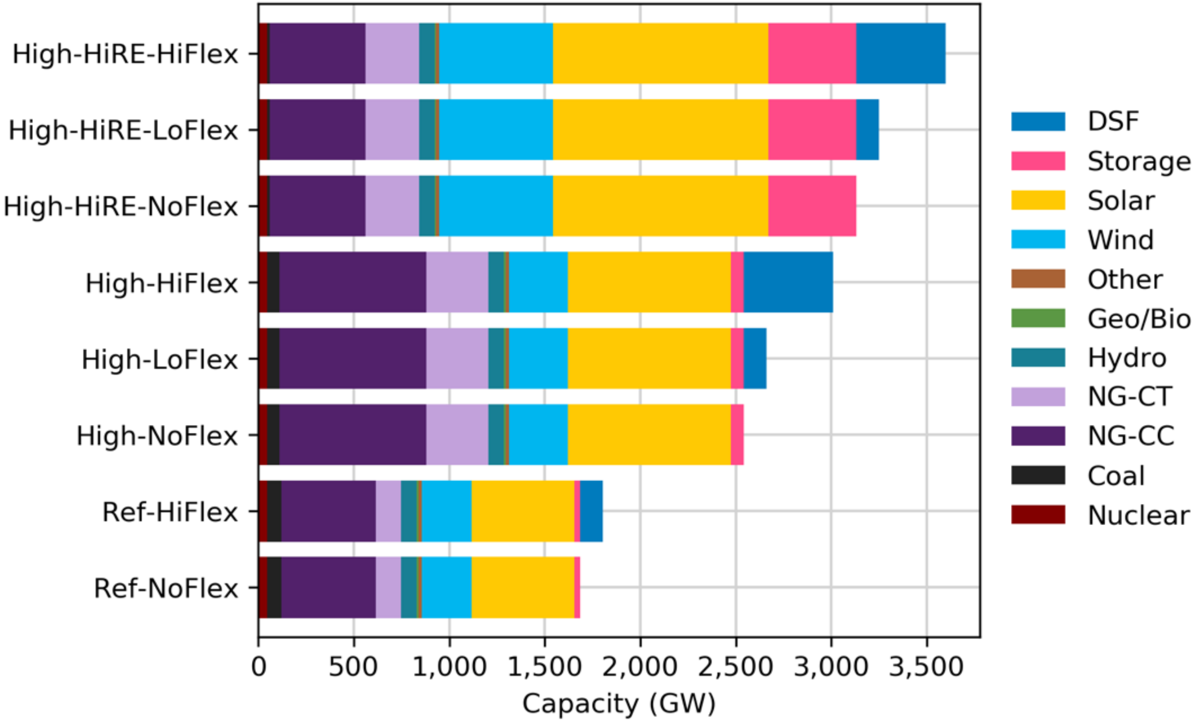
Source: Mai et al. 2018, Murphy et al. 2021, Sun et al. 2020, Zhou and Mai 2021

Electric heating impacts timing and magnitude of peak demand



Note: Summer = June–August, Fall = September – November, Winter = December – February, Spring = March – May

Power system portfolios include generation capacity, storage, and demand-side flexibility



DSF = demand-side flexibility
Geo/Bio = geothermal/ bioenergy
NG = natural gas
CT = combustion turbine
CC = combined cycle

Storage modeled in EFS includes pumped hydro storage, compressed air energy storage, and 4-hour battery storage.

Operational Modeling Method

Production Cost Modeling

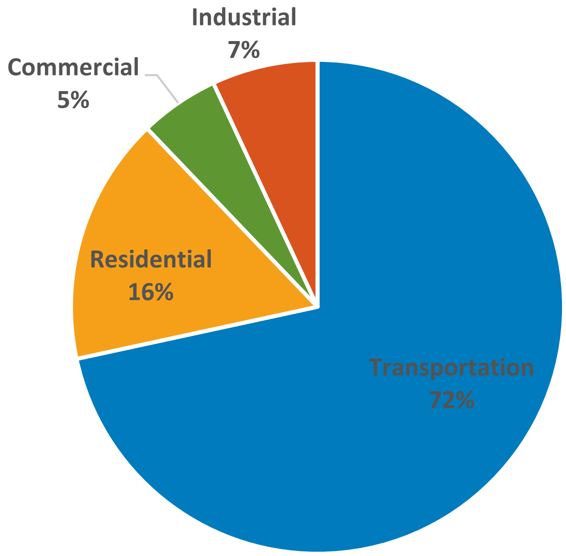
- PLEXOS
- 134 modeled balancing areas (BAs) in conterminous U.S.
- Hourly unit commitment and economic dispatch
- Co-optimization of energy and ancillary services
- Mixed integer programming

Demand-Side Flexibility (DSF) Representation

- 14 types of shiftable DSF across commercial, residential buildings, industrial, and transportation sectors for each modeled BA
- Hourly ratings for each type
- Constrained by:
  - Energy balance (daily or weekly)
  - Demand increase capacity limit
  - Shifting duration
  - Timing constraint
- No operation cost; gross benefit analysis only

Operational Modeling Method

Annual Flexible Load in High-HiFlex:
1,151 TWh (17% of total load)



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Research Questions

- How do future power systems operate to serve electricity demand with new and changing loads from widespread electrification?
- How might flexible loads be dispatched and how do they impact system operation?
- How do flexible loads operate in high renewable, high electrification futures, and what is the value of their flexibility?

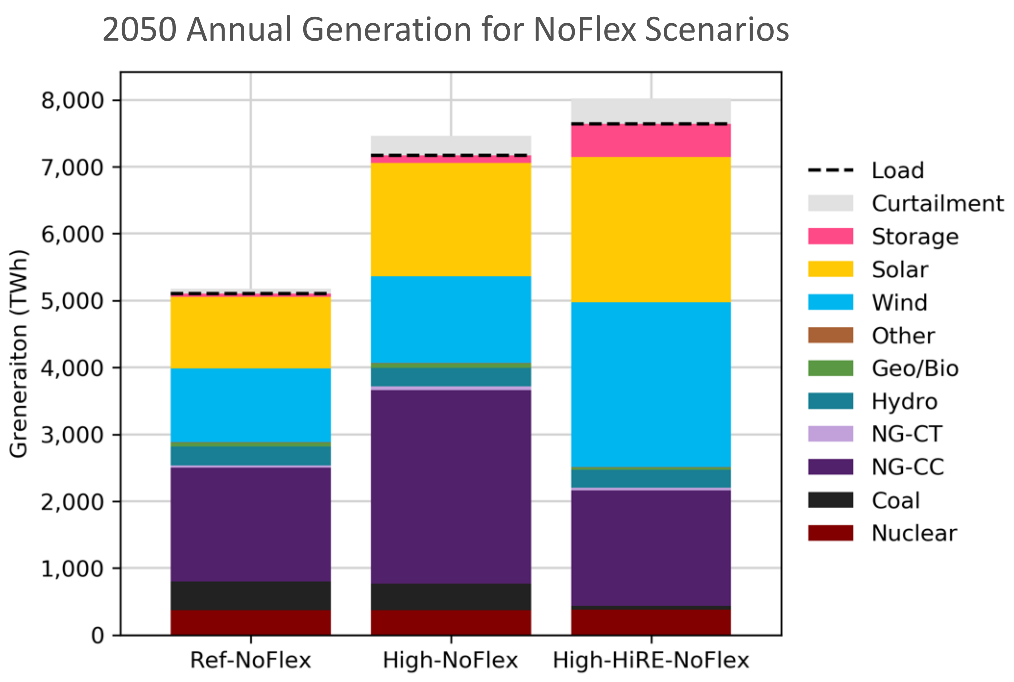
Finding 1

High electrification scenarios can be operated at hourly levels, even with high variable renewable energy (VRE) penetration

Scenarios compared in Finding 1

Electrification Level	Demand-Side Flexibility	Renewable Energy (RE) Cost Assumption	Scenario Name
Reference	No	Mid RE Costs	**Ref-NoFlex**
	Enhanced		Ref-HiFlex
High	No	Mid RE Costs	**High-NoFlex**
	Base		High-LoFlex
	Enhanced		High-HiFlex
	No	Low RE Costs	**High-HiRE-NoFlex**
	Base		High-HiRE-LoFlex
	Enhanced		High-HiRE-HiFlex

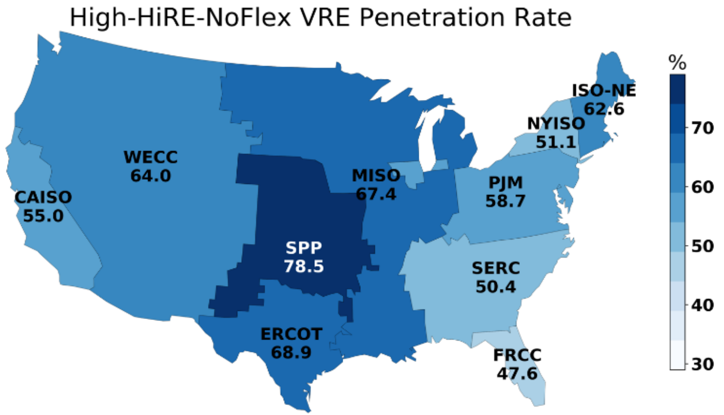
Modeled portfolios are resource adequate



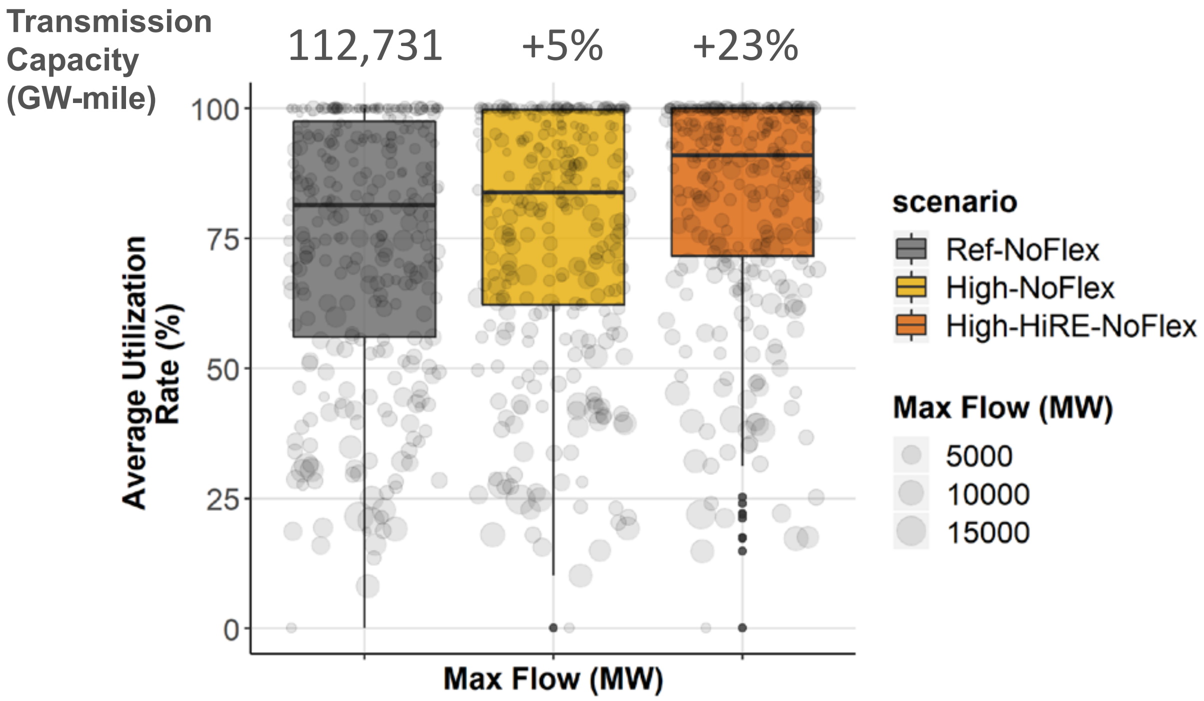
Geo/Bio = geothermal/bioenergy
NG = natural gas

CT = combustion turbine
CC = combined cycle

The system serves **more than 99.99% of the load and 99.96% of the operating reserves** in hourly simulations of all 2050 scenarios



Transmission supports high electrification, high VRE



Transmission utilization and interregional exchanges increase with electrification and VRE penetration despite additional transmission builds

Finding 2

Demand-side flexibility can increase power system operation efficiency—particularly valuable for systems under high electrification

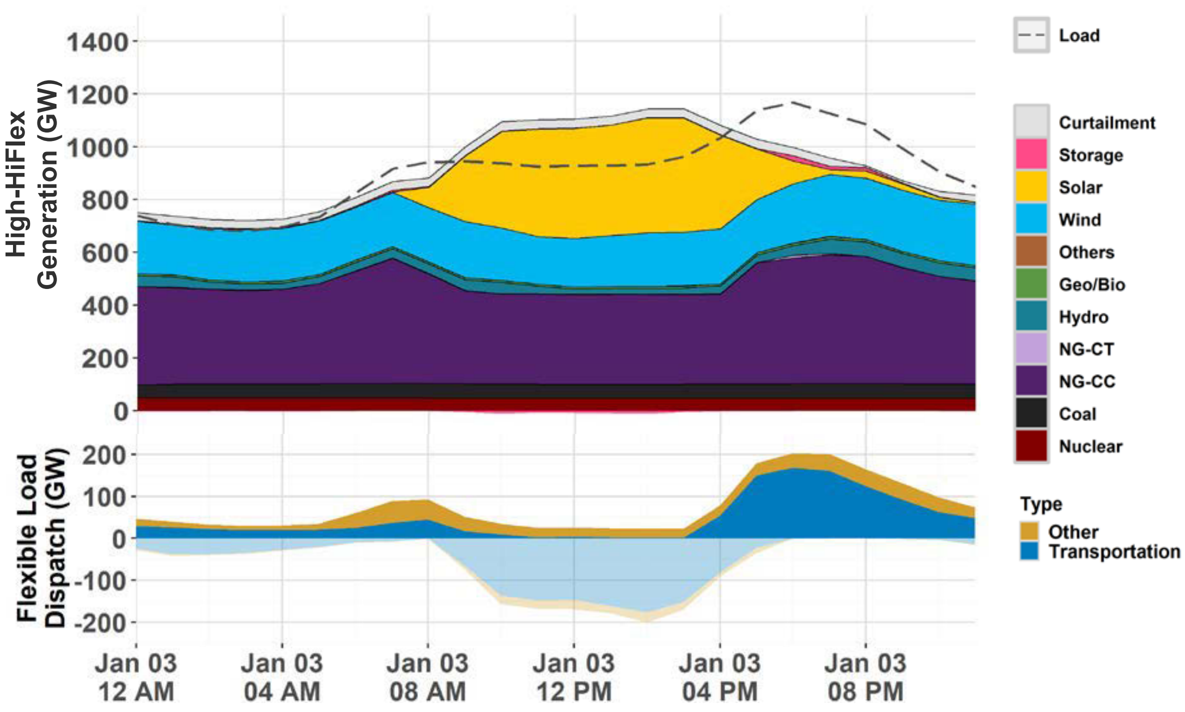
Scenarios compared in Finding 2

Electrification Level	Demand-Side Flexibility	Renewable Energy (RE) Cost Assumption	Scenario Name
Reference	No	Mid RE Costs	Ref-NoFlex
	Enhanced		Ref-HiFlex
High	No	Mid RE Costs	**High-NoFlex**
	Base		**High-LoFlex**
	Enhanced		**High-HiFlex**
	No	Low RE Costs	High-HiRE-NoFlex
	Base		High-HiRE-LoFlex
	Enhanced		High-HiRE-HiFlex

Demand-side flexibility benefits system operation through energy shifting and reserves

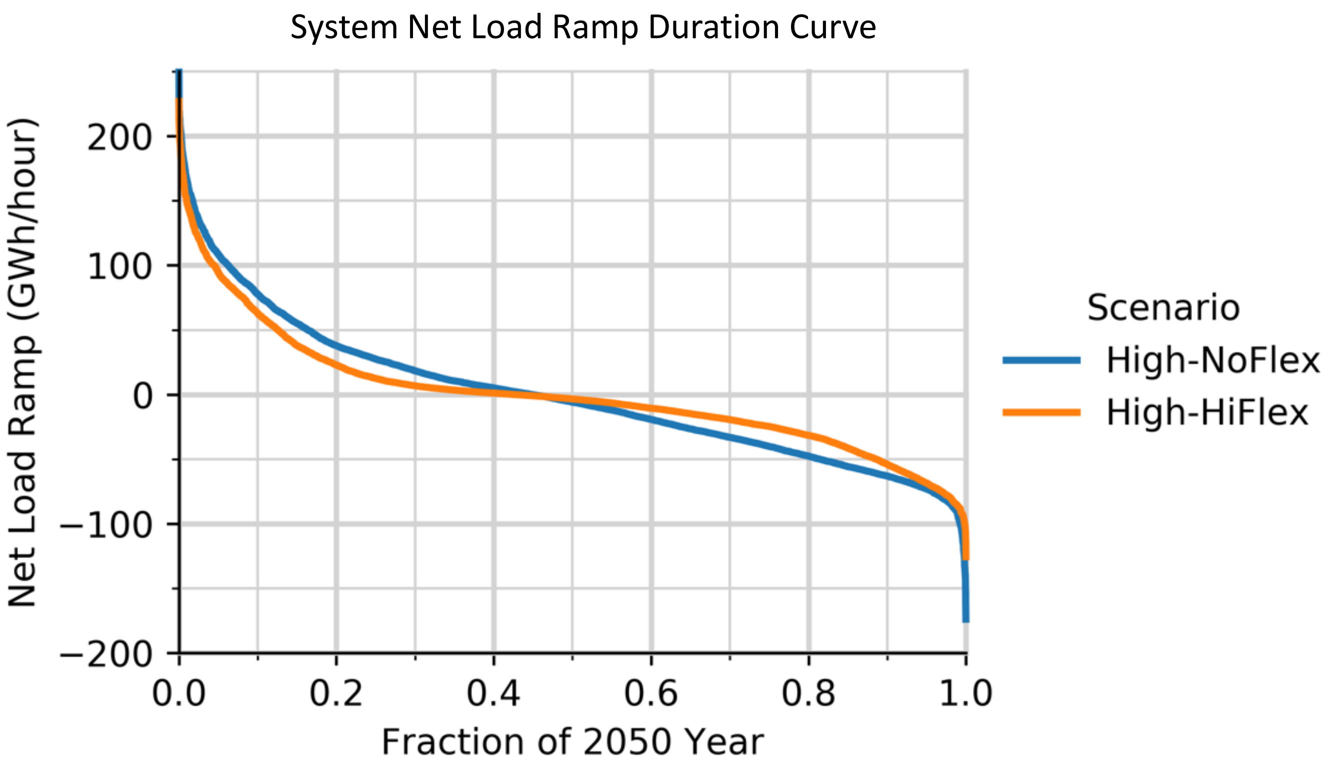
Top: Simulated dispatch on Jan. 3 in High-HiFlex (highest net load ramp day in High-NoFlex)

Bottom: Zoom-in of DSF dispatch for the same time period. Positive generation indicates reduced consumption.



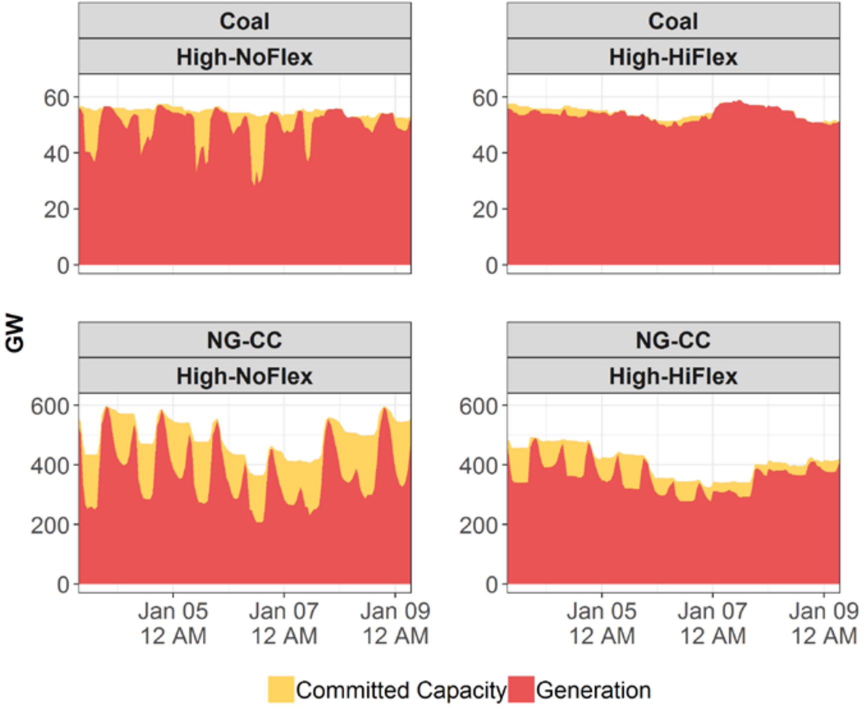
Dotted line shows original static load from High-NoFlex

Demand-side flexibility reduces system net load ramps



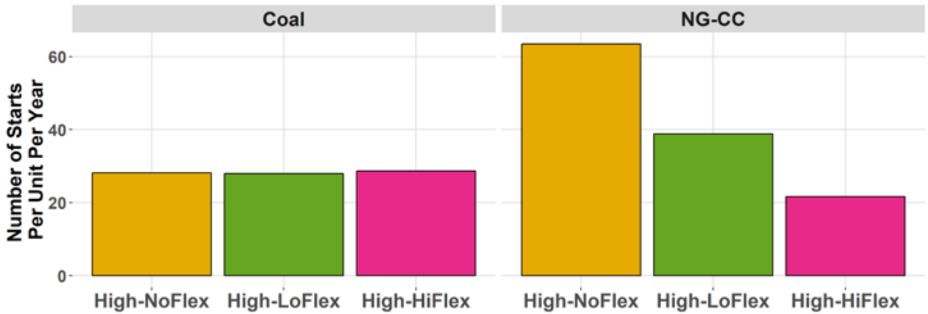
Demand-side flexibility reduces thermal plant cycling

Committed capacity and generation from coal and natural gas in a sample week in January

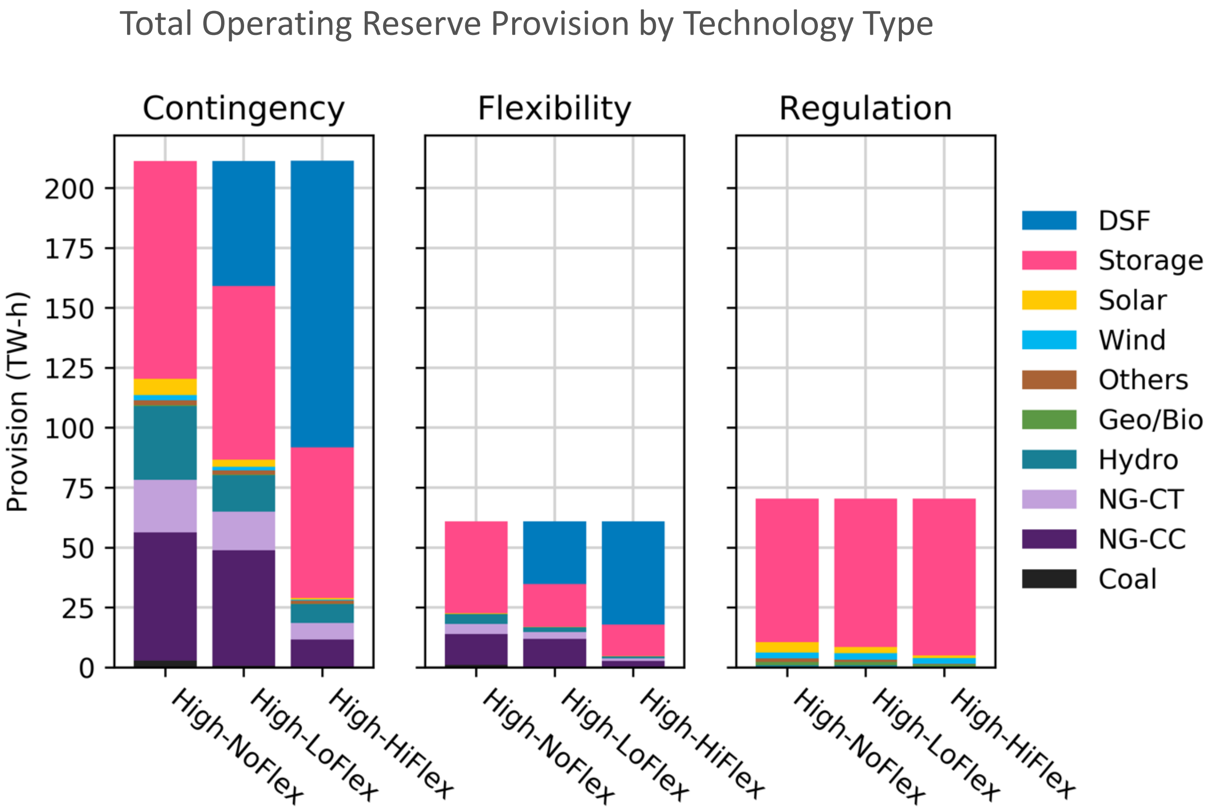


- DSF reduces committed low-load hours for thermal plants
- DSF reduces starts and shutdowns for natural gas combined-cycle units

Number of starts per unit per year

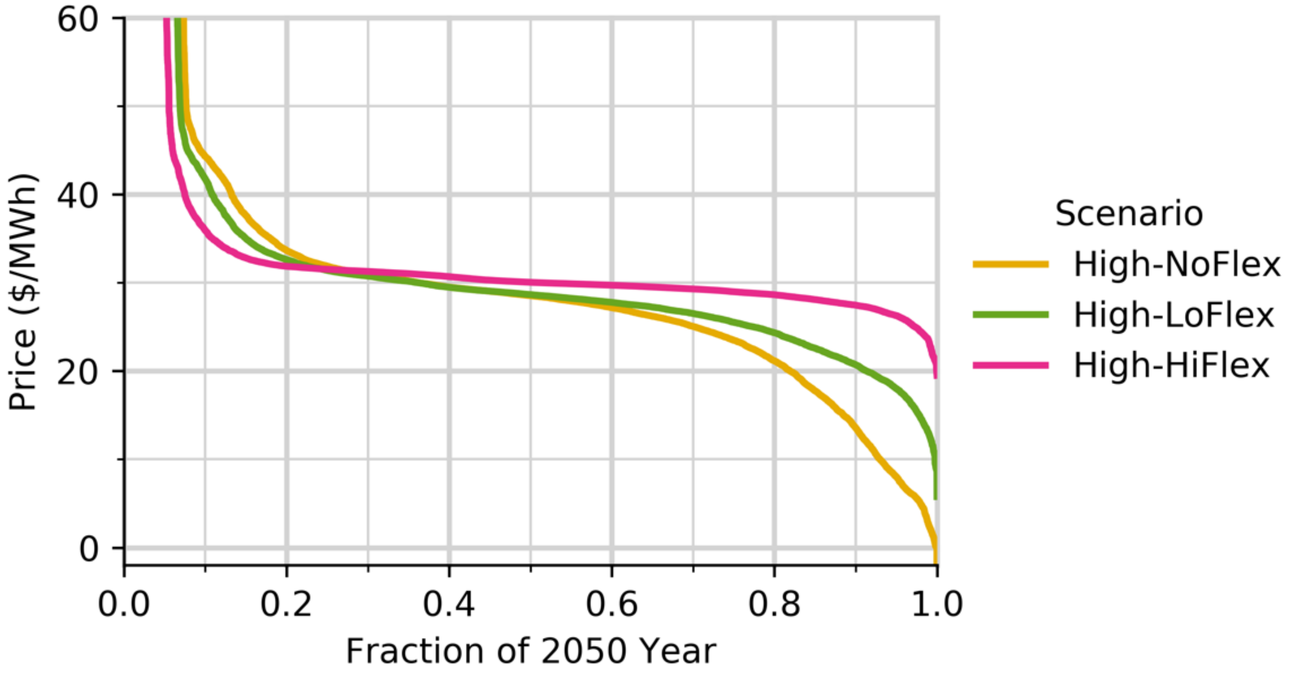


Demand-side flexibility can provide operating reserves



Demand-side flexibility reduces price volatility

Duration Curve for the National Average Marginal Hourly Price
from Each Balancing Area, Weighted by Load



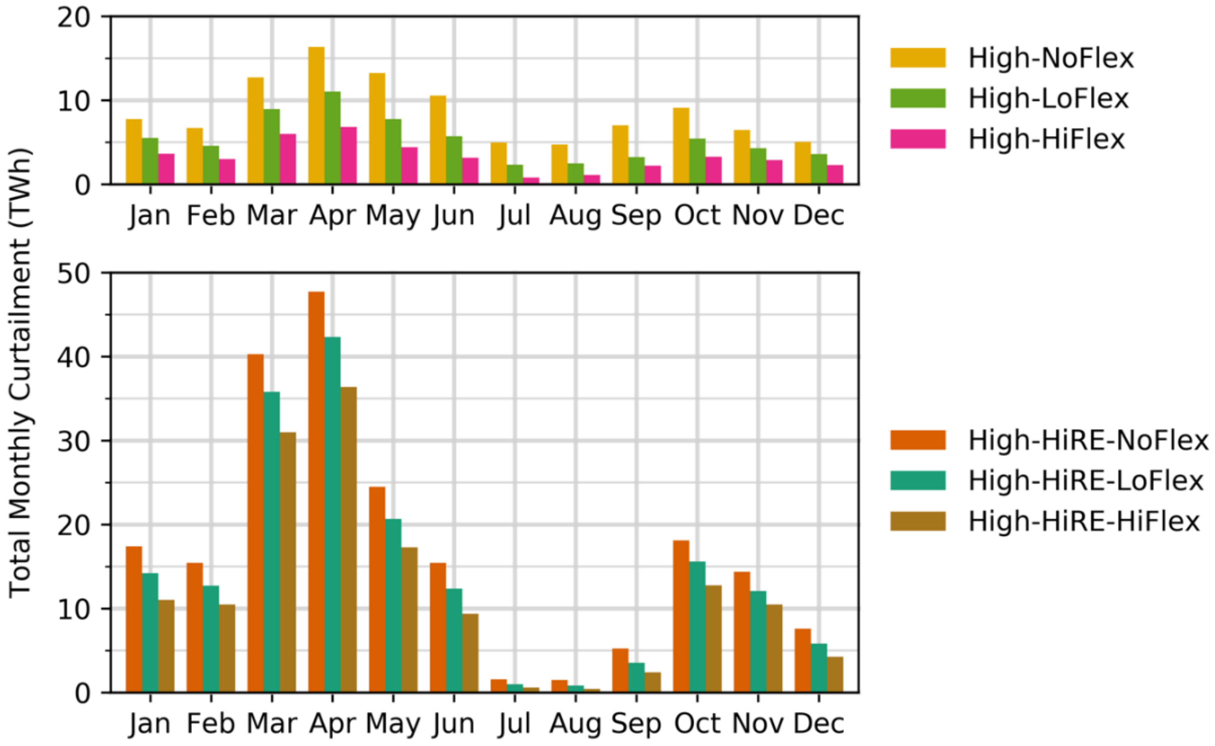
Finding 3

Demand-side flexibility can enhance operation efficiency of high electrification, high VRE systems—reducing costs and carbon emissions

Scenarios compared in Finding 3

Electrification Level	**Demand-Side Flexibility**	**Renewable Energy (RE) Cost Assumption**	**Scenario Name**
Reference	No	Mid RE Costs	Ref-NoFlex
	Enhanced		Ref-HiFlex
High	No	Mid RE Costs	**High-NoFlex**
	Base		**High-LoFlex**
	Enhanced		**High-HiFlex**
	No	Low RE Costs	**High-HiRE-NoFlex**
	Base		**High-HiRE-LoFlex**
	Enhanced		**High-HiRE-HiFlex**

Demand-side flexibility lowers VRE curtailment



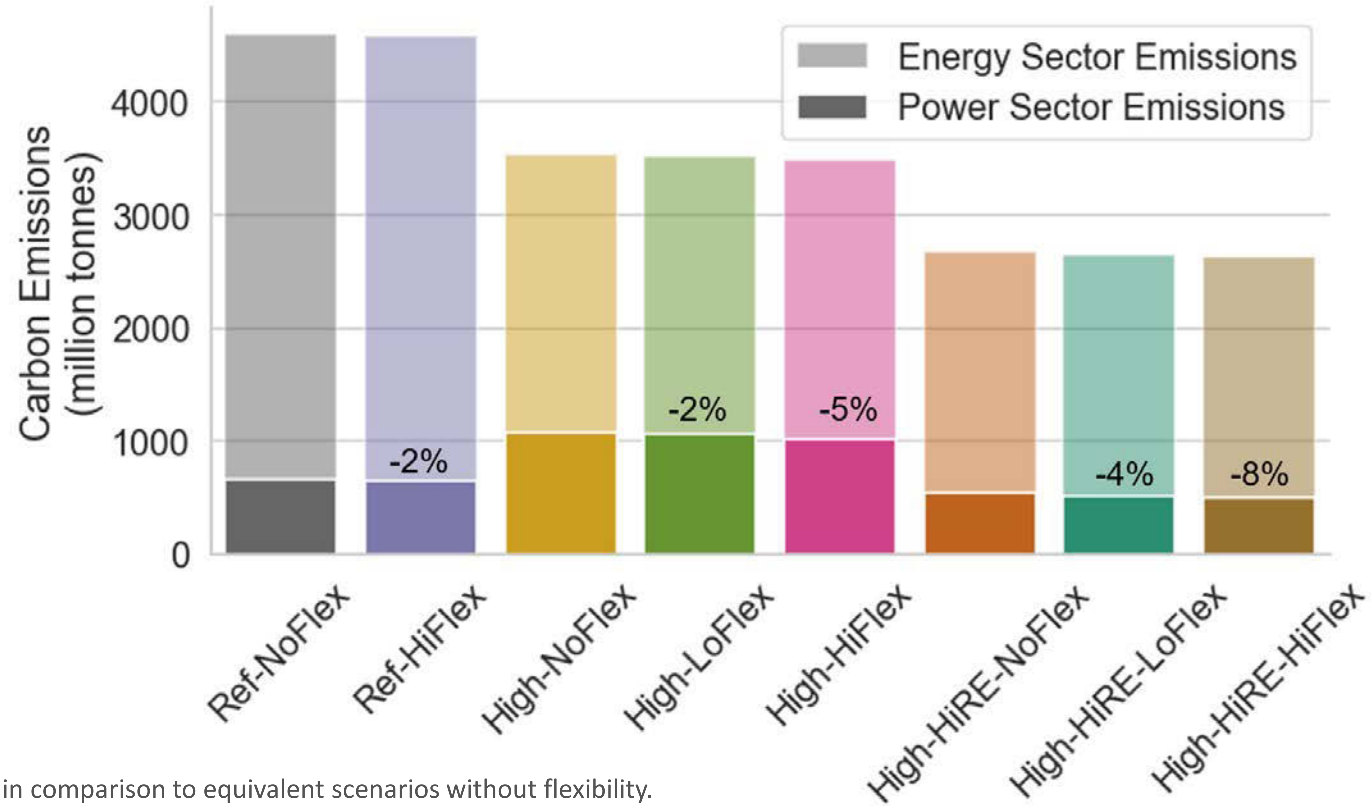
Curtailment reduced by 60 TWh (16%) in High-HiRE-HiFlex scenarios

High demand-side flexibility saves 9%–10% total system operation cost in 2050

Scenario	Total Cost Savings (Billion $)	Cost Savings from NoFlex (%)	DSF Value[a] ($/MW-h Availability)	DSF Value ($/MWh Energy Shifted)
High-LoFlex	5	4%	16	22
High-HiFlex	10	9%	9	17
High-HiRE-LoFlex	2	5%	7	12
High-HiRE-HiFlex	5	10%	4	8

[a] The DSF values are gross benefits, assuming zero operational cost.

High demand-side flexibility can reduce CO_2 emissions by 8% in High-HiRE scenarios



Percentages are in comparison to equivalent scenarios without flexibility.

Conclusions

- The study shows **the U.S. power system can operate under scenarios with widespread electrification**—and associated changes to electricity demand patterns—with high amounts of variable renewable energy (1.3 TW installed capacity, 66% of annual national generation).
- **Demand-side flexibility (dominated by electric vehicle charging under High electrification) can enhance operational efficiency** by reducing system ramps, reducing thermal plant cycling, and increasing utilization of more efficient generators, resulting in gross benefit of \$8–\$22/MWh energy shifted or \$4–\$16/MW-h of available flexible load.
- The **complementary relationship between demand-side flexibility from newly electrified load and variable renewable energy** is particularly pronounced. Flexible loads can reduce renewable curtailment, and thereby reduce power-sector CO_2 emissions, resulting in up to 10% of total system operating cost savings and 8% CO_2 reduction in High-HiRE-HiFlex compared to NoFlex.

Resources and related research at NREL

- **See www.nrel.gov/efs for more information**
  - Hourly demand data
  - Scenario data viewer
- **Standard Scenarios** – www.nrel.gov/analysis/standard-scenarios.html
- **Annual Technology Baseline** – Electricity and Transportation – atb.nrel.gov
- **Demand-side grid (dsgrid)** - www.nrel.gov/analysis/dsgrid.html
- **Transportation Energy & Mobility Pathway Options (TEMPO)** – www.nrel.gov/transportation/tempo-model.html

Thank you from the EFS team!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