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

Ella Zhou and Trieu Mai

June 17, 2021
NREL-led collaboration, multi-year study

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)

Study sponsored by U.S. DOE-EERE Strategic Analysis
EFS Scenario Analysis Phases

End-Use Technology Adoption: Demand-Side Scenarios

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

Power System Evolution: Supply-Side Scenarios

- ReEDS capacity expansion model
- dGen rooftop photovoltaic adoption model

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)

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.

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

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

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

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

<table>
<thead>
<tr>
<th>Electrification Level</th>
<th>Demand-Side Flexibility</th>
<th>Renewable Energy (RE) Cost Assumption</th>
<th>Scenario Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>Ref-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>Ref-HiFlex</td>
</tr>
<tr>
<td>High</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>High-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiFlex</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Low RE Costs</td>
<td>High-HiRE-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-HiRE-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiRE-HiFlex</td>
</tr>
</tbody>
</table>
Modeled portfolios are resource adequate

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

2050 Annual Generation for NoFlex Scenarios

Load | Curtailment | Storage | Solar | Wind | Other | Geo/Bio | Hydro | NG-CT | NG-CC | Coal | Nuclear

- Ref-NoFlex
- High-NoFlex
- High-HiRE-NoFlex

Geo/Bio = geothermal/bioenergy
NG = natural gas
CT = combustion turbine
CC = combined cycle
Transmission supports high electrification, high VRE

Transmission utilization and interregional exchanges increase with electrification and VRE penetration despite additional transmission builds.
Demand-side flexibility can increase power system operation efficiency—particularly valuable for systems under high electrification.

### Scenarios compared in Finding 2

<table>
<thead>
<tr>
<th>Electrification Level</th>
<th>Demand-Side Flexibility</th>
<th>Renewable Energy (RE) Cost Assumption</th>
<th>Scenario Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>Ref-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>Ref-HiFlex</td>
</tr>
<tr>
<td>High</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>High-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiFlex</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Low RE Costs</td>
<td>High-HiRE-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-HiRE-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiRE-HiFlex</td>
</tr>
</tbody>
</table>
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

System Net Load Ramp Duration Curve

Net Load Ramp (GWh/hour)

Fraction of 2050 Year

Scenario

- High-NoFlex
- High-HiFlex
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

![Graph showing committed capacity and generation for coal and natural gas combined-cycle units with DSF levels.]
Demand-side flexibility can provide operating reserves

Total Operating Reserve Provision by Technology Type

Contingency

Flexibility

Regulation

- DSF
- Storage
- Solar
- Wind
- Others
- Geo/Bio
- Hydro
- NG-CT
- NG-CC
- Coal
Demand-side flexibility reduces price volatility

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

Scenario
- High-NoFlex
- High-LoFlex
- High-HiFlex

Fraction of 2050 Year

Price ($/MWh)
### Finding 3

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

<table>
<thead>
<tr>
<th>Electrification Level</th>
<th>Demand-Side Flexibility</th>
<th>Renewable Energy (RE) Cost Assumption</th>
<th>Scenario Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>Ref-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>Ref-HiFlex</td>
</tr>
<tr>
<td>High</td>
<td>No</td>
<td>Mid RE Costs</td>
<td>High-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiFlex</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Low RE Costs</td>
<td>High-HiRE-NoFlex</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td></td>
<td>High-HiRE-LoFlex</td>
</tr>
<tr>
<td></td>
<td>Enhanced</td>
<td></td>
<td>High-HiRE-HiFlex</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total Cost Savings (Billion $)</th>
<th>Cost Savings from NoFlex (%)</th>
<th>DSF Value(^a) ($/MW-h Availability)</th>
<th>DSF Value ($/MWh Energy Shifted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-LoFlex</td>
<td>5</td>
<td>4%</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>High-HiFlex</td>
<td>10</td>
<td>9%</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>High-HiRE-LoFlex</td>
<td>2</td>
<td>5%</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>High-HiRE-HiFlex</td>
<td>5</td>
<td>10%</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

\(^a\) 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 CO₂ emissions, resulting in up to 10% of total system operating cost savings and 8% CO₂ reduction in High-HiRE-HiFlex compared to NoFlex.
Resources and related research at NREL

- See [www.nrel.gov/efs](http://www.nrel.gov/efs) for more information
  - Hourly demand data
  - Scenario data viewer
- **Standard Scenarios** – [www.nrel.gov/analysis/standard-scenarios.html](http://www.nrel.gov/analysis/standard-scenarios.html)
- **Annual Technology Baseline** – Electricity and Transportation – [atb.nrel.gov](http://atb.nrel.gov)
- **Demand-side grid (dsgrid)** - [www.nrel.gov/analysis/dsgrid.html](http://www.nrel.gov/analysis/dsgrid.html)
- **Transportation Energy & Mobility Pathway Options (TEMPO)** – [www.nrel.gov/transportation/tempo-model.html](http://www.nrel.gov/transportation/tempo-model.html)
Thank you from the EFS team!
Questions? Thank you.

ella.zhou@nrel.gov
trieu.mai@nrel.gov
+ EFS team

www.nrel.gov/efs