Webinar: National Renewable Energy Laboratory (NREL) Reviews the Duke Energy Carbon-Free Resource Integration Study

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Ken Jennings (Duke Energy)

January 17th, 2020

Agenda

- **Webinar Welcome and Instructions** – Terri Edwards, Duke Energy
- **Study Purpose and Background** – Ken Jennings, Duke Energy
- **Integration with Clean Energy Plan** – Tim Profeta, Nicholas Institute
- **NREL Phase 1 Analysis** – Scott Haase and Bri-Mathias Hodge, NREL
- **Next Steps, Wrap Up** – Ken Jennings, Duke Energy

Background and Overview

- Duke Energy contracted with **National Renewable Energy Laboratory (NREL),** an industry-respected, leading research institution, to conduct a study of the Carolinas' system.

- The study will be conducted in two phases. NREL recently completed **Phase 1** and has started **Phase 2.**

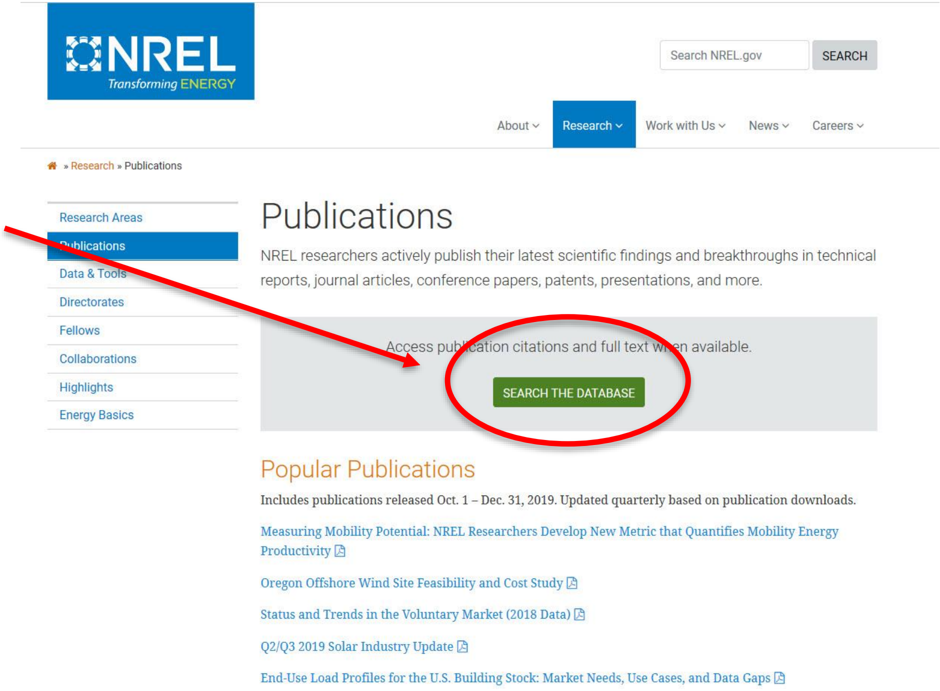
- Phase 1 is a **preliminary evaluation**; Phase 2 will incorporate costs and transmission impacts.

- As we advance towards a lower carbon future, these studies will help us understand the operational impacts, benefits and limitations of solar.

- The study will also inform other fleet transformation analyses, including how different clean energy technologies can contribute to a carbon-free future.

How to Access the Phase 1 Study

Final report posted here: https://www.nrel.gov/docs/fy20osti/74337.pdf



Phase 1: What is Covered and What Isn't

Covered	Not Covered
How different resource mixes could contribute to carbon-free energy on the DEC and DEP Systems	Comprehensive system planning including unit commitment/economic dispatch for energy and reserves
Impacts of integrating significant amounts of new solar photovoltaic (PV) power into Duke's service territory under a variety of scenarios	Constraints of thermal generation and must-run units (assumed to be flexible)
Curtailment quantities with limited system flexibility	Detailed interconnection analysis or transmission considerations
Introducing other scenarios such as wind, storage and how they contribute to total annual percentage of carbon-free generation	Market models and cost of various options

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NREL at a Glance

2,200

Employees,

including postdoctoral researchers, interns, visiting professionals, and subcontractors

World-class

facilities, renowned technology experts

over 800

Partnerships

with industry, academia, and government

Campus

campus operates as a living laboratory

$400M+ annually

Approximate Operating Budget

NREL Core Capabilities: Foundation for Innovation

Analysis and System Integration

Decision Science and Analysis

Systems Engineering and Integration

Policy and Markets

Innovation and Application

Biological and Bioprocess Engineering

Chemical Engineering

Mechanical Design and Engineering

Power Systems and Electrical Engineering

Foundational Knowledge

Applied Materials Science and Engineering

Biological Systems Science

Chemical and Molecular Science

Crosscutting

Advanced Computer Science, Visualization, and Data

Large-Scale User Facilities

Technology Focus

Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Advanced Mobility

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

Energy Systems Integration

High-Performance Computing

Data and Visualizations

Scope of Work

Net Load Analysis

- Compared estimated hourly solar, wind, net load, and system minimum generation time series for different scenarios.
- Created initial estimates of possible curtailment, key periods of ramping, and load-following requirements.

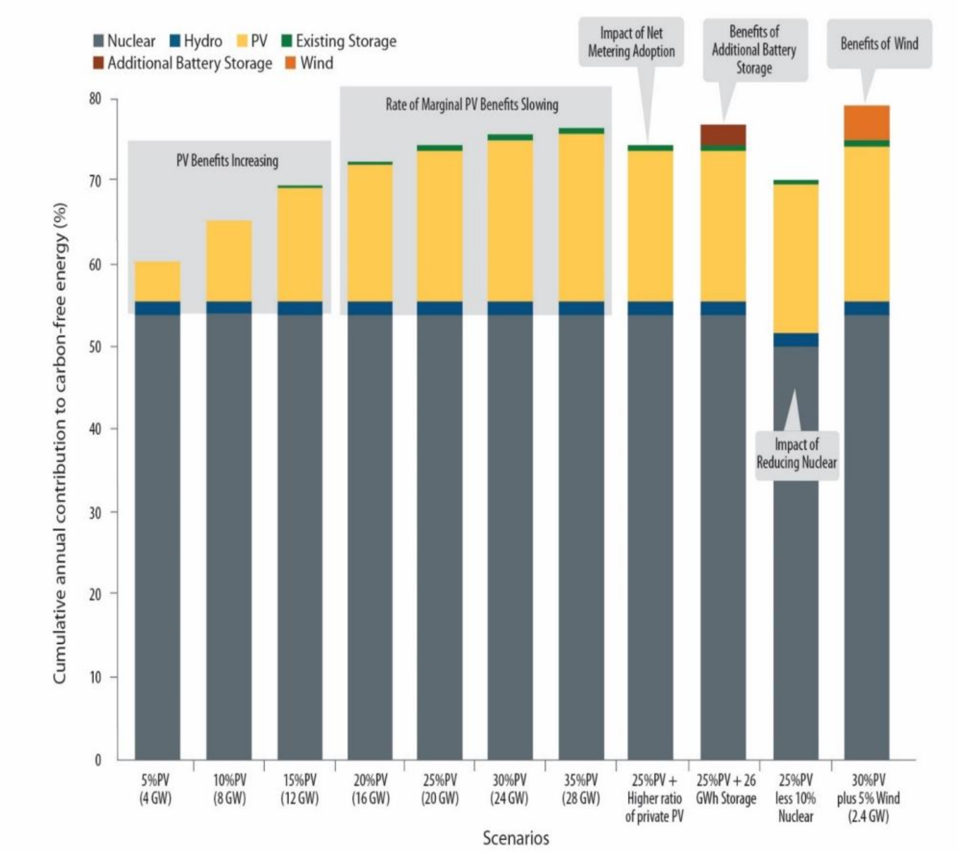
Geospatial Analysis Maps with Interactive Web App

- Created wind power and solar power resource maps with technical exclusions and interactive web application to understand potential renewable energy locations.

Literature Review

- Referenced previous studies regarding challenges and opportunities from integrating wind and solar into various power systems drawing key conclusions that likely apply to the Duke service territory.

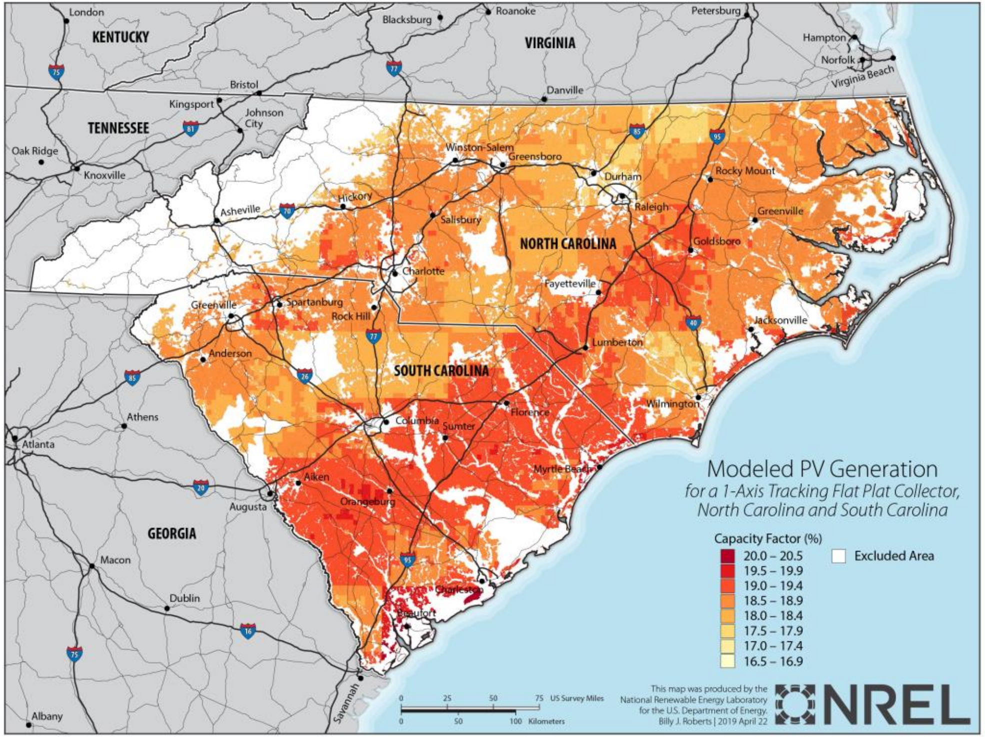
Summary of scenarios



Key Findings:

- Net load analysis highlights challenges and opportunities with integrating solar PV
- Average annual % of load met by carbon-free generation ranges from 60-79%
- Nuclear remains greatest contributor to carbon-free energy
- Above 15% solar PV, required curtailment grows
- The highest share of carbon-free generation is achieved by the scenario with the most resource diversity.
- Solar power curtailment is greater under separate balancing authorities

Solar Energy Resource in the Carolinas Region



- Uses NREL's System Advisor Model (SAM)
- Input data from the National Solar Radiation Database (NSRDB)
- Capacity factors represent mean capacity factors across all available resource years (1997 – 2017 inclusive)
- Exclusions based on land categories and use-type

Scenarios

Scenario	Definition
1. Solar energy penetration 5%	4,109 MW, 5.5% of total solar is rooftop
2. Solar energy penetration 10%	8,219 MW, 5.5% of total solar is rooftop
3. Solar energy penetration 15%	12,328 MW, 5.5% of total solar is rooftop
4. Solar energy penetration 20%	16,438 MW, 5.5% of total solar is rooftop
5. Solar energy penetration 25%	20,547 MW, 5.5% of total solar is rooftop
6. Solar energy penetration 30%	24,656 MW, 5.5% of total solar is rooftop
7. Solar energy penetration 35%	28,766 MW, 5.5% of total solar is rooftop
8. Higher ratio of distributed to utility solar added to the system	Based on the 25% solar energy penetration scenario, 18.91% of PV is uncurtailable rooftop.
9. Additional storage	Based on the 25% solar energy penetration scenario, addition of 1,000 MW of 4-hour storage, 1,000 MW of 6-hour storage, and 2,000 MW of 8-hour storage
10. Nuclear retirement	Based on the 25% solar energy penetration scenario, assume a 10% nuclear reduction
11. Additional wind energy penetration 5%	Based on the 30% solar energy penetration scenario, an additional 5% wind energy penetration is added.
12. Scenarios 1–3 modeled with two balancing authorities	Based on scenarios 1–3 inclusive, DEP and DEC are analyzed separately with an interconnection limit between, defined in the appendix

Assumptions

- 2019 hourly forecasted load data and solar PV time-series supplied by Duke Energy
- Thermal generation, excluding nuclear, has no flexibility constraints such as minimum stable level, ramp rates or outage rates
- PV is non-dispatchable
- Rooftop PV is not curtailable, utility PV is curtailable
- Existing storage is 2.2 GW of pumped storage hydropower and has sufficient energy capacity to use full pumping capacity during all hours of surplus solar power each day and is optimized for load shifting.
- Must-run units have a 1 week minimum up-time
- Nuclear units have a 0% outage rate
- No contingency reserve is considered
- No imports or exports are considered
- Individual scenarios methods explained later…

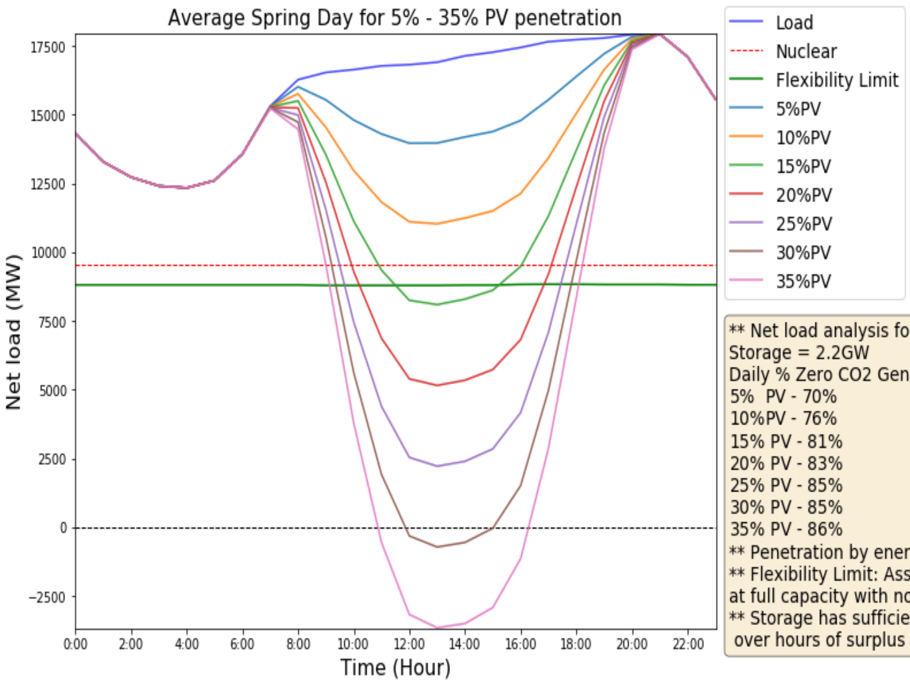
Definitions

- Penetration is in terms of annual energy and pre-curtailment
- Inflexibility limit defined by:
  - Must-run units for local voltage constraints
  - Fixed hydro power schedules
  - Nuclear output at constant maximum capacity
  - Existing storage
- Percentage of curtailed energy is a percentage of total PV output energy
- Daily percentage of carbon-free generation includes solar power, wind power, hydropower and nuclear (using storage)
- Maximum up-ramp and down-ramp times presented are ending times of each ramp

Scenarios 1 – 7: 5% - 35% Solar Energy Penetration

PV penetration (%)	5	10	15	20	25	30	35
PV capacity (MW)	4,109	8,219	12,328	16,438	20,547	24,656	28,766
Average Percentage Curtailed Energy, %	0	1	8	17	27	35	42
Marginal Curtailment, %	-	2.2	21.4	46.3	64.6	76.7	83.2
Load met by carbon-free generation, %	63	68	72	74	76	77	77

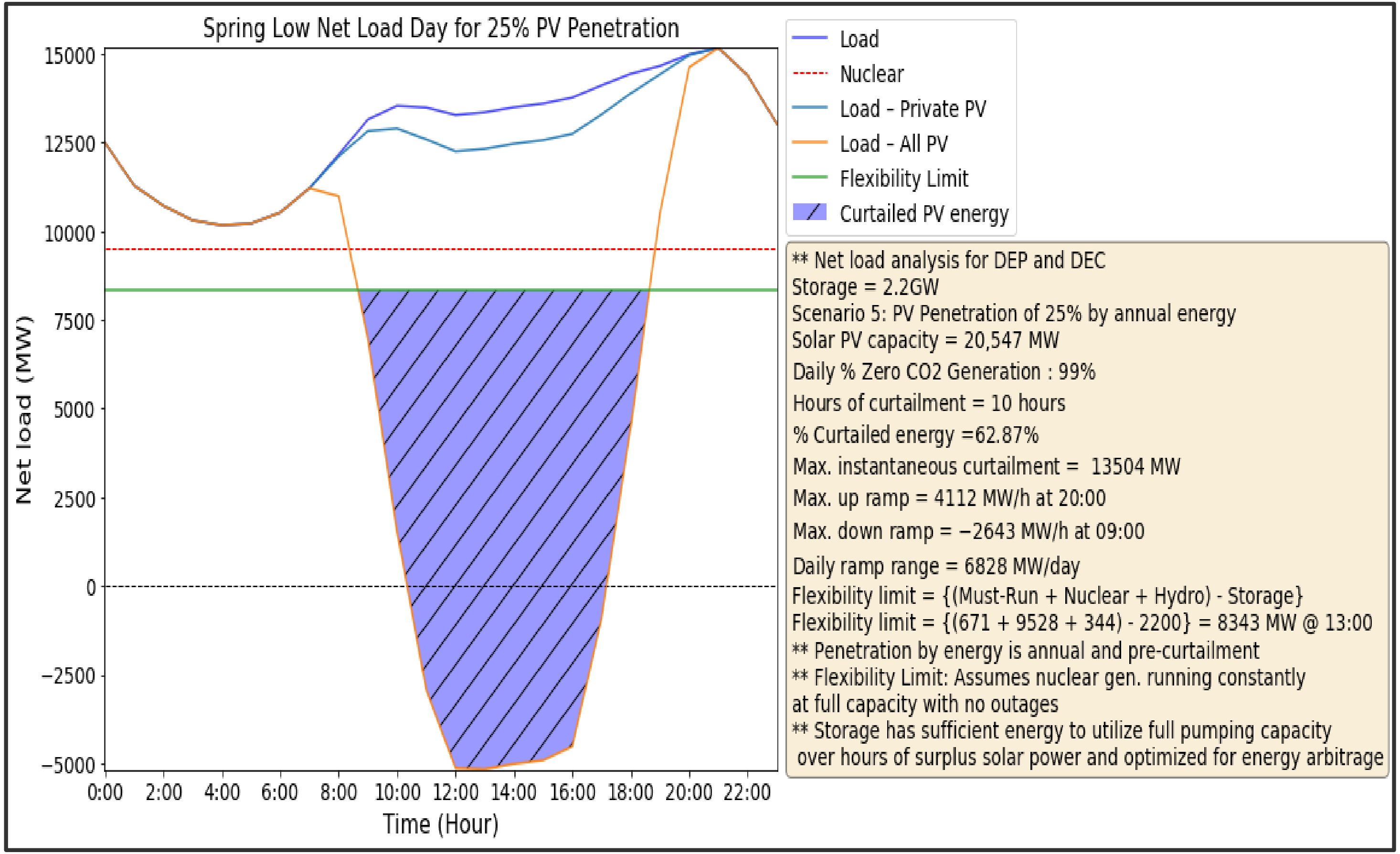
Annual Economic Indicators



** Net load analysis for DEP and DEC
Storage = 2.2GW
Daily % Zero CO2 Gen.:
5% PV - 70%
10%PV - 76%
15% PV - 81%
20% PV - 83%
25% PV - 85%
30% PV - 85%
35% PV - 86%
** Penetration by energy is annual and pre-curtailment
** Flexibility Limit: Assumes nuclear gen. running constantly at full capacity with no outages
** Storage has sufficient energy to utilize full pumping capacity over hours of surplus solar power and optimized for energy arbitrage

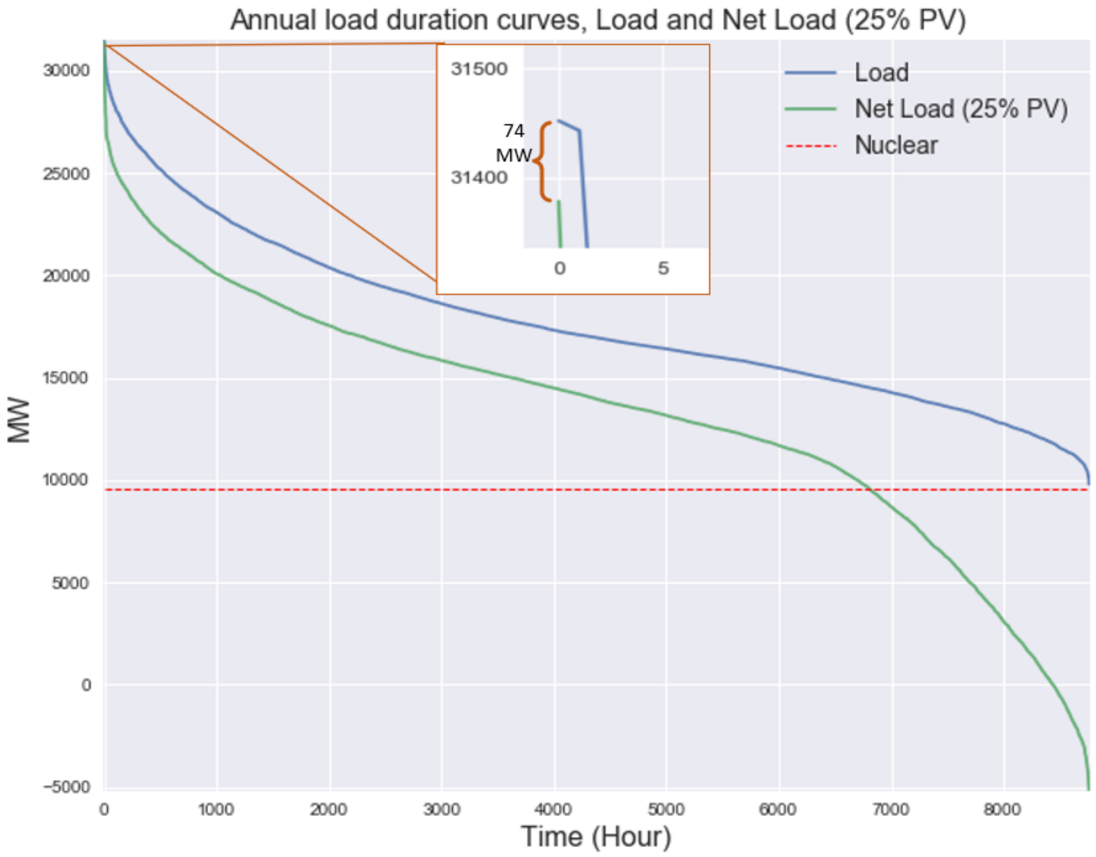
Here we show spring, as it is the highest curtailment season

Peak Load Day for 25% PV Penetration



The peak load day in summer experiences the least curtailment (2.16%)

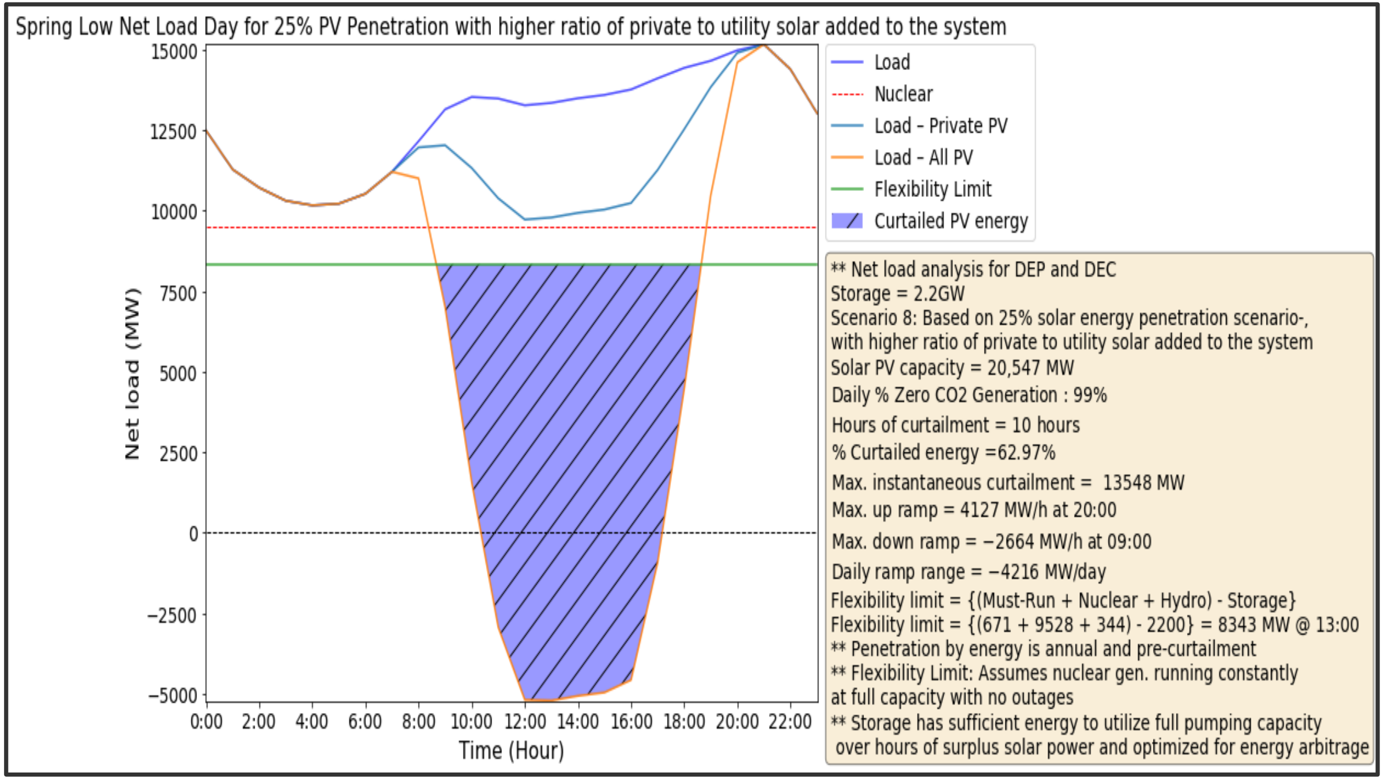
Load Duration Curves for the Existing Load and Projected 25% PV Penetration Case



With the addition of 25% PV penetration:

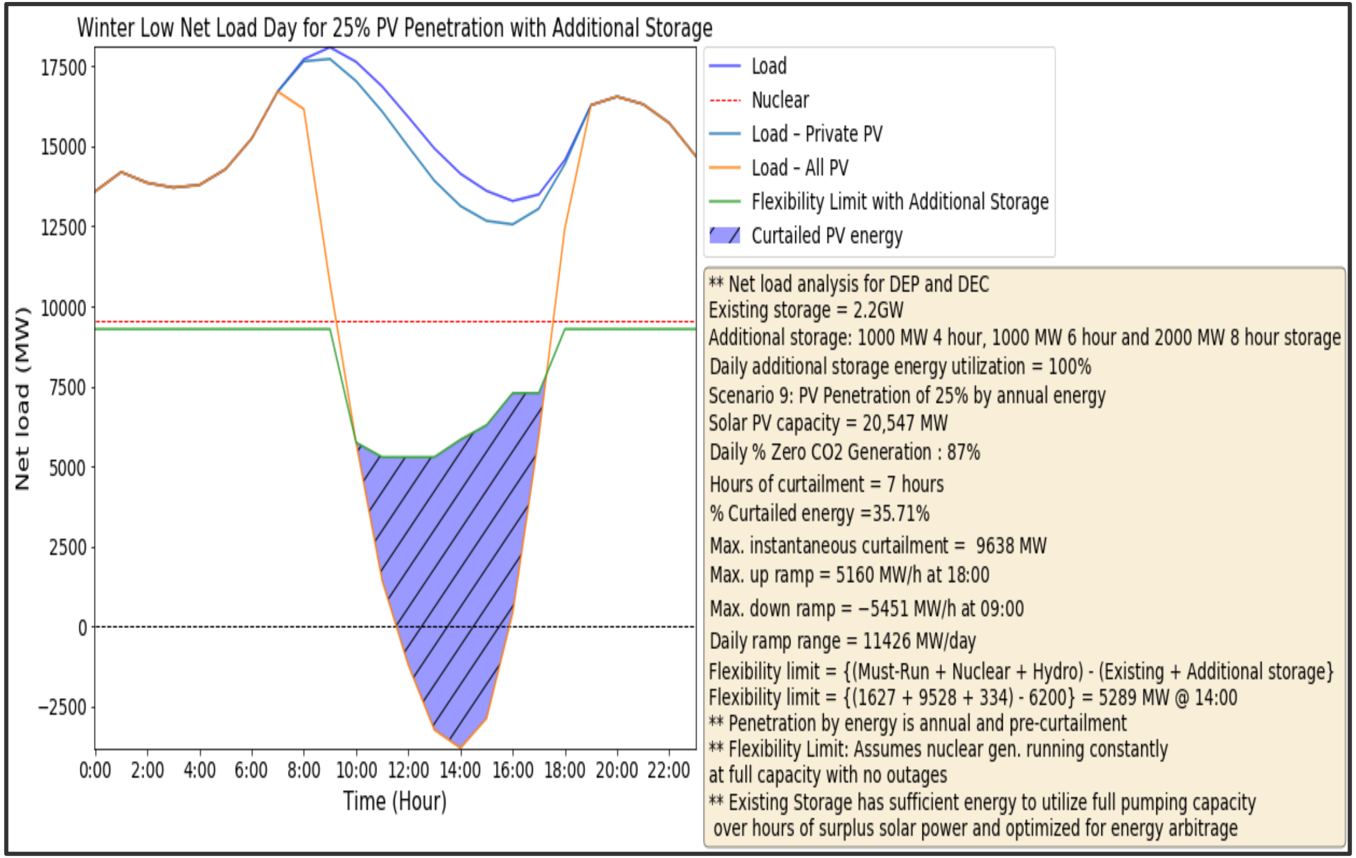
- Peak load is reduced
- Annual minimum load drops below the nuclear output

Scenario 8:
Increased Portion of Distributed Solar Energy



- Rooftop PV is not curtailable
- Based on 25% PV Penetration case
- 18.91% of PV is rooftop. This is the highest percentage from NREL-developed Standard Scenarios
- More utility PV must be curtailed
- Comparing to the base 25% case, 33.2% of utility solar is curtailed as opposed to 28.5%
- Rooftop PV never requires curtailment, even at 25% total PV penetration

Scenario 9: Additional Storage Capabilities

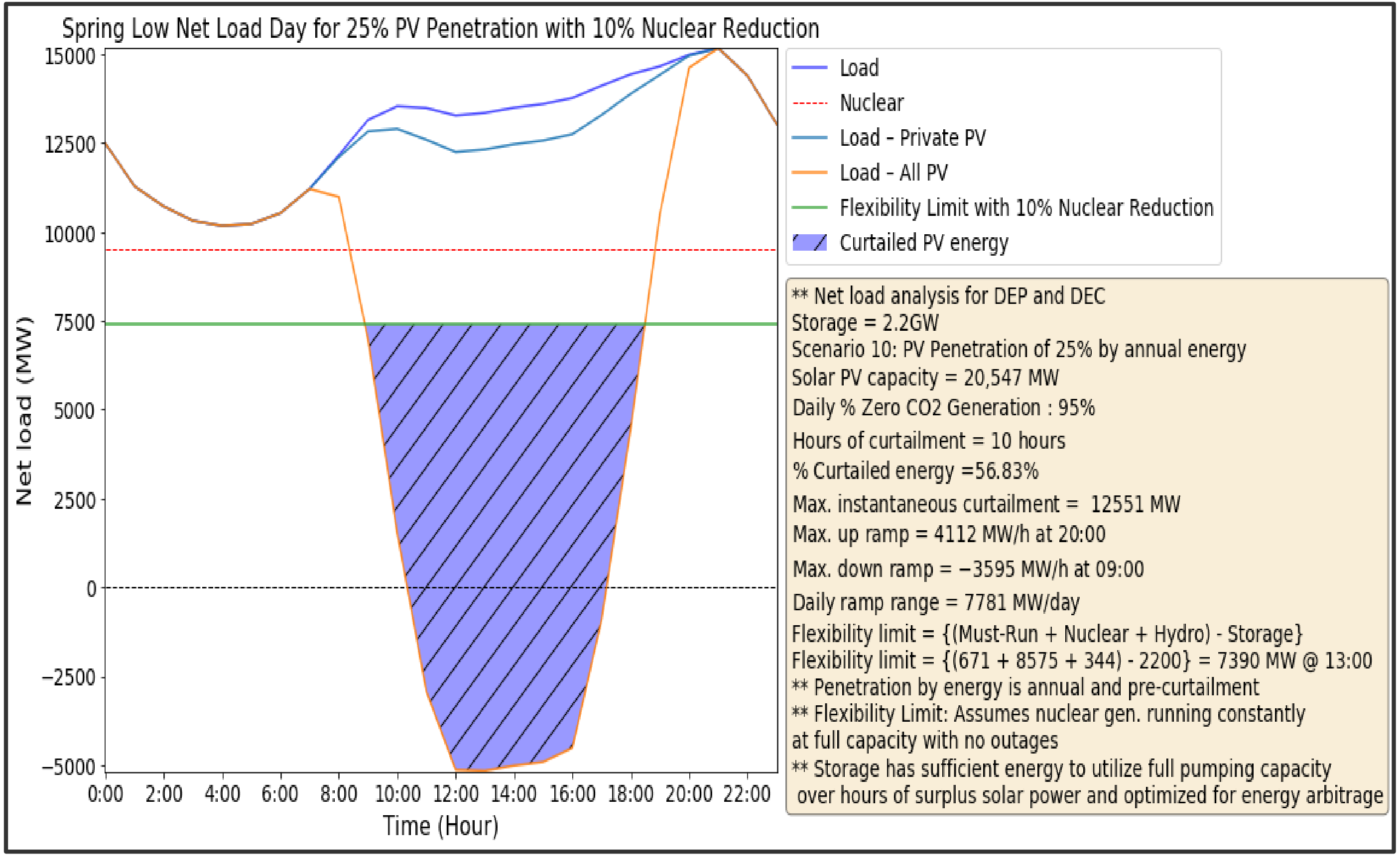


- Starts with the 25% PV penetration base case
- 1,000 MW of 4-hour, 1,000 MW of 6-hour and 2,000 MW of 8-hour (26,000 MWh)
- Annual contribution of this addition storage amounts to 3.7% of annual load
- Renewable energy is stored and released the same day with 80% round-trip efficiency

Compared to the 25% PV penetration case:

- Solar curtailment reduces from 26.9% to 14.8%
- carbon-free contribution rises from 75.7% to 78.4% (more than 35% PV penetration case

Scenario 10 : Generation Retirement

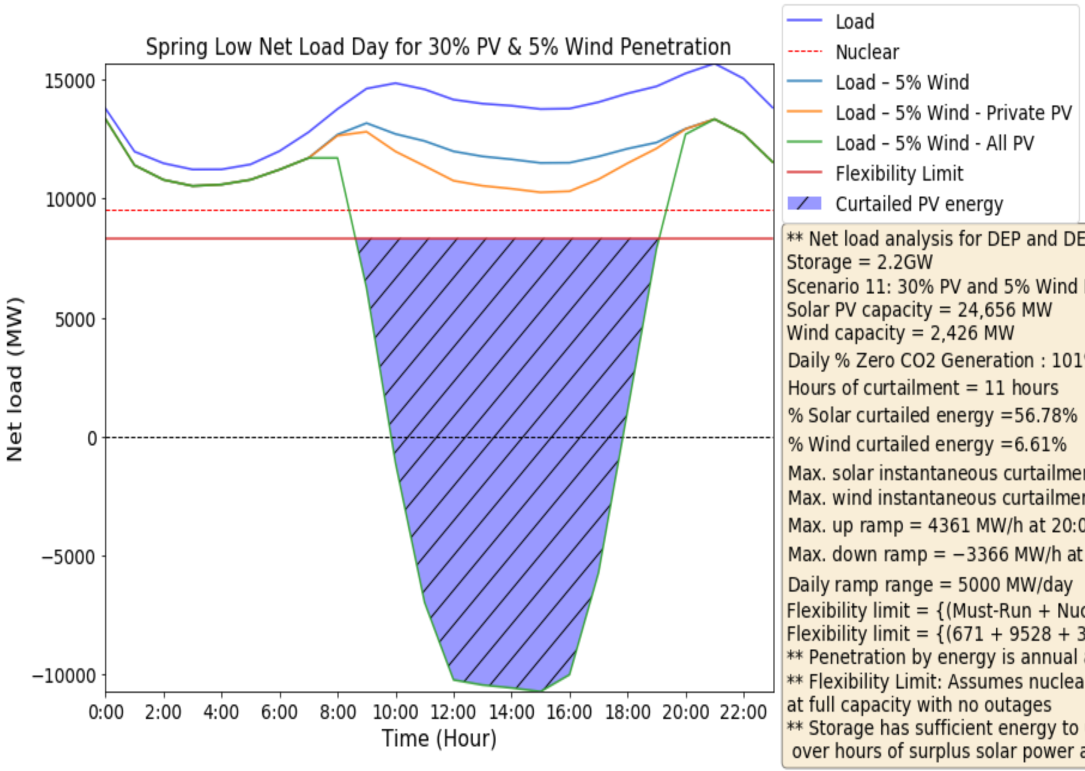


- Based on 25% PV penetration case, 10% of nuclear power is retired and assumed replaced with flexible thermal generation

Compared to the 25% PV penetration case:

- Curtailment of solar PV decreases from 26.9% to 22.2%
- Load met by carbon-free energy decreases from 75.7% to 71.2%

Scenario 11:
Additional Wind Energy Penetration



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 11: 30% PV and 5% Wind Penetration by annual energy
Solar PV capacity = 24,656 MW
Wind capacity = 2,426 MW
Daily % Zero CO2 Generation : 101%
Hours of curtailment = 11 hours
% Solar curtailed energy =56.78%
% Wind curtailed energy =6.61%
Max. solar instantaneous curtailment = 17295 MW
Max. wind instantaneous curtailment = 1763 MW
Max. up ramp = 4361 MW/h at 20:00
Max. down ramp = −3366 MW/h at 09:00
Daily ramp range = 5000 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(671 + 9528 + 344) - 2200} = 8343 MW @ 15:00
** Penetration by energy is annual and pre-curtailment
** Flexibility Limit: Assumes nuclear gen. running constantly at full capacity with no outages
** Storage has sufficient energy to utilize full pumping capacity over hours of surplus solar power and optimized for energy arbitrage

- Based on 30% PV penetration case, 5% penetration of wind power added

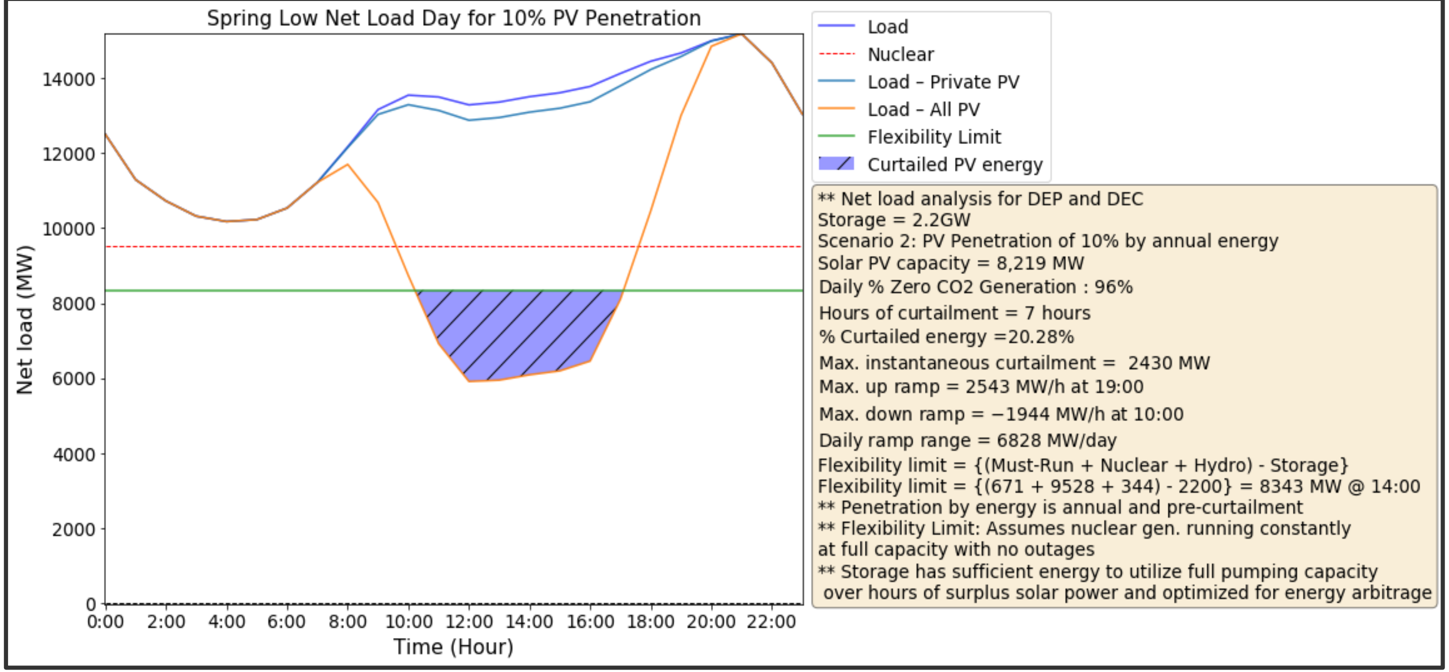
Compared to the 35% PV penetration case:

- Total renewable energy curtailment is reduced from 42% to 33.9% (37.6% solar is curtailed and 8.1% wind is curtailed)
- Total renewable energy marginal curtailment is reduced from 83.2% to 26.3%
- Load met by carbon-free increases from 77.5% to 80.7% (greatest of all scenarios)

Scenario 12:

DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

Chart
DEP and DEC modeled as a single region with unlimited transmission capabilities



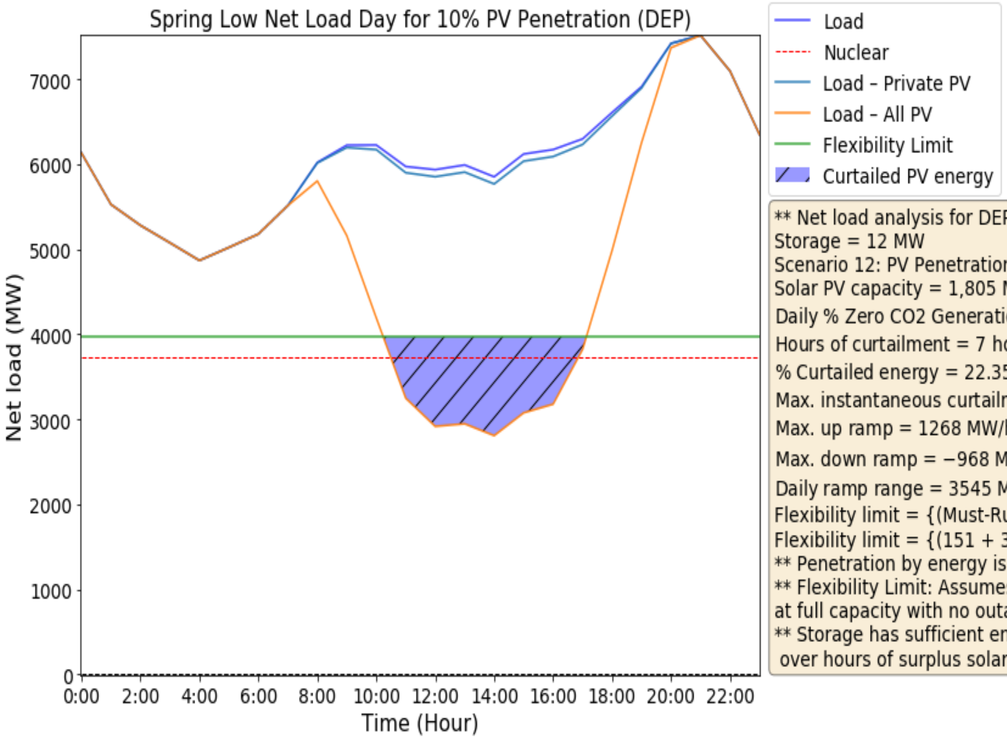
10% PV penetration is the lowest PV penetration scenario where curtailment occurs and the day pictured here has the highest curtailment at 20.28%.

- Based on 5%, 10% and 15% solar PV penetration case
- DEC and DEP are modeled separately with the inflexibility line, solar power profiles and load split between the two regions
- JDA interconnection is modeled with values that are directional and time dependent (night / day)
- Interconnection balances net load without an understanding of markets

Scenario 12:

DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

Chart
DEP after interconnection



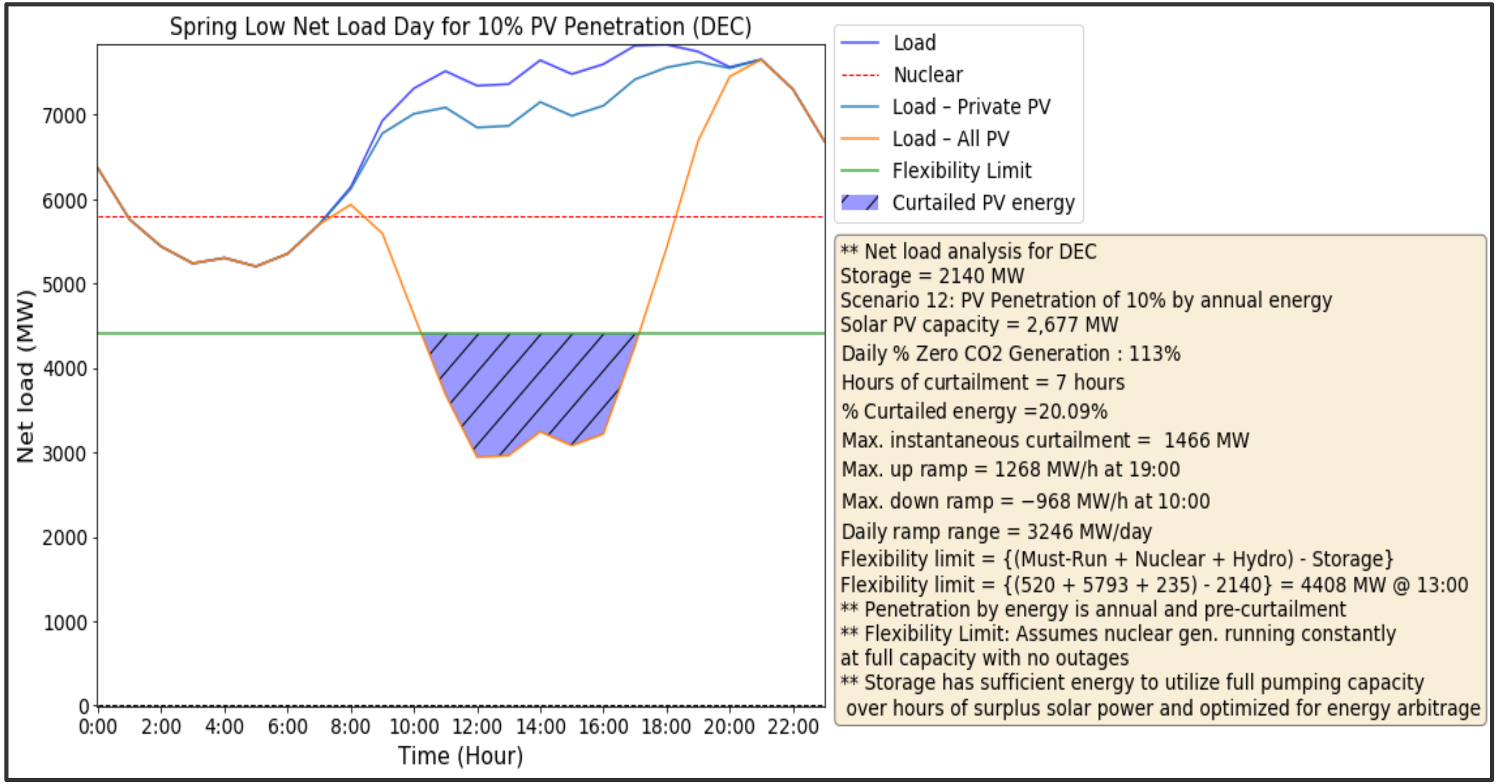
** Net load analysis for DEP
Storage = 12 MW
Scenario 12: PV Penetration of 10% by annual energy
Solar PV capacity = 1,805 MW
Daily % Zero CO2 Generation : 77%
Hours of curtailment = 7 hours
% Curtailed energy = 22.35%
Max. instantaneous curtailment = 1164 MW
Max. up ramp = 1268 MW/h at 19:00
Max. down ramp = −968 MW/h at 10:00
Daily ramp range = 3545 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(151 + 3735 + 98) - 12} = 3972 MW @ 14:00
** Penetration by energy is annual and pre-curtailment
** Flexibility Limit: Assumes nuclear gen. running constantly at full capacity with no outages
** Storage has sufficient energy to utilize full pumping capacity over hours of surplus solar power and optimized for energy arbitrage

- Curtailed energy = 22.35%

Scenario 12:

DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

Chart
DEC after interconnection



Curtailed energy = 20.09%

Scenario 12:

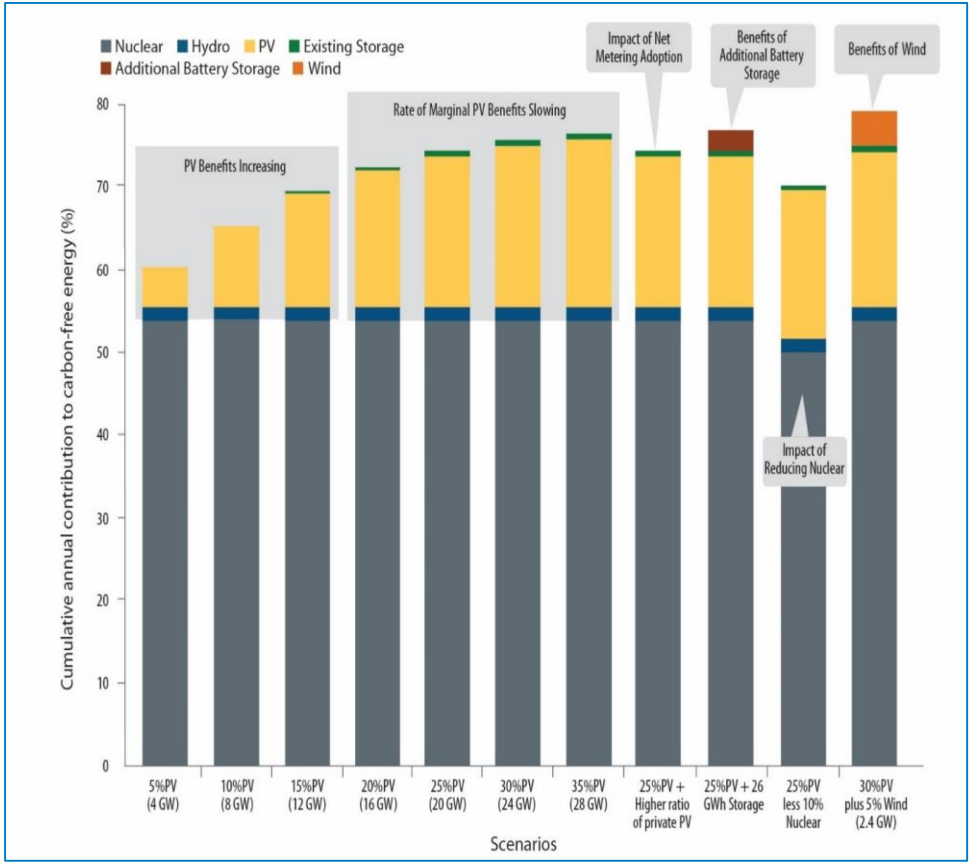
DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

Comparison of Curtailment of the System Modeled With and Without the Interconnection Modeled

% PV Penetration	Copper plate Curtailment (MW)	Copper plate Percentage Curtailment	Curtailment with JDA modeled (MW)	Percentage Curtailment with JDA modeled
5%	1,570	0.0%	1,361	0.0%
10%	172,444	1.1%	191,306	1.2%
15%	1,824,853	7.9%	1,928,162	8.3%

- This table shows the potential reduction in curtailment possible by upgrading the interconnection between DEP and DEC
- Considering the location of new solar can help minimize transmission constraints, especially for large penetrations

Summary of scenarios



Key Findings:

- Net load analysis highlights challenges and opportunities with integrating solar PV
- Average annual % of load met by carbon-free generation ranges from 60-79%
- Nuclear remains greatest contributor to carbon-free energy
- Above 15% solar PV, required curtailment grows
- The highest share of carbon-free generation is achieved by the scenario with the most resource diversity.
- Solar power curtailment is greater under separate balancing authorities

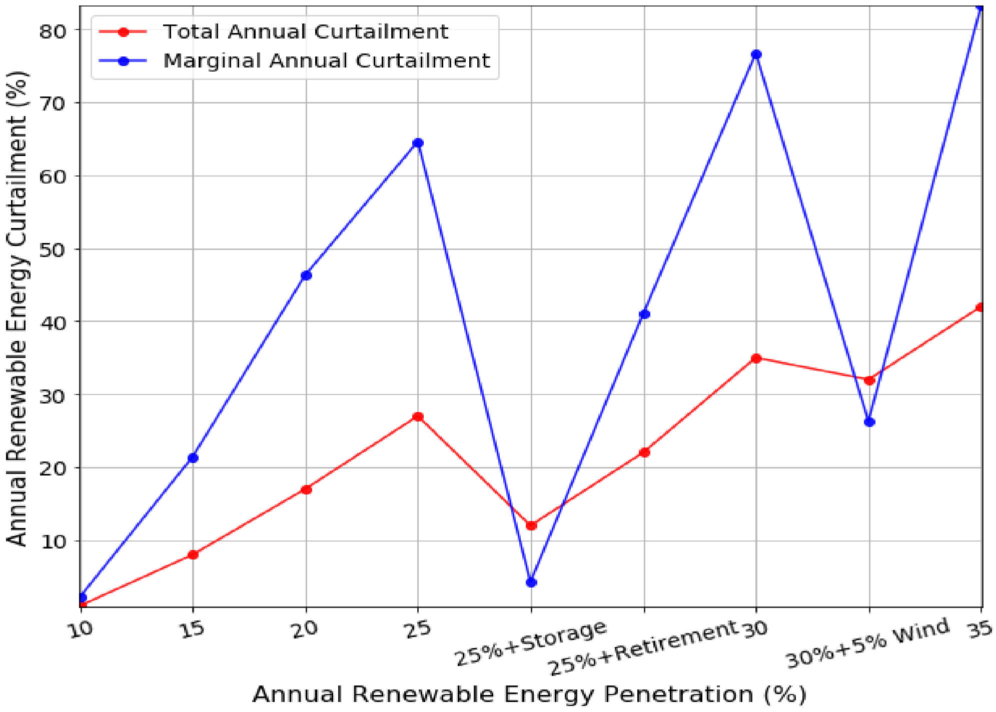
Annual Summary of Flexibility Metrics

Annual Flexibility Indicators

Scenario	5%	10%	15%	20%	25%	30%	35%	High DPV	Storag e	Nuclear Retirement	Wind
Load met by carbon-free generation, %	63	68	72	74	76	77	77	76	78	71	81
Maximum Instantaneous Curtailment, MW	530	3,323	6,618	10,003	13,504	17,207	20,909	13,548	11,073	12,551	17,486
Maximum up-ramp, MW/h	4,039	4,384	5,341	6,609	7,252	8,362	9,472	7,278	7,876	7,481	8,401
Maximum down-ramp, MW/h	5,873	5,873	5,873	6,699	7,894	9,090	10,286	7,906	7,894	7,894	9,555

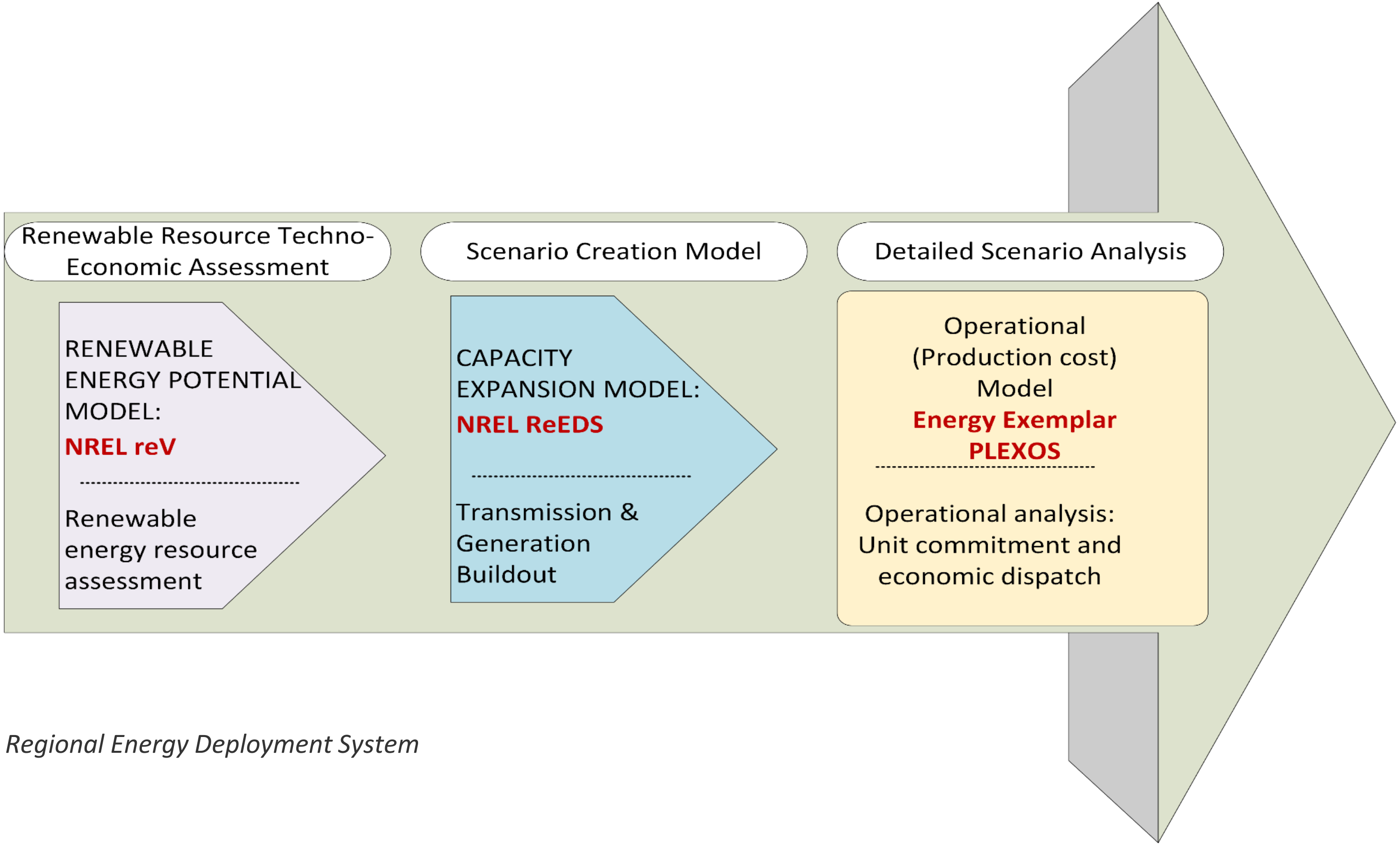
- Maximum instantaneous curtailment occurs in winter for penetrations up to and including 20% and then occurs in spring
- All maximum ramps happen in winter
- Transmission and nuclear retirement are both challenges with increasing PV penetration

Annual Summary of Opportunities and Conclusion



- Duke Energy endeavors to increase the portion of load met by carbon-free generation
- This net load analysis highlights challenges and opportunities with integrating solar PV and applying a selection of solutions
- Curtailment will likely begin at 10% PV penetration
- Greatest curtailment occurs during spring which is also when the greatest portion of load is met by carbon-free generation
- The benefits of adding wind power compared to solar power increase as solar PV penetration increases
- Further analysis with more advanced models would better evaluate options and impacts

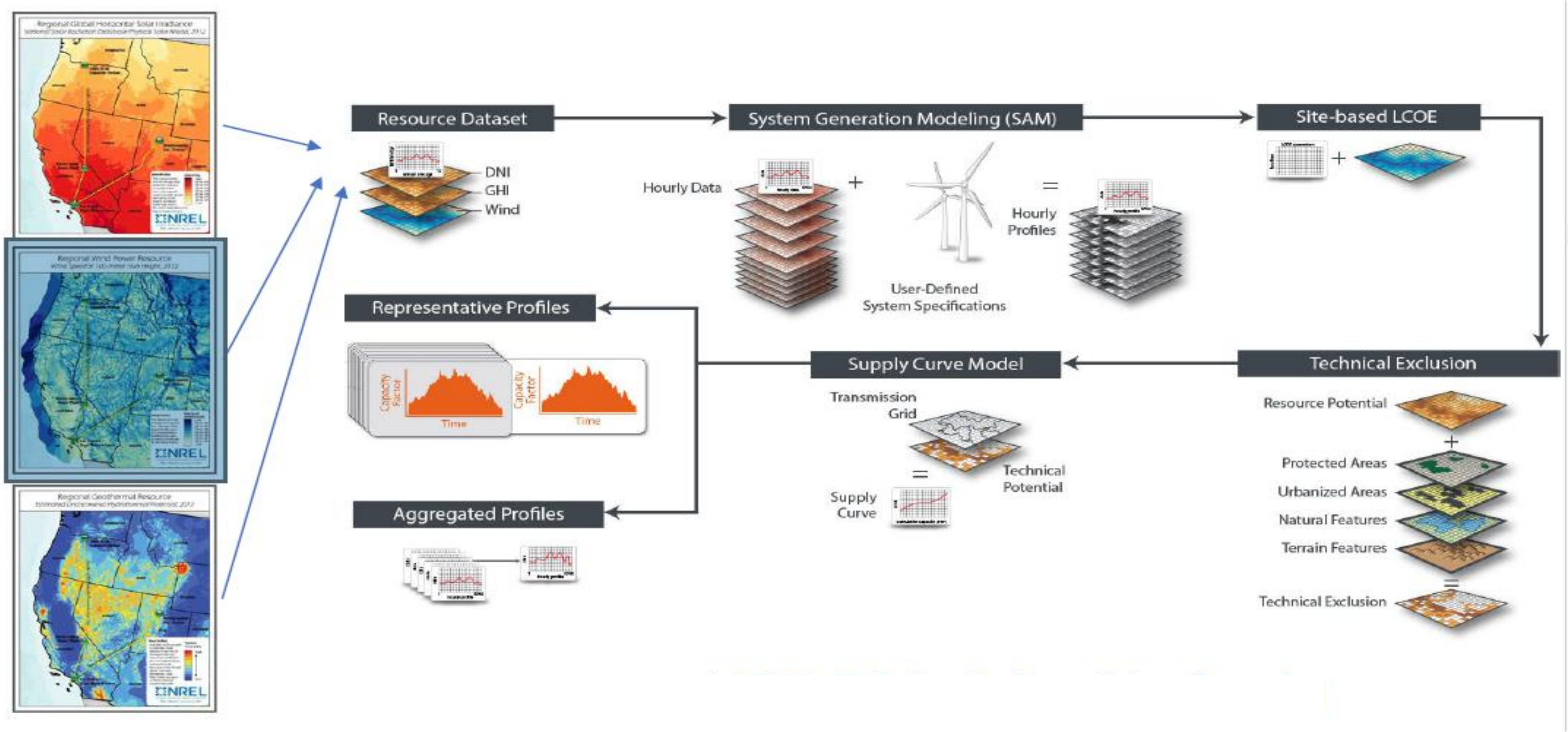
Carbon-Free Resource Integration Study – Phase 2



**ReEDS: Regional Energy Deployment System*

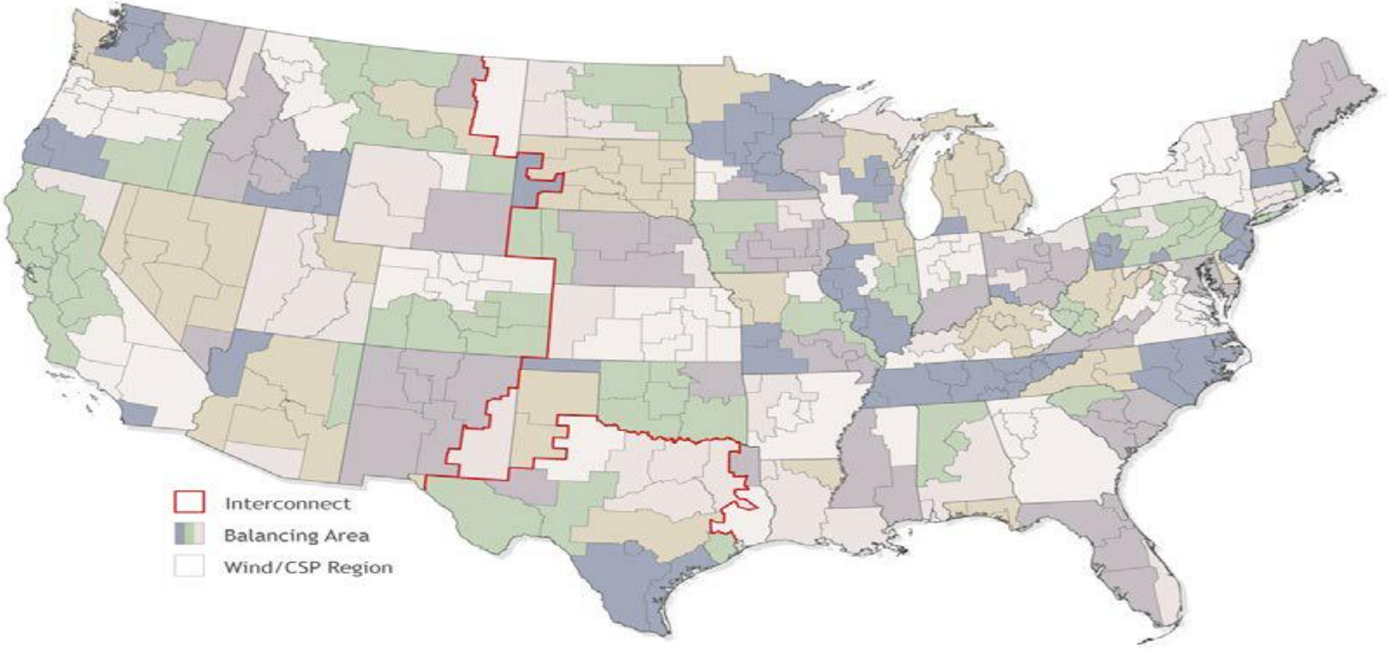
Renewable Energy Potential Model – NREL reV

- Resource Assessment (Geospatial data science modeling)



Capacity Expansion Model – NREL ReEDS

- ReEDS includes 3 interconnections, 134 model BAs, and 356 Wind and CSP resource regions
- Transmission and generation buildout
- Scenario creation model
- Optimal investment pathways



Summary of the Standard Scenarios

Non-Policy Scenarios

Fuel Cost
- High Oil & Gas Resource (AEO 2018)
- Low Oil & Gas Resource (AEO 2018)

Demand
- Low Demand
- High Demand
- Vehicle Electrification

Other
- Extended Cost Recovery
- Climate Change Impacts
- Reduced RE Resource
- Transmission Expansion Barriers
- Restricted Cooling Water

Mid-case
- Reference or Mid-level Assumptions

Technology Cost
- Low RE Cost
- High RE Cost
- Low Wind Cost
- Low PV Cost
- Low Geo Cost
- Low CSP Cost
- Low Hydro Cost
- Low Offshore Wind Cost
- Nuclear Breakthrough
- Low Battery Cost
- High Battery Cost

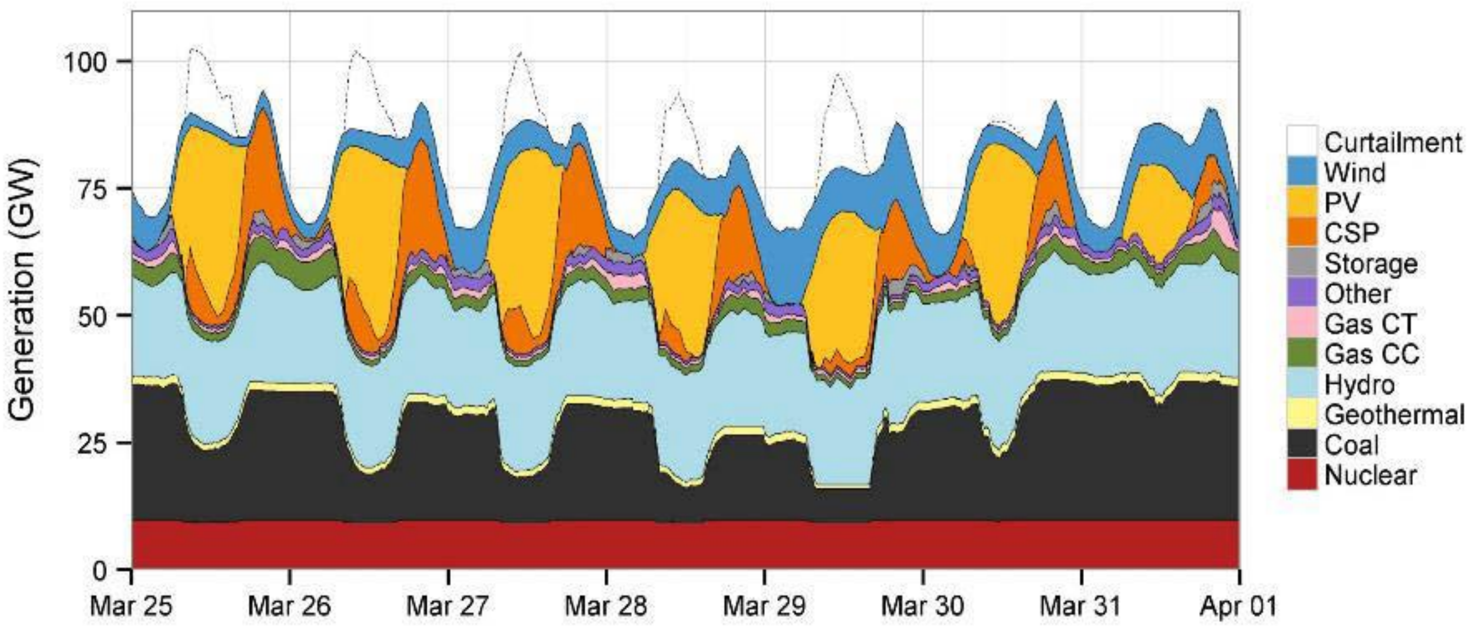
Combinations
- Low/High NG Price with
  - Low/High RE Cost
  - Low/High Geo Cost
  - Low/High CSP Cost
  - Low/High Hydro Cost
  - Low/High Offshore Wind Cost

Retirements
- 80 Year Nuclear
- 60 Year Nuclear
- Accelerated Nuclear Retirement
- Accelerated Retirements
- Extended Lifetimes

Policy
- National 80% RPS by 2050
- 83% CO_2 Reduction by 2050
- ITC & PTC Extension to 2030

Operational (Production cost) Model – Energy Exemplar PLEXOS

- Detailed scenario analysis from NREL ReEDS simulations
- Optimizes unit commitment and economic dispatch up to 5-minute resolution
- Minimizes the cost of power system operations



Thank you – any questions?

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APPENDIX

Scenario	Definition	Annual Load Met by Carbon Free Generation (%)	Annual Curtailed Energy (%)	Annual Hours of Curtailment	Annual Maximum Instantaneous Curtailment (MW)
1. Solar energy penetration 5%—both balancing authorities as a single region	4,109 MW, 5.5% of total solar is rooftop	63%	0%	6	530
2. Solar energy penetration 10%—both balancing authorities as a single region	8,219 MW, 5.5% of total solar is rooftop	68%	1%	179	3,323
3. Solar energy penetration 15%—both balancing authorities as a single region	12,328 MW, 5.5% of total solar is rooftop	72%	8%	882	6,618
4. Solar energy penetration 20%—both balancing authorities as a single region	16,438 MW, 5.5% of total solar is rooftop	74%	17%	1,506	10,003
5. Solar energy penetration 25%—both balancing authorities as a single region	20,547 MW, 5.5% of total solar is rooftop	76%	27%	2,016	13,504
6. Solar energy penetration 30%—both balancing authorities as a single region	24,656 MW, 5.5% of total solar is rooftop	77%	35%	2,355	17,207
7. Solar energy penetration 35%—both balancing authorities as a single region	28,766 MW, 5.5% of total solar is rooftop	77%	42%	2,587	20,909
8. Higher ratio of distributed to utility solar added to the system—both balancing authorities as a single region	Based on the 25% solar energy penetration scenario, 18.91% of PV is uncurtailable rooftop.	76%	36%	2,017	13,548
9. Additional storage—both balancing authorities as a single region	Based on the 25% solar energy penetration scenario, addition of 1,000 MW of 4-hour storage, 1,000 MW of 6-hour storage, and 2,000 MW of 8-hour storage	78%	12%	1,239	11,073
10. Nuclear retirement—both balancing authorities as a single region	Based on the 25% solar energy penetration scenario, assume a 10% nuclear reduction	71%	22%	1,804	12,551
11. Additional wind energy penetration 5—both balancing authorities as a single region	Based on the 30% solar energy penetration scenario, an additional 5% wind energy penetration is added.	81%	32%	2,486	17,486
12—DEC 5%	Based on scenarios 1–3 inclusive, DEP and DEC are analyzed separately with an interconnection limit between	73%	0%	5	246
12—DEC 10%		78%	1%	213	1,886
12—DEC 15%		94%	7%	912	3,418
12—DEP 5%		52%	0%	5	246
12—DEP 10%		56%	1%	205	1,600
12—DEP 15%		60%	10%	905	3,418

Average Seasonal Percentage of Load Met by Carbon-Free Generation for Each Scenario

Scenario	Spring	Summer	Fall	Winter	Annual
1. Solar energy penetration 5%—both balancing authorities as a single region	70%	56%	67%	59%	63%
2. Solar energy penetration 10%—both balancing authorities as a single region	76%	60%	72%	63%	68%
3. Solar energy penetration 15%—both balancing authorities as a single region	81%	65%	75%	65%	72%
4. Solar energy penetration 20%—both balancing authorities as a single region	83%	69%	78%	67%	74%
5. Solar energy penetration 25%—both balancing authorities as a single region	84%	71%	79%	68%	76%
6. Solar energy penetration 30%—both balancing authorities as a single region	85%	73%	80%	69%	77%
7. Solar energy penetration 35%—both balancing authorities as a single region	86%	74%	81%	69%	77%
8. Higher ratio of distributed to utility solar added to the system—both balancing authorities as a single region	84%	71%	79%	68%	76%
9. Additional storage—both balancing authorities as a single region	88%	72%	82%	70%	78%
10. Nuclear retirement—both balancing authorities as a single region	80%	67%	74%	64%	71%
11. Additional wind energy penetration 5—both balancing authorities as a single region	90%	76%	84%	73%	81%
12 – DEC 5%	82%	63%	78%	68%	73%
12 – DEC 10%	89%	68%	84%	72%	78%
12 – DEC 15%	106%	86%	100%	86%	94%
12 – DEP 5%	57%	47%	54%	48%	52%
12 – DEP 10%	63%	52%	59%	52%	56%
12 – DEP 15%	66%	56%	62%	54%	60%

Average Percentage Curtailed Energy

Scenario	Spring	Summer	Fall	Winter	Annual
1	0%	0%	0%	0%	0%
2	2%	0%	1%	2%	1%
3	12%	1%	10%	10%	8%
4	25%	4%	22%	22%	17%
5	36%	12%	32%	31%	27%
6	44%	21%	40%	39%	35%
7	50%	29%	46%	45%	42%
8	47%	16%	42%	41%	36%
9	19%	2%	15%	14%	12%
10	30%	8%	27%	26%	22%
11	40%	20%	36%	34%	32%
12 – DEC 5%	0%	0%	0%	0%	0%
12 – DEC 10%	2%	0%	1%	1%	1%
12 – DEC 15%	11%	1%	9%	10%	7%
12 – DEP 5%	0%	0%	0%	0%	0%
12 – DEP 10%	2%	0%	1%	1%	1%
12 – DEP 15%	15%	2%	30%	31%	10%

Hours of Curtailment per Season

Scenario	Spring	Summer	Fall	Winter	Annual
1	0	0	0	6	6
2	76	0	45	58	179
3	351	36	275	220	882
4	533	216	403	354	1,506
5	636	458	494	428	2,016
6	707	598	562	488	2,355
7	752	700	610	525	2,587
8	634	454	496	433	2,017
9	484	136	341	278	1,239
10	593	363	457	391	1,804
11	746	650	584	506	2,486
12 – DEC 5%	0	0	0	5	5
12 – DEC 10%	91	2	54	66	213
12 – DEC 15%	358	53	278	223	912
12 – DEP 5%	0	0	0	5	5
12 – DEP 10%	90	1	51	63	205
12 – DEP 15%	361	45	282	217	905

Maximum instantaneous curtailment of each season (MW)

Scenario	Spring	Summer	Fall	Winter
1	0	0	0	530
2	2430	0	2752	3233
3	6113	2913	5897	6618
4	9801	6106	9183	10003
5	13504	9299	12560	13389
6	17207	12542	16023	16774
7	20909	16143	19689	20271
8	13548	9248	12568	13452
9	11073	5769	9185	9842
10	12551	8346	11607	12436
11	17486	13326	16273	17084
12 – DEC 5%	0	0	0	246
12 – DEC 10%	1466	252	1390	1886
12 – DEC 15%	3116	1878	2958	3418
12 – DEP 5%	0	0	0	246
12 – DEP 10%	1234	117	1390	1600
12 – DEP 15%	3116	1630	2958	3418