Carbon-Free Resource Integration Study

Reiko Matsuda-Dunn, Michael Emmanuel, Erol Chartan, Bri-Mathias Hodge, and Gregory Brinkman

National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

List of Acronyms

DEC	Duke Energy Carolinas
DEP	Duke Energy Progress
NREL	National Renewable Energy Laboratory
PV	photovoltaic
WIND	Wind Integration National Dataset

Foreword

This report covers the results of a preliminary phase 1 analysis conducted by the National Renewable Energy Laboratory (NREL) with Duke Energy, who funded this work and whose expertise, specialist knowledge, and diligence has helped guide the process. This initial effort is a net load analysis which compares estimated hourly solar, wind, net load, and system minimum generation time series for different scenarios. It aims primarily to set up a baseline for more detailed modeling as part of a larger effort between Duke Energy and NREL expected to last multiple years. The full analysis will provide a broader insight into the costs, challenges, and opportunities of renewable energy integration in the Duke Energy service territory in the Carolinas. This report and the full analysis are not financial plans and are not intended to replace Duke Energy's integrated resource planning process. Rather, they examine the operational considerations of integrating additional carbon-free resources onto the Duke Energy Carolinas and Duke Energy Progress system.

Executive Summary

This report presents a net load analysis, geospatial analysis, and a web application for the Duke Energy Carbon-Free Resource Integration Study. In this collaborative engagement, the National Renewable Energy Laboratory (NREL) provides research support to Duke Energy to analyze the impacts of integrating significant amounts of new solar photovoltaic (PV) power into its service territory under a variety of scenarios. This analysis covers Duke Energy's territories in North Carolina and South Carolina, including two balancing authorities—Duke Energy Progress (DEP) and Duke Energy Carolinas (DEC)—with detailed assessments and discussions of the operations of the existing fleet, particularly nuclear generation, under high-penetration scenarios of solar PV. In addition to quantifying the solar potential, NREL is working with Duke Energy to identify possible opportunities for wind, storage, demand-side resources, and other technologies.

Scenario Analysis

This analysis looks at a variety of solar power penetration levels in Duke Energy's service territory in the Carolinas—compared to load and system-wide minimum generation levels—that best represent potential challenges and opportunities for renewable generation integration. An example of this includes an analysis of balancing solar and load for typical days during different seasons and extreme days, such as minimum and peak net load days. Net load is defined as the customer load less wind power and solar power generation. This analysis is performed by comparing estimated hourly solar, wind, net load, and system minimum generation time series for the different scenarios. The overall aim is to help Duke Energy understand initial estimates of possible curtailment, key periods of ramping, and load-following requirements. Further, this analysis captures net load impacts across different seasons and operational issues related to generation flexibility limit during periods of low load with high penetrations of solar energy.

Key Findings

Table ES-1 shows the results of the annual metrics, including annual percentage of load met by carbon-free generation, annual percentage of curtailed energy, annual hours of curtailment, and annual maximum instantaneous curtailment for all scenarios. For scenarios 1 through 11, both balancing authorities (DEC and DEP) are modeled as a single region, whereas Scenario 12 models DEP and DEC separately with an interconnection limit between them.

In scenarios 1 through 7, as solar energy penetration increases, the percentage of load met by carbon-free generation increases, until the flexibility limit is reached, when PV production must be curtailed, and additional solar power has a marginal impact. The average annual percentage of load met by carbon-free generation ranges from 60% to 77%, for these aforementioned scenarios, as shown in Table ES-1. As the PV penetration level increases, the marginal contribution to carbon-free generation suffers diminishing returns, due to the inability to shift the timing of PV generation to match the early and late hour net demand, especially from 20% through 35% PV energy penetration.

Table ES-1. Annual Metrics Evaluation for All Scenarios in the Net Load Analysis

Scenario	DEP and DEC Modeled as a Single Region or Separately	Definition	Annual Load Met by Carbon-Free Generation (%)	Annual Curtailed Renewable Energy (%)	Annual Hours of Curtailment	Annual Maximum Instantaneous Curtailment (MW)
1. Solar energy penetration 5%	Single region	4,109 MW, 5.5% of total solar is rooftop	60.4%	0%	6	530
2. Solar energy penetration 10%	Single region	8,219 MW, 5.5% of total solar is rooftop	65.5%	1%	179	3,323
3. Solar energy penetration 15%	Single region	12,328 MW, 5.5% of total solar is rooftop	69.7%	8%	882	6,618
4. Solar energy penetration 20%	Single region	16,438 MW, 5.5% of total solar is rooftop	72.5%	17%	1,506	10,003
5. Solar energy penetration 25%	Single region	20,547 MW, 5.5% of total solar is rooftop	74.4%	27%	2,016	13,504
6. Solar energy penetration 30%	Single region	24,656 MW, 5.5% of total solar is rooftop	75.6%	35%	2,355	17,207
7. Solar energy penetration 35%	Single region	28,766 MW, 5.5% of total solar is rooftop	76.5%	42%	2,587	20,909
8. Higher ratio of distributed to utility solar added to the system	Single region	Based on the 25% solar energy penetration scenario, 18.91% of PV is uncurtailable rooftop	74.4%	27%	2,017	13,548

Scenario	DEP and DEC Modeled as a Single Region or Separately	Definition	Annual Load Met by Carbon-Free Generation (%)	Annual Curtailed Renewable Energy (%)	Annual Hours of Curtailment	Annual Maximum Instantaneous Curtailment (MW)
9. Additional storage	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	77.1%	12%	1,239	11,073
10. Nuclear retirement	Single region	Based on the 25% solar energy penetration scenario, assume a 10% nuclear reduction	70.2%	22%	1,804	12,551
11. Additional wind energy at 5% penetration	Single region	Based on the 30% solar energy penetration scenario, an additional 5% wind energy penetration is added	79.4%	32%	2,486	17,486
12—DEC 5%	Separate regions	Based on scenarios 1–3 inclusive, DEP and DEC are analyzed separately with an interconnection limit between	70%	0%	5	246
12—DEC 10%	Separate regions		75%	1%	213	1,886
12—DEC 15%	Separate regions		80%	7%	912	3,418
12—DEP 5%	Separate regions		50%	0%	5	246
12—DEP 10%	Separate regions		54%	1%	205	1,600
12—DEP 15%	Separate regions		58%	10%	905	3,418

For scenarios 2 through 7 (solar energy penetration levels of 10% to 35% inclusive), analysis shows that the annual percentage curtailment ranges from 1% to 42% of total solar energy as PV penetration increases from 10% to 35%. The majority of the solar energy curtailment occurs during the spring and fall seasons, which are characterized with low load and high renewable energy production. Also, Scenario 7, which has a solar energy penetration level of 35% and models both balancing authorities as one region, experienced the highest maximum instantaneous curtailment and hours of curtailment: 20,909 MW and 2,587 hours, respectively.

The increased proportion of private solar PV analyzed in Scenario 8 does not materially affect the curtailment required. This does not infer that significant amount of rooftop will have no impact on system balancing. Given the assumptions of this study, with increasing penetration of rooftop solar from 5.5% of the total to 18.9% of the total, there is still sufficient curtailable solar to balance load and generation. Annual curtailment is 33% of utility solar and 27% of the total solar, which is the same as the baseline in Scenario 5.

The additional storage (26,000 MWh)[1] modeled in Scenario 9 results in a 3% increase in the amount of load met by carbon-free generation compared with the baseline in Scenario 5, which has 25% PV penetration. Also, the percentage of renewable energy curtailed decreases by 15%, whereas the 10% nuclear retirement scenario leads to a 4% decrease in the amount of load met by carbon-free generation and curtailed solar energy.

Further, the addition of 5% wind energy penetration to 30% solar energy in Scenario 11 results in a 2% increase in carbon-free energy production compared with the 35% solar energy penetration case. Also, the renewable energy curtailed decreases by 10% of the total renewable energy production. Thus, this shows that a balanced mix of renewable resources might reduce curtailment and the overall system cost compared to a similar penetration of PV-only generation

When DEC and DEP are modeled as individual balancing authorities with existing limited interconnection between them, Scenario 12 shows that DEP experiences a lower average percentage of load met by carbon-free generation, ranging from 50% to 58%, compared to DEC, which ranges from 70% to 80%. A production cost optimization would enable simulation of the interconnection and other transmission constraints in a more realistic manner.

Figure ES-1 (below) shows the annual contribution to carbon-free energy from all the scenarios considered in this study. The largest contribution resource to carbon-free energy is the nuclear power plant, followed by the increasing penetration of PV. Also, Figure ES-1 shows the impact of resource diversity with wind integration in the amount of carbon-free energy contribution with DEP and DEC modeled as a single balancing authority. Scenario 11, with 30% PV and 5% wind energy penetration, results in the highest contribution: 79%.

Another important metric used to assess the diminishing returns of increasing levels of variable generation resources added to the system is marginal curtailment.[2] As PV penetration levels increase, marginal curtailment increases more rapidly than total curtailment, as shown in Figure ES-2. This indicates that an increasing proportion of solar energy capacity will be curtailed as the system approaches high penetration levels of variable solar generation without adding sufficient system flexibility; however, solutions such as the addition of storage and wind power instead of additional solar power result in the marginal curtailment being reduced, as shown in Figure ES-2.

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[1] This study did not consider the value stacking of storage units (i.e., using storage for other ancillary services, such as frequency regulation, voltage support, spinning and nonspinning reserves); therefore, the load-shifting and flexibility benefit presented in this report cannot be used solely for the economic assessment of storage deployment in the grid.
[2] The marginal curtailment rate refers to the curtailment from an additional unit of variable generation capacity added to the system. For example, when increasing the variable generation penetration level from 10% to 15%, the marginal curtailment is the curtailment rate of the additional 5% of variable generation.

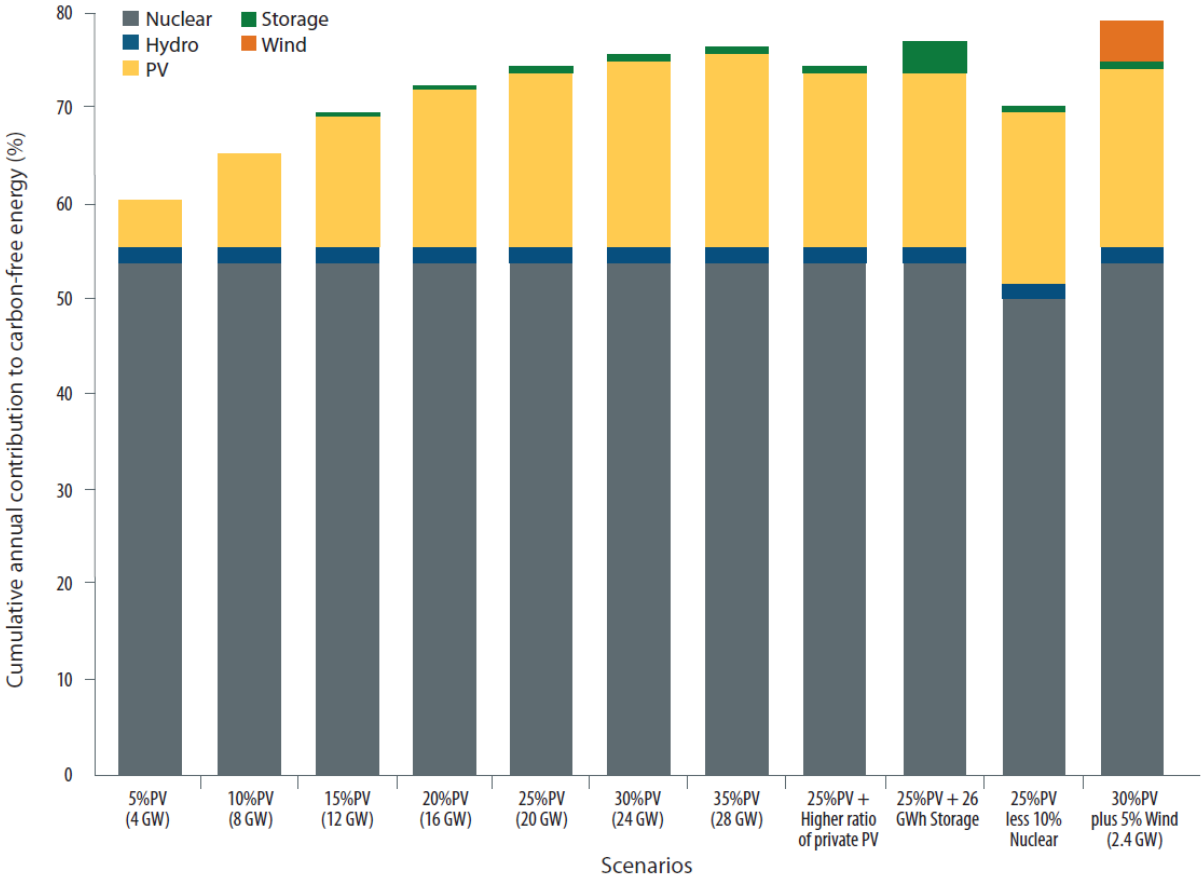

Figure ES-1. Percentage of annual carbon-free energy and contribution from each energy resource with increasing PV penetration, generation retirement, storage, and wind integration

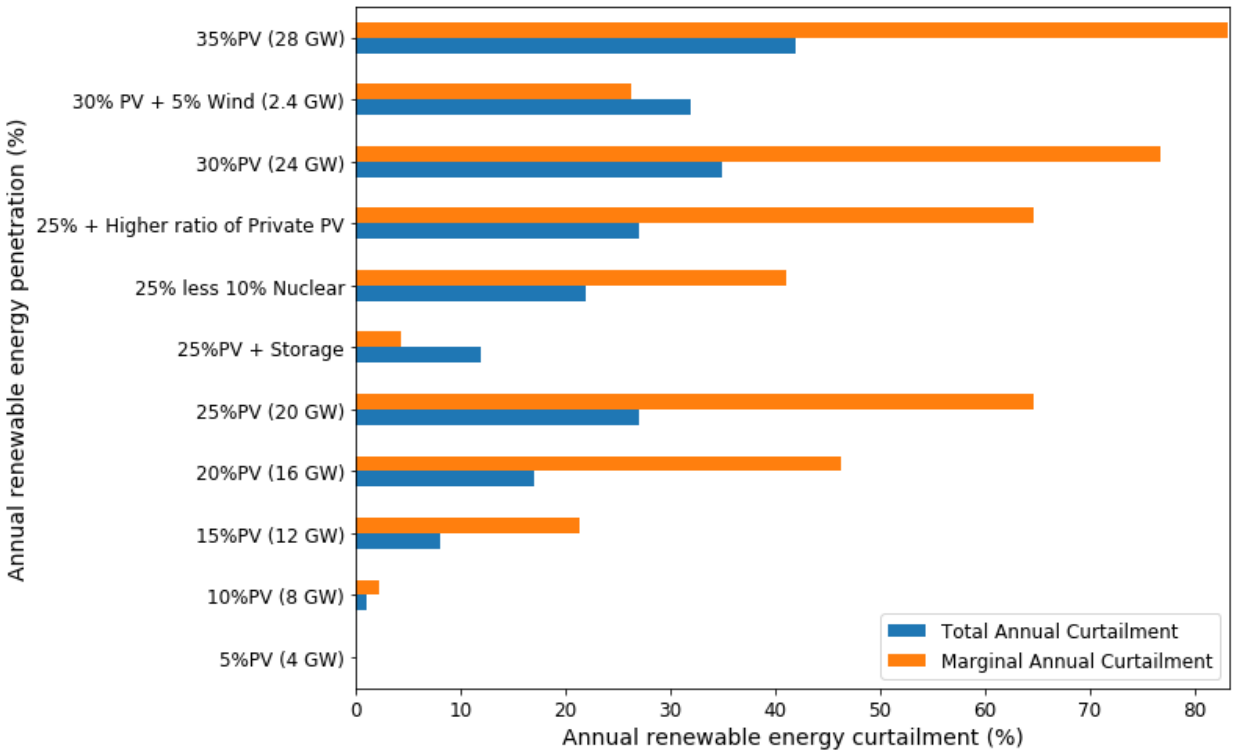

Figure ES-2. Marginal and total curtailment with increasing PV penetration, generation retirement, storage, and wind integration

Conclusions

The results and analysis of Phase 1 of the Carbon-Free Resource Integration Study presented in this report will help NREL and Duke Energy scope future work in this area to examine and address the identified grid integration challenges in greater technical detail. Further analysis with more advanced models—such as unit commitment and economic dispatch, capacity expansion planning, and dynamic analysis models—will be required to more fully assess system impacts with increasing variable generation penetration levels as well as flexibility opportunities to accommodate variable renewable energy sources to achieve the carbon-free goals of Duke Energy.

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1 Introduction

Duke Energy is one of the largest electric power holding companies in the United States. It has more than 30,000 distributed energy resource facilities, with a combined capacity of more than 3,700 MW operating across all Duke Energy jurisdictions. More than 90% of this capacity is in the Carolinas, where more than 16,000 distributed energy resource sites generate more than 3,200 MW on the transmission and distribution systems, making the Duke Carolinas a national leader for integrating utility-scale solar generation. Duke Energy continues to strengthen its commitment toward carbon-free electricity generation, and during the next several years the capacity of solar generation across Duke Energy is expected to at least double. The incentivization of commercial solar by Duke Energy coupled with the recently launched proposal for 6800 MW under the North Carolina House Bill 589, as well as plans to add 700 MW of solar facilities in Florida, continue to drive the rapid adoption of solar generation across Duke Energy's service territory (Duke Energy, 2018).

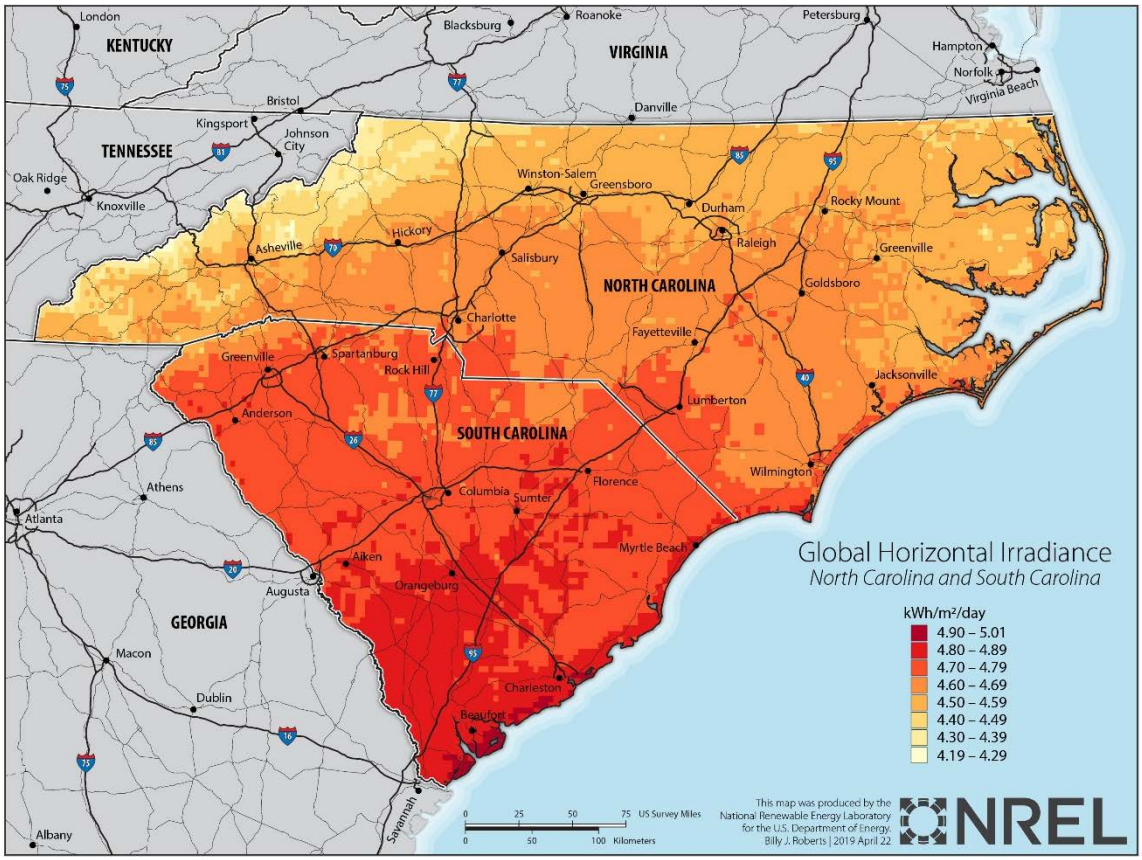

Figure 1. Solar energy resource in the Carolinas region

Duke Energy is seeking to analyze the impacts of integrating significant amounts of new carbon-free power sources into the Duke Energy power system under a variety of penetrations levels. This report focuses on investigating the addition of solar power along with understanding how the integration of variable generation sources, especially at high penetration levels, comes with potential challenges to reliable power system operations. The variability and uncertainty of renewable energy sources are two major constraints to integrating them into the power system. In

power network operations, generation planners will always need to ensure that there is enough capacity to serve load at any given time. Characterizing variable generation resources in planning operations becomes a challenge because of their tendency to disrupt the balance of the generation portfolio. Consequently, thermal and hydro generators are operated differently to accommodate the variability and uncertainty of renewable electricity generators (Lew, 2013).

Additionally, the integration of variable and uncertain power generation from wind and solar units at high penetration levels introduces another pivotal variable: net load (normal load less wind power and solar power). This creates a new set of requirements for integrated and reliable power system planning operations. The net load variability has created a further need to evaluate system flexibility because of its impacts on system operating costs. The ability of the power system to integrate additional renewable resources is largely a function of its flexibility, which is chiefly driven by the ability of individual plants to change their output to serve these variations in net electricity consumption (Ela, 2014). The key to managing the variability and uncertainty of variable generation sources is to increase the system-wide flexibility in the power system (Mai, et al., 2012).

Duke Energy is committed to creating a carbon-free power system of the future. Currently, the large nuclear fleet contributes to load greatly as carbon-free generation. With the current cost of solar power, it makes sense to investigate increasing solar power capacity to meet higher carbon-free goals. This will likely increase the requirement for Duke's thermal generation sources to be flexible, which will be limited by their nuclear power plants, which typically run only at full output. A detailed understanding of power system flexibility characteristics has become critical because high levels of variable generation will have significant impacts on the operation of the traditional thermal generation fleet.

This report analyzes the net load and presents the impact of high penetration levels of variable generation on the operation of Duke Energy's power system given the flexibility limits set by a combination of the must-run units, hydro schedules, nuclear generators, and storage. These limits dictate curtailing excess solar power during times when there is a greater amount of solar photovoltaic (PV) generation than can be accommodated.

To contextualize subsequent discussions in this report, it is important to define variable generation penetration levels. One power-based definition considers the ratio of variable generation nameplate capacity to system peak load. The definition of penetration level by energy often estimates the amount of renewable energy (pre-curtailment) injected into the grid during a period of time and helps to quantify the amount of displaced fossil-fueled generation, fuel consumption savings, and avoided carbon emissions. The energy-based definition is useful when considering very large systems and long time frames, and it has been adopted in many renewable portfolio standards (Bebic, 2008). Therefore, the analysis presented in this report uses the energy-based definition of penetration level on an annual basis.

In scoping Phase 1 of this collaborative engagement, the National Renewable Energy Laboratory (NREL), in consultation with Duke Energy, designed the scenarios to be considered, as shown in Table 1. These scenarios are analyzed and documented in this report. Note that the penetration levels used in naming the scenarios are approximate numbers based on annual energy before curtailment.

Table 1. Scenarios for Net Load Analysis

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, assumes 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

This report examines the amount of renewable energy curtailment as well as the particular hours of curtailment for these scenarios. This report also presents an evaluation of the daily percentage of carbon-free generation from carbon-free plants.

Note that there are some limitations to the net load analysis presented in this report. This analysis does not include unit commitment and economic dispatch models; interconnection to neighbors; market models; system stability metrics such as voltage and/or frequency; or costs—all of which would be essential in recommending a pathway to the future.

2 Characterizing the Net Load

As power system planning continues to move toward adopting an integrated planning approach caused by increasing variable generation integration, it is now critical to begin characterizing the net load. The net load—defined here as the total customer demand minus the variable generation—gives the demand that must be met by traditional dispatchable generation. For this analysis, solar PV is considered to be non-dispatchable, though the utility solar power can be curtailed down. Therefore, its contribution to meeting reserve margins is quantified by how it changes the net load.

The net load analysis can be of interest for several reasons, including:

- At high penetration levels, variable generation can cause a significant shift in the timing of both the minimum and peak net load relative to the system or gross load, which can impact the system generation scheduling, cost of generation, and daily unit commitment and dispatch.
- During low-load conditions, which typically occur during the spring, high penetrations of variable generation can violate the system flexibility limit and result in significant integration issues. Consequently, during such periods renewable generation must be curtailed, which can adversely impact variable generation project economics or contractual arrangements with renewable generators.
- Net load analysis can be a useful tool in assessing power system flexibility in the presence of varying penetration levels of variable generation. Because increasing variable generation penetration levels can lead to increases in net load variability, and thus required thermal unit ramp rates and ramping ranges, the need for the power system to become more flexible increases. This scenario demands that conventional power plants would need to change their output more frequently than traditionally. Situations when the system flexibility requirements are not met could impact the reliable and economic operations of the grid. Impacts could include variable generation curtailment, reserve shortfalls, and potential frequency violations as a result of over- and undergeneration (Milligan, 2015)
- Outputs from net load analysis such as maximum renewable curtailment and the number of hours of curtailment are important metrics that can be used to evaluate system flexibility. Detailed flexibility evaluation, however, requires further analysis using different modeling methods, such as production cost modeling, capacity expansion planning, and dynamic stability analysis.

3 Scenario Analysis

This net load analysis covers the Duke Energy Carolinas (DEC) and Duke Energy Progress (DEP) balancing authorities, with 2019 hourly forecasted load data supplied by Duke Energy. Maintaining load and renewable resource coincident relationships is a primary consideration in net load analysis and assessing its impact on the system operational requirements, such as determining minimum generation levels (GE Energy, 2010). Spatial and temporal correlation of the load and variable generation sources are needed to accurately reflect the underlying weather patterns that drive both load and variable generation.

This report uses 2019 forecasted annual load and solar PV time-series profiles supplied by Duke Energy and based on the same weather period to ensure that the solar profiles are synchronized with the weather assumed in the load. For the net load analysis, thermal generation outside of nuclear, hydropower, and must-run units is considered to be entirely flexible—i.e., there are no constraints on minimum stable level, ramp rates, and outage rates. Rooftop solar is non-curtailable, utility solar is curtailable, and the must-run units are used for local voltage constraints. Table 8, in the appendix, shows a list of assumptions and definitions used for the net load analysis.

The generation flexibility limit consists of nuclear, hydropower units, and must-run units, offset by the hydropower pumped storage capacity (see Equation 1 in the appendix). Nuclear is assumed to run at 100% capacity for this analysis. From the data supplied by Duke Energy, note that the must-run units have hourly triggers and therefore could change intra-daily, whereas hydro schedules vary monthly. This explains why the generation flexibility limit line could change seasonally, and possibly daily, which is reflective of the inherent characteristics of the must-run units and hydro capacity considered in this analysis. The renewable energy curtailment per hour is the net load below the flexibility limit, which is calculated using Equation 2 in the appendix. The daily percentage of carbon-free generation includes solar power, wind power, hydropower, and nuclear (using storage), and it is calculated in Equation 3 in the appendix. The presented maximum up-ramp and down-ramp times are based on the ending times of each ramp.

An analysis of the average, minimum, and maximum net load days is performed to illustrate the varying impact of the net load variability across different seasons on key metrics, such as daily percentage of carbon-free generation, percentage of curtailed energy, maximum instantaneous curtailment, and hours of curtailment. The net load curves, as presented in this section, help capture the net load demand that the system must meet in real time for reliable operation of the grid.

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

Seven different levels of solar energy penetration are explored, beginning with 5% penetration and increasing in 5% increments through 35% penetration. The solar output before curtailment is the 2019 PV time series provided by Duke Energy scaled to the specified percentage of the total load. The scalars used for each scenario are provided in Table 3 of the appendix and are calculated using Equation 4. Higher penetrations of solar power are expected to experience geographical smoothing, which the scalers do not account for and thus overestimate the variability. Ramp rates for all the scenarios are calculated as the difference between the net load at a given hour and the hour immediately prior.

Solar PV capacities for each level of solar penetration are shown in Table 2.

Table 2. PV Capacities for Penetration Levels Defined by Scenarios 1–7

PV penetration in terms of annual energy before curtailment (%)	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 daily values for load, generation flexibility limit, rooftop, and all PV plants are estimated across all seasons. Figure 2 shows these data for scenarios 1–7 in the spring season, which has the highest curtailment. Graphs for the three remaining seasons are available in the appendix. In low penetrations of PV, adding more PV increases the percentage of load met by carbon-free generation until the flexibility limit is reached, at which point curtailment increases and additional solar power has diminishing returns.

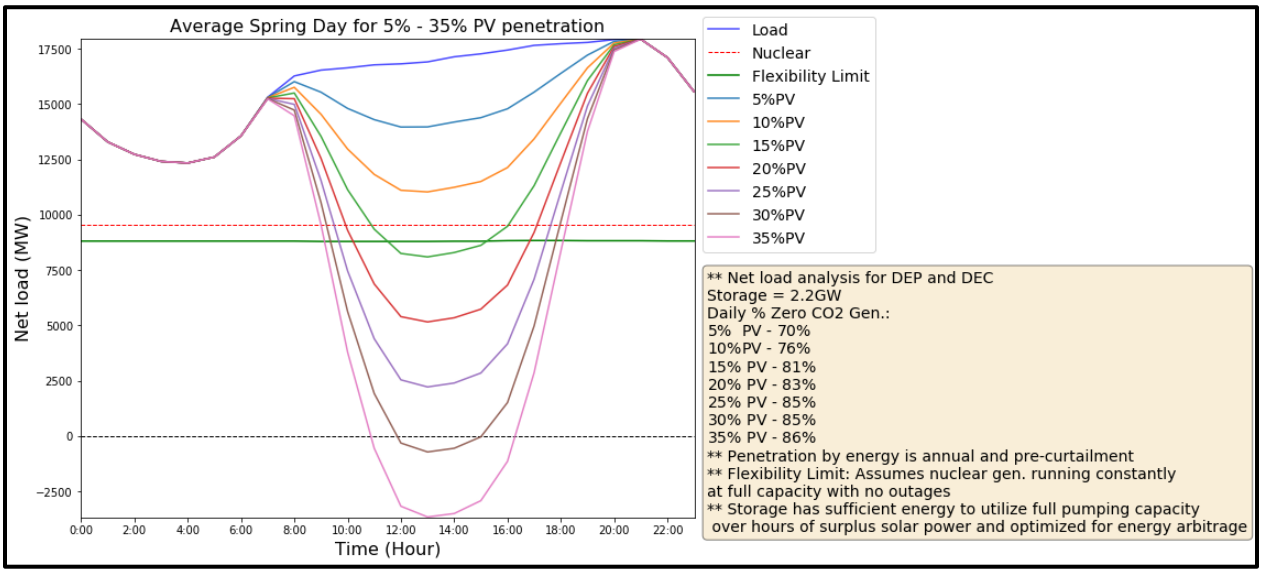

Figure 2. Average net load for all scenarios for spring

Annual average carbon-free generation ranges from 60% to 77% from the 5% PV penetration case to the 35% case, respectively. Seasonal values are shown in Table 3.

Table 3. Average Seasonal Percentage of Load Met by Carbon-Free Generation for Each Scenario

Scenario	Spring	Summer	Fall	Winter	Annual
1. Solar energy penetration 5%	69%	54%	65%	57%	60%
2. Solar energy penetration 10%	75%	59%	70%	61%	65%
3. Solar energy penetration 15%	80%	64%	74%	63%	70%
4. Solar energy penetration 20%	83%	68%	76%	65%	73%
5. Solar energy penetration 25%	84%	71%	78%	66%	74%
6. Solar energy penetration 30%	85%	73%	79%	67%	76%
7. Solar energy penetration 35%	86%	74%	80%	68%	77%
8. Increase proportion of distributed solar	84%	71%	78%	66%	74%
9. Additional storage	88%	73%	81%	68%	77%
10. Nuclear retirement	80%	67%	73%	62%	70%
11. Additional wind energy penetration 5%	90%	76%	83%	71%	79%
12. Two balancing authorities: DEC 5%	80%	61%	76%	66%	70%
12. Two balancing authorities: DEC 10%	87%	66%	82%	70%	75%
12. Two balancing authorities: DEC 15%	93%	71%	87%	73%	80%
12. Two balancing authorities: DEP 5%	56%	45%	53%	47%	50%
12. Two balancing authorities: DEP 10%	62%	50%	57%	50%	54%
12. Two balancing authorities: DEP 15%	65%	55%	60%	53%	58%

With the current flexibility limit, curtailment is necessary at PV penetration levels of 10% and more. Duke Energy will first experience significant curtailment at the 10% PV penetration level, at an annual average of 1.1%. Figure 3 shows a low net load day in spring, during which 20% curtailment will occur. With 10% PV energy, 65% of the annual load is met by carbon-free generation, indicating that in this case nearly 65% of energy from carbon-free sources could be achieved before any curtailment is needed. In Scenario 12, where DEP and DEC are modeled separately with a total PV penetration of 15%, DEC in spring achieves a carbon-free contribution of more than 100%. This is because we assume that existing storage can charge with energy that would otherwise be curtailed and then release the corresponding energy within the same day. This value suggests that this operation would result in a surplus of generation.

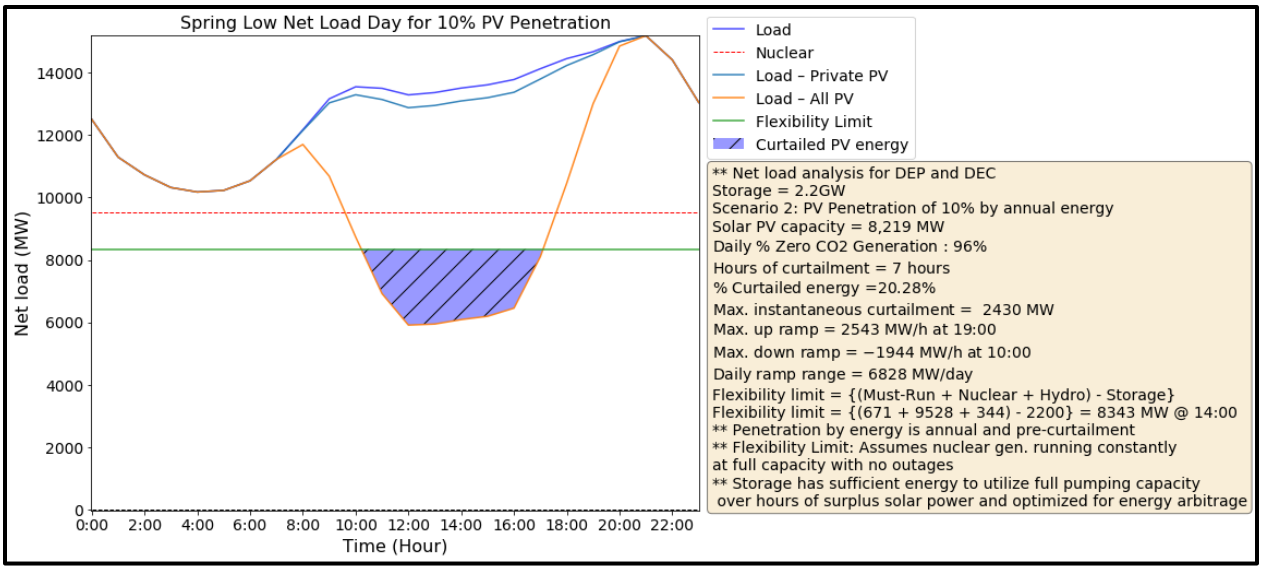

Figure 3. Minimum net load day for spring with 10% PV penetration

Annual percentage of curtailment ranges from 1.1% to 42% of total solar energy for scenarios 2–7. Seasonal and annual percentages of curtailment are shown in Table 4, and hours of curtailment are shown in Table 5. Seasonal maximum instantaneous curtailment is given in Table 13 in the appendix. Generally, the highest curtailment occurs in spring and the lowest in summer.

Table 4. Average Percentage Curtailed Energy

Scenario	Spring	Summer	Fall	Winter	Annual
1. Solar energy penetration 5%	0%	0%	0%	0%	0%
2. Solar energy penetration 10%	2%	0%	1%	2%	1%
3. Solar energy penetration 15%	12%	1%	10%	10%	8%
4. Solar energy penetration 20%	25%	4%	22%	22%	17%
5. Solar energy penetration 25%	36%	12%	32%	31%	27%
6. Solar energy penetration 30%	44%	21%	40%	39%	35%
7. Solar energy penetration 35%	50%	29%	46%	45%	42%
8. Increase proportion of distributed solar	36%	12%	32%	31%	27%
9. Additional storage	19%	2%	15%	14%	12%
10. Nuclear retirement	30%	8%	27%	26%	22%
11. Additional wind energy penetration 5%	40%	20%	36%	34%	32%
12. Two balancing authorities: DEC 5%	0%	0%	0%	0%	0%
12. Two balancing authorities: DEC 10%	2%	0%	1%	1%	1%
12. Two balancing authorities: DEC 15%	11%	1%	9%	10%	7%
12. Two balancing authorities: DEP 5%	0%	0%	0%	0%	0%
12. Two balancing authorities: DEP 10%	2%	0%	1%	1%	1%
12. Two balancing authorities: DEP 15%	15%	1%	13%	13%	10%

Table 5. Hours of Curtailment per Season

Scenario	Spring	Summer	Fall	Winter	Annual
1. Solar energy penetration 5%	0	0	0	6	6
2. Solar energy penetration 10%	76	0	45	58	179
3. Solar energy penetration 15%	351	36	275	220	882
4. Solar energy penetration 20%	533	216	403	354	1,506
5. Solar energy penetration 25%	636	458	494	428	2,016
6. Solar energy penetration 30%	707	598	562	488	2,355
7. Solar energy penetration 35%	752	700	610	525	2,587
8. Increase proportion of distributed solar	634	454	496	433	2,017
9. Additional storage	484	136	341	278	1,239
10. Nuclear retirement	593	363	457	391	1,804
11. Additional wind energy penetration 5%	746	650	584	506	2,486
12. Two balancing authorities: DEC 5%	0	0	0	5	5
12. Two balancing authorities: DEC 10%	91	2	54	66	213
12. Two balancing authorities: DEC 15%	358	53	278	223	912
12. Two balancing authorities: DEP 5%	0	0	0	5	5
12. Two balancing authorities: DEP 10%	90	1	51	63	205
12. Two balancing authorities: DEP 15%	361	45	282	217	905

In Duke Energy's current system, low load days are important because of the lack of flexible thermal generation that can be relied on to reduce power output, if needed. In the case of high solar power penetration, such as the 25% case shown in Figure 4, the minimum net load days are more important because the system becomes more sensitive to solar power forecasting errors and causes greater ramps and variability. In this case, the average curtailment for this season is 25%; however, this particular day shows a sunny low load day reaching 62.9% curtailment.

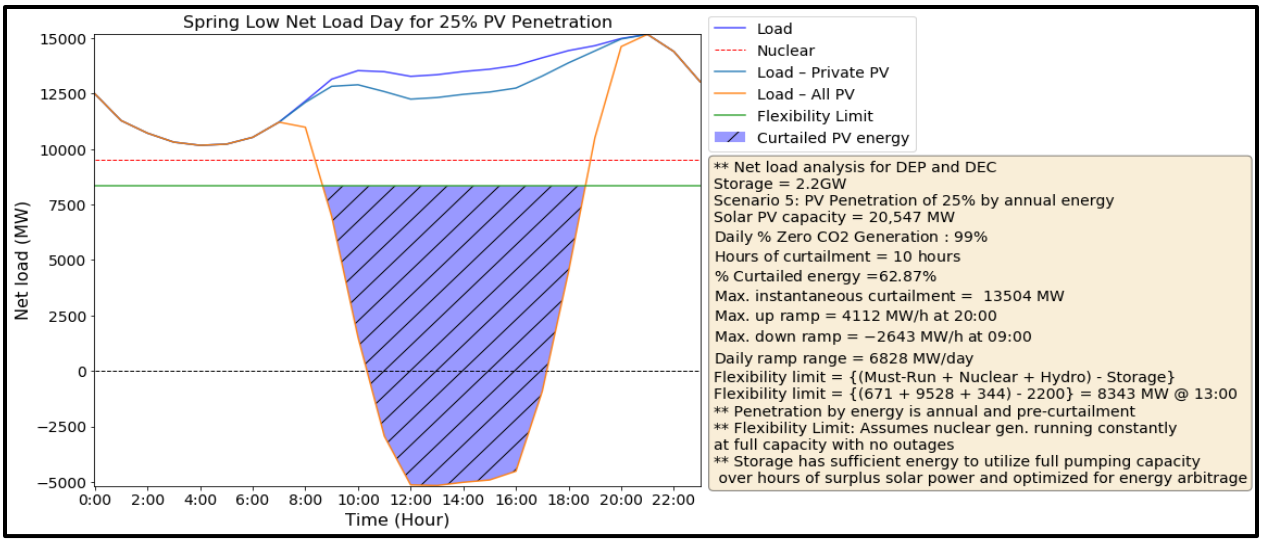

Figure 4. Minimum net load day for spring, the highest curtailment season, with 25% solar energy penetration

At higher loads, such as the peak load day of summer, which has 25% PV penetration, shown in Figure 5, flexible thermal generation needs to increase output, and therefore the system has a greater ability to reduce generation to be replaced with solar power during the day, and less curtailment is required. This is evident in Table 4, which shows that the curtailment during the summer is the minimum of all the values of seasonal curtailment across all scenarios.

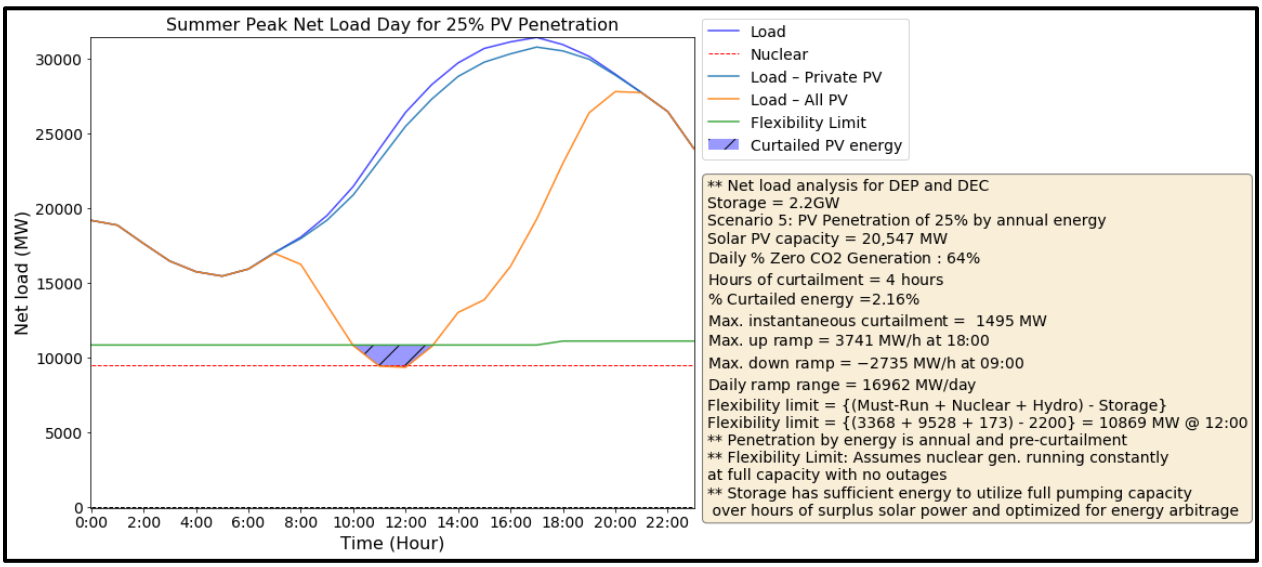

Figure 5. Max net load day for lowest curtailment season, summer, with 25% solar energy penetration

Marginal curtailment is defined as the percentage of the additional renewable energy that would be curtailed as the penetration level is increased by 5% of the load. The curtailment of each scenario is compared to that of the scenario with 5% less solar. Or, in the case of Scenario 11, which has 5% wind and 30% solar penetration, the curtailment is compared to that of Scenario 6, which has 30% solar. The marginal curtailment for all applicable scenarios is shown in Table 6.

Table 6. Percentage Marginal Curtailment

Scenario	% Marginal Curtailment
2. Solar energy penetration 10%	2.2%
3. Solar energy penetration 15%	21.4%
4. Solar energy penetration 20%	46.3%
5. Solar energy penetration 25%	64.6%
6. Solar energy penetration 30%	76.7%
7. Solar energy penetration 35%	83.2%
9. Additional storage	4.3%
10. Nuclear retirement	41.0%
11. Additional wind energy penetration 5%	26.3%
12. Two balancing authorities: 10% penetration	2.5%
12. Two balancing authorities: 15% penetration	22.9%

The load duration curve can also be a useful tool to illustrate the impact of variable generation penetration on the system peak and light loads. Load duration curves for the total system load and net load with 25% PV penetration are shown in Figure 6. The annual peak load is insignificantly reduced by the integration of solar PV because it occurs in winter before sunrise. During certain periods (1,947 hours), however, this penetration level reduces the annual minimum load to less than the minimum generation level set by the nuclear line. This implies that as PV penetration increases, solar PV will start to offset baseload generation or must be curtailed. This effect could vary based on the generation flexibility limit line imposed by the must-run units, hydro schedules, and energy storage systems.

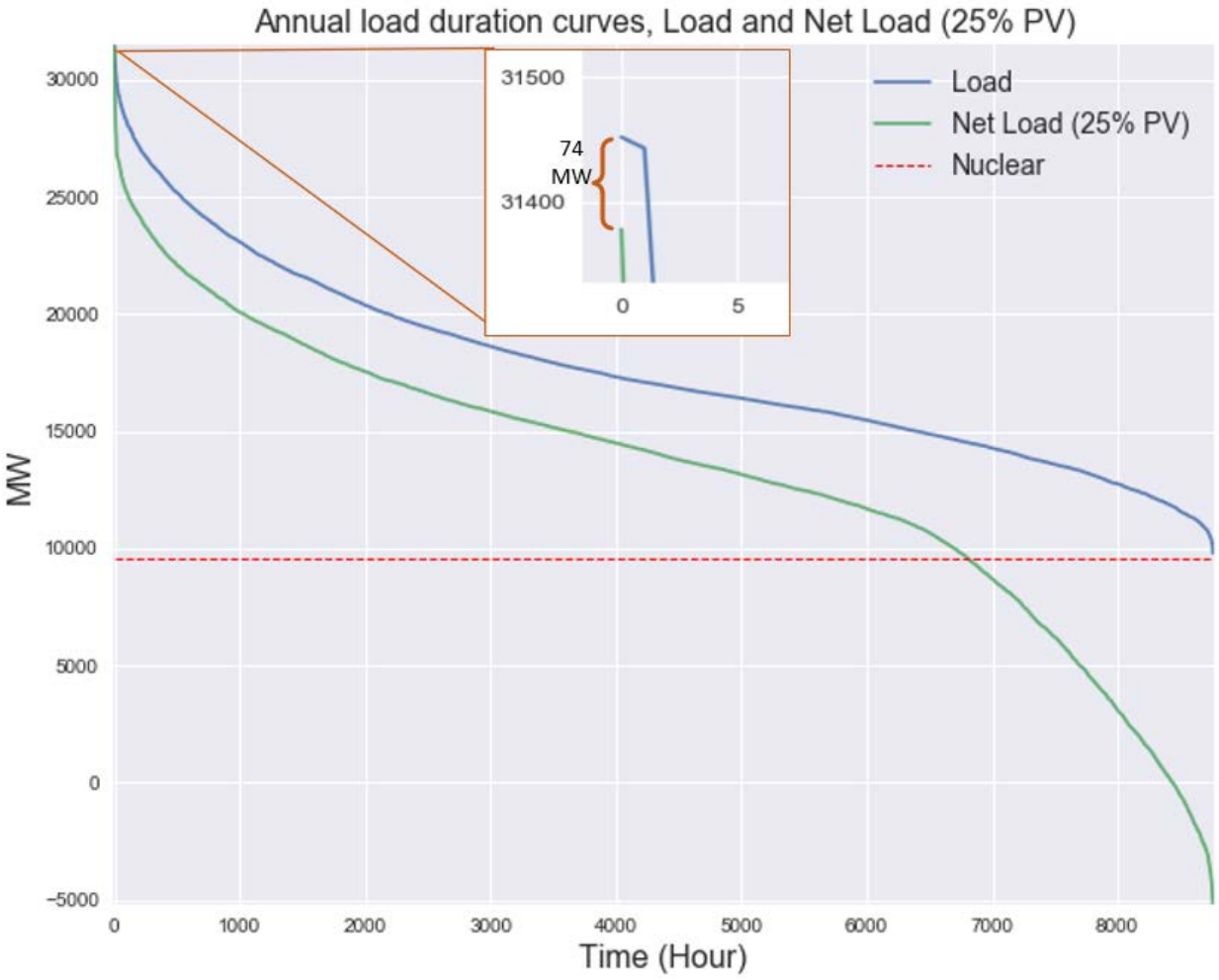

Figure 6. Annual load duration curves, load, and net load with 25% PV penetration

3.2 Scenario 8: Increased Proportion of Distributed Solar Energy

A portion of the PV generation, rooftop PV, is not curtailable by Duke Energy. Scenario 8 examines a relatively high solar penetration scenario of 25%, with the maximum expected proportion of the solar energy from rooftop solar. A model with such a large percentage of rooftop PV for the 25% solar power penetration by energy case will improve understanding of how the requirements for curtailment of additional PV might change with increased adoption of behind-the-meter solar PV. The PV time series provided by Duke includes separate profiles for rooftop and utility-scale solar energy, so the rooftop time series and utility time series are both scaled to forecast a higher proportion of rooftop solar generation. The scalars and equations used to calculate these profiles are shown in the appendix.

To capture an increase in rooftop PV by 2030, the maximum percentage of total solar PV that might be rooftop PV was assumed to be 18.91%. This percentage was obtained using the NREL-

developed standard scenarios of the U.S. power sector tool,[3] which models 42 different scenarios to capture the impacts of fuel prices, demand growth, retirements, technology and financing costs, transmission and resource restrictions, and policy considerations on possible power system capacity expansion futures. The scenario predicting the largest ratio of rooftop solar to utility solar in the Carolinas in 2030 accounts for extended lifetimes of current generation facilities. This Extended Lifetimes Scenario assumes that coal power plant lifetimes are increased by 10 years, there are no retirements of underused coal power plants, and all nuclear power plants have 80-year lifetimes.

Using Scenario 5 (25% solar energy penetration) as a baseline, the effect of an increased proportion of distributed PV energy to utility PV energy is modeled. The PV time series corresponding to 25% solar penetration was scaled by the projected percentage of utility PV energy and the percentage of distributed PV energy to calculate the two projected time series.

The analysis assumes that rooftop PV cannot be curtailed, so an increase in the percentage of rooftop PV results in an increase in utility PV that must be curtailed. Comparing the results of Scenario 8 to Scenario 5 (25% PV penetration) shows that 33.2% of utility solar would be curtailed provided a maximum increase in the proportion of rooftop PV versus utility PV, whereas 28.5% of utility PV would be curtailed if this proportion remains unchanged from the assumptions used in scenarios 1–7.

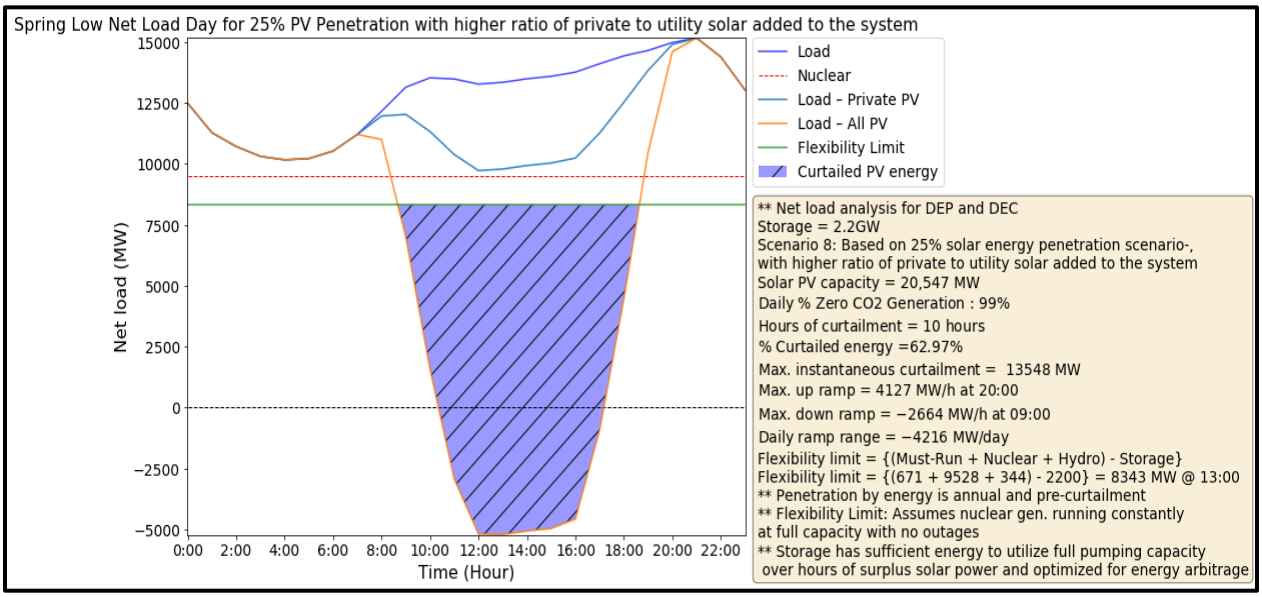

Figure 7. Minimum net load day with an increase in rooftop PV

As shown in Figure 7, even with a maximum increase in rooftop PV to 18.91%, the difference between load and solar as a result of rooftop generation never crosses the flexibility limit at 25% solar penetration.

[3] https://openei.org/apps/reeds/#

3.3 Scenario 9: Additional Storage Capabilities

Scenario 9 captures the effect of an increase in storage with 25% solar energy penetration and demonstrates how this additional technology resource might reduce the curtailment required in a high solar penetration scenario. The hypothetical storage is charged entirely with surplus renewable energy sources and is assumed to discharge throughout the remainder of the day with a round-trip efficiency of 80%. The storage stores energy only during hours of surplus generation. In addition to the existing storage consisting of 2,200 MW of pumped storage hydropower, the additional storage modeled is 1,000 MW of 4-hour storage, 1,000 MW of 6-hour storage, and 2,000 MW of 8-hour storage. This is a total of 26,000 MWh of storage.

The storage is given a hierarchy of use preferences: for each modeled day, the 8-hour storage is used to capacity first, followed by the 6-hour storage, and finally the 4-hour storage is used. The generation flexibility limit line is then adjusted to incorporate the additional used storage, and curtailment is adjusted to fit the new flexibility limit.

The addition of such storage results in an improvement in the percentage of renewable energy curtailed from 26.9% (Scenario 5) to 14.8%. The greatest improvement is seen in the winter, during which time the curtailment decreases from 31.3% to 14%. The minimum net load day in the winter of Scenario 9 is shown in Figure 6, and that of Scenario 5 is shown in Figure 9.

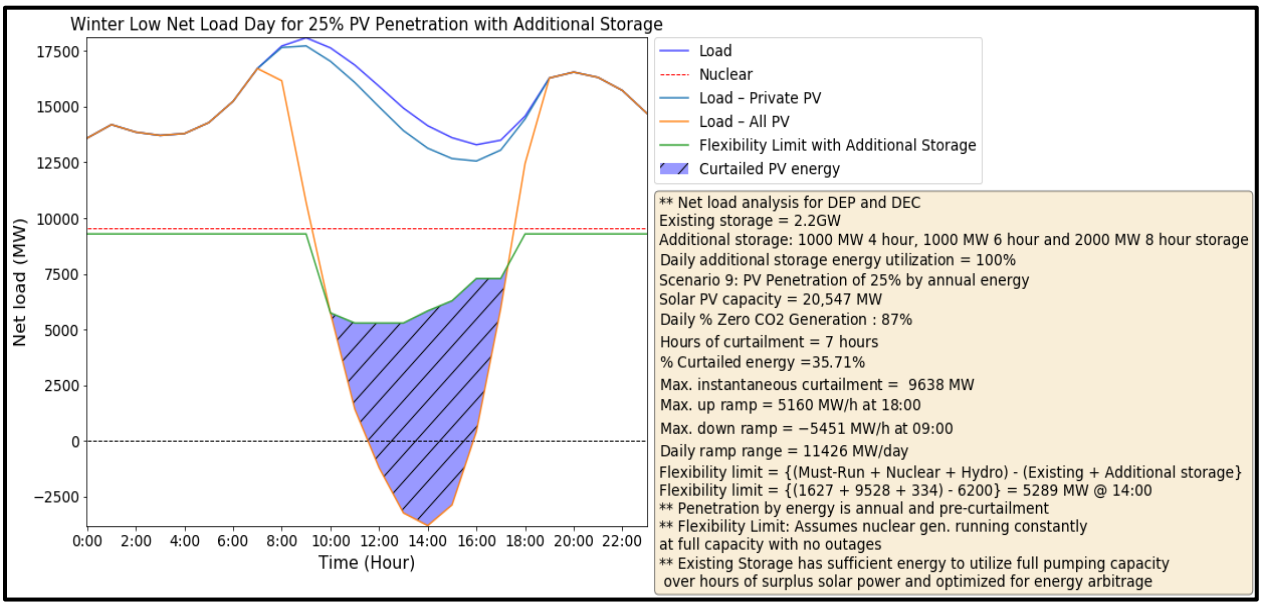

Figure 8. Minimum net load day in winter with additional storage

The additional storage modeled accounts for 7% of the load on this day. The annual contribution to this additional storage amounts to 3.7% of annual load.

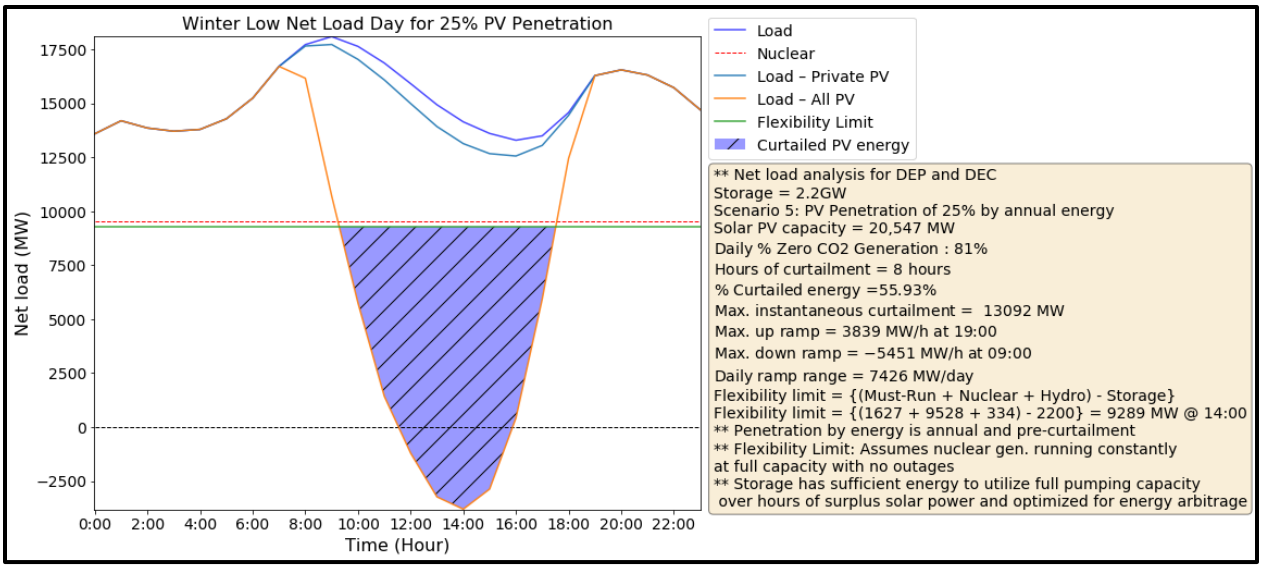

Figure 9. Minimum net load day in winter without additional storage

The smallest impact occurs in the summer, with an improvement from 11.8% curtailment to 2.3%. For this analysis, storage is assumed to be used exclusively for load-shifting. In reality, storage could also potentially provide ancillary services, such as regulation reserves, especially in the summer seasons, when the load-shifting requirement is minimal. Further, if transmission constraints were considered, the total contribution of storage to saving renewable energy curtailment could be higher.

In this model, energy storage devices are charging only during times of overgeneration. The additional storage modeled results in an annual average of 77% carbon-free energy, whereas the carbon-free percentage of Scenario 5 is 74%. The additional storage yields a greater percentage of the carbon-free energy resource than that of Scenario 7, the 35% solar energy penetration model (77%).

Further analysis should examine a unit commitment and economic dispatch model, which could help understand the most economical and effective storage solutions to meet the proposed extra flexibility here, including the potential to use controllable electric vehicle charging. Further, such detailed analysis would quantify the economic value and system stability benefits of the additional storage through such examples as additional capacity, enabling higher penetrations of low-cost solar power and providing ancillary services.

3.4 Scenario 10: Generation Retirement

The portion of energy from nuclear sources is unique in the Duke Energy Carolinas region, contributing to a large amount of carbon-free generation. For this analysis, the possibility of ramping down nuclear is excluded (see assumptions in Table 8). The flexibility of nuclear is limited, and therefore it impacts the amount of variable energy that must be curtailed, particularly at high penetrations of solar. As current nuclear generation facilities are retired, the generation flexibility limit could decrease, especially if the energy is replaced with flexible thermal sources, allowing for larger contributions from solar and wind energy resources. Scenario 10 looks at the required curtailment resulting from the retirement of 10% of the nuclear

generation, again using 25% solar penetration. A new generation flexibility limit is calculated with the nuclear generation reduced to 90% to reflect the nuclear retirement. It is assumed that the generation is replaced with flexible thermal generation. The other components of the flexibility limit are the same as those used in scenarios 1–7, including inflexible hydropower units and must-run units, with additional flexibility provided by hydropower pumped storage.

This reduction in the nuclear generation of the system with 25% solar penetration reduces the necessary curtailment from 26.9% of total renewable energy to 22.2%. Despite greater quantities of carbon-free solar power contributing to load, however, the percentage of carbon-free energy is reduced from 74% to 70%, which is to be expected because nuclear energy is carbon-free and generates consistently throughout the day.

3.5 Scenario 11: Additional Wind Energy Penetration

Duke Energy will work toward the goal of carbon-free energy generation primarily by incorporating solar power because solar is a plentiful resource in the Carolinas regions (see Figure 1). As the penetration of solar power increases, however, the imbalance in the availability of solar during a day—with increased power during daylight hours and a complete lack of power otherwise—becomes more problematic. It is therefore beneficial to consider an additional renewable source that can generate at different times of the day, such as wind. Scenario 11 examines the incorporation of 5% of the annual load generated by wind energy in addition to 30% solar energy penetration. A map of the wind resource is shown in Figure 10.

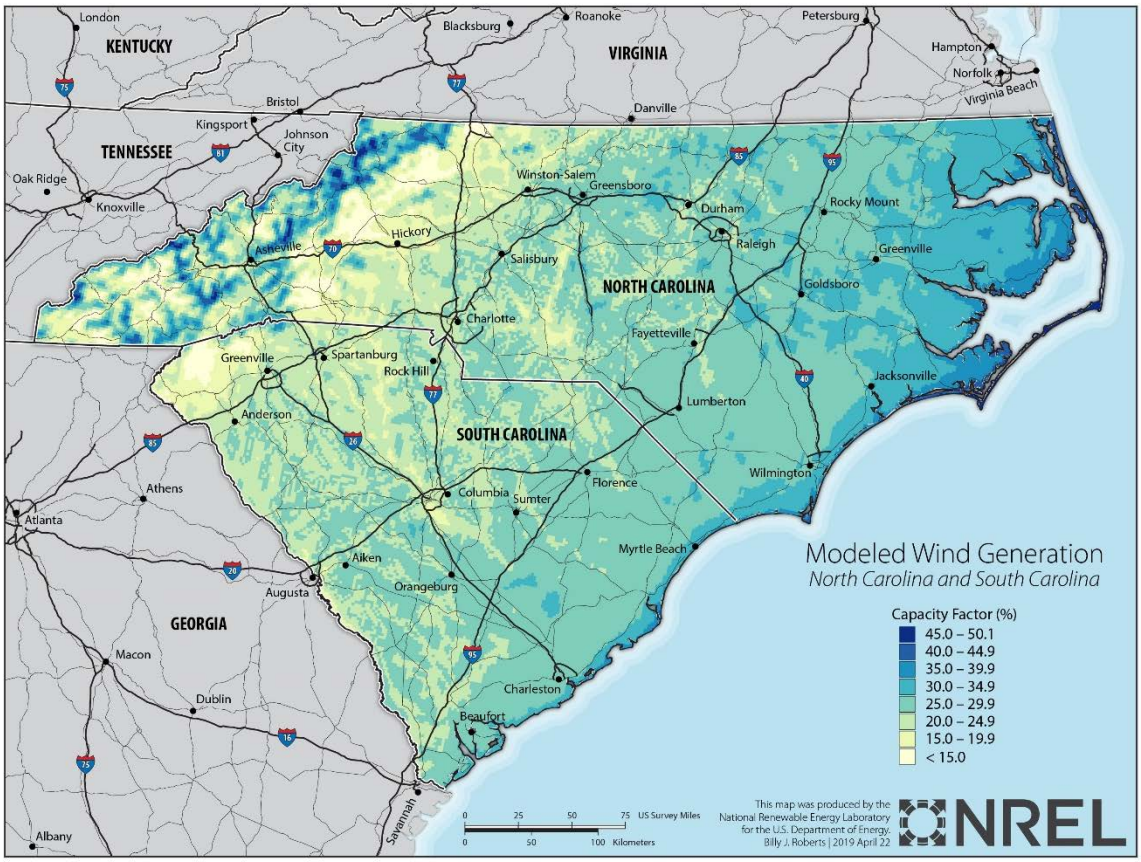

Figure 10. Wind capacity factors in the Carolinas

The wind time series is a simulated power output from NREL's Wind Integration National Dataset (WIND) Toolkit (Draxl, et al., 2015) based on the 2006 meteorological year. The 5% wind is calculated in a manner similar to the percentage of solar penetration levels (see Equation 5 in the appendix). The wind power profiles were taken from offshore profiles where the wind resource is high. Further, because the profiles are offshore, we assume that they are insignificantly correlated with load. The wind energy profile was scaled to match 5% of the load. The net load for this scenario is calculated as the remaining load after the contribution of the 5% wind and 30% solar penetration. The curtailment of wind and solar is proportional to the generation of wind and solar, respectively.

Building off of the 30% PV scenario (Scenario 6), there is an interesting comparison between adding another 5% of PV (to get 35% PV, Scenario 7)) or adding 5% wind (Scenario 11). Adding another 5% PV (to get to a total of 35% PV) leads to 83.2% of that additional 5% of solar being curtailed, while adding 5% wind (to 30% PV) requires only 26.3% of that additional wind to be curtailed. Looking at the total renewable curtailment of Scenario 11 compared to Scenario 7 (35% PV), adding wind improves the total renewable energy curtailment from 42% to 33.9%.

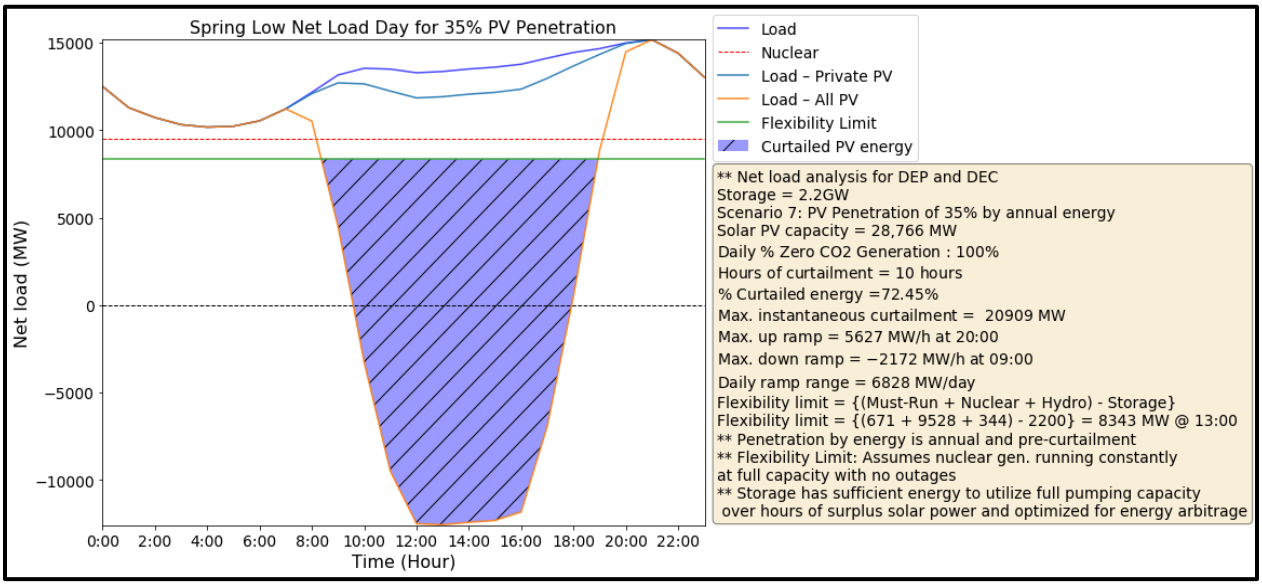

Figure 11. Minimum net load day in spring with 35% PV energy penetration

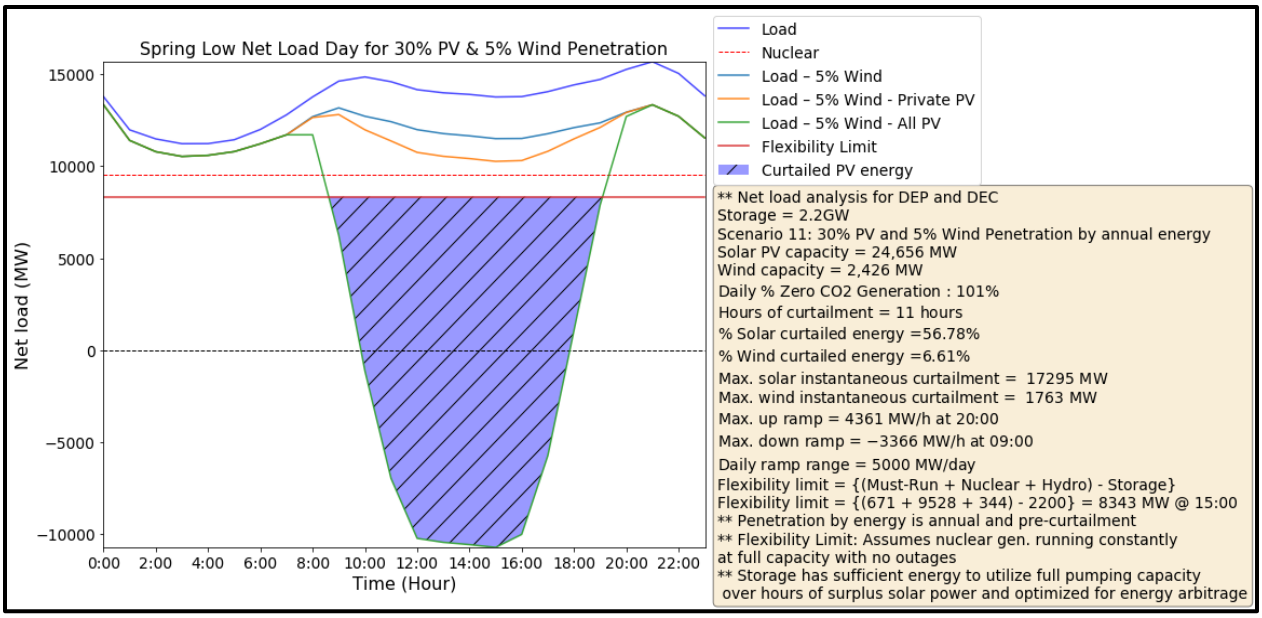

Figure 12. Minimum net load day in spring with 30% PV plus 5% wind energy penetration

And, since curtailment is reduced, that also means energy from carbon-free sources improves compared to Scenario 7. The average annual percentage of carbon-free energy in a 35% PV penetration scenario is 77%, whereas the percentage of carbon-free energy in a 30% PV, 5% wind penetration scenario is 79%, the greatest of all examined scenarios.

3.6 Scenario 12: DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

All prior scenarios assume unlimited transfer capability in the Carolinas region. Scenario 12 separates DEC and DEP into separate regions with Duke Energy's existing transfer capability to observe the effect on the net load and curtailment given 5%, 10%, and 15% solar penetration levels by energy. The interconnection limit is provided by Duke Energy. It is directional and has different values for nighttime (0 h–7 h) and daytime (8 h–23 h). The separate loads are also provided by Duke Energy (all loads in prior analyses are the sum of these two loads). The generation totals of the must-run units for all prior scenarios are also calculated first for DEC and DEP and then summed, so the isolated values are used in Scenario 12. The generation flexibility limit is parsed between the two balancing authorities by separating must-run units, hydropower (see appendix for hydro assignments to DEC and DEP), nuclear (hourly generation values for DEC and DEP are provided by Duke Energy), and pumped storage (values also provided by Duke Energy). The equation for calculating each generation flexibility limit is the same as that used to calculate the generation flexibility limit for the total area (see Equation 1).

The interconnection is simulated to maintain the same difference between the net load and the flexibility limit of each balancing authority, provided that the transfer limit is not exceeded. This assumption of operating the interconnection to minimize the possibility of curtailment in high solar penetration scenarios was decided with Duke Energy. A production cost optimization would enable simulation of the interconnection and other transmission in a more realistic manner. If the difference between the net load of one balancing authority and its flexibility limit

is less than that of the other, load is transferred until the difference is equal or the transfer limit in that direction, for that time of day, is met. This analysis uses 12 different equations to calculate 12 different scenarios resulting from variations in the calculations because of the sign and magnitude of the differences and the times of day (see appendix). The results of these 12 scenarios are then summed to produce a time series of load transfer, which is then used to calculate the net load of each balancing authority after the transfer. To calculate the transfer, load transfer to DEC is arbitrarily defined as negative, whereas load transfer to DEP is defined as positive. The resulting net loads of DEC and DEP are calculated with the transfer amount (see appendix).

The sum of the required solar power curtailment for both regions after the interconnection is modeled is greater than the curtailment that results when they are modeled as one balancing authority, or a region without transmission limitations. As shown in Table 7, an increase in transmission capabilities would support increased solar energy penetration. This benefit is minimal at low levels of PV penetration, but it increases at higher percentages.

Table 7. Comparison of Curtailment of the System Modeled With and Without Transmission Limitations

Percentage PV Penetration	Curtailment with Infinite Transmission (MWh)	Percentage Curtailment with Infinite Transmission	Curtailment with Limited Transmission (MWh)	Percentage Curtailment with Limited Transmission
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%

The minimization of curtailment with an increase in transmission capacity is illustrated when the minimum net load days to DEP and DEC, shown in Figure 13 and Figure 14, respectively, are compared to Figure 15. The first two figures of the separate balancing areas display 22% curtailed energy in DEP and 20% and DEC, whereas Figure 15 shows 20% curtailment on the minimum load day when DEP and DEC are modeled as one balancing area with unlimited transmission capabilities.

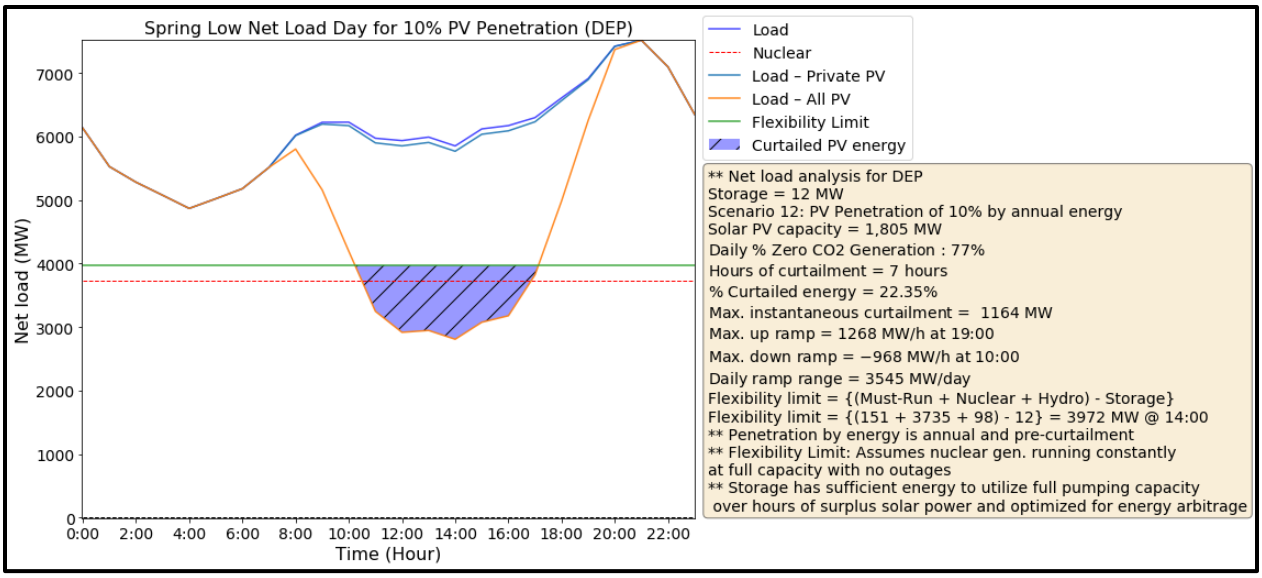

Figure 13. Low net load day for the DEP balancing authority with 10% PV penetration in spring

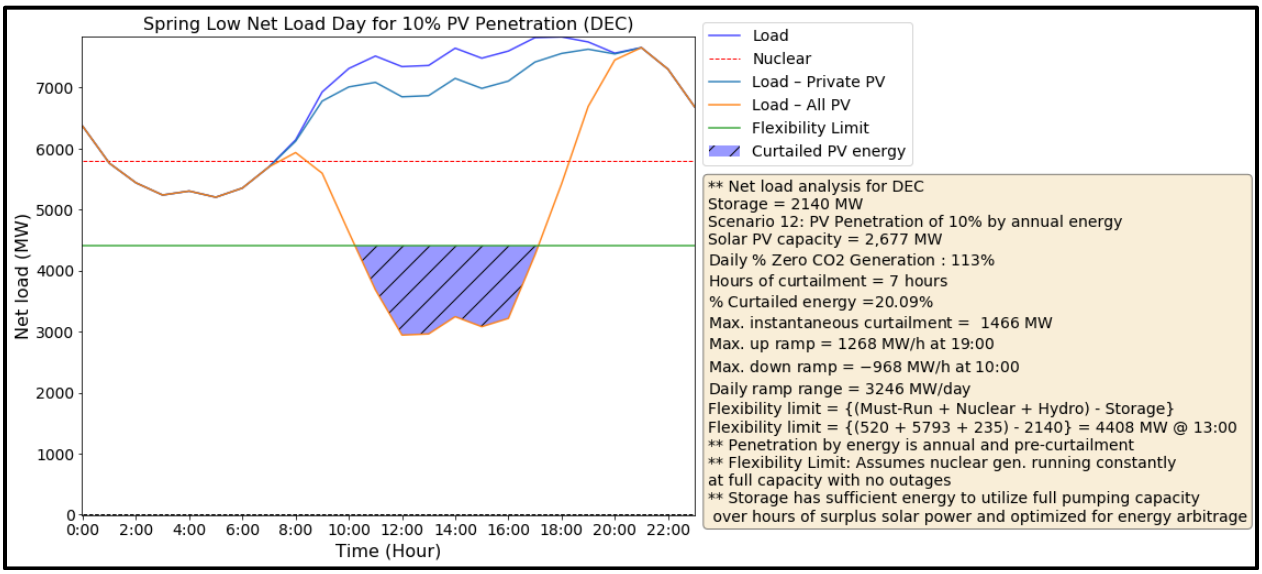

Figure 14. Low net load day for the DEC balancing authority with 10% PV penetration in spring

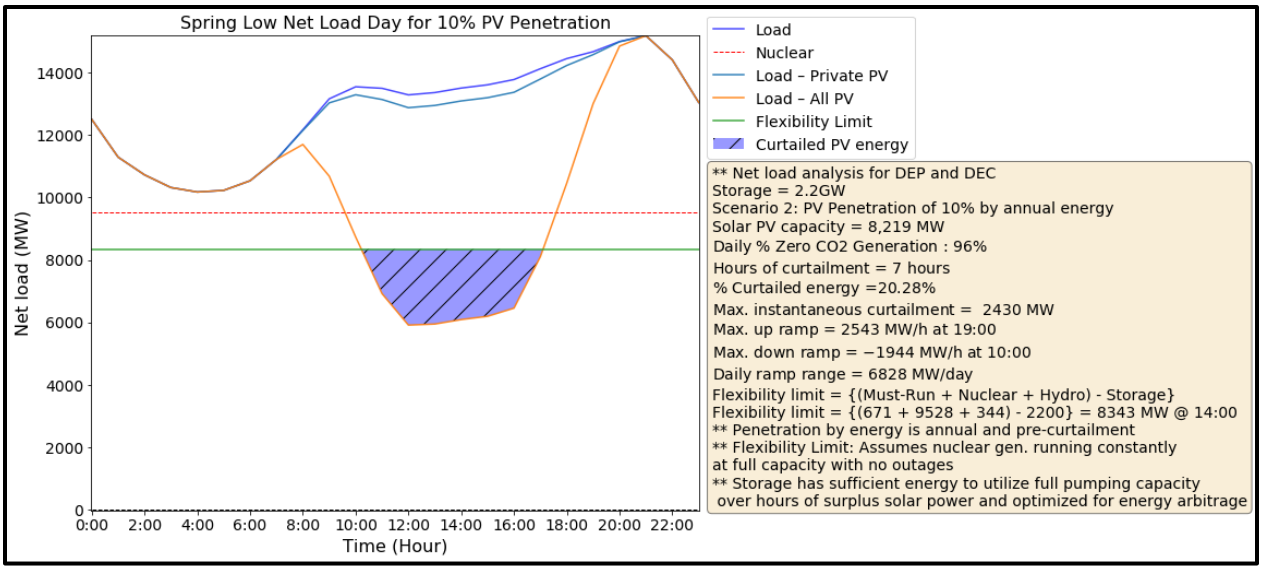

Figure 15. Low net load day with 10% PV penetration in spring when the Duke Carolinas territory is modeled with unlimited transmission capabilities

There is a difference in solar power output between the two balancing areas, such that DEP currently has roughly twice the solar capacity of DEC. The location of additional solar capacity will affect transmission constraints.

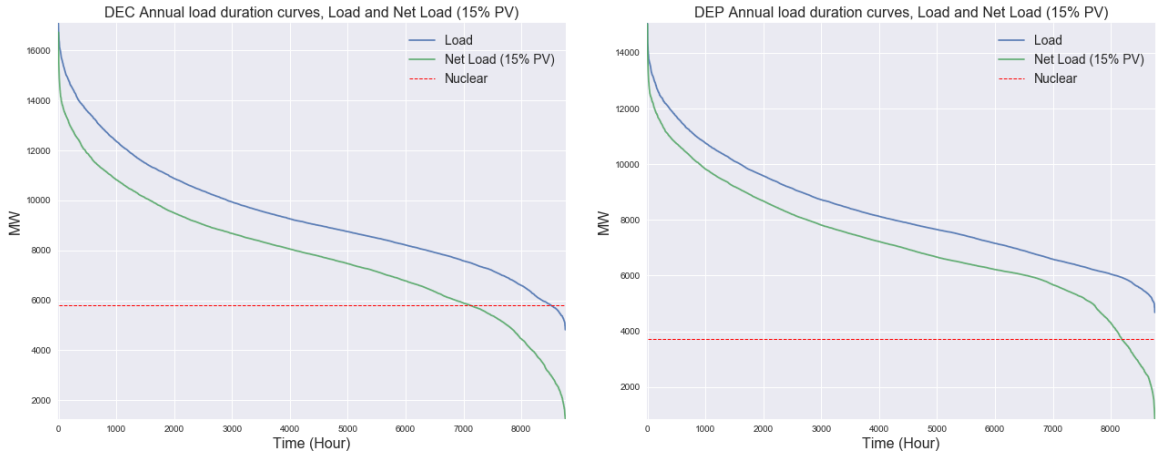

Figure 16. DEC and DEP load duration curves at 15% PV penetration

The load duration curves of the separate balancing authorities shown in Figure 16 show that at 15% PV energy penetration, there are 1,635 hours during which the net load dips below the nuclear generation limit in DEC and 577 hours in DEP, summing to 2,212 total hours. The load duration curve of the single balancing authority shown in Figure 17 shows an improvement, with 930 hours during which the net load is less than the nuclear limit.

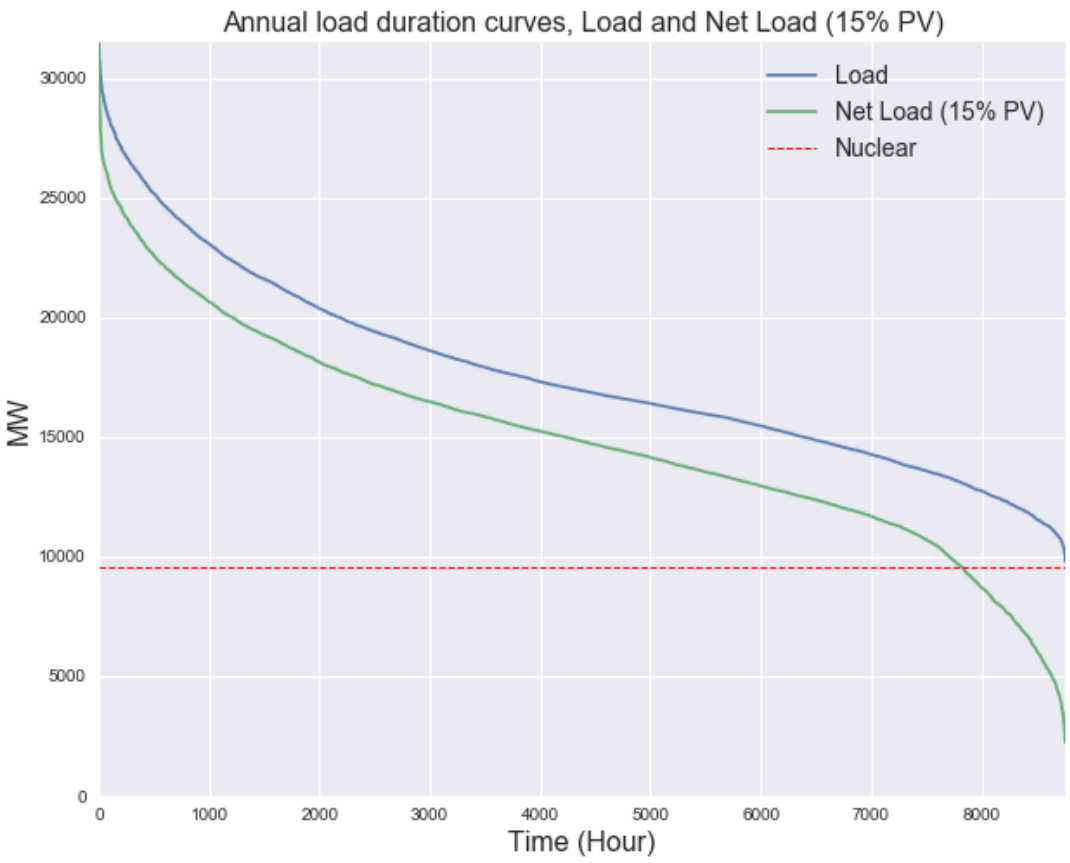

Figure 17. Load duration curve of the Duke Carolinas region modeled as one balancing area at 15% PV penetration

4 Geospatial Analysis

Several maps and an online application were created by the geospatial analysis team at NREL to visualize the solar and wind resources in the Duke Carolinas territory. The solar energy resource is characterized by global horizontal irradiance, and the wind energy resource is characterized by wind speed. Capacity factors were produced to visualize solar and wind generation, and exclusions[4] were made based on land categories and use type (see appendix for details). One such map is shown in Figure 18, which shows the capacity factors that are not in excluded areas of the region.

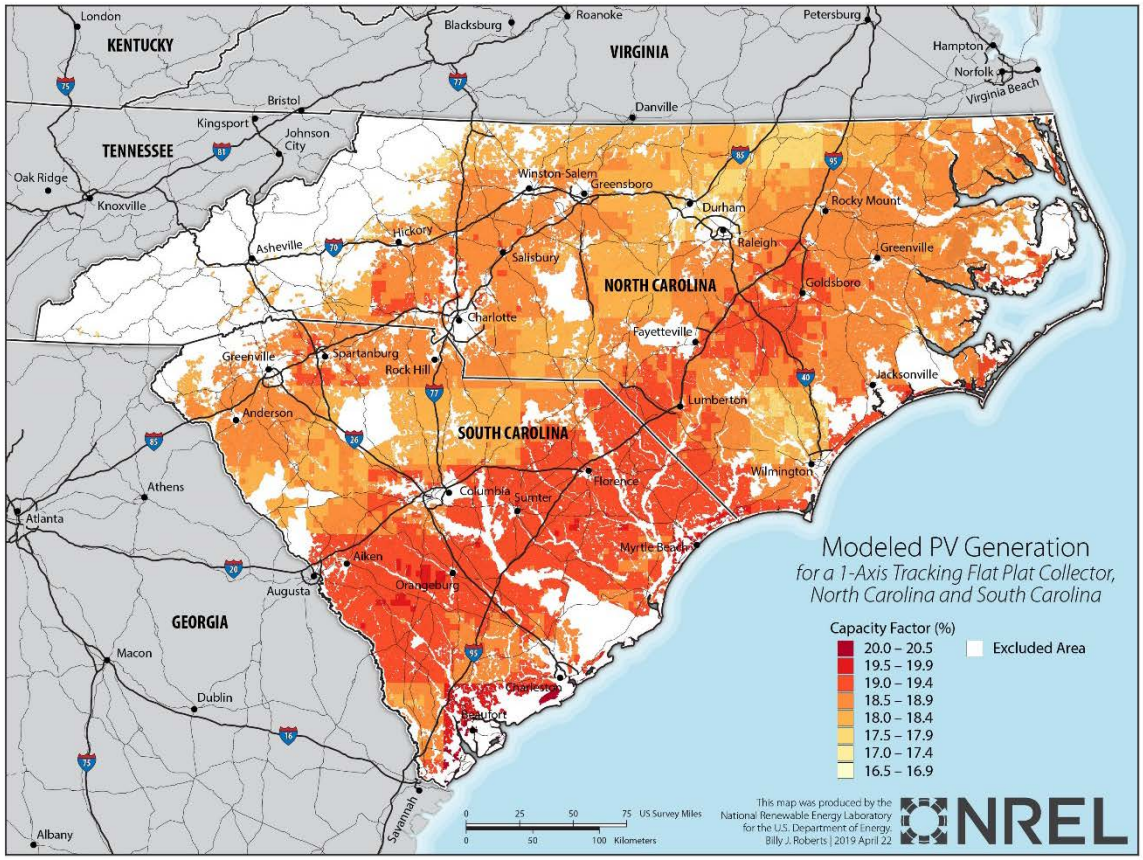

Figure 18. Multiyear mean capacity factors

The web application allows the user to examine these three layers of generation, energy resource, and exclusions for both wind and solar. The URL for the website is: https://maps.nrel.gov/duke. Note, please use Firefox, or Chrome for best results. The following layers are available on the web application:

- Solar exclusions: solar-categorized exclusions

[4] Exclusions include a slope >5%, urban areas, water and wetlands, parks and landmarks, national parks, and other environmentally or culturally sensitive areas.

- Solar generation: multiyear mean PV capacity factors using the listed PV system configurations
- Solar energy resource: Multiyear mean global horizontal irradiance
- Wind exclusions: wind-categorized exclusions. Both 100% exclusions and 50% exclusions are listed in this layer, depicting locations that are 100% excluded and other locations that are 50% excluded. The decision for 50% exclusions is based on assumptions used in Lopez (2012).
- Wind generation: multiyear mean wind capacity factors using the listed wind system configurations
- Wind energy resource: multiyear mean wind speed.

The web application allows the user to navigate geospatially and zoom in and out of areas of interest. Any combination of data layers can be displayed at once, including exclusions, generation, and energy resource for solar power and wind power. The legend tab enables the user to filter for ranges of data within each layer and control the transparency to maintain visual clarity, depending on the number of layers selected. This is shown in Figure 19. The query tab enables the user to intuitively retrieve the data being visualized by one of the four following options: the user can (1) select an individual point on the map, (2) query an entire region, (3) draw a custom shape of interest, and (4) filter based on specific attributes. The data behind this web app make it a useful tool to explore future development in the form of production cost models for the continued study of carbon-free resource integration.

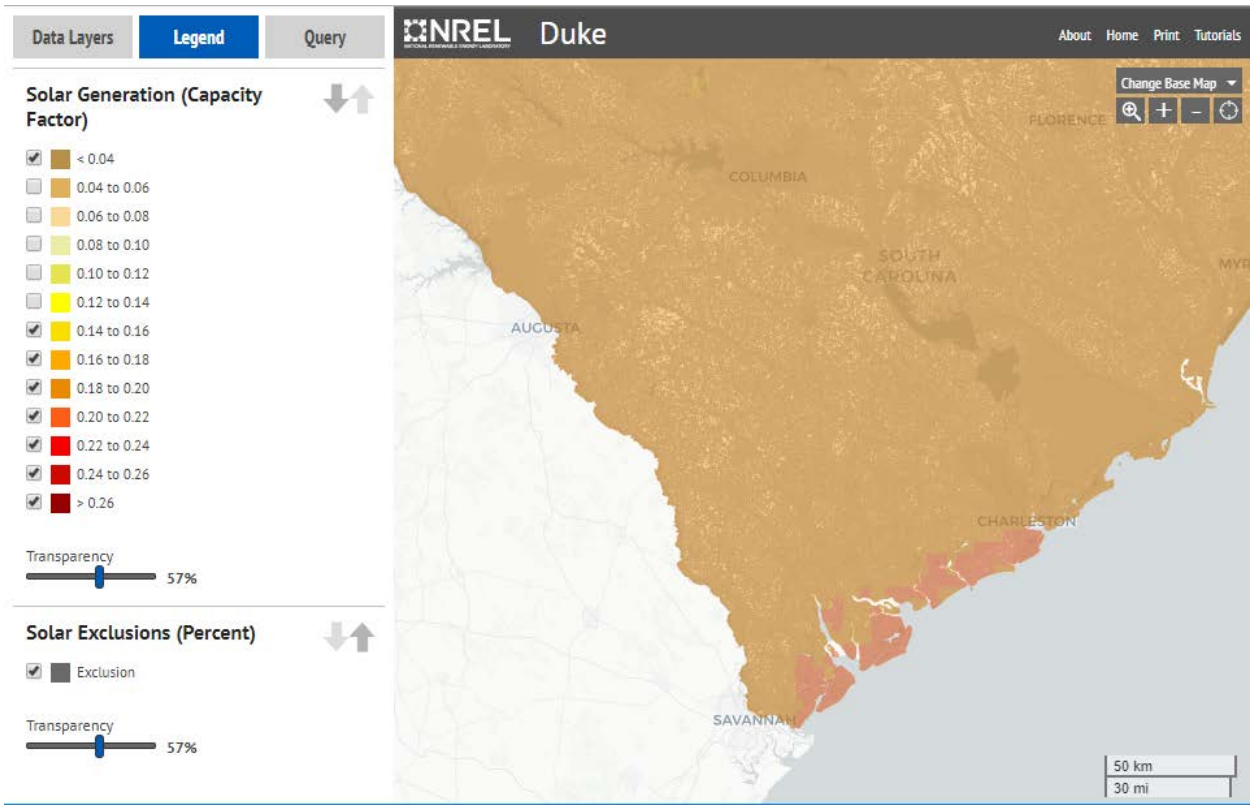

Figure 19. Screenshot of geospatial web application

5 Conclusion

Duke Energy endeavors to increase the proportion of load met by carbon-free generation. With high quantities of nuclear power currently providing carbon-free generation, and given their great solar irradiance resource, Duke Energy seeks to analyze the impact of integrating significant amounts of new solar power into its power system under a variety of penetration levels. This additional solar power will help reach carbon-free goals; however, with the high minimum generation level of existing nuclear power, this net load analysis concludes that curtailment of solar is likely to begin at 10% solar energy penetration. Thus, the net load analysis becomes an important initial step in realizing this goal while maintaining a reliable and economically viable grid.

This net load analysis shows:

- The greatest curtailment occurs during the spring, which is usually characterized by low load and an oversupply of solar PV power output during the middle of the day.
- The largest ramps remain in winter, through all solar PV penetrations, and for all seasons the ramps increase as solar PV penetration increases.
- The largest maximum instantaneous curtailment, percentage of curtailed energy, and duration of curtailment occur during the spring.
- The system experiences the largest percentage of daily carbon-free generation during the spring, which is the highest compared with other seasons.
- The net load analysis shows a significant reduction in the peak net load and a shift in the timing of the minimum and peak net load. This effect is most significant during the summer because of the time-coincident correlation between the demand and solar output. Thus, solar PV can significantly contribute capacity value to the system during the summer peak load; however, the shift in timing minimum and peak net loads can affect generator outage and maintenance scheduling, and this should be investigated further using unit commitment and economic dispatch models.
- Even at high solar penetration levels of 25%, with the highest anticipated level of rooftop solar, curtailment rights of utility solar is sufficient to avoid an imbalance of supply and load. This net load analysis shows that building wind power after high levels of solar power curtailment are reached and building storage are two solutions that can aid in increasing the share of carbon-free emission generation in Duke Energy's system.
- The analysis of scenarios 12 and 10 show that transmission constraints and nuclear retirement both work against the goal of meeting load with carbon-free generation.

A key constraint in accommodating additional variable generation penetration is the ramping ability of conventional generators, to change their output in response to the fluctuating renewables. For instance, during the spring minimum net load day shown in Figure 4, the traditional generator fleet is required to increase the output rapidly as the sun sets. For Duke Energy, because the nuclear fleet has a high minimum generation limit, increasing system flexibility with technologies that provide fast ramp rates and control over load should be examined to accommodate higher PV penetrations.

In addition, managing system flexibility requires serious operational adjustments coupled with a resource mix that can quickly respond to the balance of electricity demand and net load

variability. The result of this study further reveals that exceeding 15% PV penetration could lead to serious integration issues, especially during the spring, which is characterized by low load and a possible frequent overgeneration scenario.

Further analysis with more advanced models—such as unit commitment and economic dispatch, capacity expansion planning, and dynamic analysis models—will be required to more fully assess system impacts with increasing variable generation penetration as well as flexibility opportunities for accommodating variable renewable energy sources with conventional generation.

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Appendix

A.1 Data Sources and Assumptions

In the context of data and files provided by Duke Energy, for both Duke Energy Progress and Duke Energy Corporation, the capacity factors from the "Third Party Non-Curtailable" sheet are multiplied by the rooftop solar capacity for 2019. The capacity factors from the "Utility Owned" tab are multiplied by the sum of the utility nameplate capacities. "Net Metered (Rooftop) Solar" is assumed to be rooftop solar PV, whereas "D-Tied Universal Solar" and "T-Tied Universal Solar" are assumed to be utility. Hydro schedules are from "Carolinas Hydro Schedules_Capacity and Energy_Confidential.xlsx."

Table 8. Assumptions and Definitions for the Net Load Analysis

Assumptions for Scenarios 1 - 7
Penetration by energy is annual and pre-curtailment.
Storage is 2.2 GW, which represents the existing pumped hydro storage capacity.
Storage has sufficient energy capacity to use full pumping capacity during hours of surplus solar power and is optimized for energy arbitrage.
The percentage of curtailed energy is estimated as a percentage of total PV output energy.
Must-run units are defined relative to the highest load within the last week because the majority of must-run units have a weeklong minimum up time.
Nuclear runs consistently at full capacity and has no outages.
No contingency reserve is added to the flexibility limit line.
Interconnections to neighboring regions are not considered

A.2 Equations for Scenario Analysis

The inflexibility generation limit line, Gen_{inflex}, is given as:

$$Gen_{inflex} = \left\{(\text{MustRun units} + \text{Nuclear capacity} + \text{Hydro units}) - \text{Storage}^{5}\right\} MW \quad (1)$$

Renewable energy curtailment is given as:

$$VG^{6}\ curtailment = \begin{cases} Gen_{inflex} - Net\ load, & Gen_{inflex} > Net\ load \\ 0, & Gen_{inflex} < Net\ load \end{cases} \quad (2)$$

Daily ratio of carbon-free generation is given as:

$$\sum_{n=1}^{24} \frac{(Nuclear_n + Hydro_n + 0.8 * Storage_n + VG\ precurtailment_n - VG\ curtailment_n)}{Total\ load_n} \quad (3)$$

Table 9. Scalars Used to Calculate PV Penetration

Scenario No.	Scalar
1	0.9642
2	1.9284
3	2.8926
4	3.8568
5	4.8210
6	5.7852
7	6.7494

The scalars to calculate the solar penetration required to meet the specified percentage of load were found with the following Equation:

$$\{(\text{Percent Penetration}) \cdot (AnnualLoad)/(AnnualPV)\} \quad (4)$$

[5] Storage represents the total pumped storage hydropower pumping capacity.
[6] V*ariable generation* refers to solar and wind (where applicable) power plants.

The solar time-series was then multiplied by each scalar to produce the appropriate amount of annual solar to achieve the targeted penetration level for each Scenario. For example, to create the PV time-series for Scenario 1 with 5% solar penetration, the solar time-series was multiplied by 0.9642.

In Scenario 8 illustrates 25% solar energy penetration with 18.91% of solar due to rooftop solar generation. 18.91% of 25% of the load was calculated to find the amount of rooftop PV. A scalar to adjust the rooftop PV time-series was calculated similarly to the scalars used to calculate the time-series for Scenarios 1-7:

$$\{(\text{Percent Rooftop}) \cdot (25\% of AnnualLoad)/(AnnualRooftopPV)\} \quad (5)$$

The calculation for the remaining 89.09% of solar from utility is analogous:

$$\{(\text{Percent Utility}) \cdot (25\% of AnnualLoad)/(AnnualUtilityPV)\} \quad (6)$$

Additional storage in Scenario 9 is calculated according to the following rules:

If the curtailment is required, eight-hour storage is used to store as much of the curtailment required as possible, limited to 2000 MW inside of an hour. The maximum eight-hour storage over a 14-hour window is 2000 MW * 8 hours =16000 MWh, so any renewable generation beyond that must be stored by the six- or four-hour storage units. Next, the six-hour storage is used to store up to 1000 MW of excess energy in an hour, with the maximum storage over a 14-hour window of 6000 MWh. Finally, the four-hour storage is used to store up to 1000 MW of excess energy in an hour, with the maximum storage over a 14-hour window of 4000 MWh.

In Scenario 11, the wind time series is scaled by 0.6680 to match 5% of the total load, and is found with:

$$\{(0.05) \cdot (AnnualLoad)/(AnnualWind)\} \quad (7)$$

The wind time-series was then multiplied by 0.6680 to produce an annual generation equal to 5% of the load.

For Scenario 12, the location of hydropower units in each of the modelled BAs is as follows:

Table 10. Hydropower units corresponding to each region

DEC	DEP
Cowans Ford Hydro Keowee Hydro Lower Catawba Hydro Misc ROR Hydro Nantahala Hydro Upper Catawba Hydro	Blewett Hydro Marshall Hydro Tillery Hydro Walters Hydro

The Equations for calculating load transfer are listed in Table 11. "DEC" refers to the net load of DEC minus the flexibility limit of DEC, while "DEP" refers to the net load of DEP minus the flexibility limit of DEP.

Table 11. Equations to Calculate Load Transfer from DEC to DEP

(Net Load –Flexibility Limit)			Time of Day	Equation
DEC	DEP	Comparison		
<0	<0	|DEC|<|DEP|	8:00-23:00	*If*(|DEC-DEP|<1820): *If*($DEP_{NetLoad}$ +|DEC-DEP|> $DEC_{NetLoad}$ -|DEC-DEP|): *Average*(DEC,DEP)-*Min*(DEC,DEP) *Else:* |DEC-DEP| *Else If*($DEP_{NetLoad}$+1820> $DEC_{NetLoad}$-1820): *Average* (DEC,DEP)-*Min*(DEC,DEP) *Else:* 1820
<0	<0	|DEC|>|DEP|	8:00-23:00	*If*(|DEC-DEP|<1050): *If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:* -|DEC-DEP| *Else If*($DEC_{NetLoad}$+1050> $DEP_{NetLoad}$-1050): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* -1050
<0	>0		8:00-23:00	*If*(|DEC-DEP|>1050): *If*($DEC_{NetLoad}$+1050> $DEP_{NetLoad}$-1050): *-(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else: -1050* *Else If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* -|DEC-DEP|
>0	<0		8:00-23:00	*If*(|DEC-DEP|>1820): *If*($DEC_{NetLoad}$+1820> $DEP_{NetLoad}$-18200): *Average*(DEC,DEP)-*Min*(DEC,DEP) *Else:* 1820 *Else If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* |DEC-DEP|
>0	>0	|DEC|<|DEP|	8:00-23:00	*If*(|DEC-DEP|<1820): *If*($DEP_{NetLoad}$ +|DEC-DEP|> $DEC_{NetLoad}$ -|DEC-DEP|): *-(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:*- |DEC-DEP| *Else If*($DEP_{NetLoad}$+1820> $DEC_{NetLoad}$-1820): *-(Average* (DEC,DEP)-*Min*(DEC,DEP))

(Net Load –Flexibility Limit)			Time of Day	Equation
DEC	DEP	Comparison		
				Else: -1820
>0	>0	|DEC|>|DEP|	8:00-23:00	*If*(|DEC-DEP|<1050): *If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:* |DEC-DEP| *Else If*($DEC_{NetLoad}$+1050> $DEP_{NetLoad}$-1050): *(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* 1050
<0	<0	|DEC|<|DEP|	0:00-7:00	*If*(|DEC`-DEP|<2933): *If*($DEP_{NetLoad}$ +|DEC-DEP|> $DEC_{NetLoad}$ -|DEC-DEP|): *Average*(DEC,DEP)-*Min*(DEC,DEP) *Else:* |DEC-DEP| *Else If*($DEP_{NetLoad}$+2933> $DEC_{NetLoad}$-2933): *Average* (DEC,DEP)-*Min*(DEC,DEP) *Else:* 2933
<0	<0	|DEC|>|DEP|	0:00-7:00	*If*(|DEC-DEP|<1036): *If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:* -|DEC-DEP| *Else If*($DEC_{NetLoad}$+1036> $DEP_{NetLoad}$-1036): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* -1036
<0	>0		0:00-7:00	*If*(|DEC-DEP|>1036): *If*($DEC_{NetLoad}$+1036> $DEP_{NetLoad}$-1036): *-(Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:* -1036 *Else If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* -|DEC-DEP|
>0	<0		0:00-7:00	*If*(|DEC-DEP|>2933): *If*($DEC_{NetLoad}$+2933> $DEP_{NetLoad}$-2933): *Average*(DEC,DEP)-*Min*(DEC,DEP) *Else:* 2933 *Else If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): *-(Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* |DEC-DEP|
>0	>0	|DEC|<|DEP|	0:00-7:00	*If*(|DEC-DEP|<2933): *If*($DEP_{NetLoad}$ +|DEC-DEP|> $DEC_{NetLoad}$ -|DEC-DEP|): *-(Average*(DEC,DEP)-*Min*(DEC,DEP))

(Net Load –Flexibility Limit)			Time of Day	Equation
DEC	DEP	Comparison		
				Else:- |DEC-DEP| *Else If*($DEP_{NetLoad}$+2933> $DEC_{NetLoad}$-1820): -(*Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* -2933
>0	>0	|DEC|>|DEP|	0:00-7:00	*If*(|DEC-DEP|<1036): *If*($DEC_{NetLoad}$ +|DEC-DEP|> $DEP_{NetLoad}$ -|DEC-DEP|): (*Average*(DEC,DEP)-*Min*(DEC,DEP)) *Else:* |DEC-DEP| *Else If*($DEC_{NetLoad}$+1036> $DEP_{NetLoad}$-1036): (*Average* (DEC,DEP)-*Min*(DEC,DEP)) *Else:* 1036

Equations 8 and 9 show how the net load of each BA is changed by the interconnection after the load transfer is calculated.

$$\{(\text{DEC Net Load Before}) - (\text{Load Transfer}) = (\text{DEC Net Load After})\} \quad (8)$$

$$\{(\text{DEP Net Load Before}) + (\text{Load Transfer}) = (\text{DEP Net Load After})\} \quad (9)$$

A.3 Seasonal Metrics

The dates of each season are defined in Table 12.

Table 12. Season definitions

	Start Date	End Date
Spring	3/1/2019	5/31/2019
Summer	6/1/2019	8/31/2019
Fall	9/1/2019	11/30/2019
Winter	12/1/2019	2/28/2019

Table 13. 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

Table 14. Maximum up ramp of each season (MW/h)

Scenario	Spring	Summer	Fall	Winter
1	2927	2355	3839	4039
2	3244	2272	3839	4384
3	4539	3294	4412	5341
4	5443	4316	5474	6609
5	5964	5338	5960	7252

Scenario	Spring	Summer	Fall	Winter
6	6277	6360	6813	8362
7	6583	6360	7508	9472
8	5924	5408	5986	7278
9	6873	5338	6717	7876
10	6564	5338	6489	7481
11	6179	5943	6757	8401
12 – DEC 5%	1724	1369	1900	2594
12 – DEC 10%	1722	1539	2093	2594
12 – DEC 15%	2306	2242	2988	3030
12 – DEP 5%	1502	1130	1941	2003
12 – DEP 10%	1629	1754	1941	2309
12 – DEP 15%	2266	2385	2102	3068

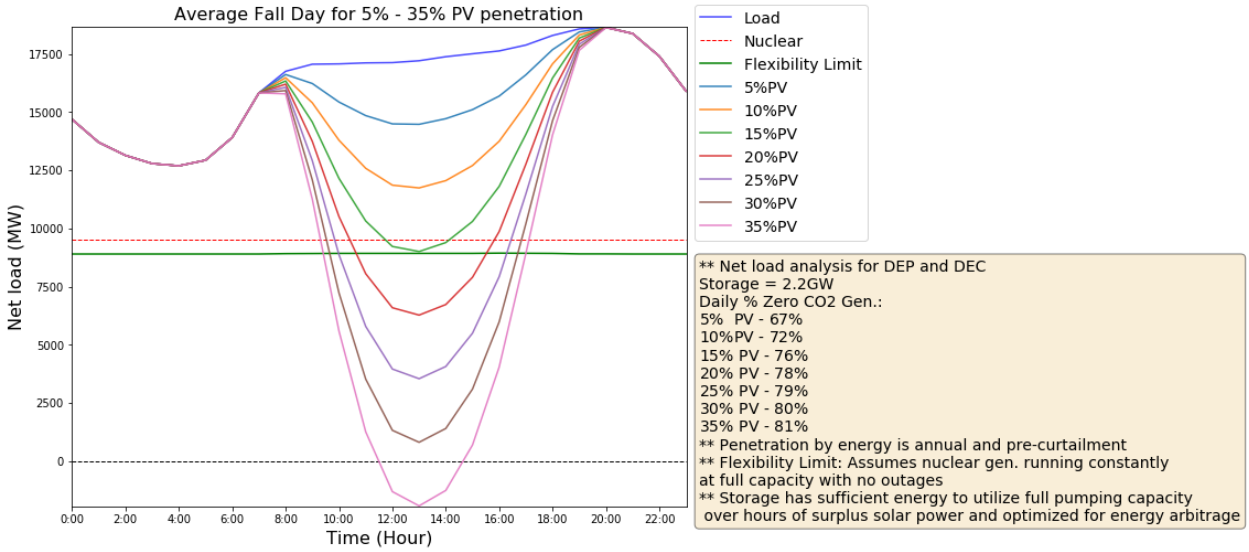
Table 15. Maximum down ramp of each season (MW/h)

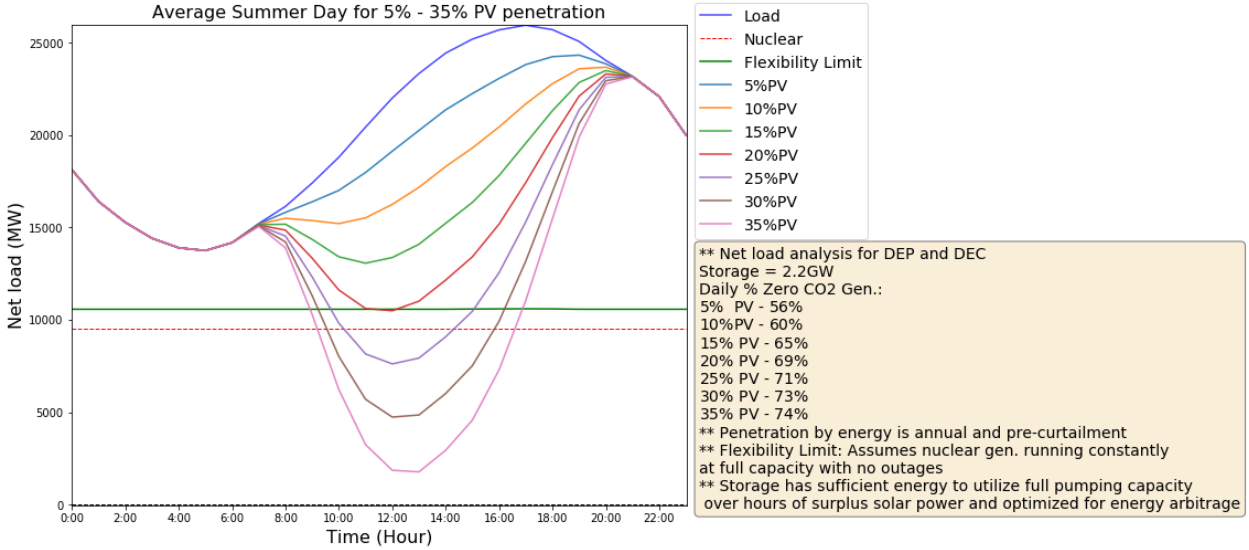
Scenario	Spring	Summer	Fall	Winter
1	-3080	-4090	-2830	-5873
2	-3406	-4090	-3403	-5873
3	-4712	-4090	-4354	-5873
4	-6069	-4090	-5658	-6699
5	-7427	-4090	-6964	-7894
6	-8784	-4406	-8270	-9090
7	-9869	-4482	-9577	-10286
8	-7419	-4090	-6951	-7906
9	-7427	-4090	-6964	-7894
10	-7427	-4090	-6964	-7894
11	-8673	-4461	-8427	-9555
12 – DEC 5%	-2047	-2313	-1480	-3122
12 – DEC 10%	-2047	-2313	-1865	-3122
12 – DEC 15%	-2413	-2313	-2621	-3320
12 – DEP 5%	-1390	-1874	-1660	-2750
12 – DEP 10%	-1707	-1874	-1714	-2750
12 – DEP 15%	-2349	-1874	-2519	-2750

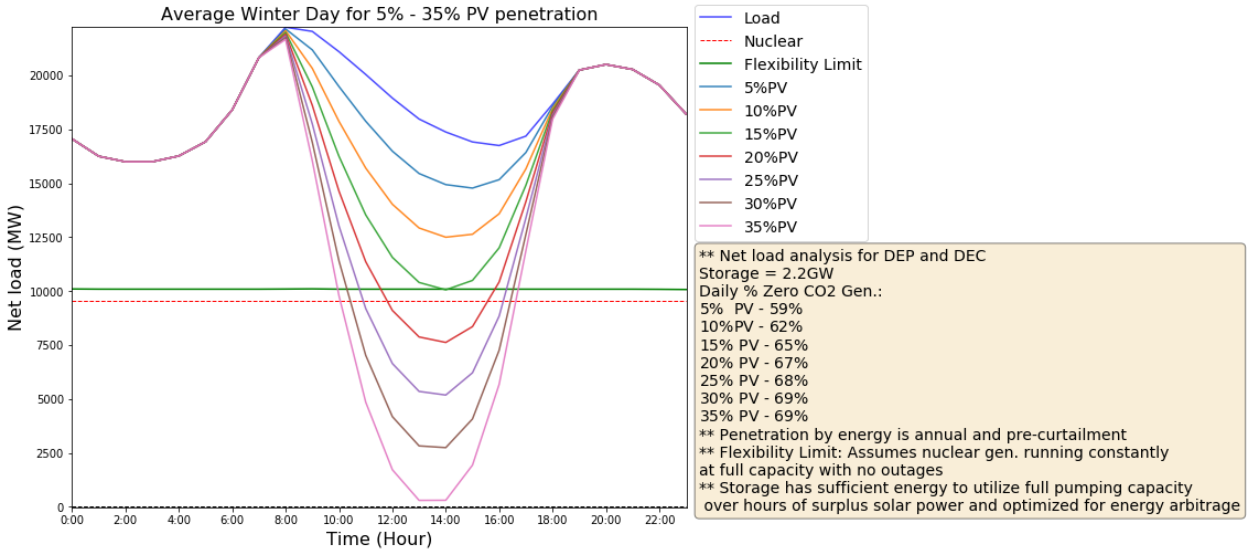
A.4 Additional Figures

Scenarios 1-7

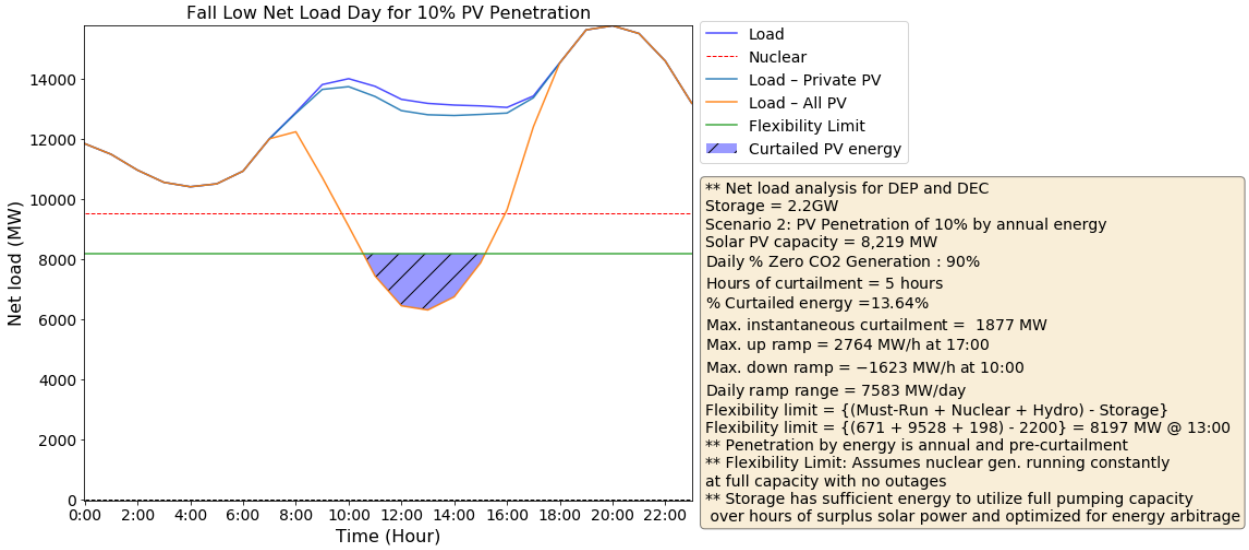
Seasonal Average for 5%-35% PV Penetration



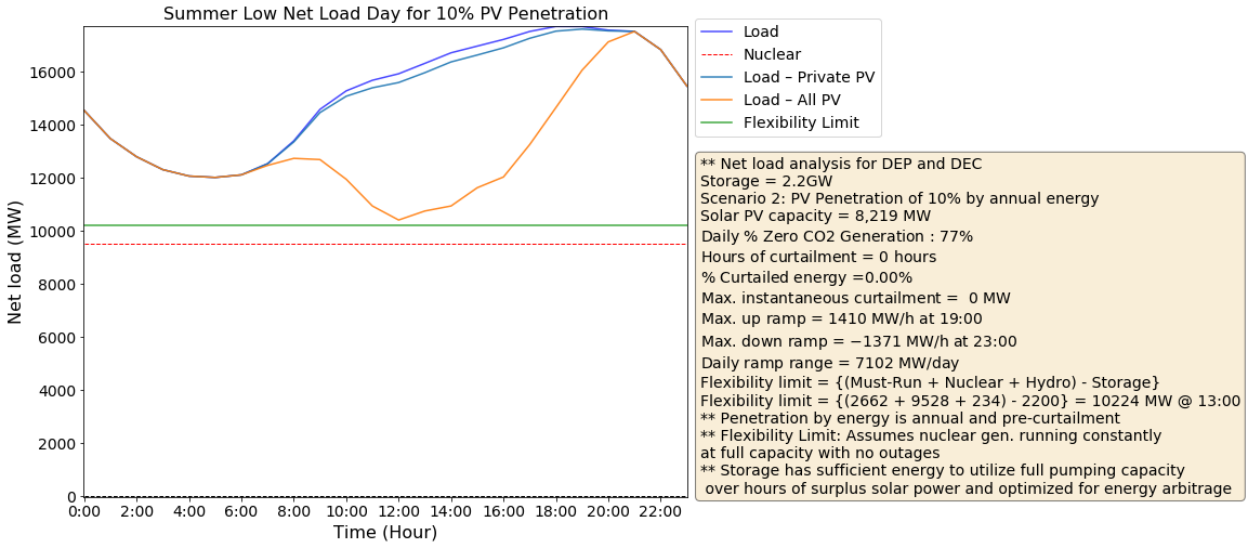




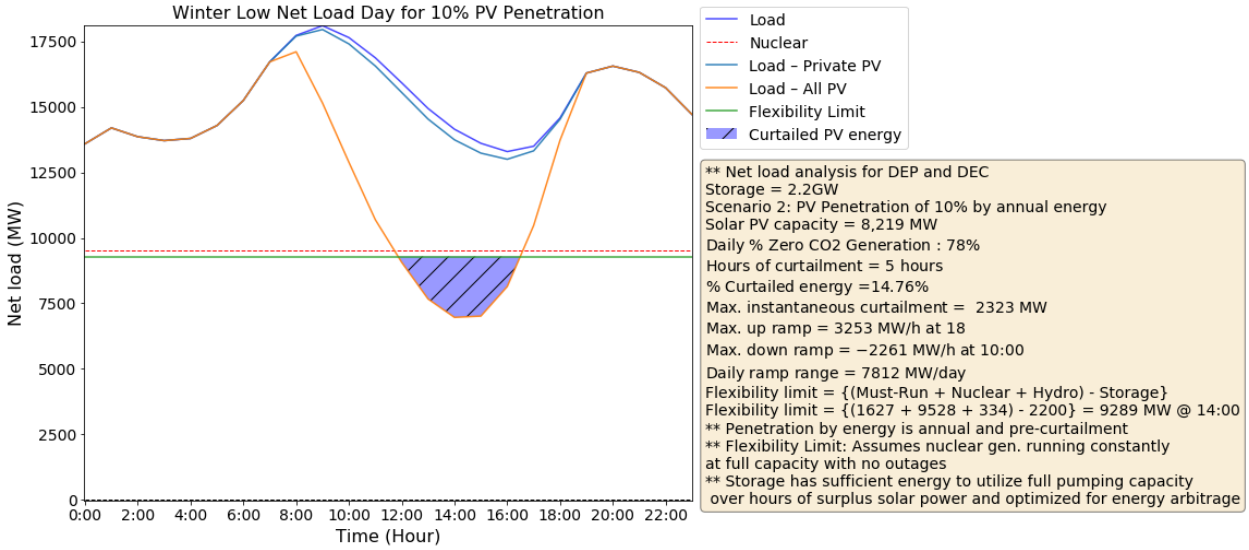
Seasonal Low Net Load Days: 10% PV Penetration



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 8,219 MW
Daily % Zero CO2 Generation : 90%
Hours of curtailment = 5 hours
% Curtailed energy =13.64%
Max. instantaneous curtailment = 1877 MW
Max. up ramp = 2764 MW/h at 17:00
Max. down ramp = −1623 MW/h at 10:00
Daily ramp range = 7583 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(671 + 9528 + 198) - 2200} = 8197 MW @ 13:00
** 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

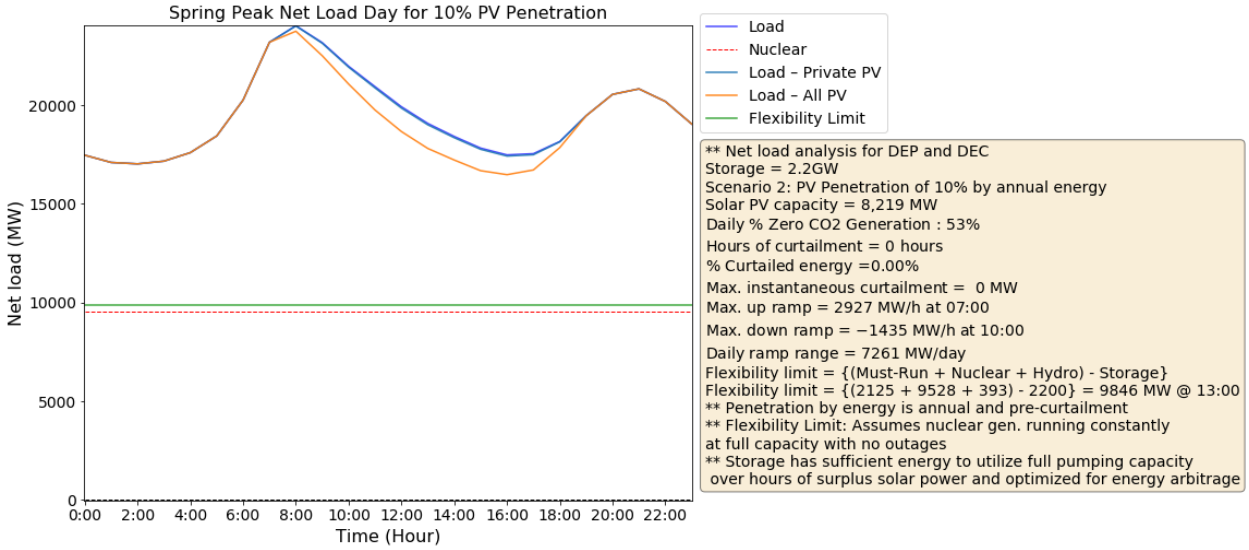


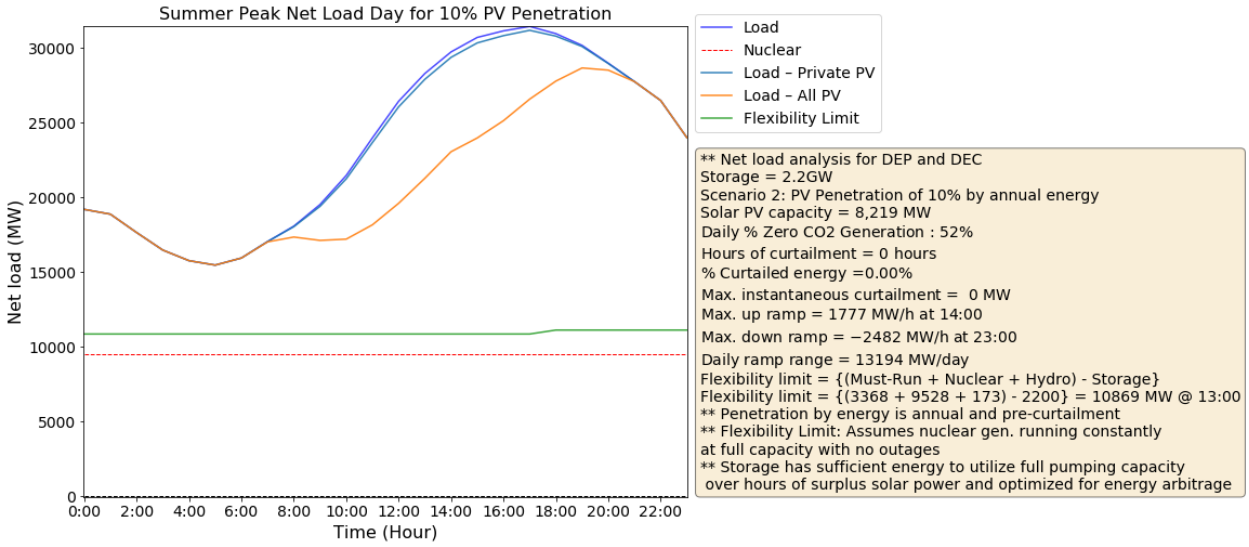
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 8,219 MW
Daily % Zero CO2 Generation : 77%
Hours of curtailment = 0 hours
% Curtailed energy =0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1410 MW/h at 19:00
Max. down ramp = −1371 MW/h at 23:00
Daily ramp range = 7102 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2662 + 9528 + 234) - 2200} = 10224 MW @ 13:00
** 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

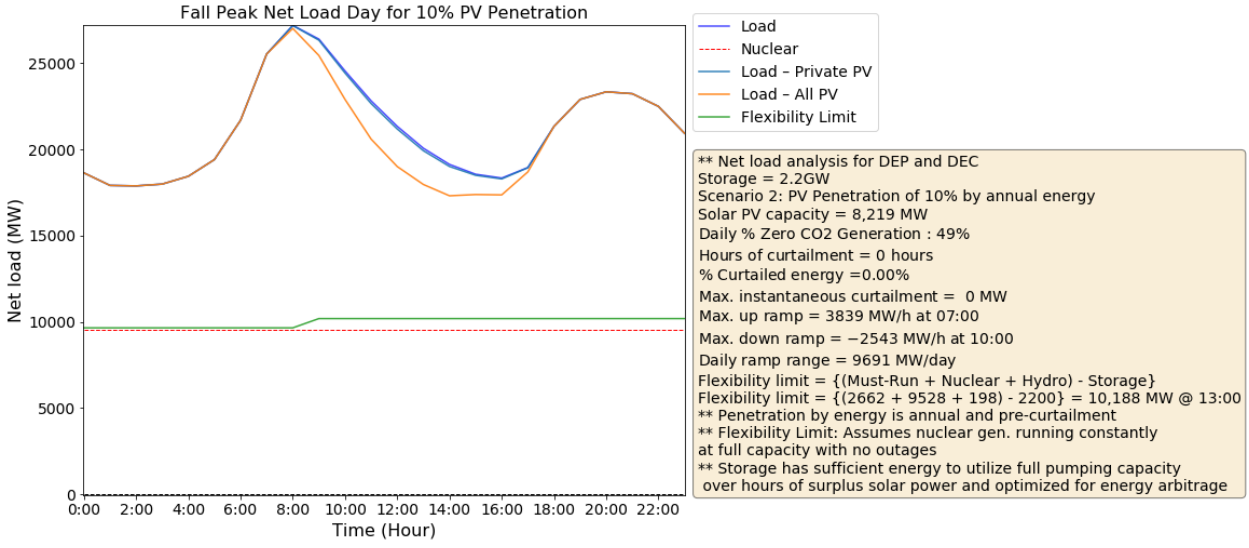


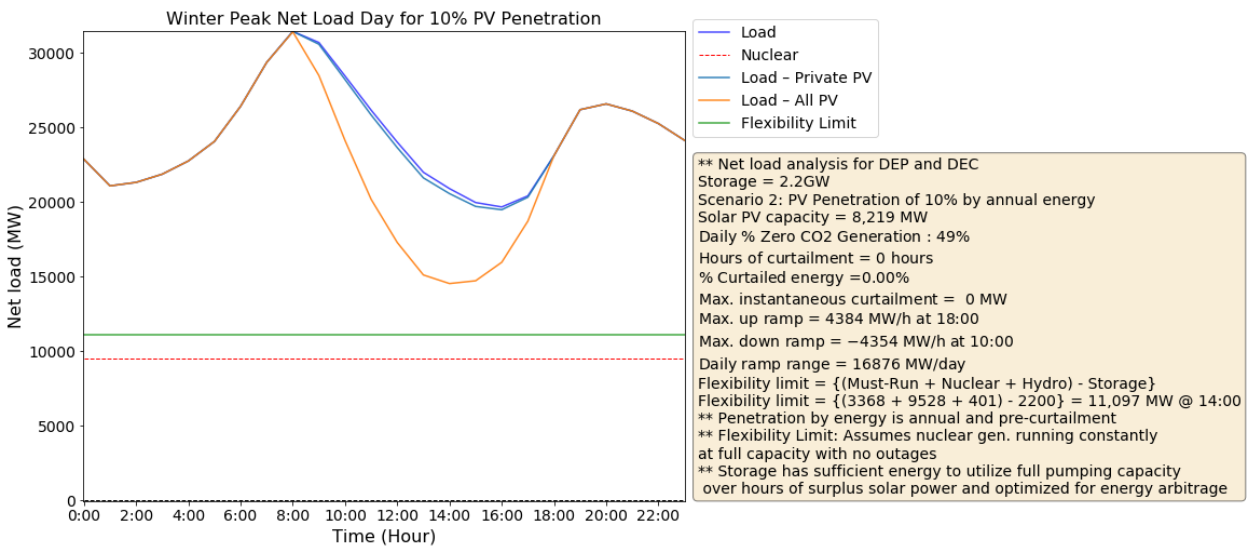
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 8,219 MW
Daily % Zero CO2 Generation : 78%
Hours of curtailment = 5 hours
% Curtailed energy =14.76%
Max. instantaneous curtailment = 2323 MW
Max. up ramp = 3253 MW/h at 18
Max. down ramp = −2261 MW/h at 10:00
Daily ramp range = 7812 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1627 + 9528 + 334) - 2200} = 9289 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

Seasonal Peak Net Load Days: 10% PV Penetration

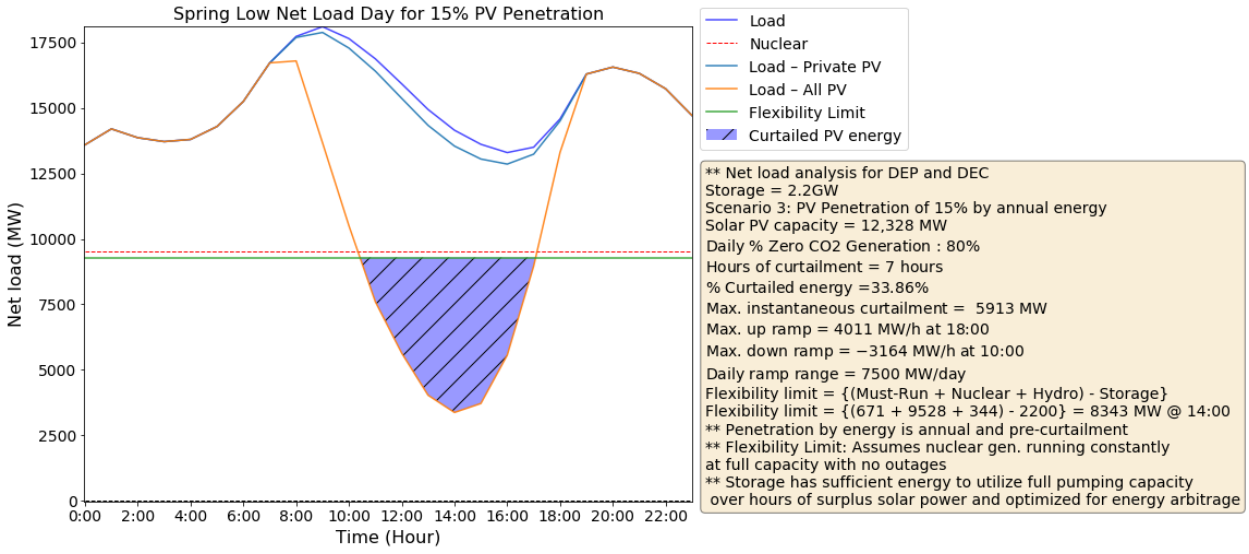


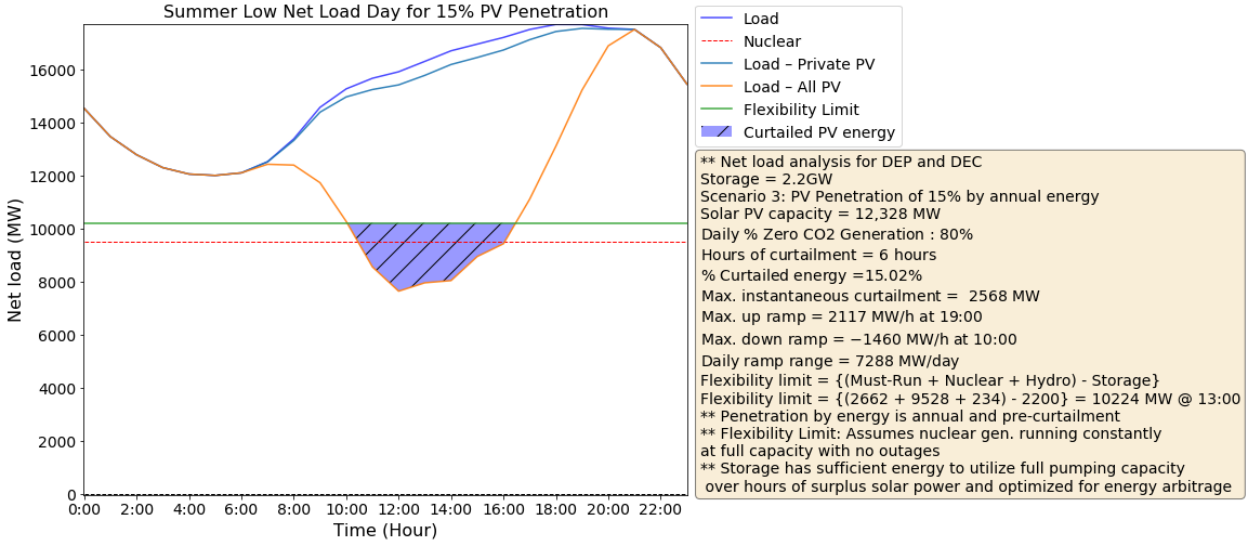


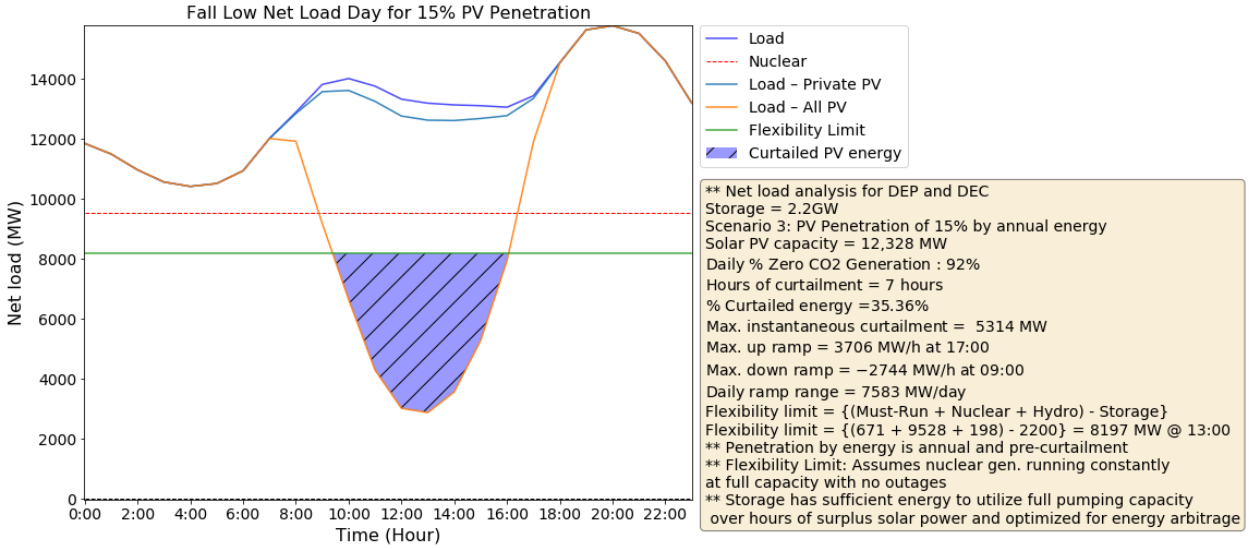


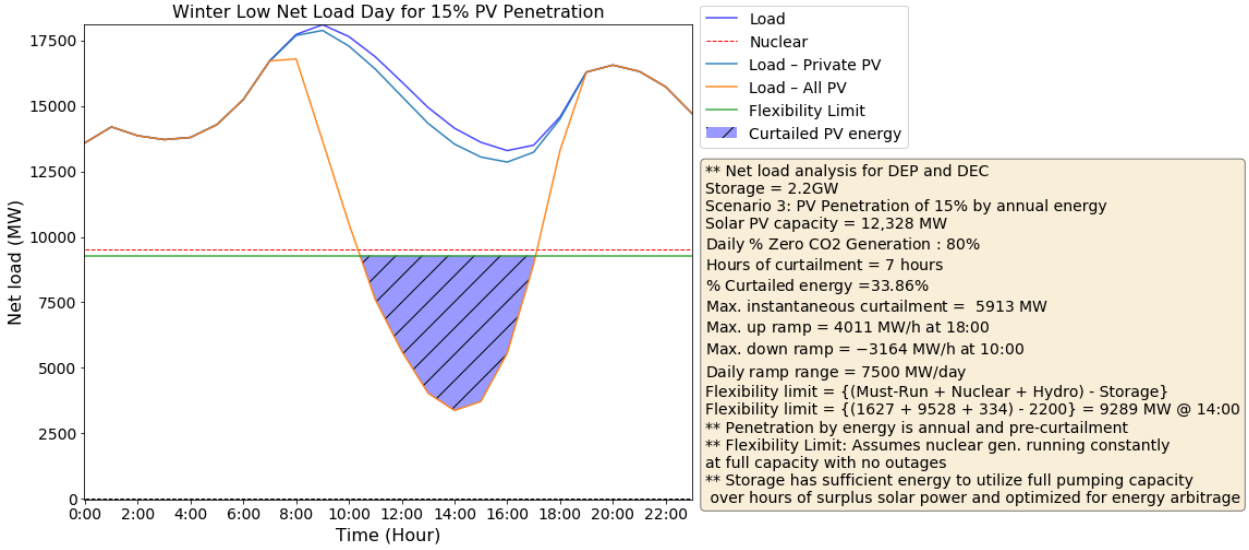


Seasonal Low Net Load Days: 15% PV Penetration

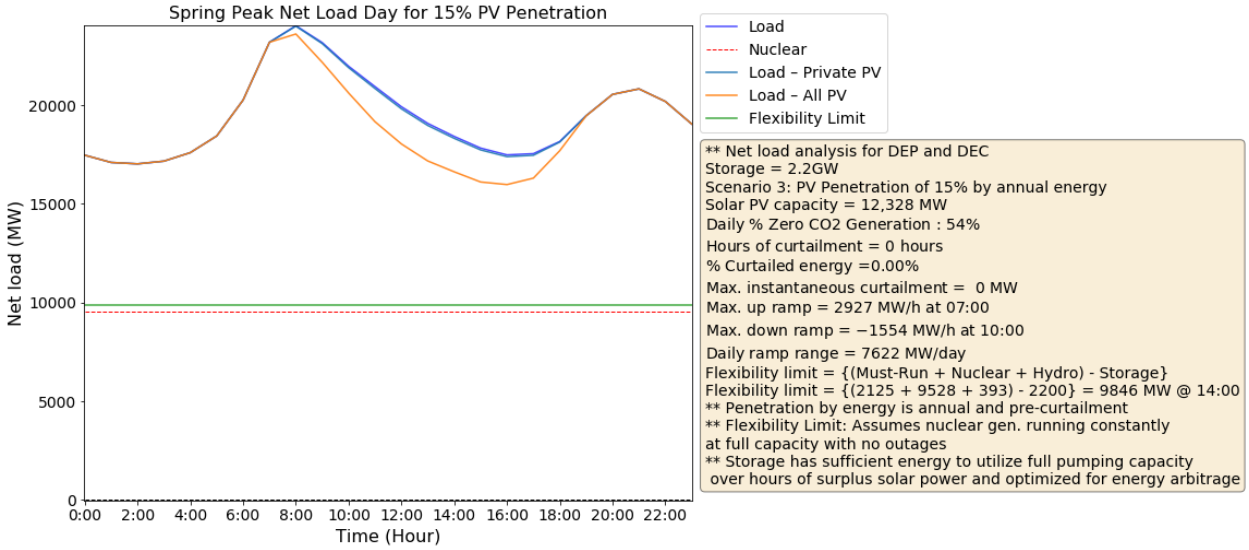


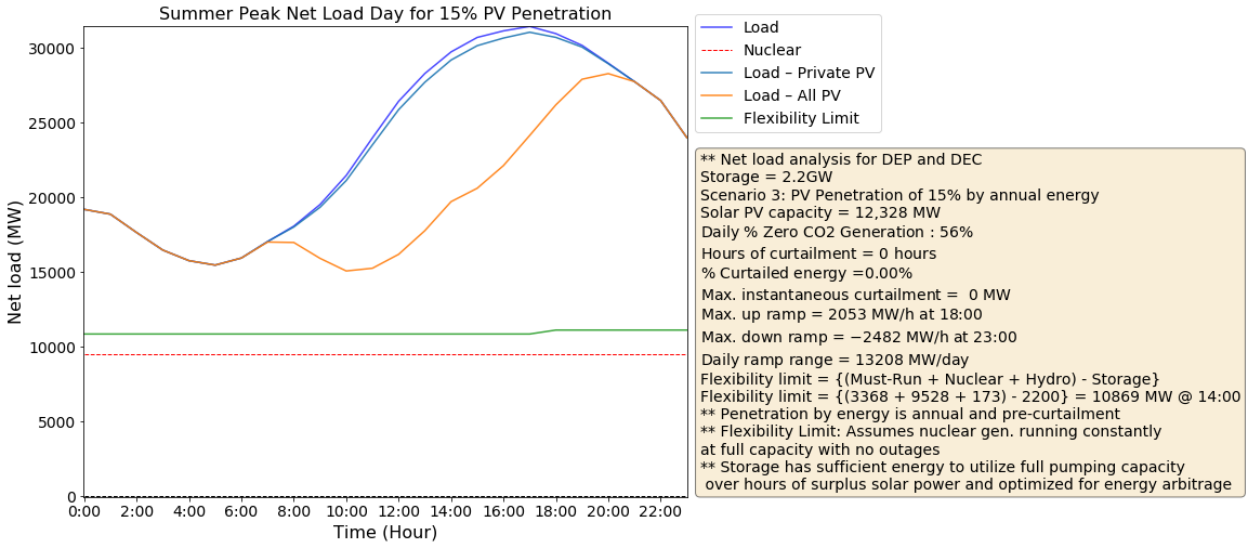


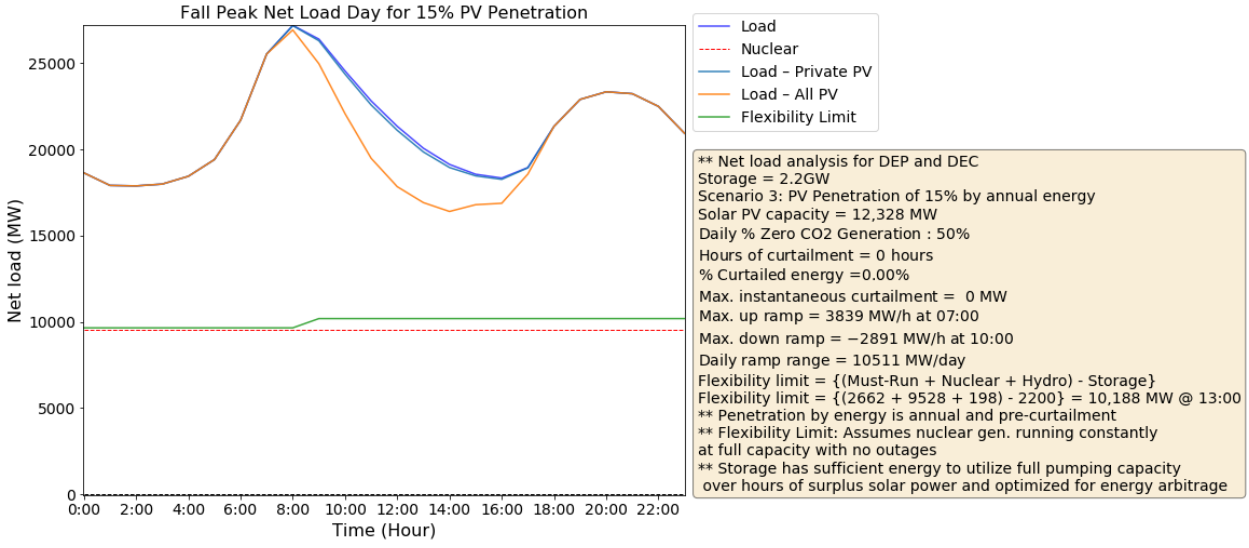


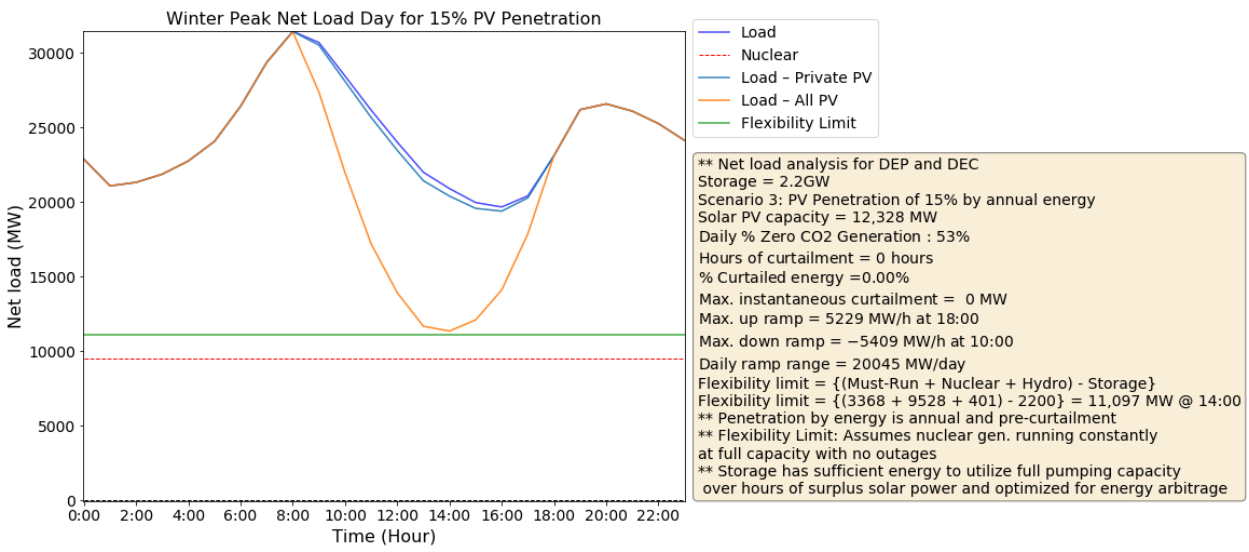


Seasonal Peak Net Load Days: 15% PV Penetration

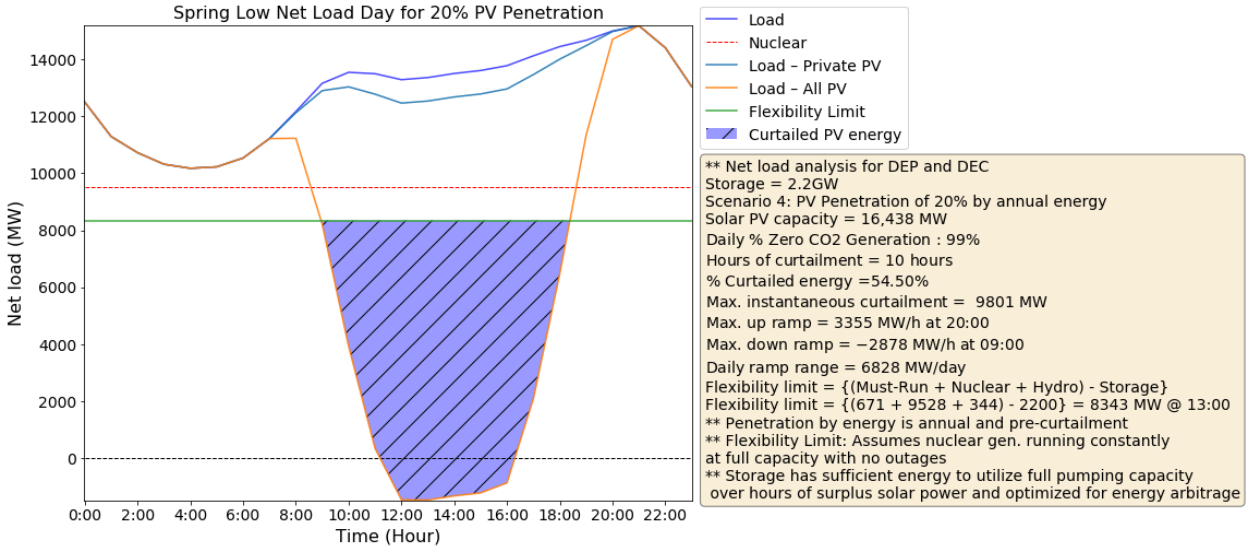


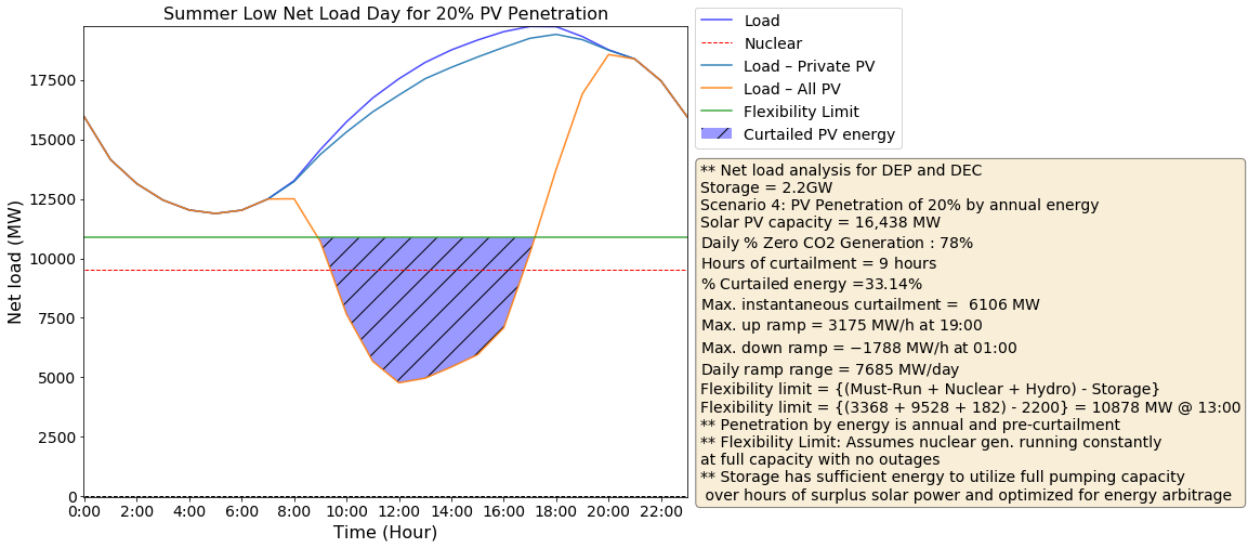


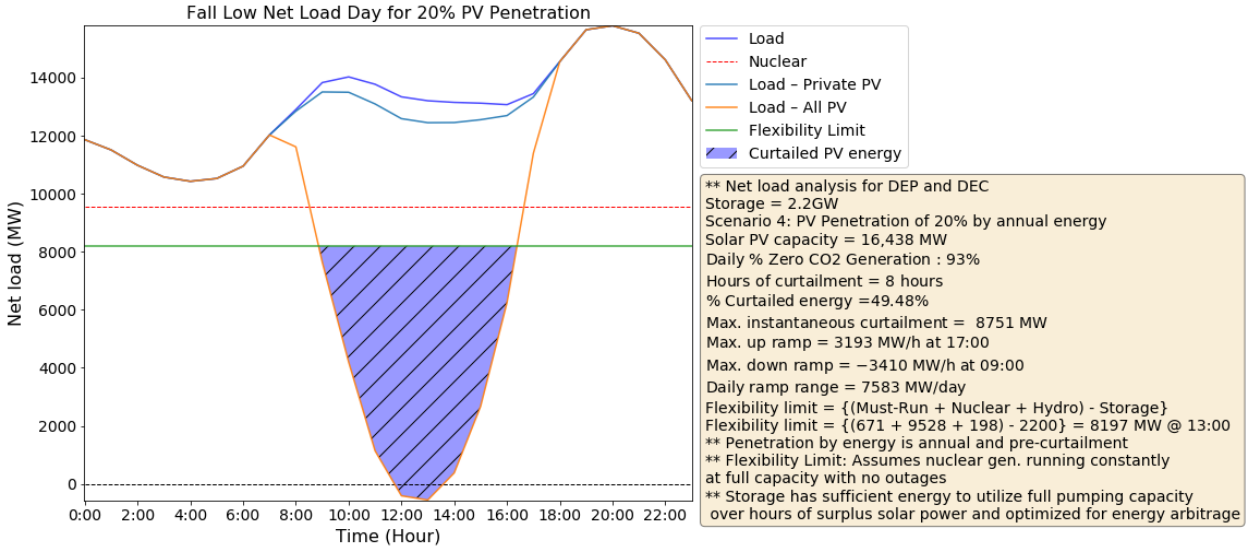


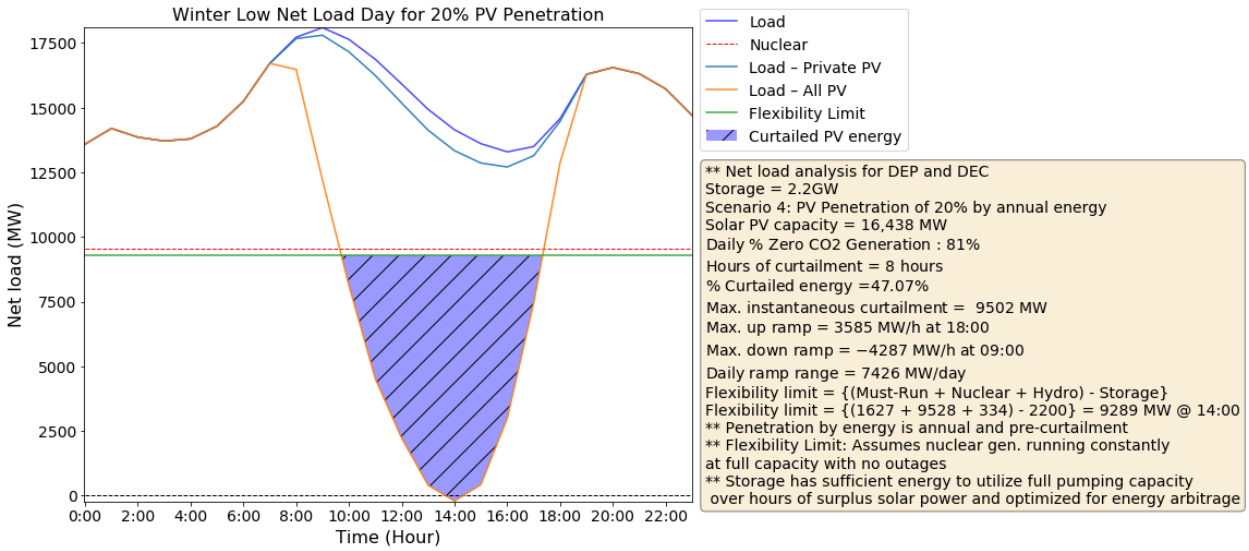


Seasonal Low Net Load Days: 20% PV Penetration

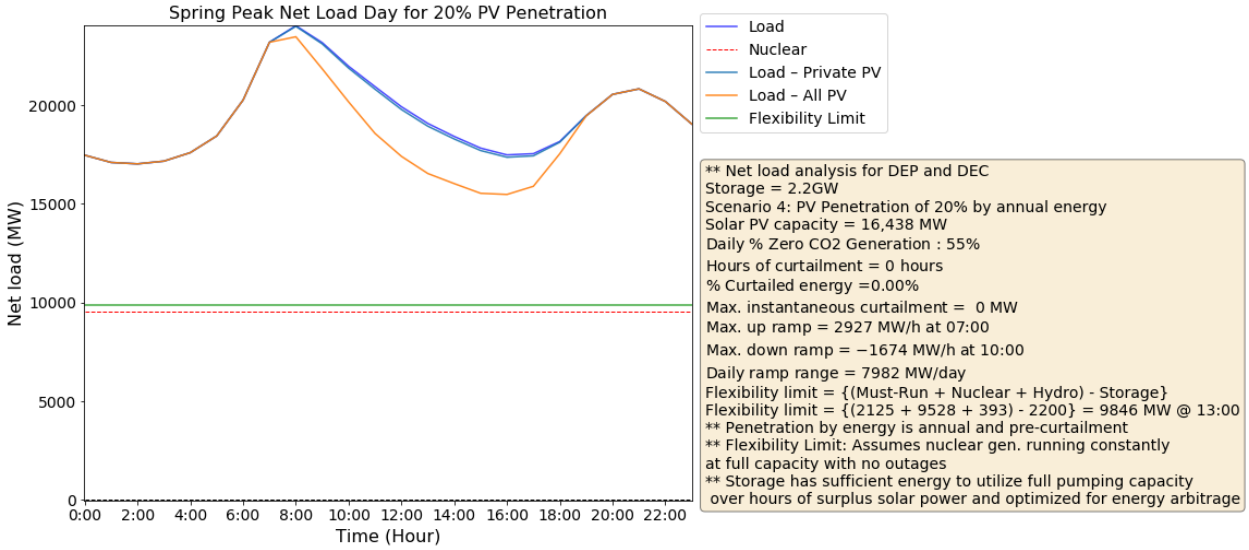


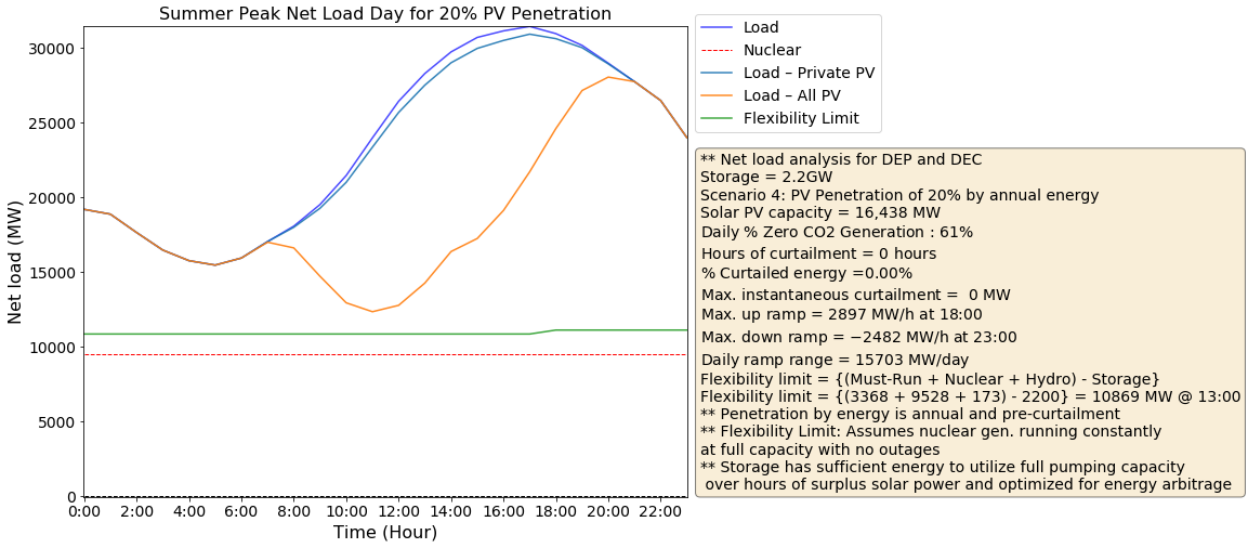


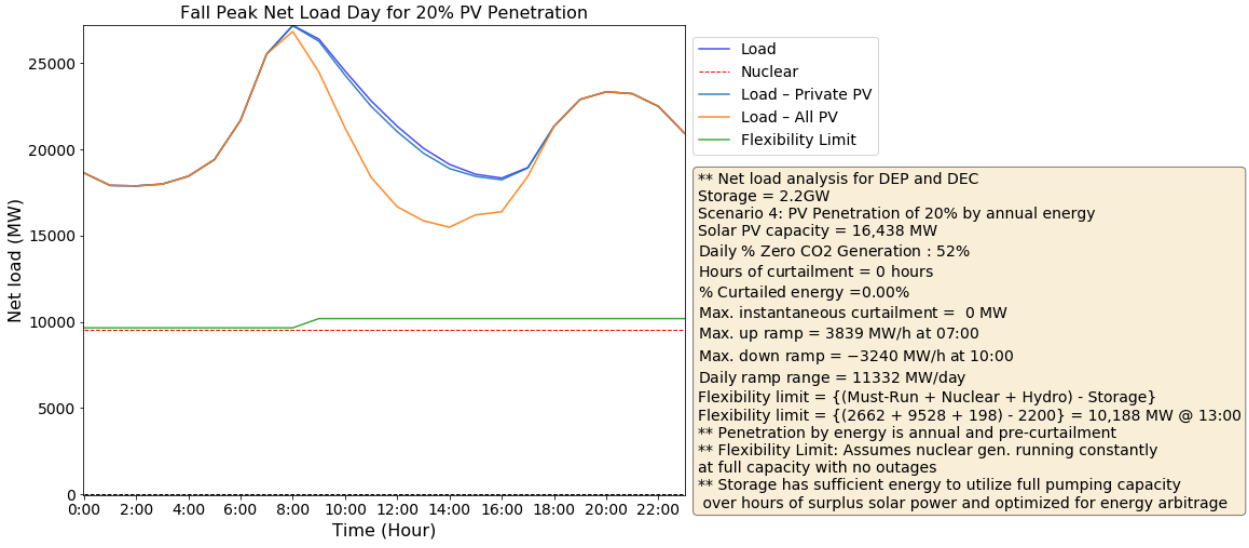


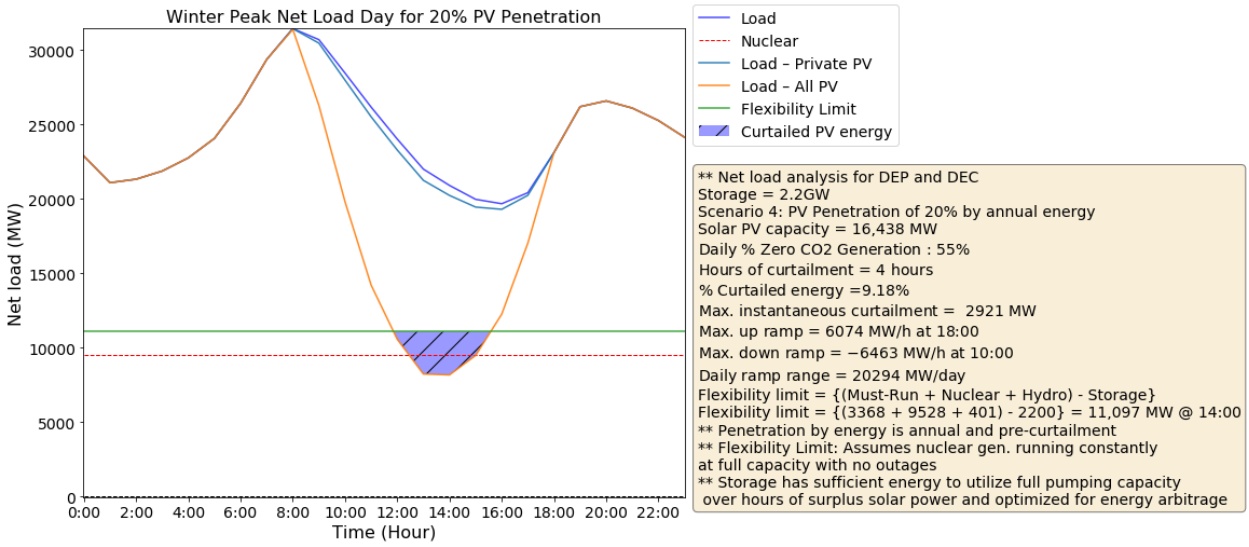


Seasonal Peak Net Load Days: 20% PV Penetration

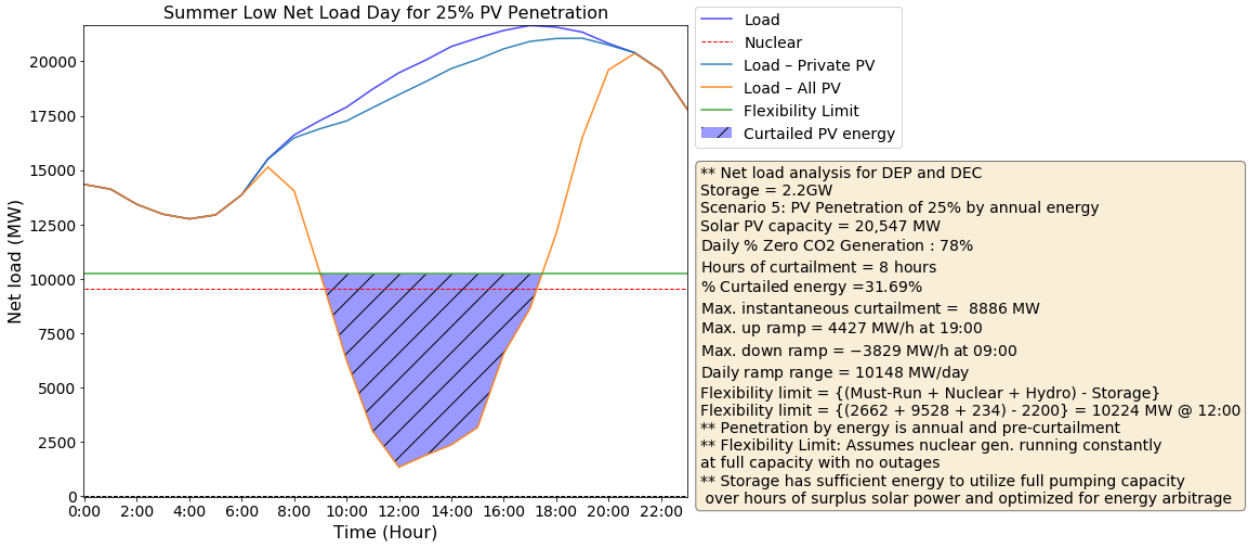




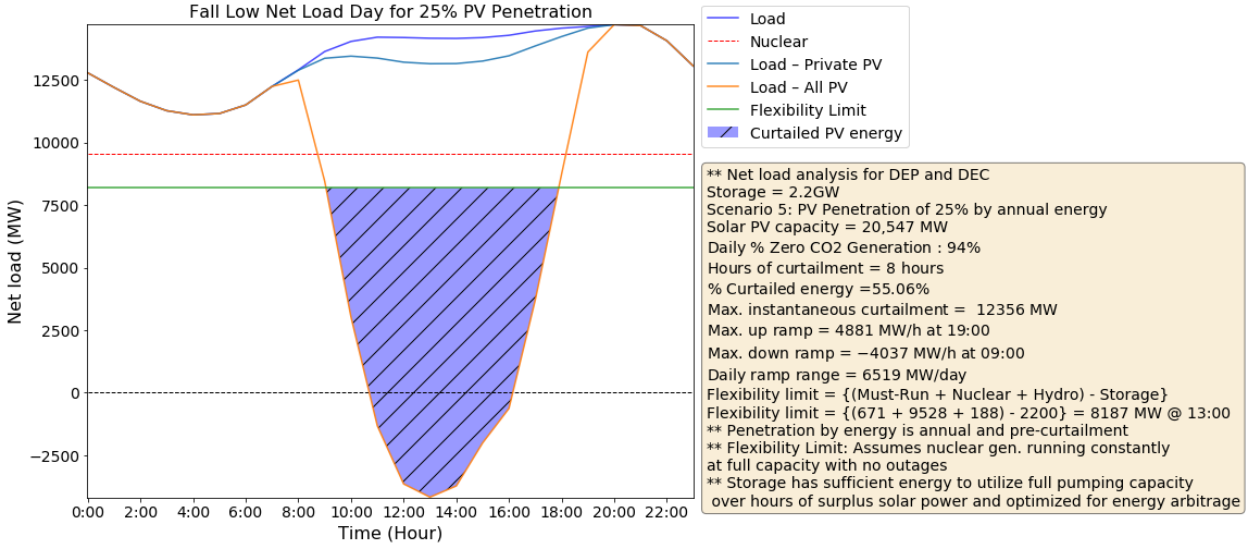




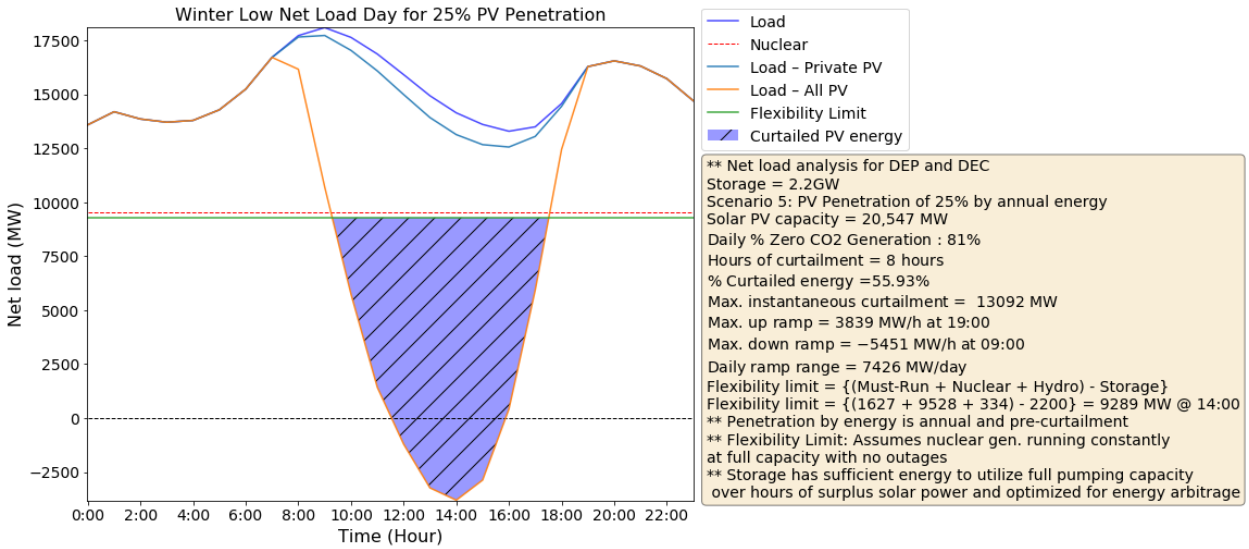
Seasonal Low Net Load Days: 25% PV Penetration



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 5: PV Penetration of 25% by annual energy
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 78%
Hours of curtailment = 8 hours
% Curtailed energy =31.69%
Max. instantaneous curtailment = 8886 MW
Max. up ramp = 4427 MW/h at 19:00
Max. down ramp = −3829 MW/h at 09:00
Daily ramp range = 10148 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2662 + 9528 + 234) - 2200} = 10224 MW @ 12:00
** 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

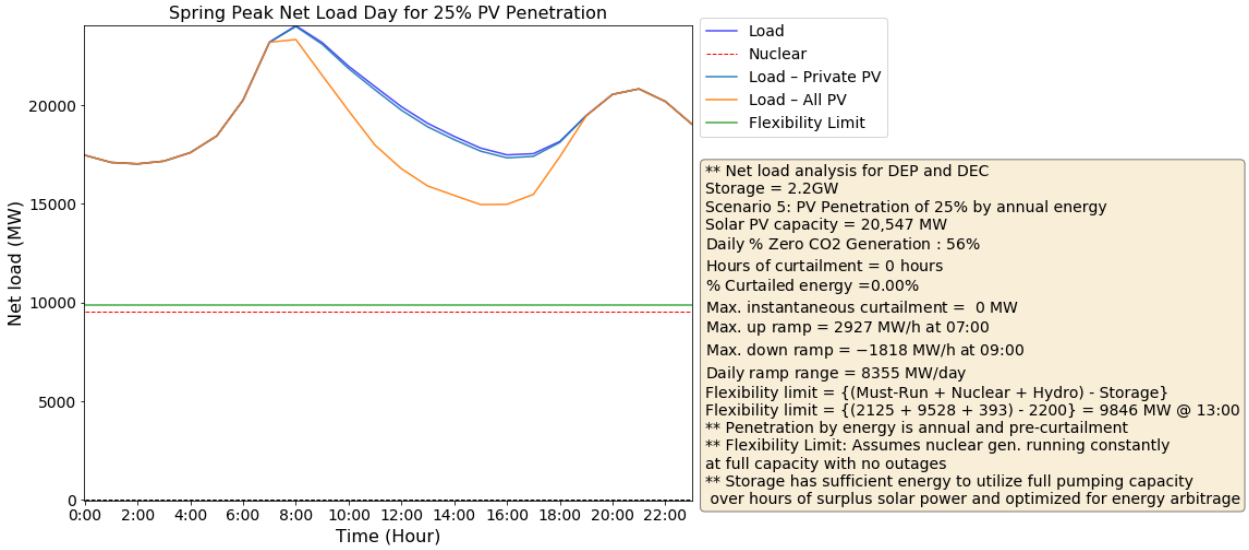


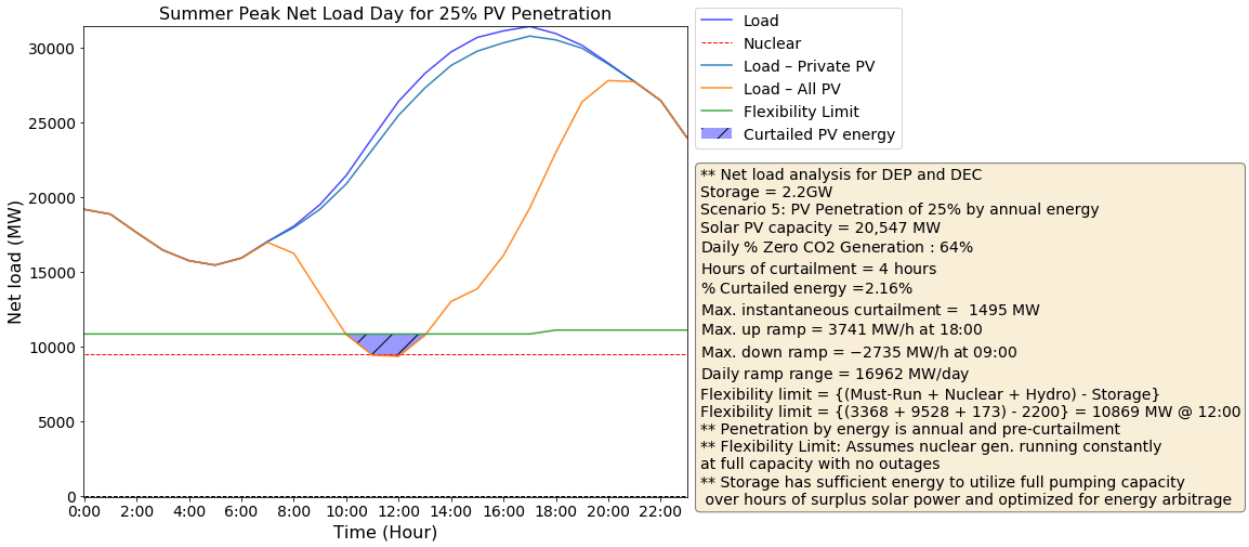
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 5: PV Penetration of 25% by annual energy
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 94%
Hours of curtailment = 8 hours
% Curtailed energy =55.06%
Max. instantaneous curtailment = 12356 MW
Max. up ramp = 4881 MW/h at 19:00
Max. down ramp = −4037 MW/h at 09:00
Daily ramp range = 6519 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(671 + 9528 + 188) - 2200} = 8187 MW @ 13:00
** 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

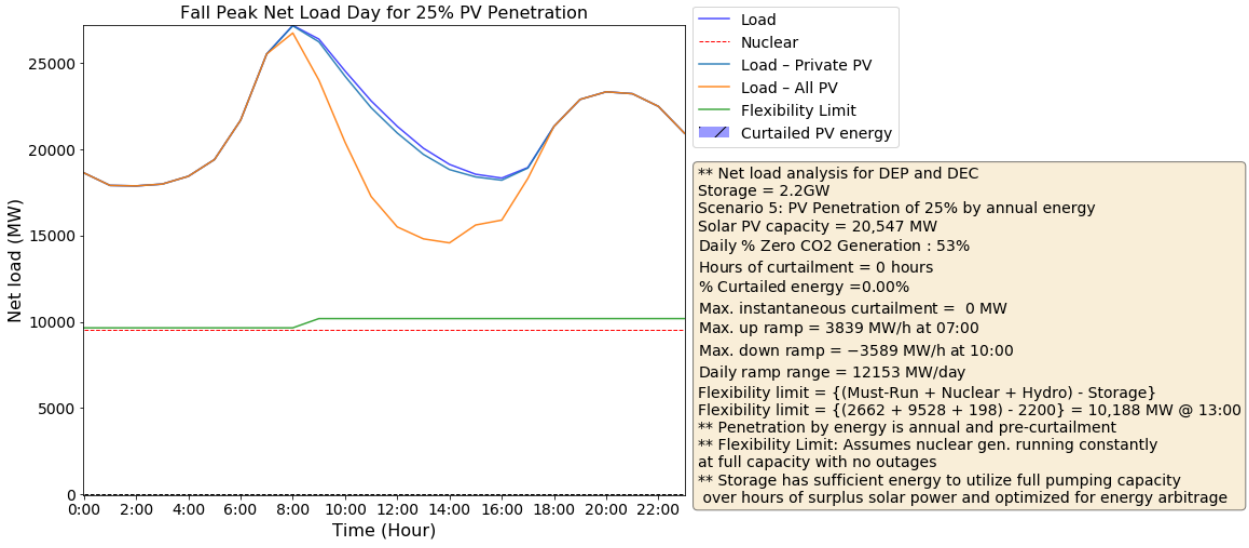


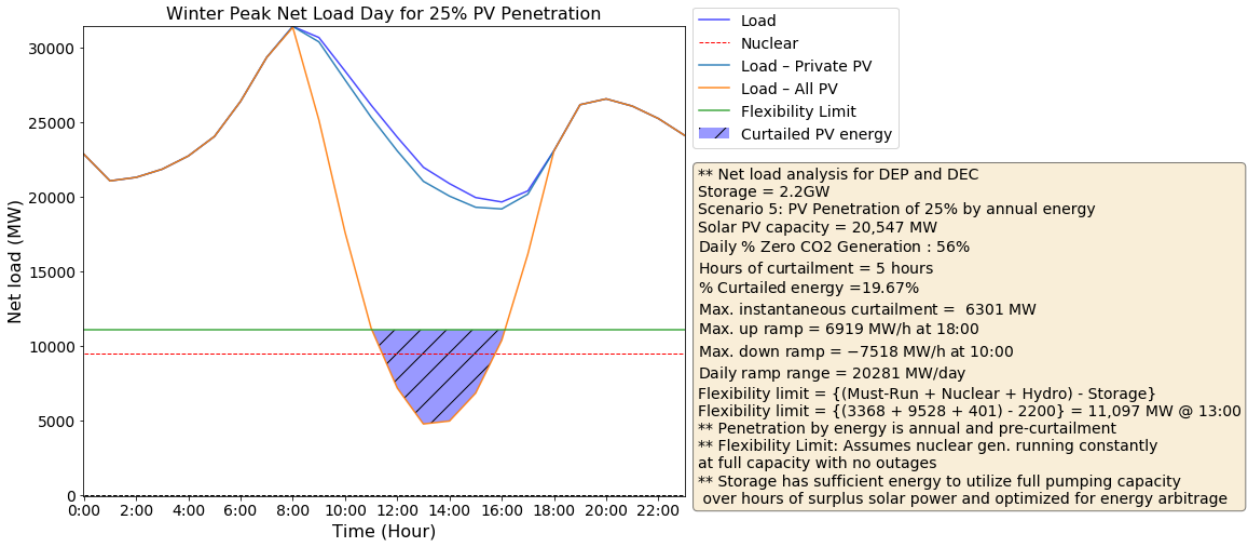
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 5: PV Penetration of 25% by annual energy
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 81%
Hours of curtailment = 8 hours
% Curtailed energy =55.93%
Max. instantaneous curtailment = 13092 MW
Max. up ramp = 3839 MW/h at 19:00
Max. down ramp = −5451 MW/h at 09:00
Daily ramp range = 7426 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1627 + 9528 + 334) - 2200} = 9289 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

Seasonal Peak Net Load Days: 25% PV Penetration

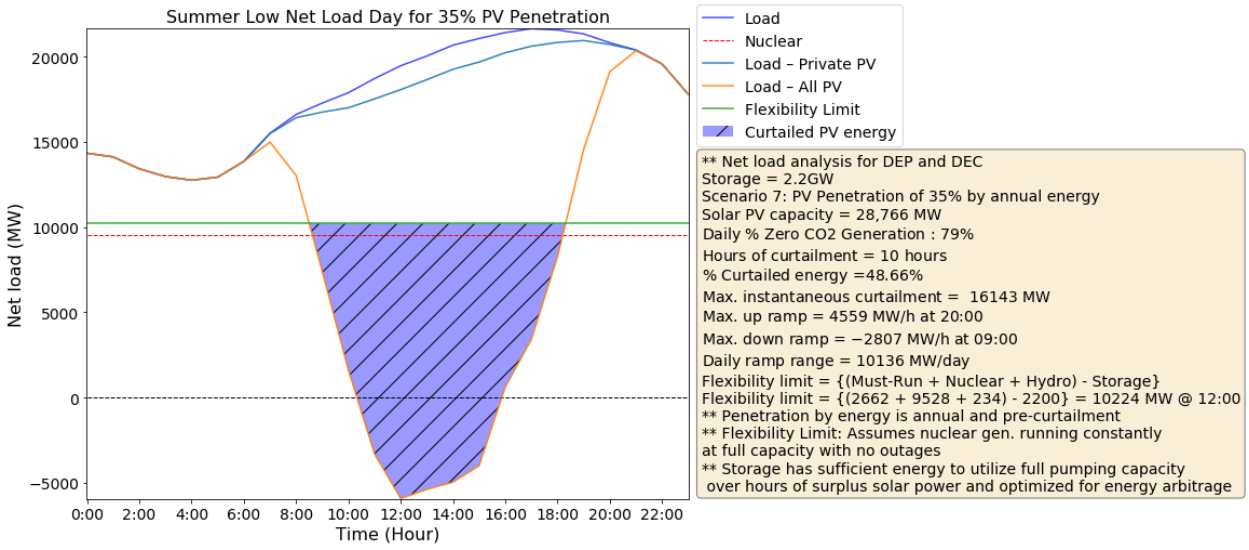


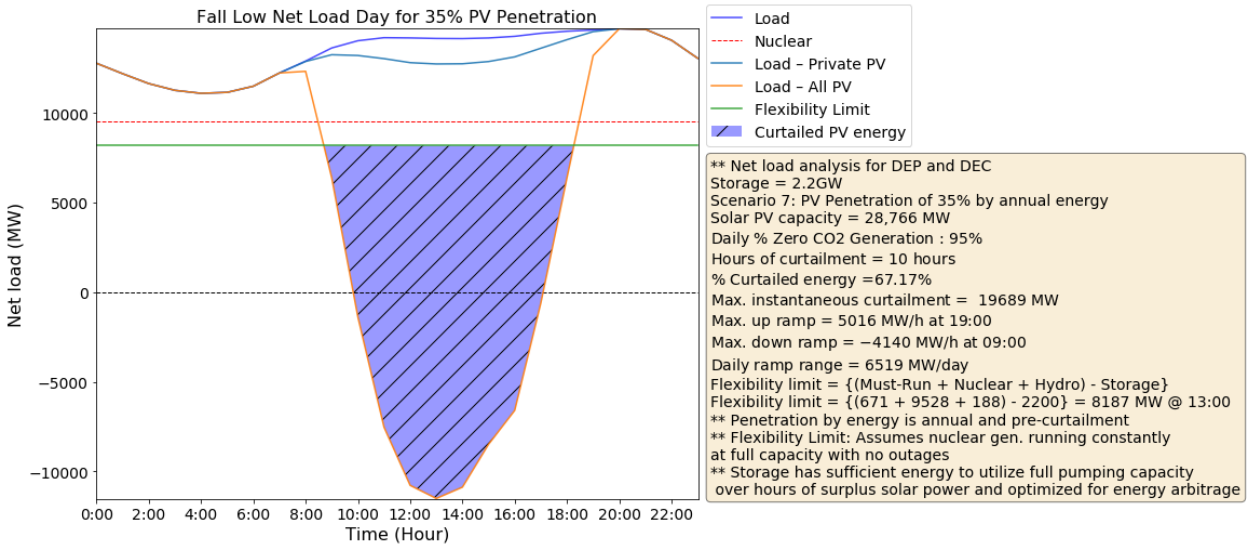


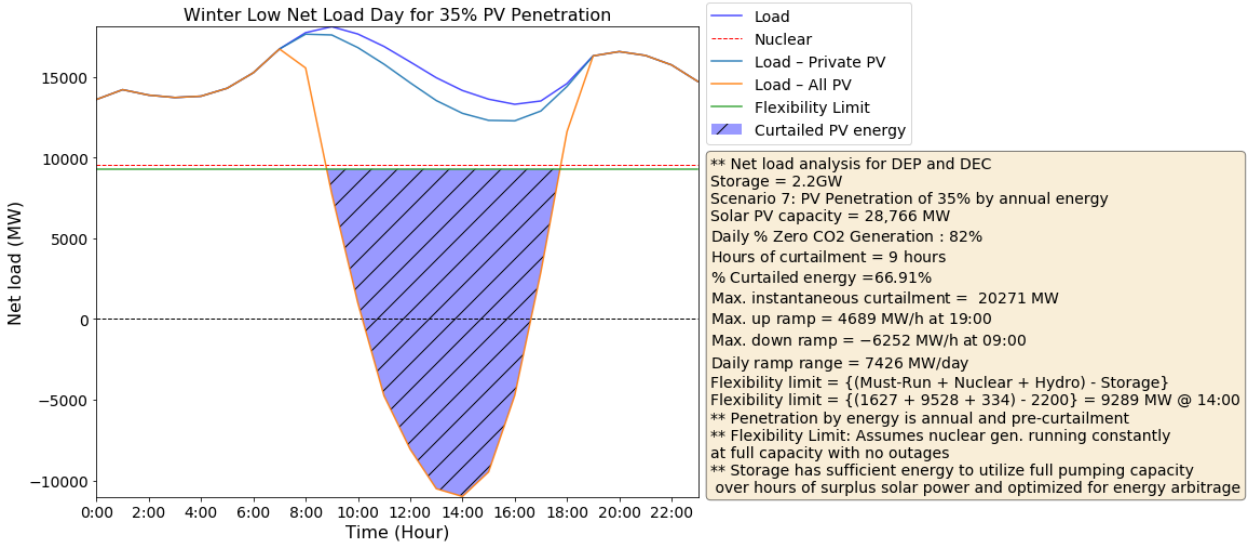




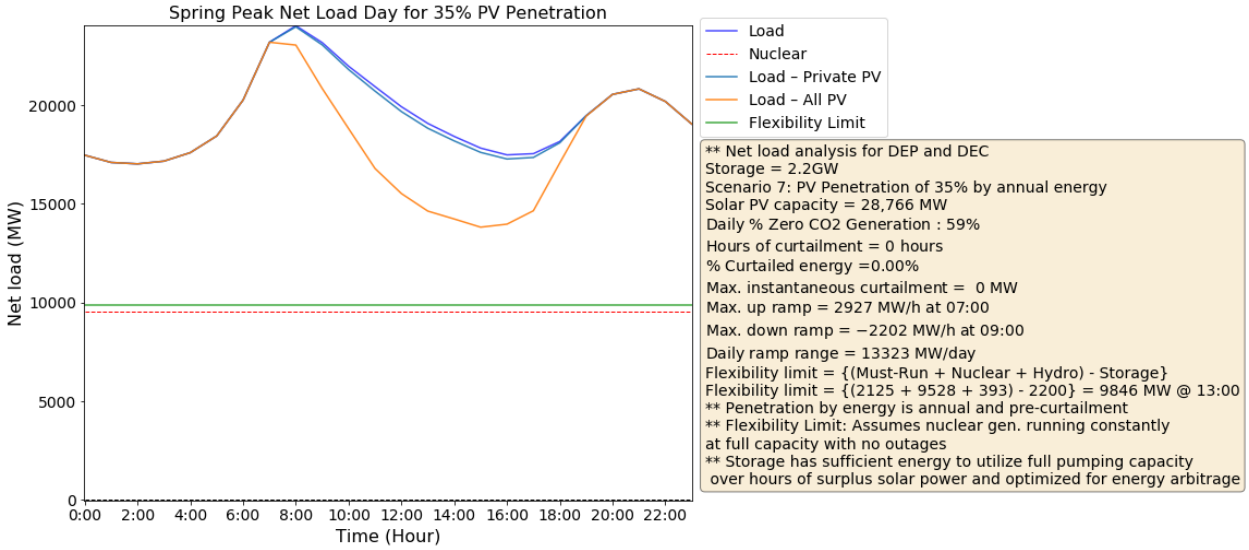
Seasonal Low Net Load Days: 35% PV Penetration

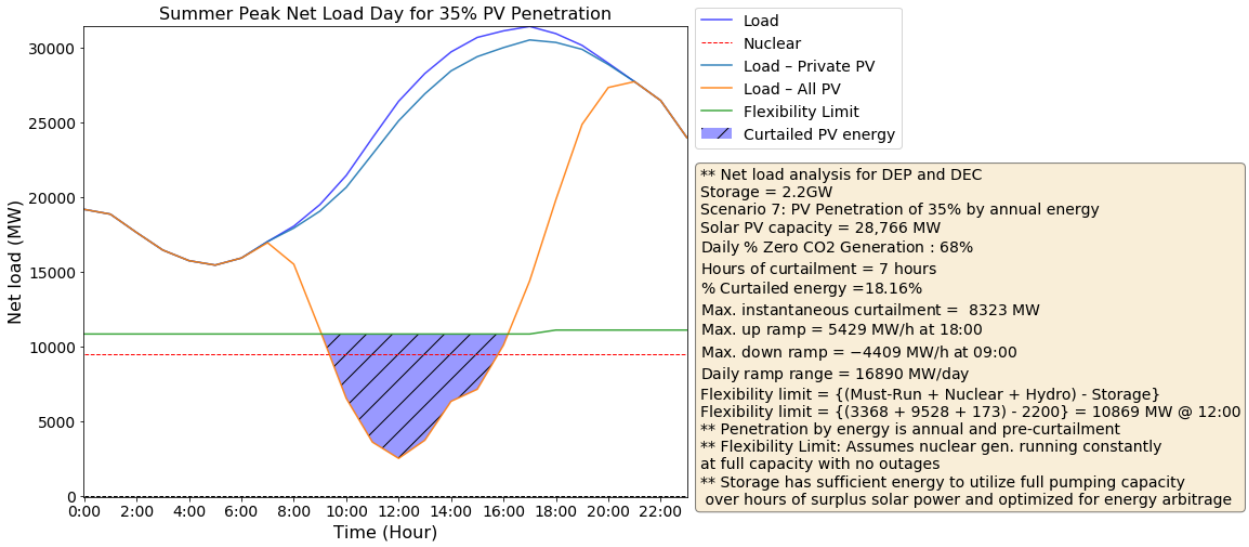


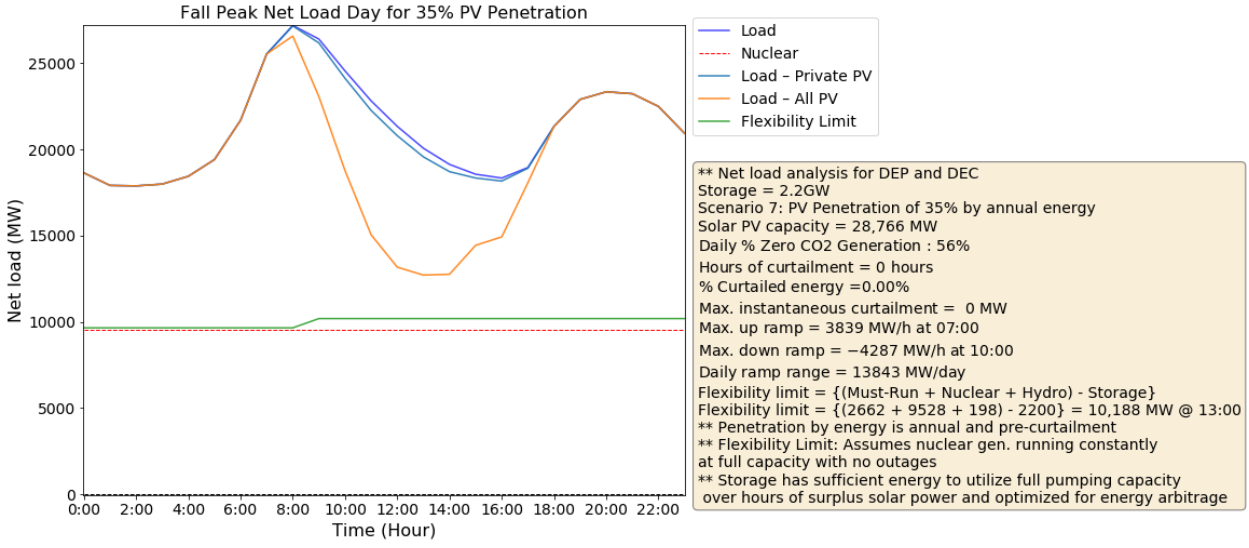


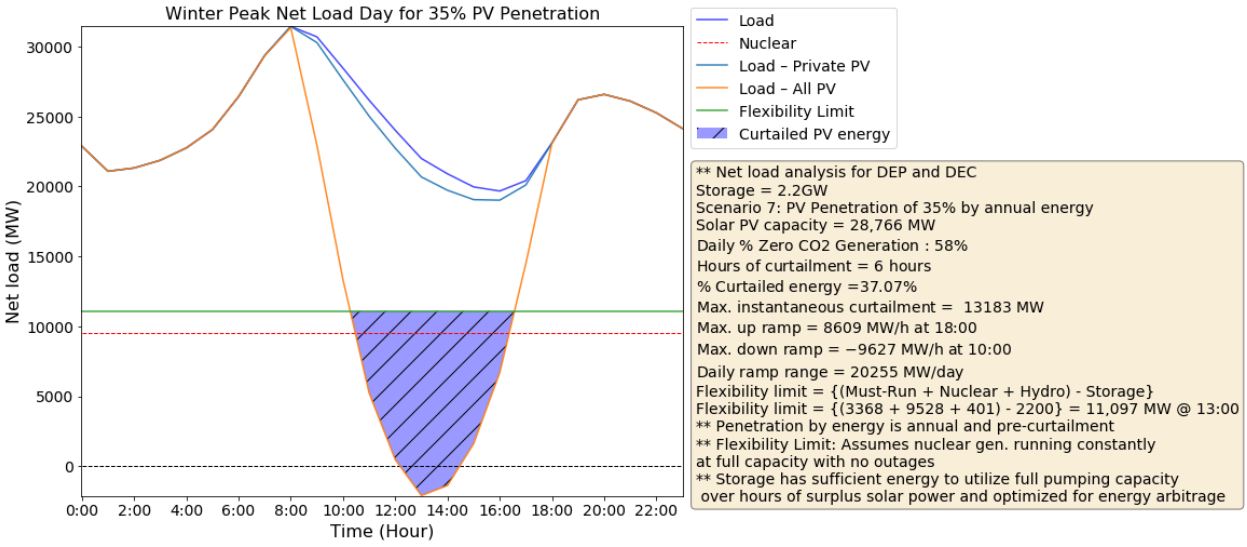


Seasonal Peak Net Load Days: 35% PV Penetration





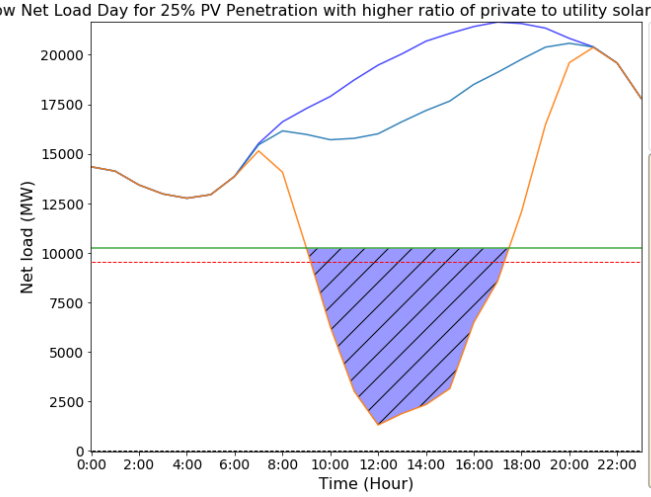




Scenario 8: 25% PV Penetration and Increased Proportion of Distributed Solar

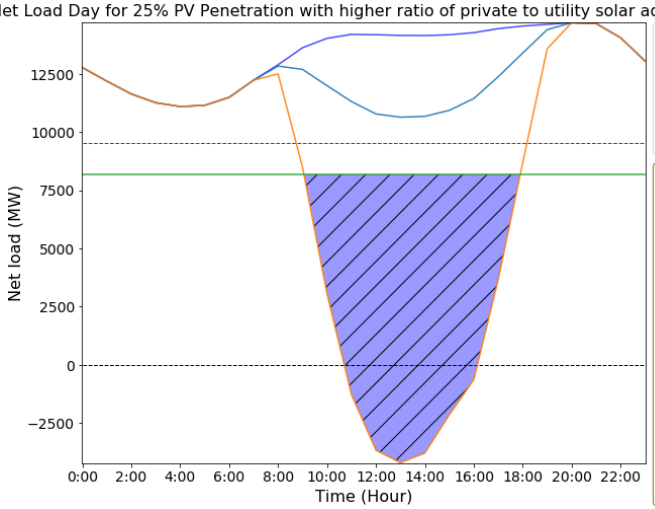
Seasonal Low Net Load Days

Summer Low Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



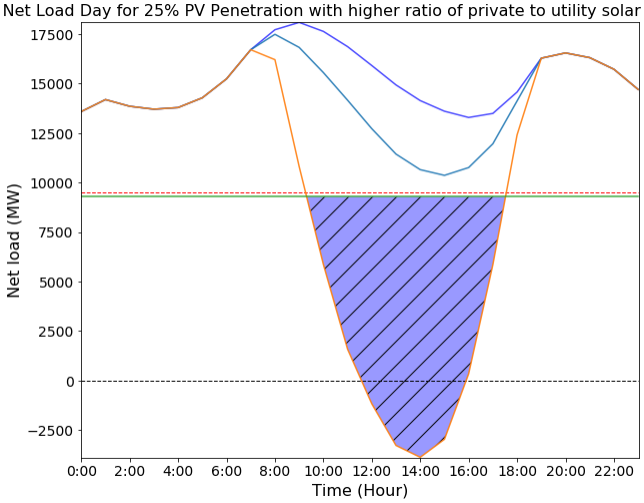
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario-,
with higher ratio of private to utility solar added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 78%
Hours of curtailment = 8 hours
% Curtailed energy =31.80%
Max. instantaneous curtailment = 8914 MW
Max. up ramp = 4398 MW/h at 19:00
Max. down ramp = −3829 MW/h at 09:00
Daily ramp range = −5826 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2662 + 9528 + 234) - 2200} = 10224 MW @ 12:00
** 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

Fall Low Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario-,
with higher ratio of private to utility solar added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 94%
Hours of curtailment = 8 hours
% Curtailed energy =55.23%
Max. instantaneous curtailment = 12393 MW
Max. up ramp = 4902 MW/h at 19:00
Max. down ramp = −4016 MW/h at 09:00
Daily ramp range = −3285 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(671 + 9528 + 188) - 2200} = 8187 MW @ 13:00
** 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

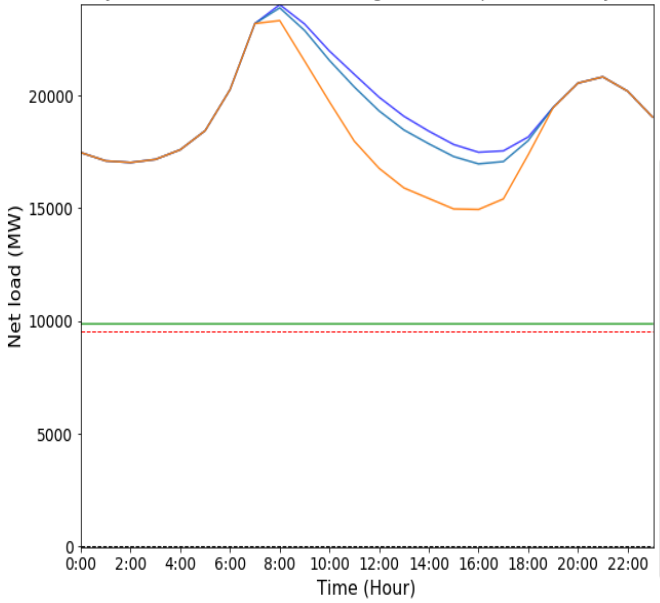
Winter Low Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario-,
with higher ratio of private to utility solar added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 81%
Hours of curtailment = 8 hours
% Curtailed energy =55.96%
Max. instantaneous curtailment = 13163 MW
Max. up ramp = 3874 MW/h at 19:00
Max. down ramp = −5399 MW/h at 09:00
Daily ramp range = −5415 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1627 + 9528 + 334) - 2200} = 9289 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

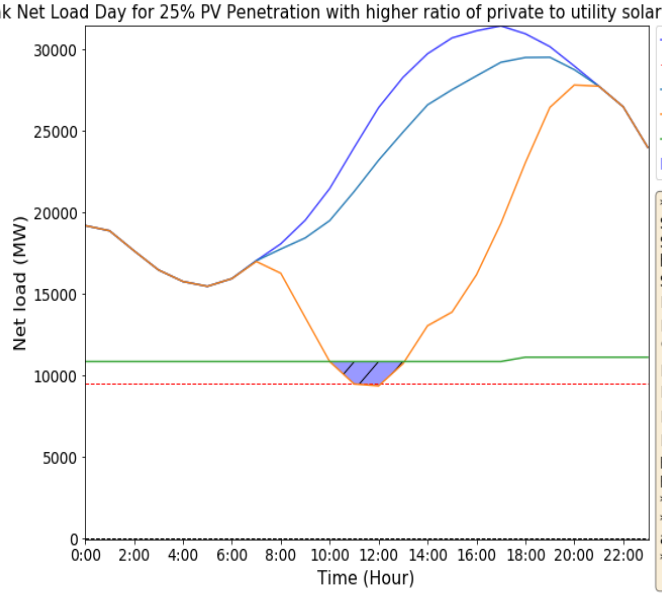
Seasonal Peak Net Load Days

Spring Peak Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



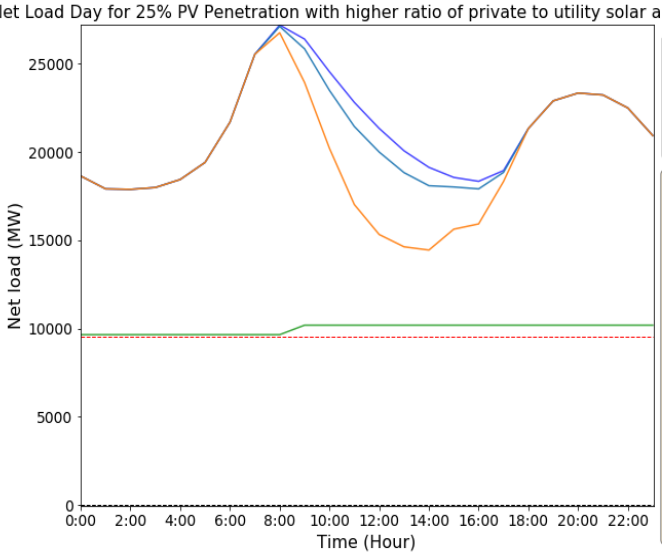
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario, higher ratio of private to utility solar are added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 57%
Hours of curtailment = 0 hours
% Curtailed energy =0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 2927 MW/h at 07:00
Max. down ramp = −1806 MW/h at 10:00
Daily ramp range = 4733 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2125 + 9528 + 393) - 2200} = 9846 MW @ 13:00
** 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

Summer Peak Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



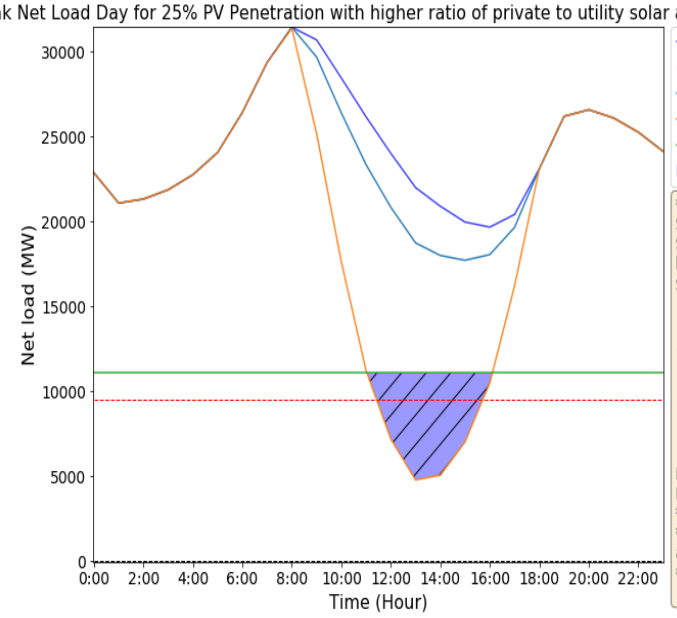
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario, higher ratio of private to utility solar are added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 64%
Hours of curtailment = 4 hours
% Curtailed energy =2.13%
Max. instantaneous curtailment = 1496 MW
Max. up ramp = 3722 MW/h at 18:00
Max. down ramp = −2716 MW/h at 09:00
Daily ramp range = −7147 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(3368 + 9528 + 173) - 2200} = 10869 MW @ 12:00
** 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

Fall Peak Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system



** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario,
higher ratio of private to utility solar are added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 53%
Hours of curtailment = 0 hours
% Curtailed energy =0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 3839 MW/h at 07:00
Max. down ramp = −3719 MW/h at 10:00
Daily ramp range = 7558 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2662 + 9528 + 198) - 2200} = 10,188 MW @ 13:00
** 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

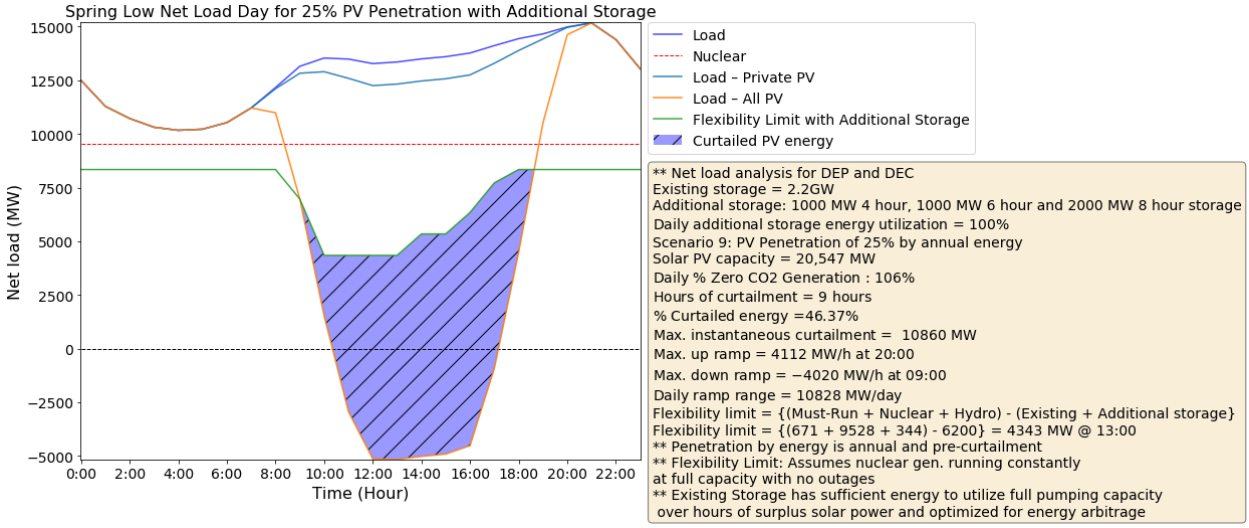
Winter Peak Net Load Day for 25% PV Penetration with higher ratio of private to utility solar added to the system

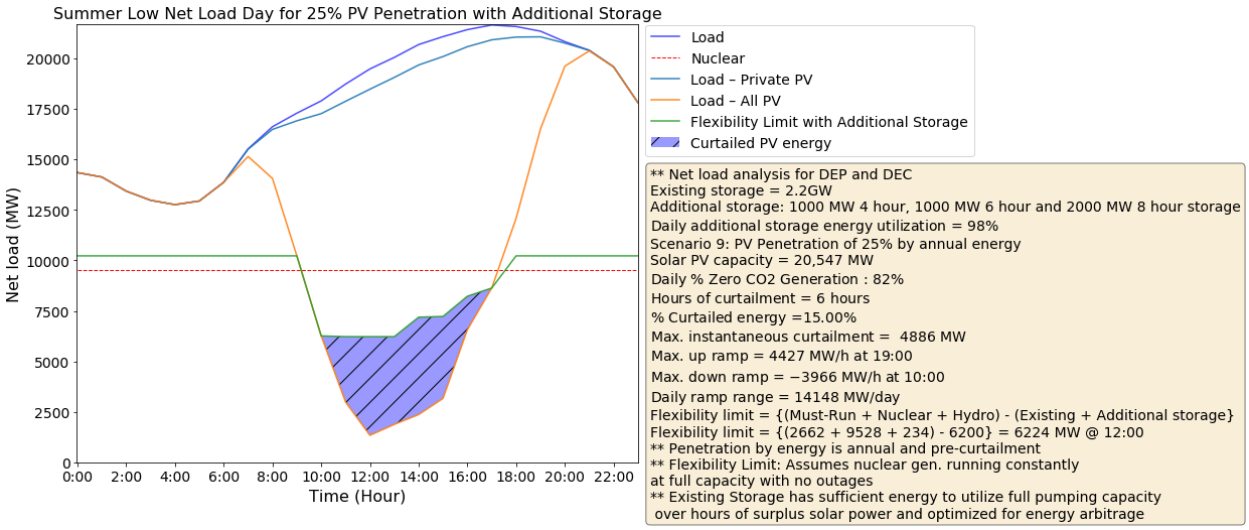


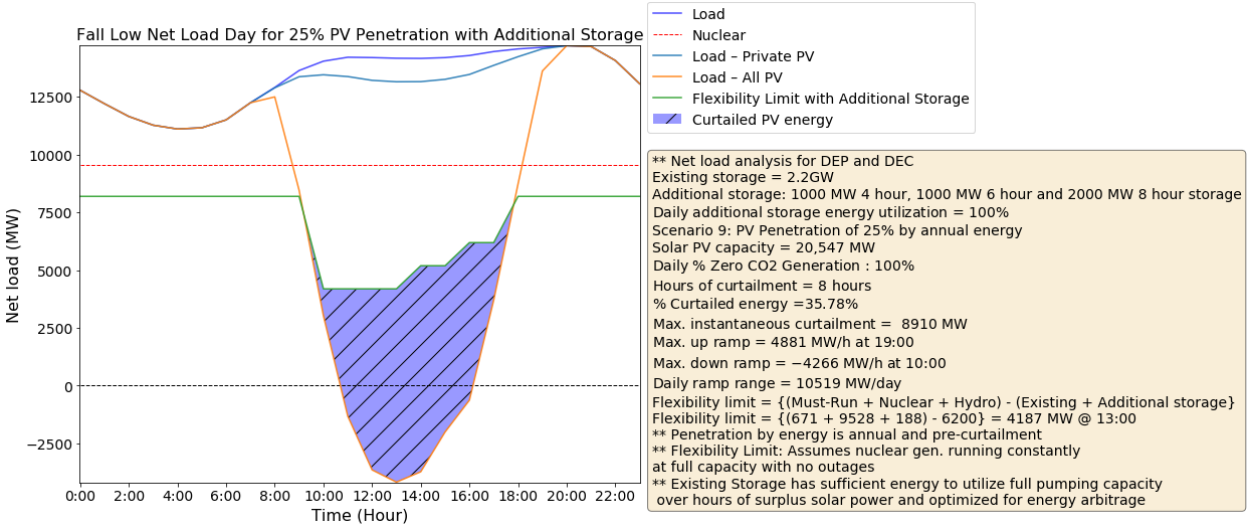
** Net load analysis for DEP and DEC
Storage = 2.2GW
Scenario 8: Based on 25% solar energy penetration scenario,
higher ratio of private to utility solar are added to the system
Solar PV capacity = 20,547 MW
Daily % Zero CO2 Generation : 56%
Hours of curtailment = 5 hours
% Curtailed energy =19.34%
Max. instantaneous curtailment = 6302 MW
Max. up ramp = 6887 MW/h at 18:00
Max. down ramp = −7553 MW/h at 10:00
Daily ramp range = −4210 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(3368 + 9528 + 401) - 2200} = 11,097 MW @ 13:00
** 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

Scenario 9: 25% PV Penetration and Additional Storage

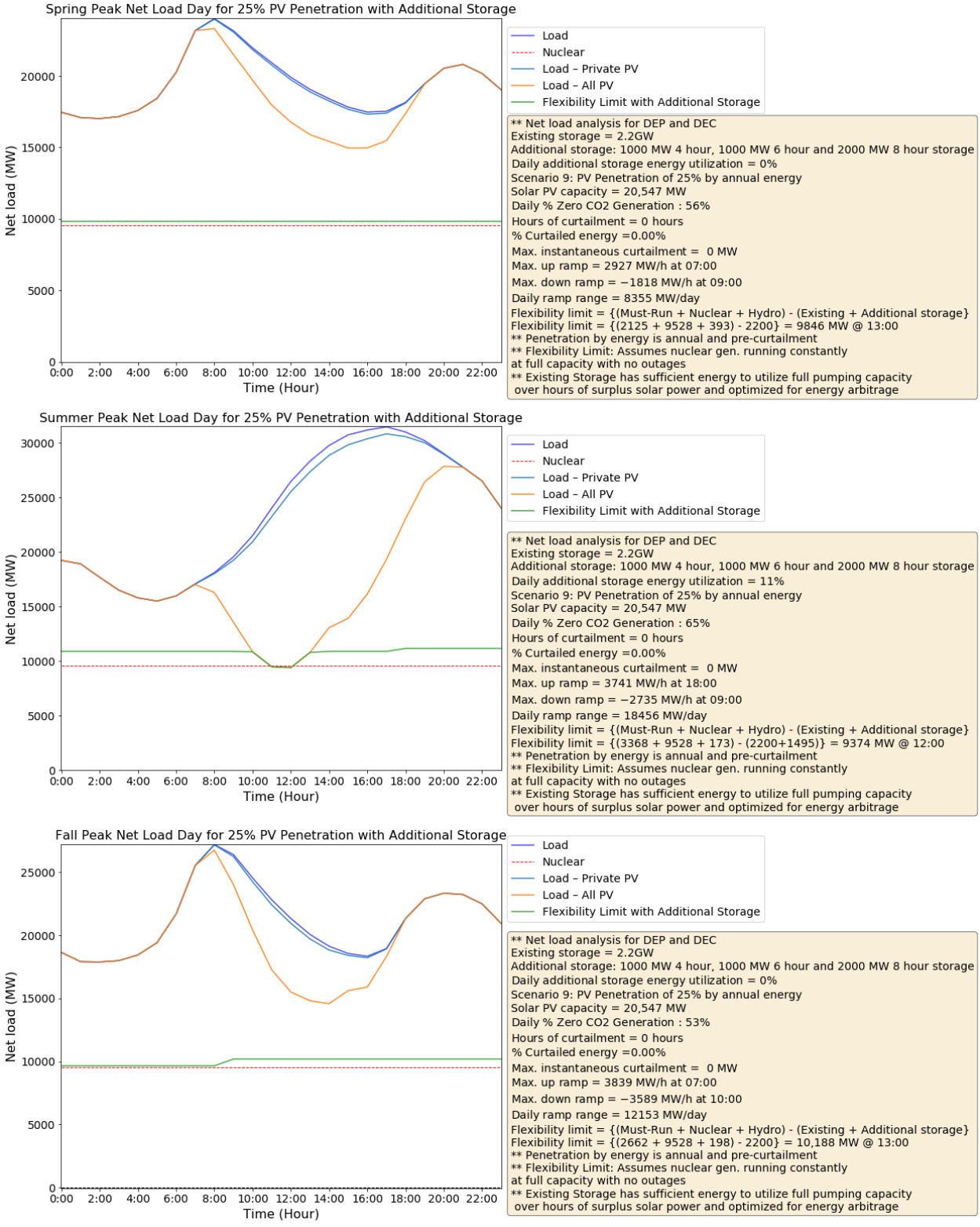
Seasonal Low Net Load Days

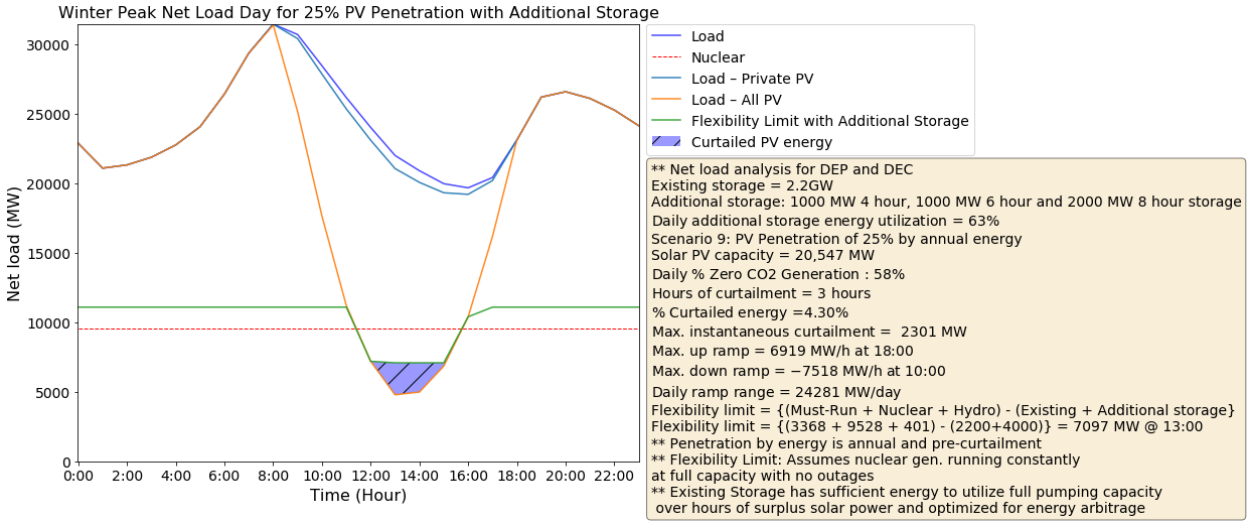






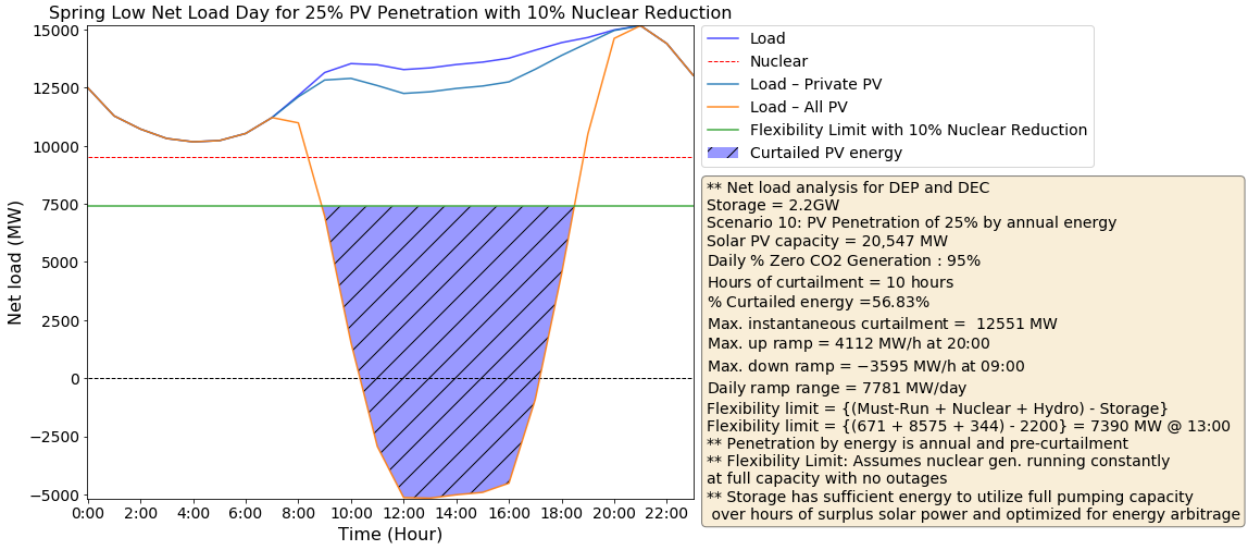
Seasonal Peak Net Load Days

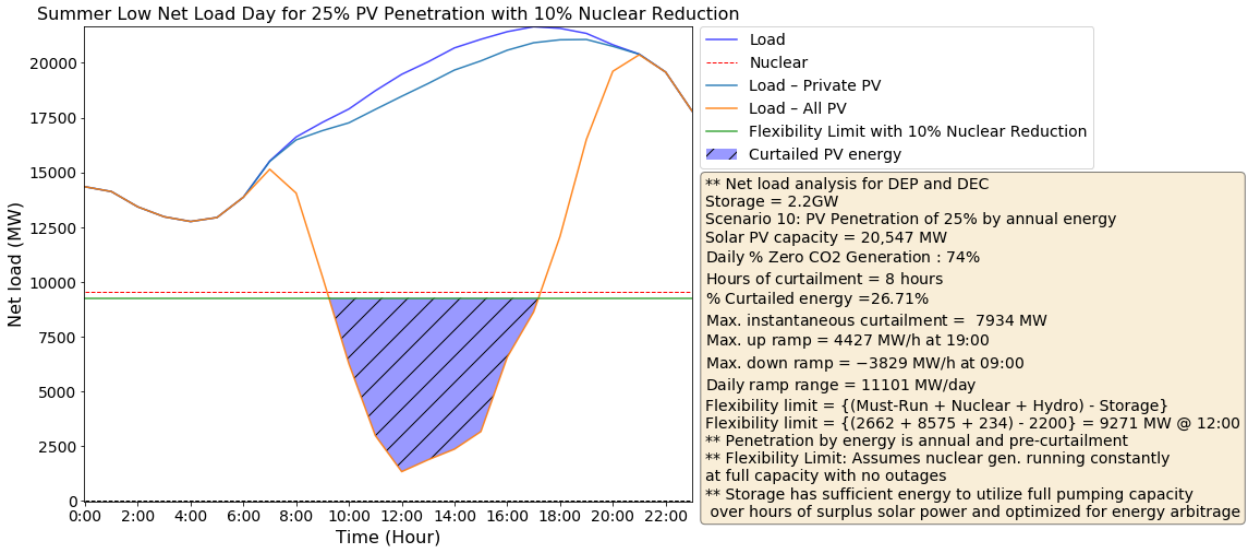


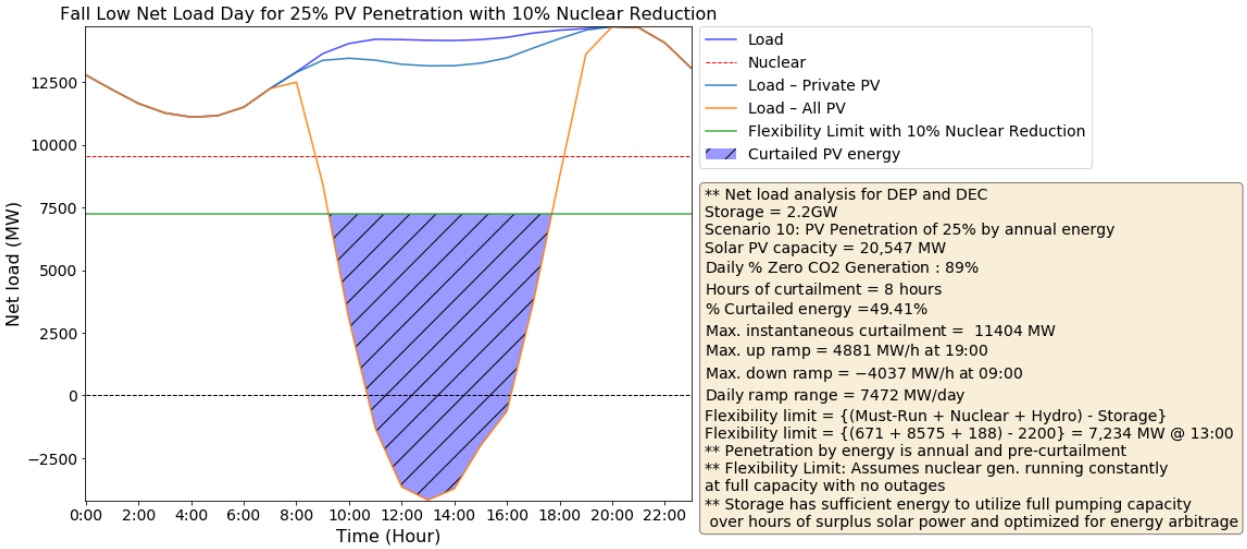


Scenario 10: 25% PV Penetration and Generation Retirement

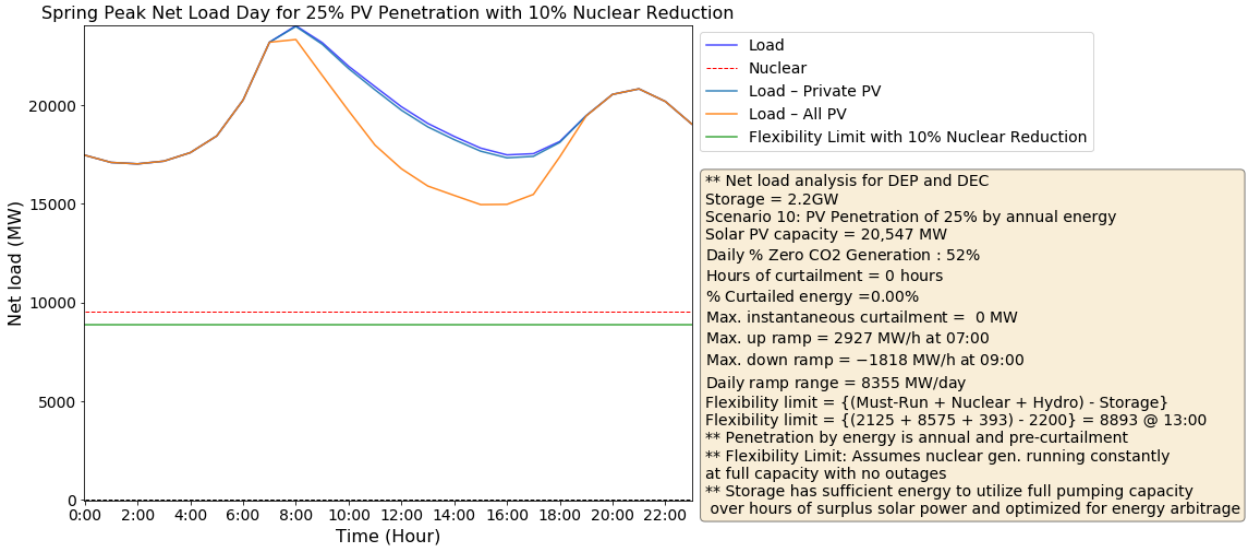
Seasonal Low Net Load Days

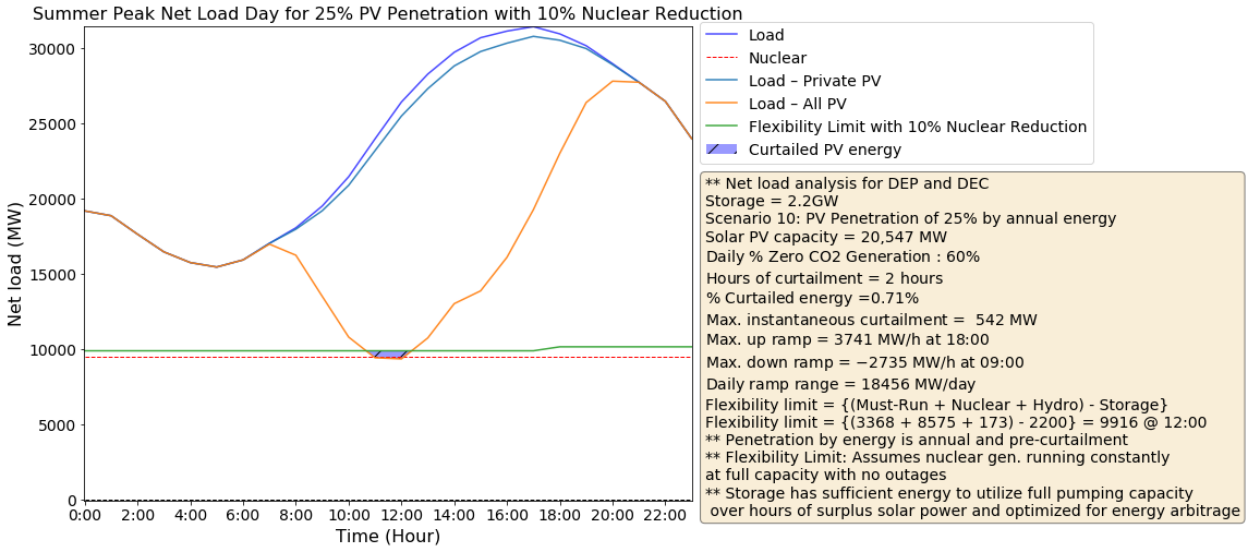


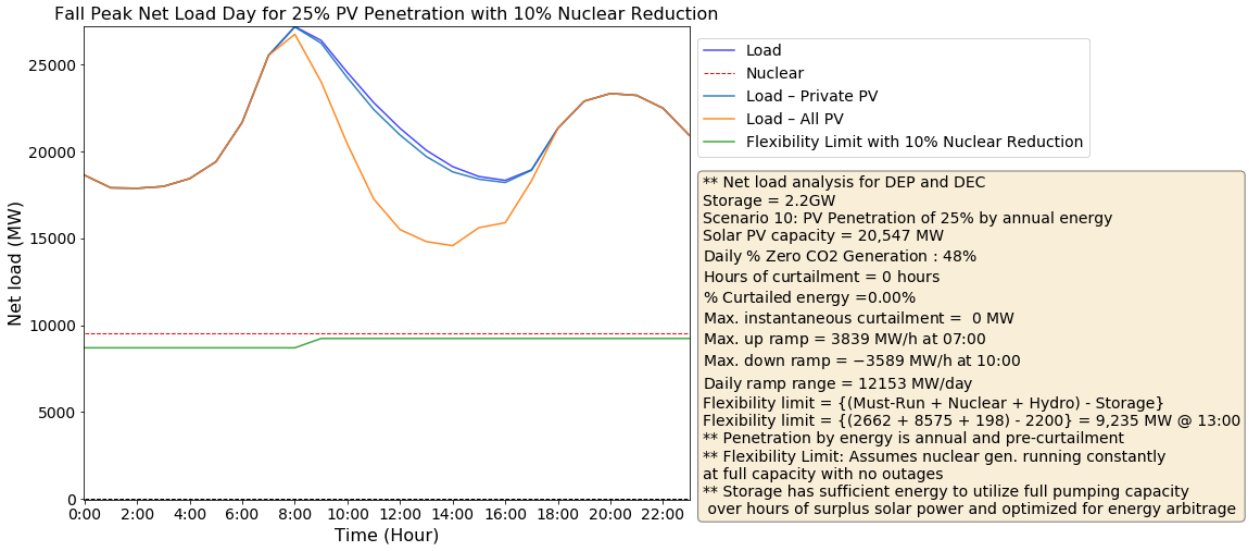


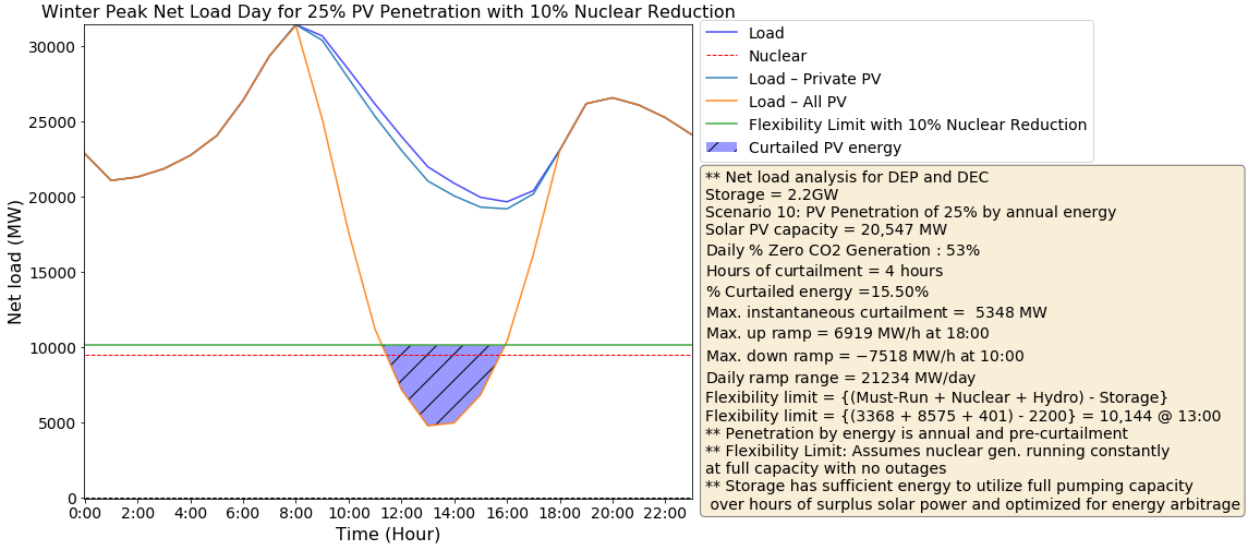


Seasonal Peak Net Load Days



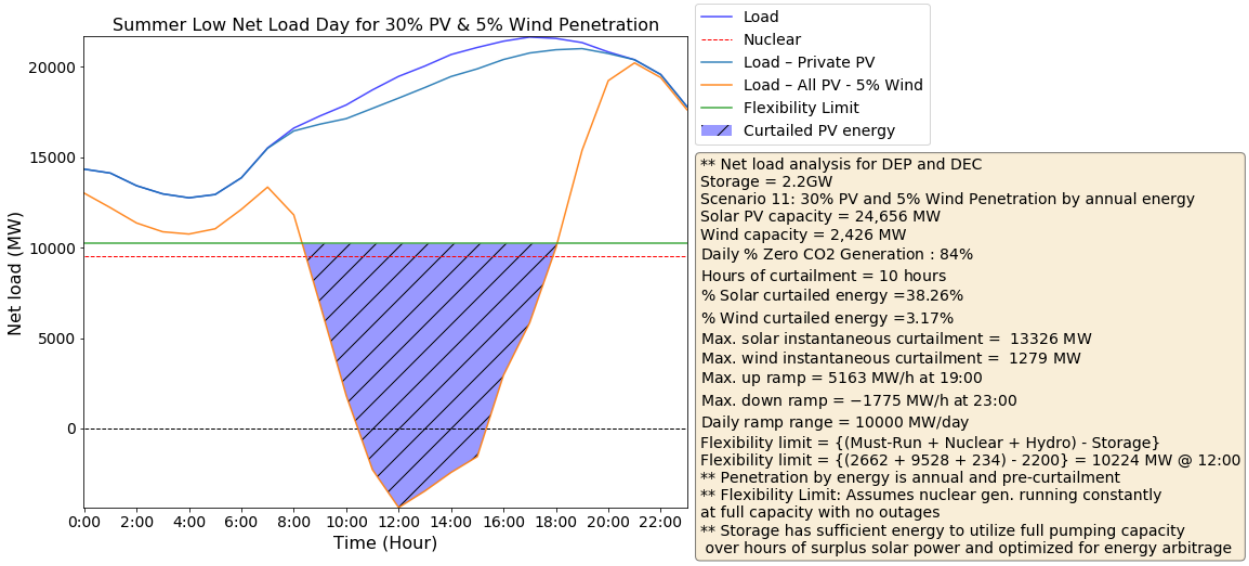


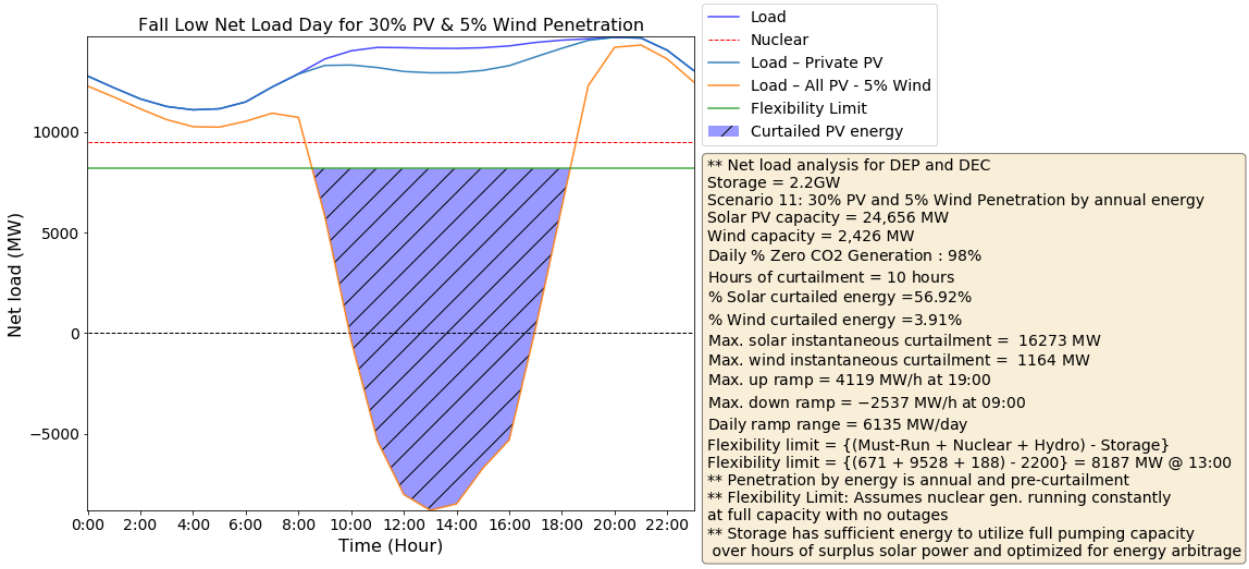


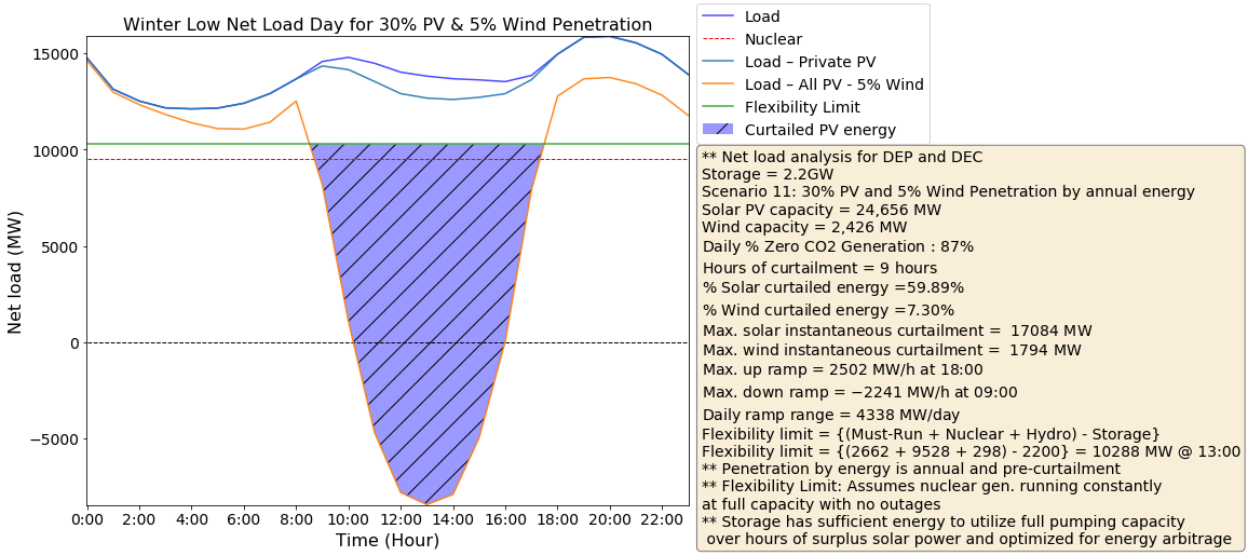


Scenario 11: 30% PV and 5% Wind Penetration

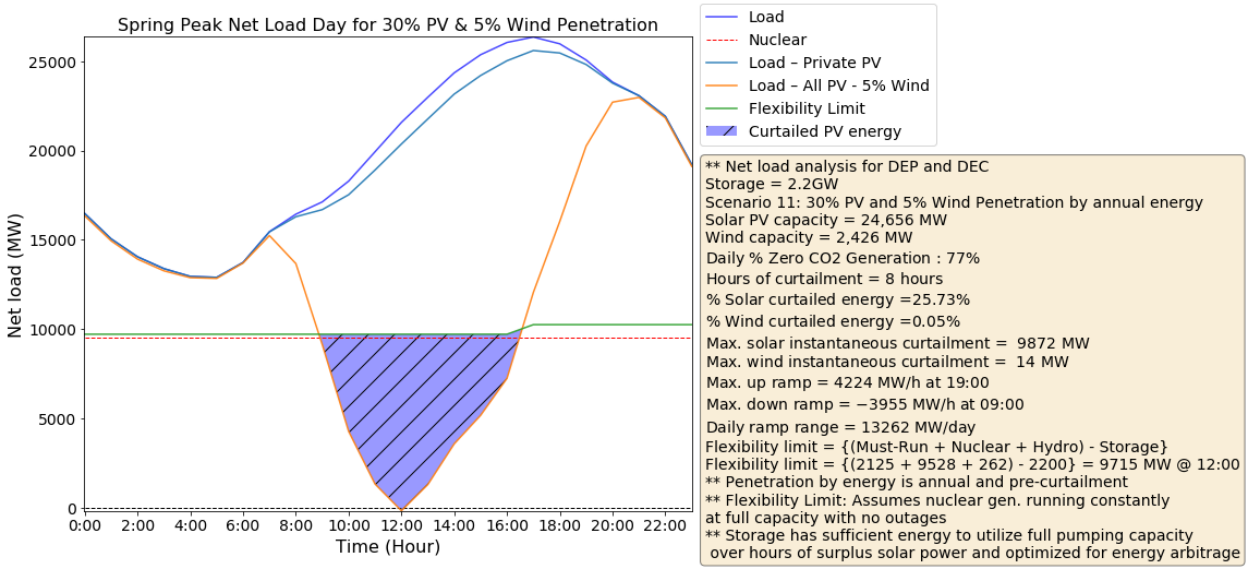
Seasonal Low Net Load Days

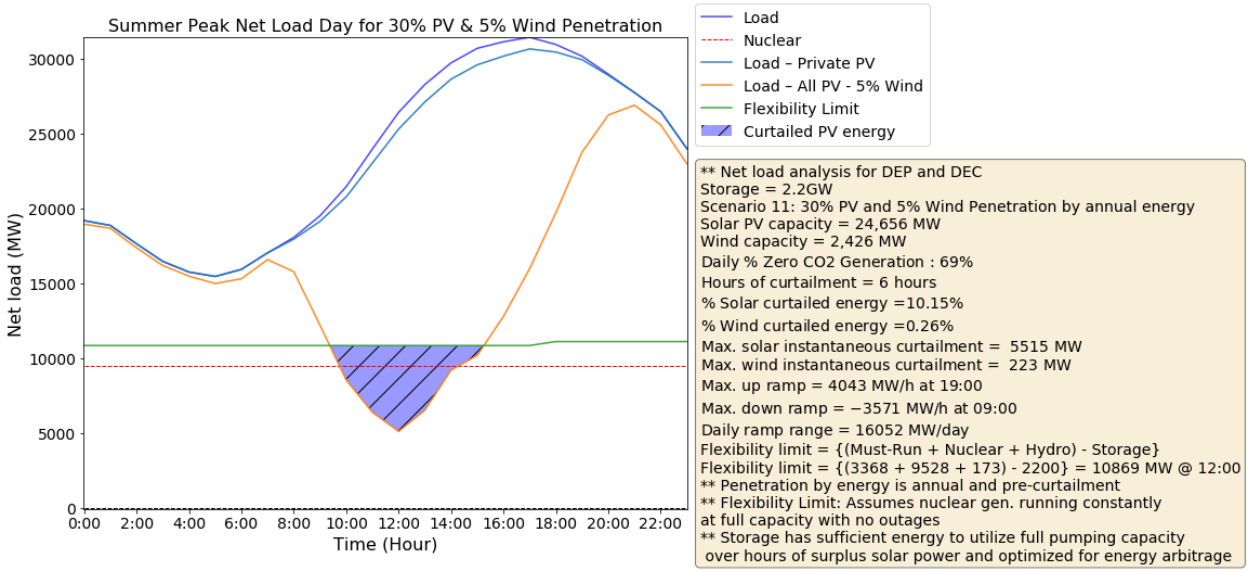


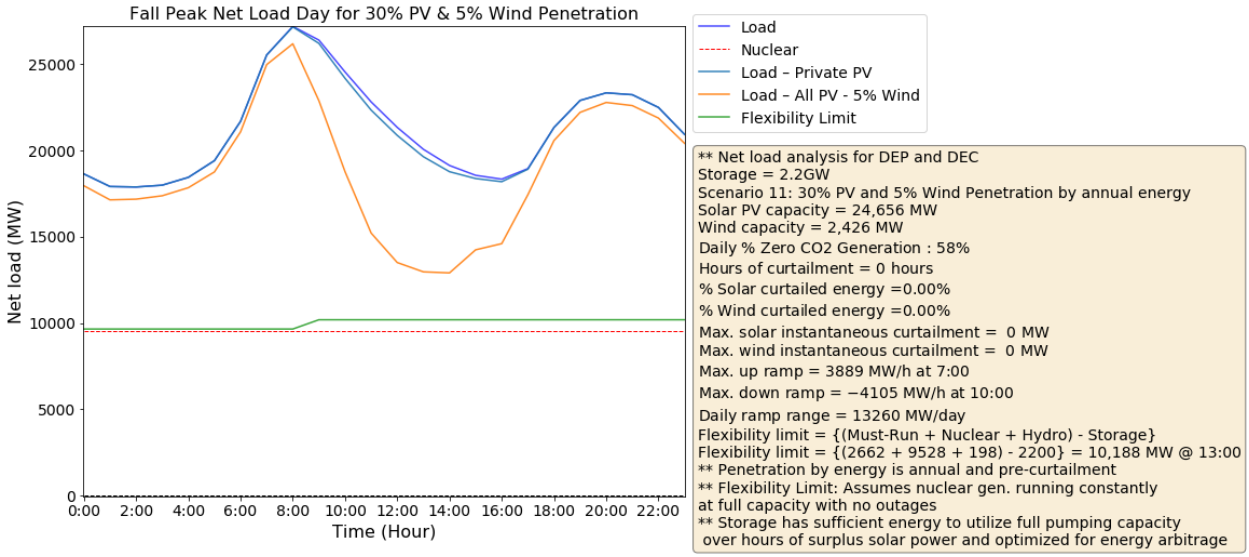


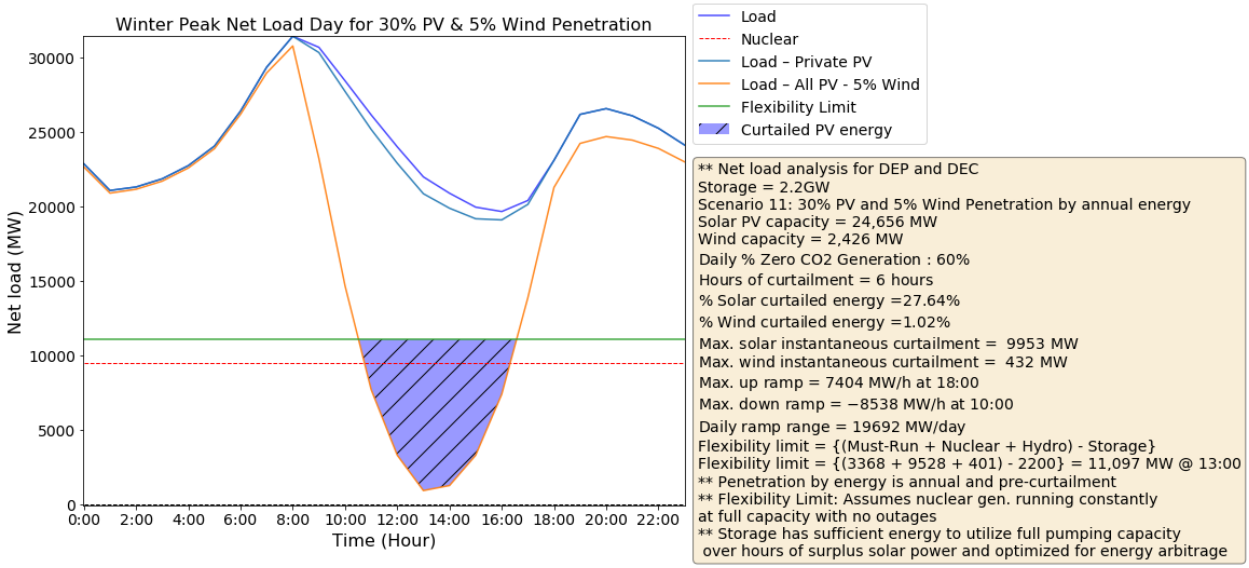


Seasonal Peak Net Load Days



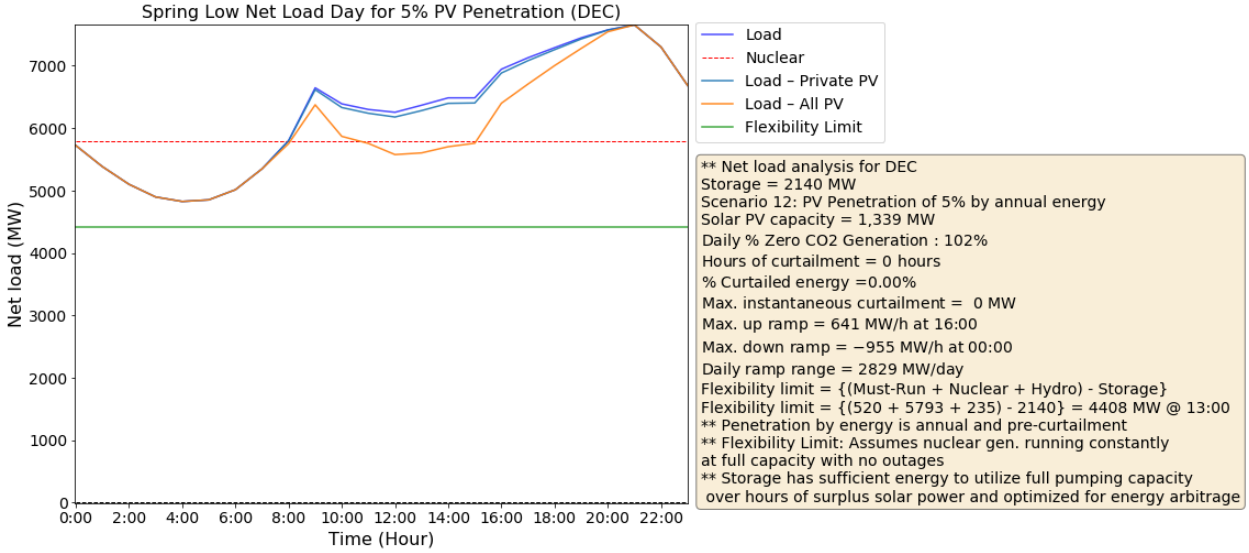


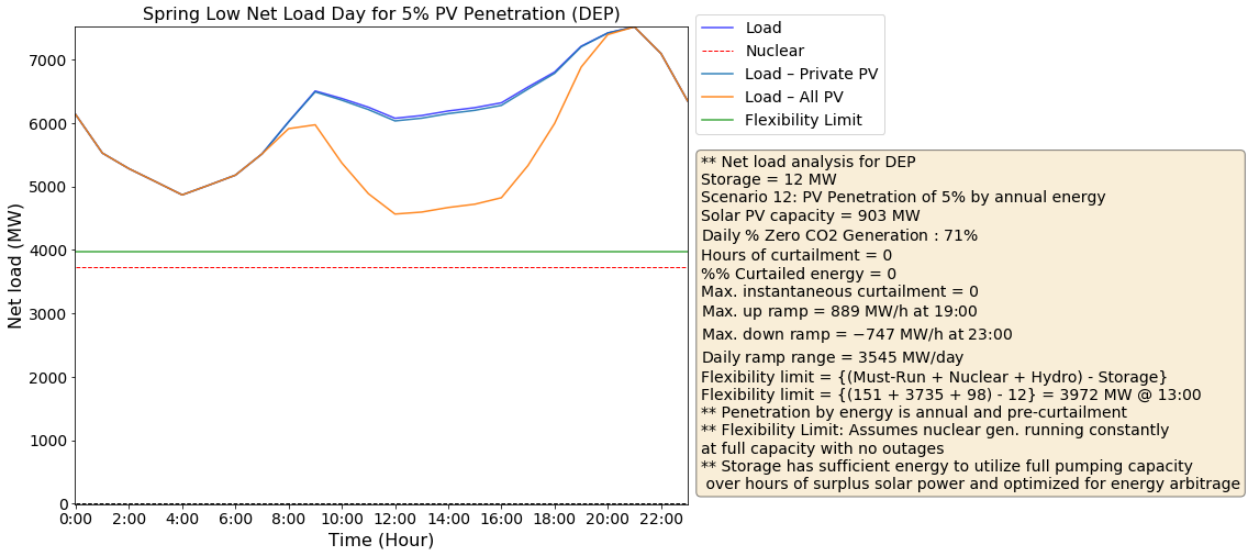


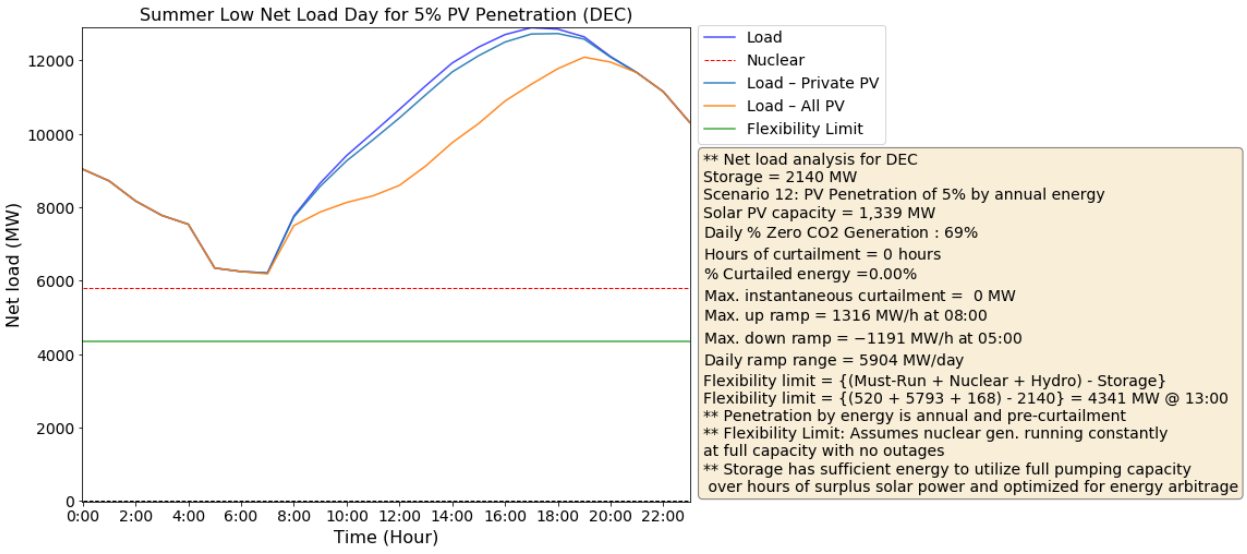


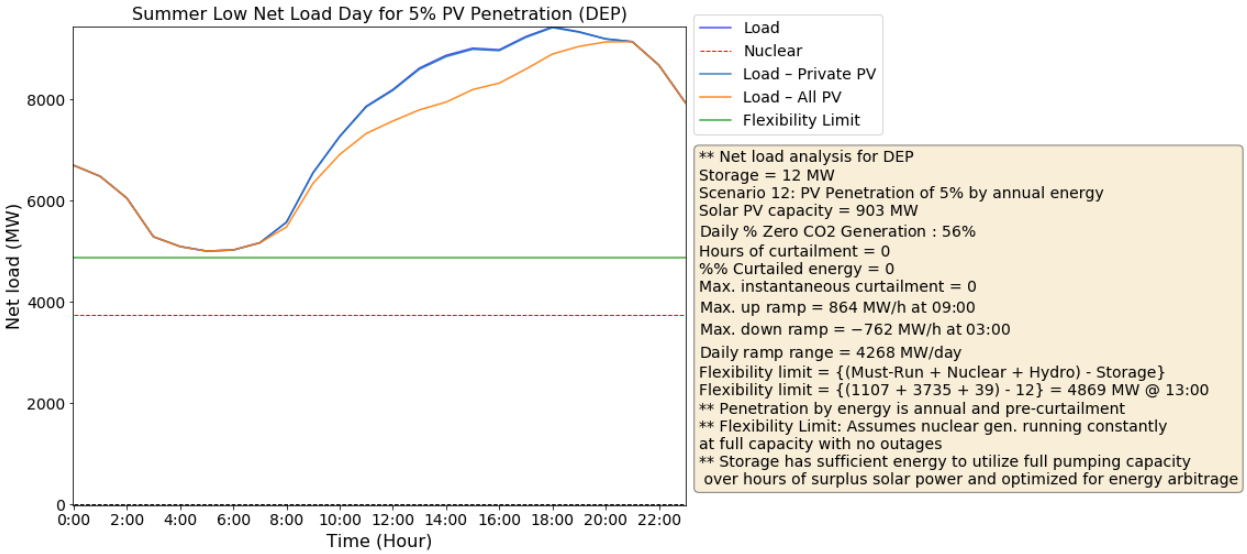
Scenario 12: DEC and DEP Modeled as Separate Balancing Authorities with 5%, 10%, and 15% PV Penetration

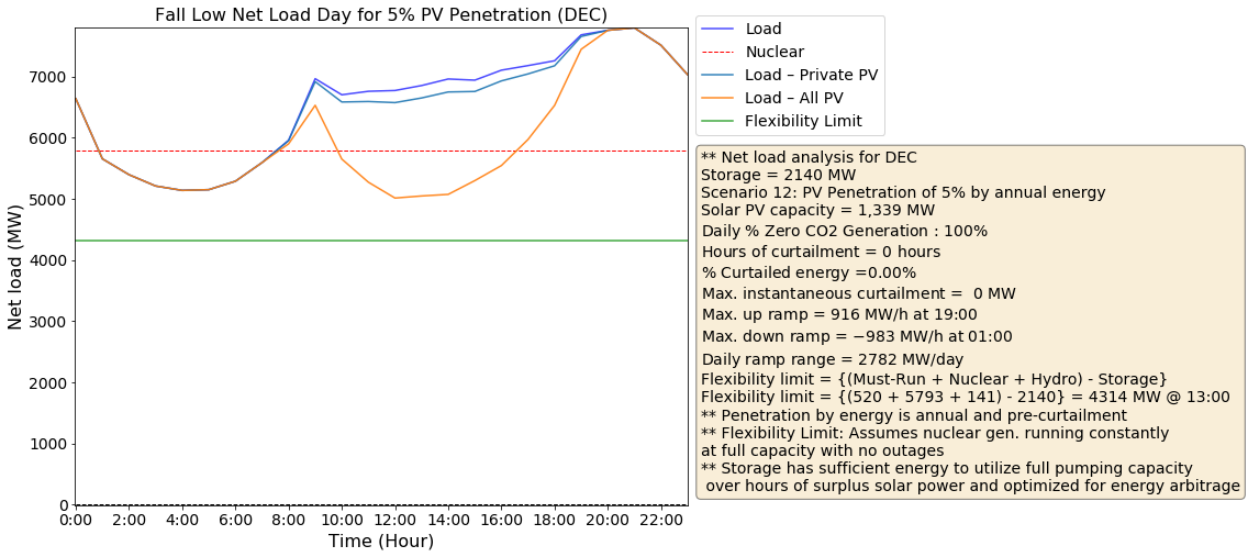
Seasonal Low Net Load Days: 5% PV Penetration

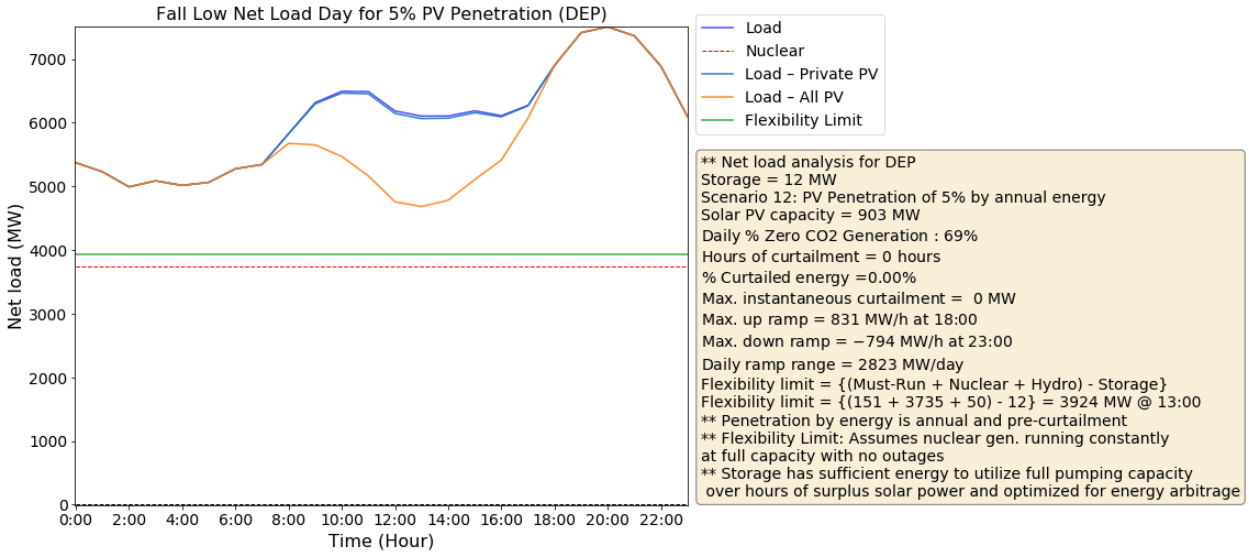


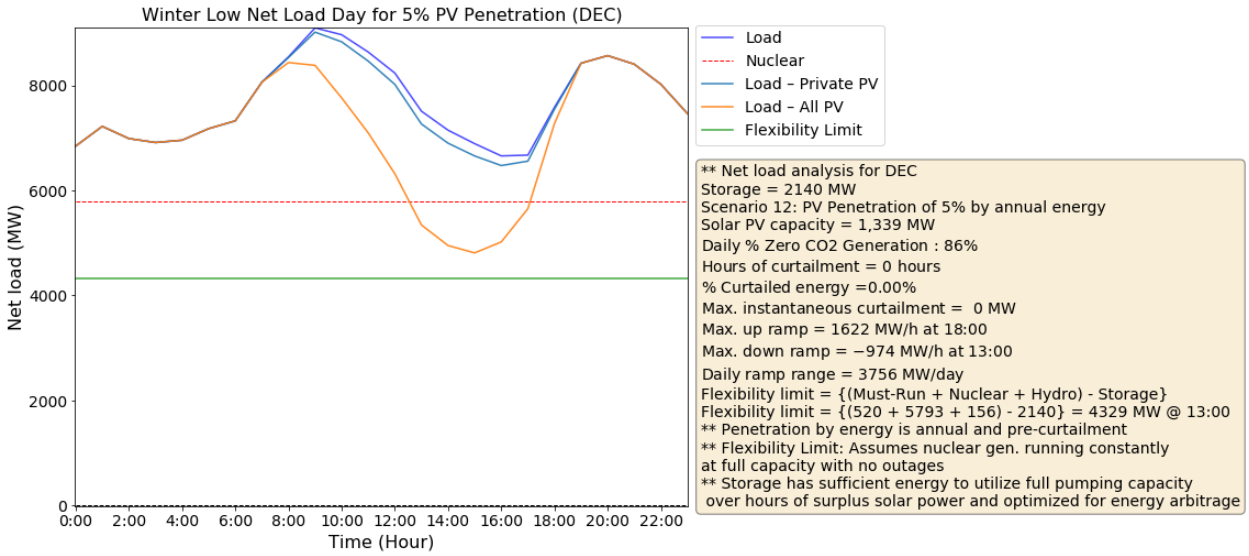


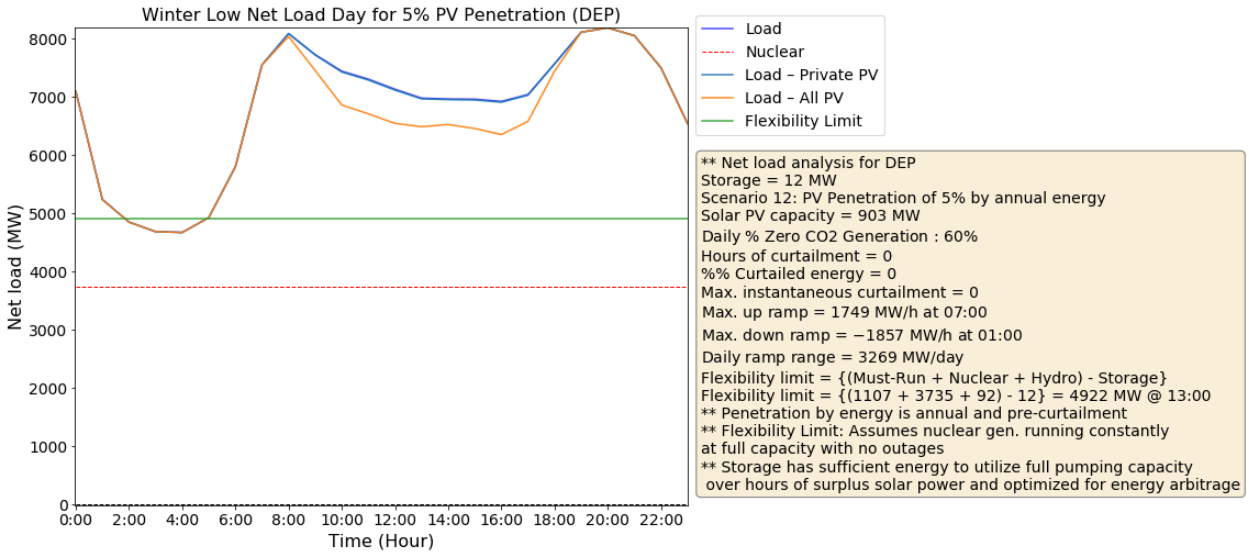




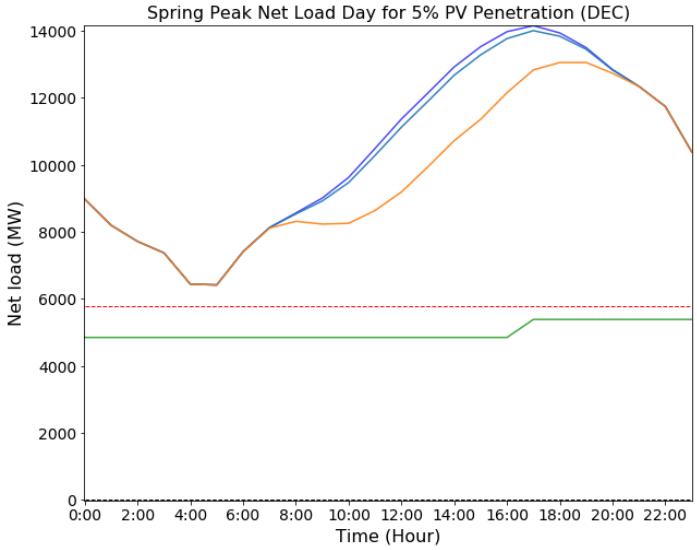




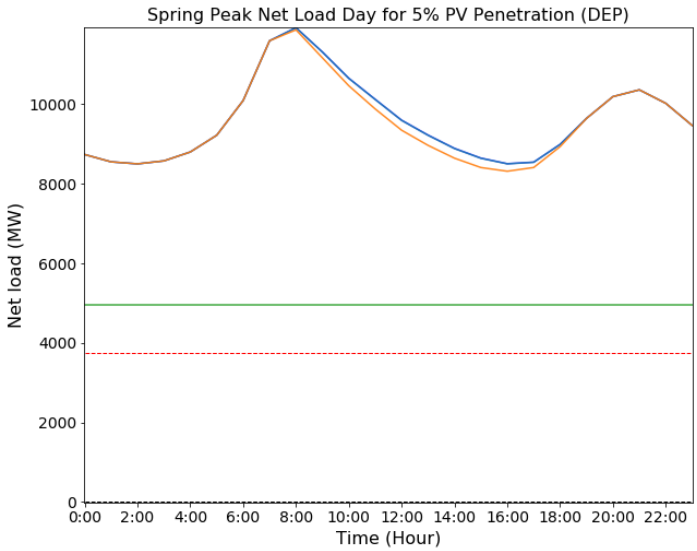




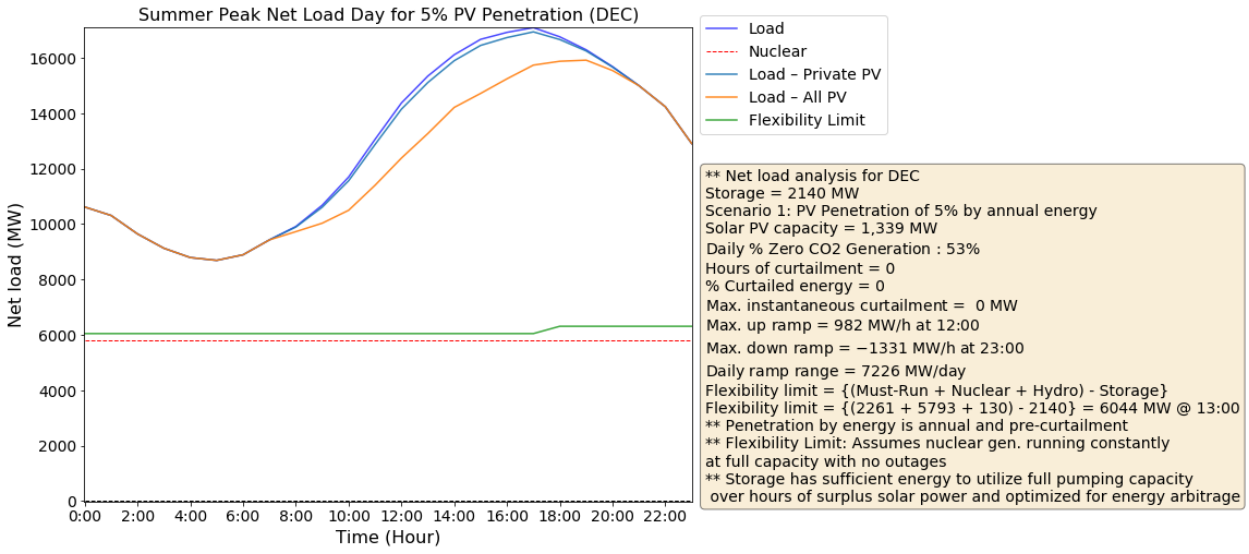
Seasonal Peak Net Load Days: 5% PV Penetration

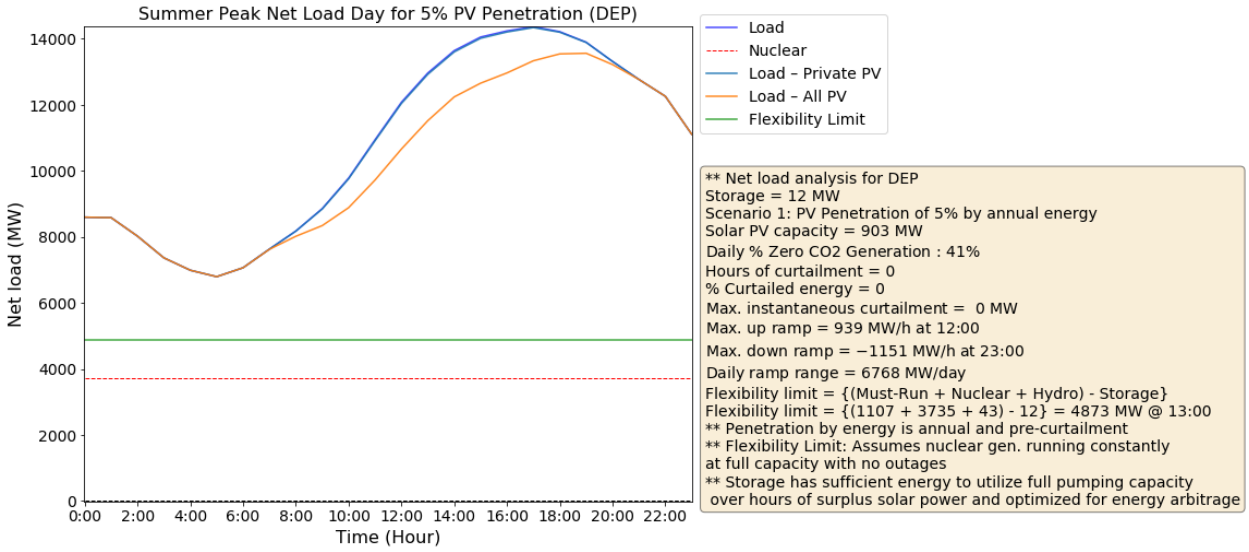


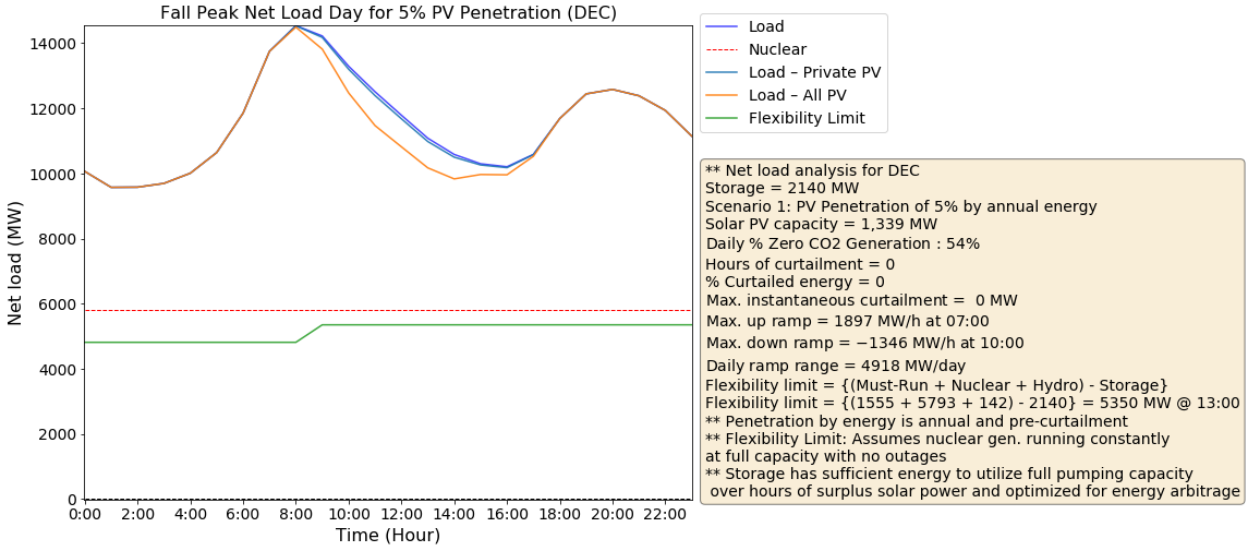
** Net load analysis for DEC
Storage = 2140 MW
Scenario 1: PV Penetration of 5% by annual energy
Solar PV capacity = 1,339 MW
Daily % Zero CO2 Generation : 67%
Hours of curtailment = 0
% Curtailed energy = 0
Max. instantaneous curtailment = 0 MW
Max. up ramp = 994 MW/h at 06:00
Max. down ramp = −1355 MW/h at 23:00
Daily ramp range = 6642 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1018 + 5793 + 180) - 2140} = 4851 MW @ 13:00
** 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

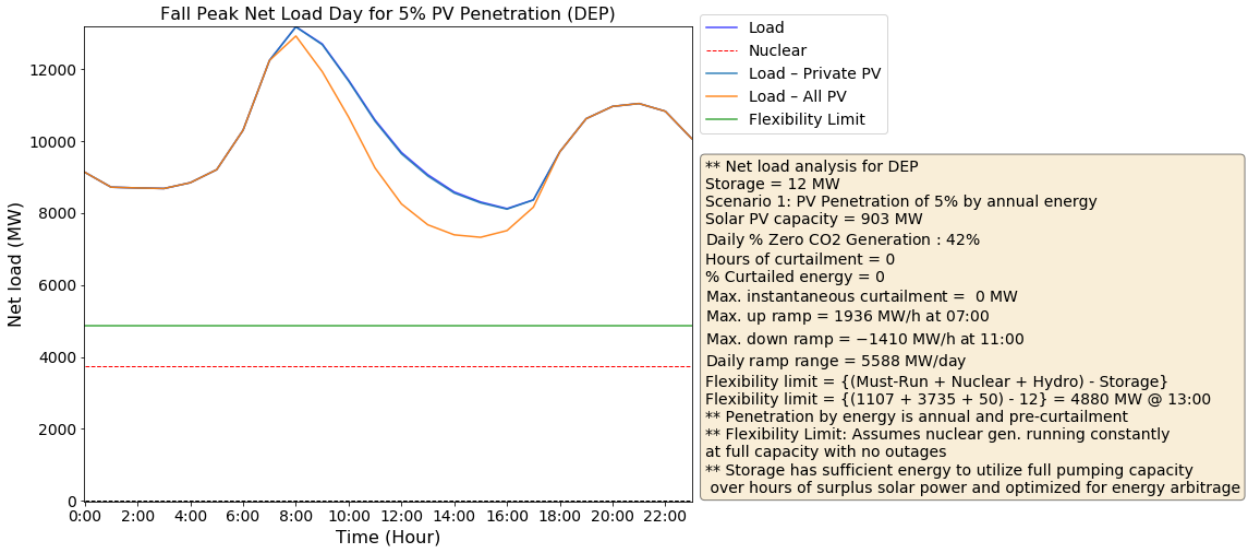


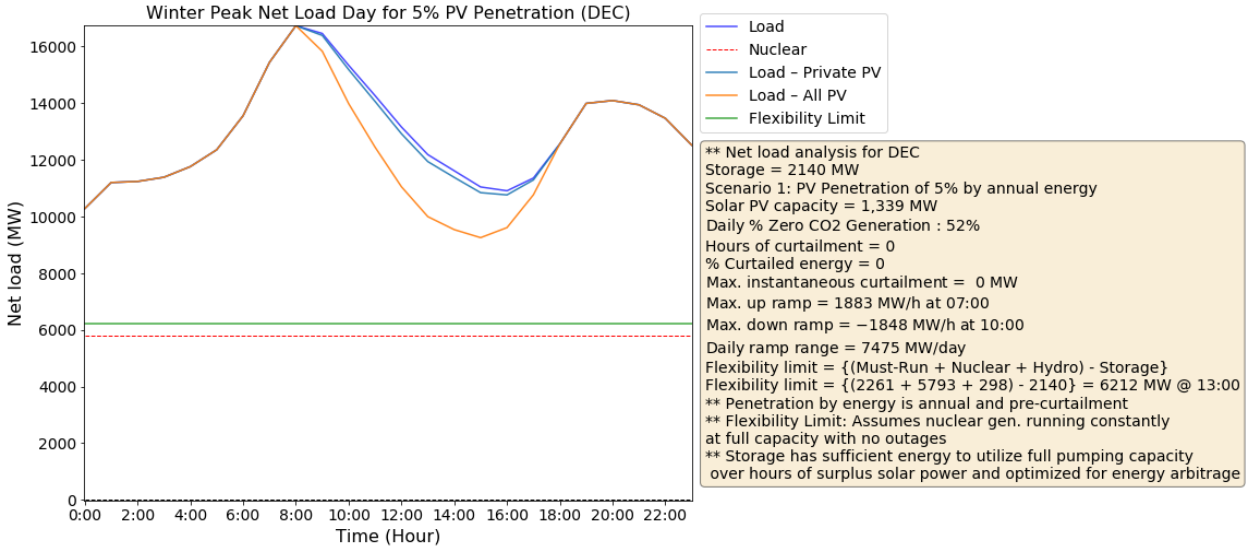
** Net load analysis for DEP
Storage = 12 MW
Scenario 1: PV Penetration of 5% by annual energy
Solar PV capacity = 903 MW
Daily % Zero CO2 Generation : 41%
Hours of curtailment = 0
% Curtailed energy = 0
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1502 MW/h at 07:00
Max. down ramp = −703 MW/h at 09:00
Daily ramp range = 3552 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1107 + 3735 + 120) - 12} = 4950 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

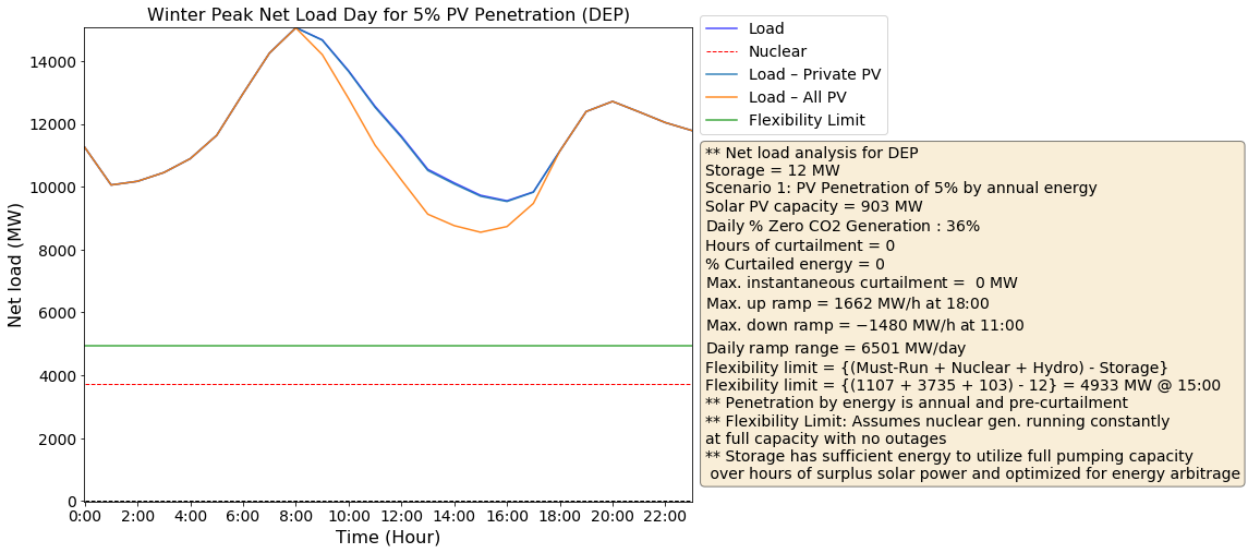




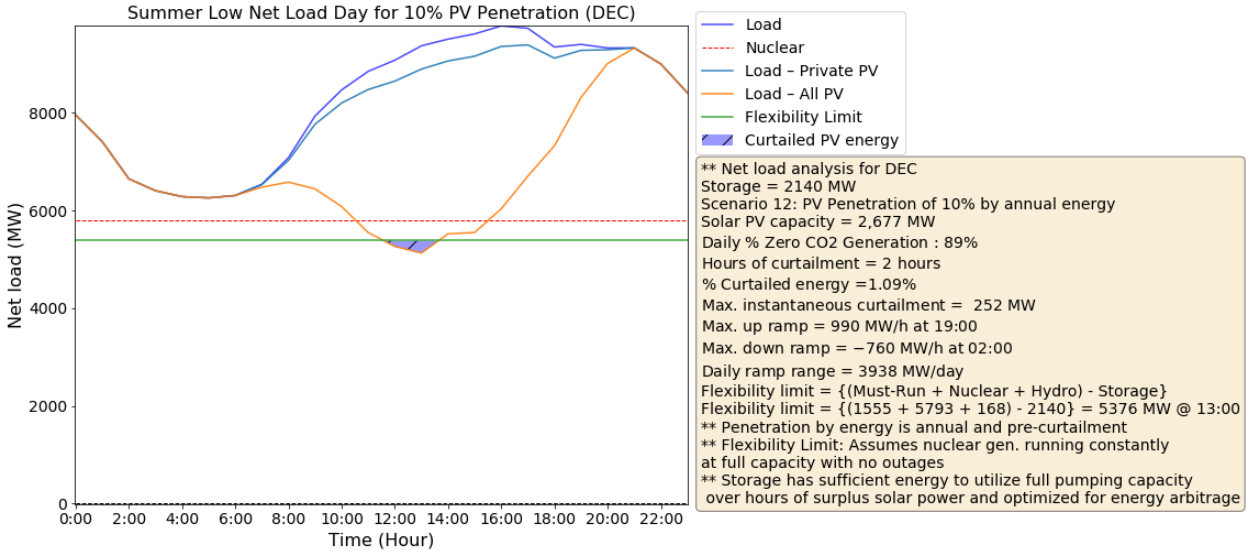


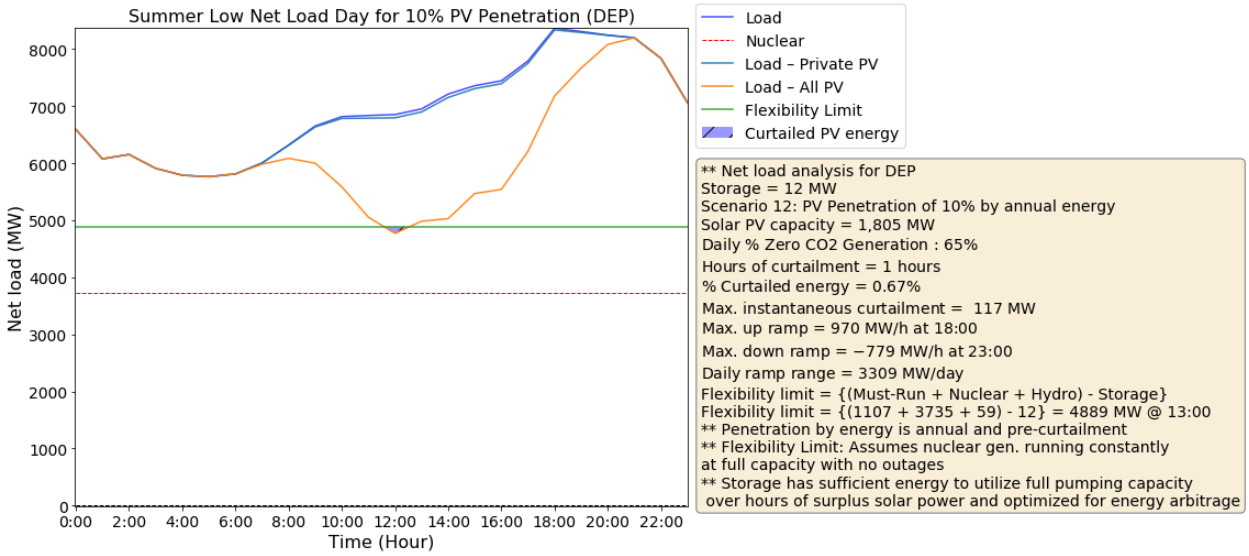


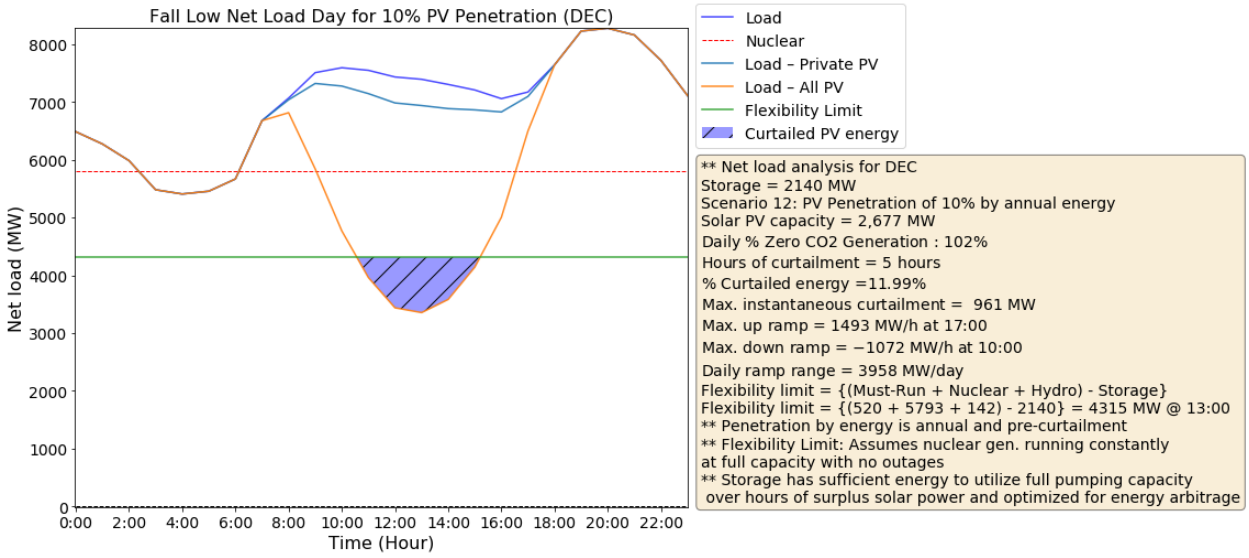


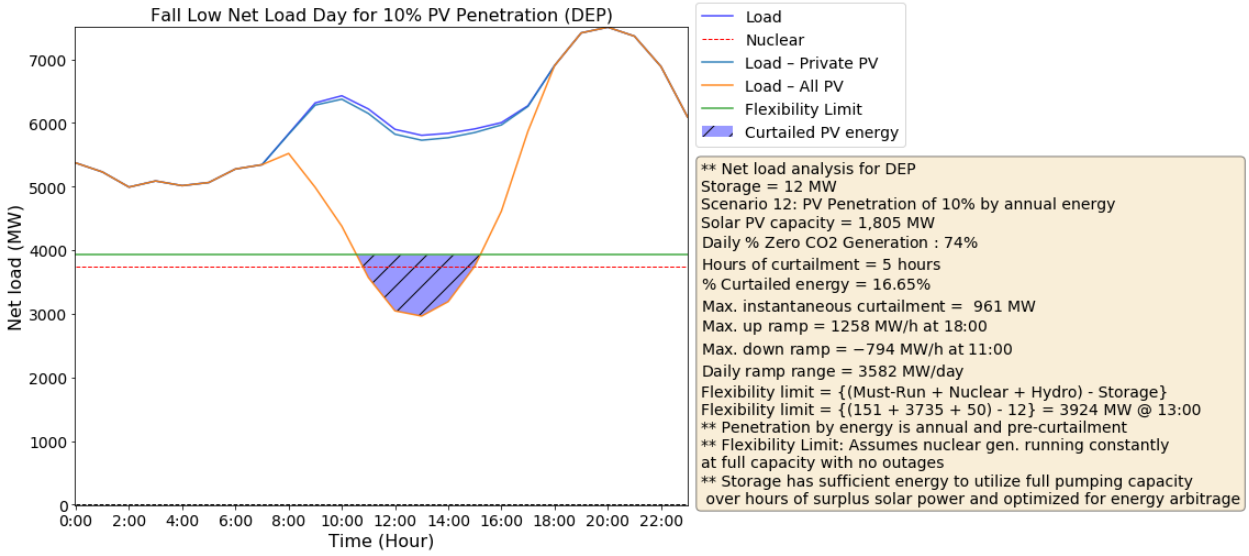


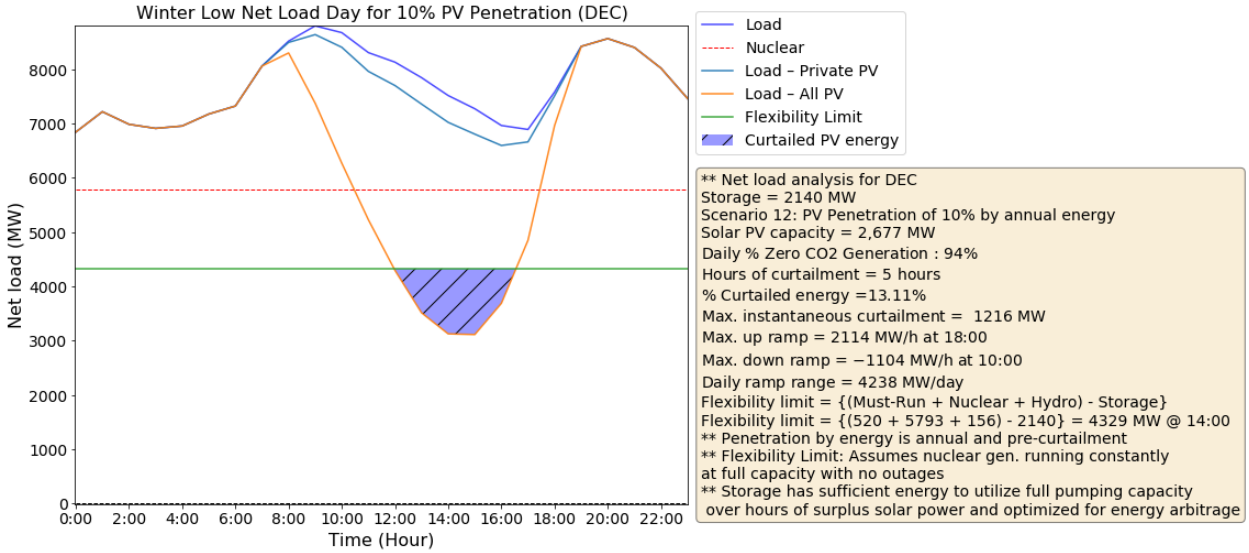
Seasonal Low Net Load Days: 10% PV Penetration

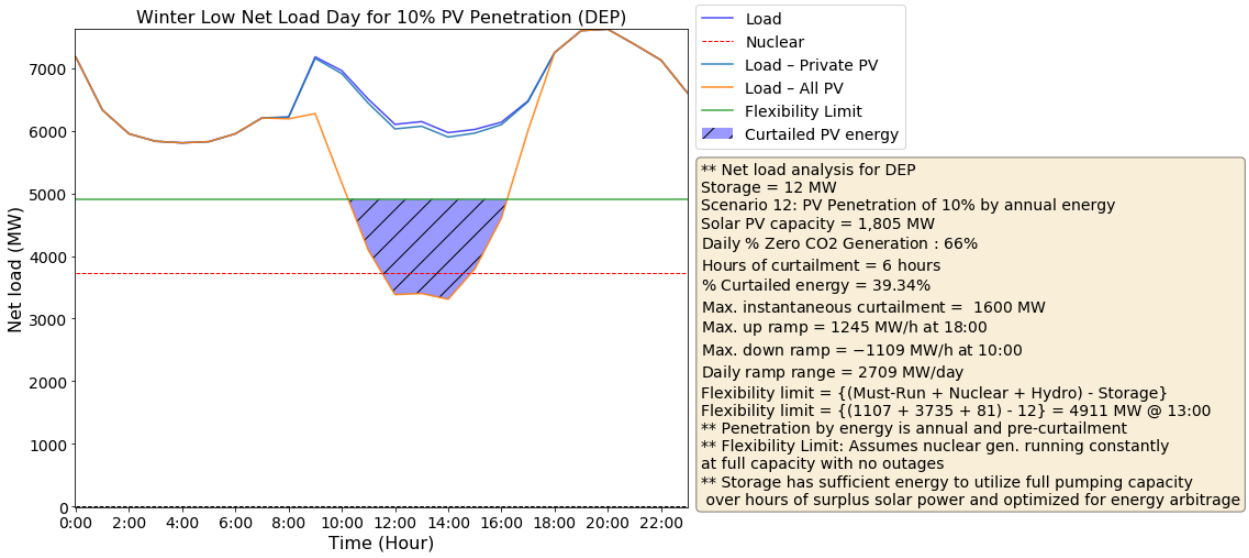




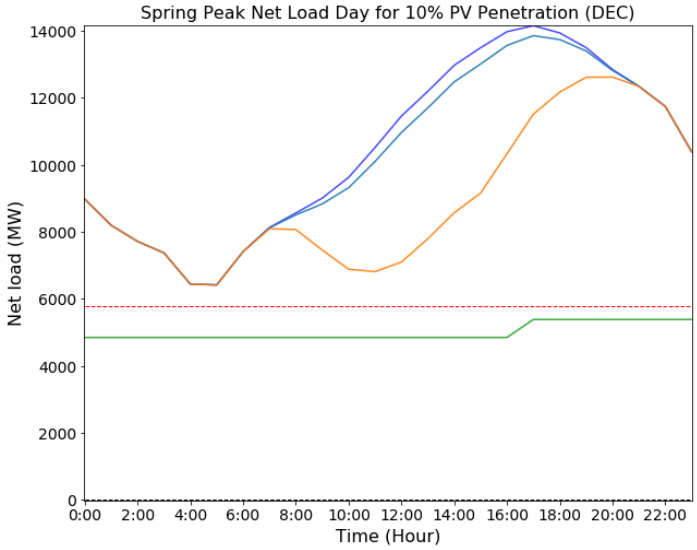




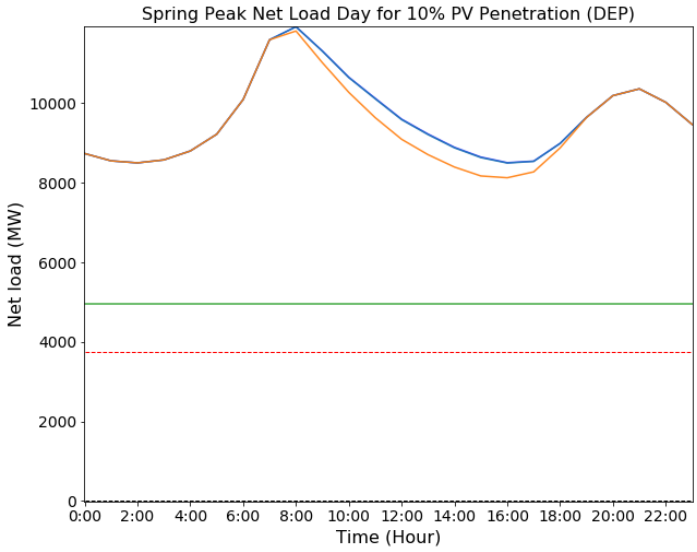




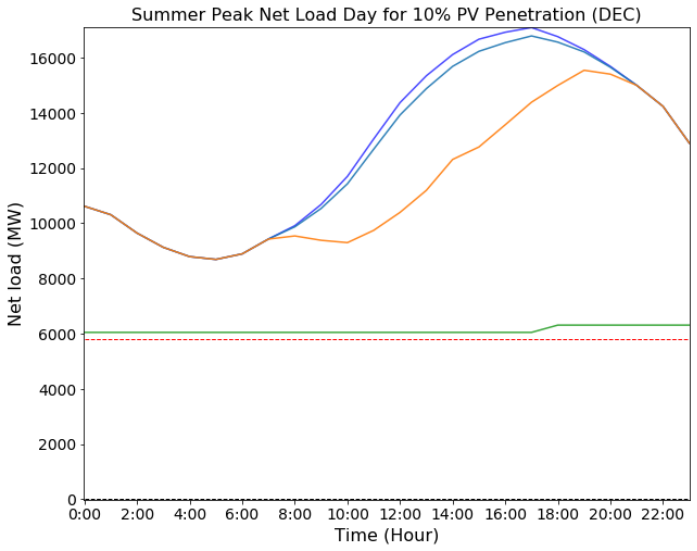
Seasonal Peak Net Load Days: 10% PV Penetration



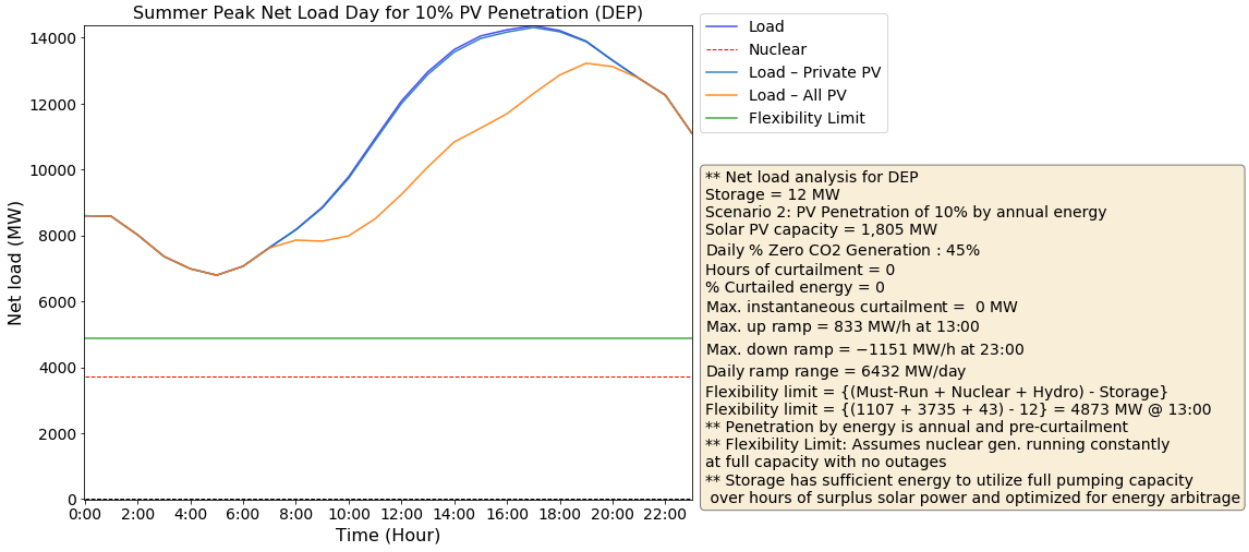
** Net load analysis for DEC
Storage = 2140 MW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 2,677 MW
Daily % Zero CO2 Generation : 73%
Hours of curtailment = 0
% Curtailed energy = 0
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1182 MW/h at 17:00
Max. down ramp = −1355 MW/h at 23:00
Daily ramp range = 6205 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1018 + 5793 + 180) - 2140} = 4851 MW @ 13:00
** 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

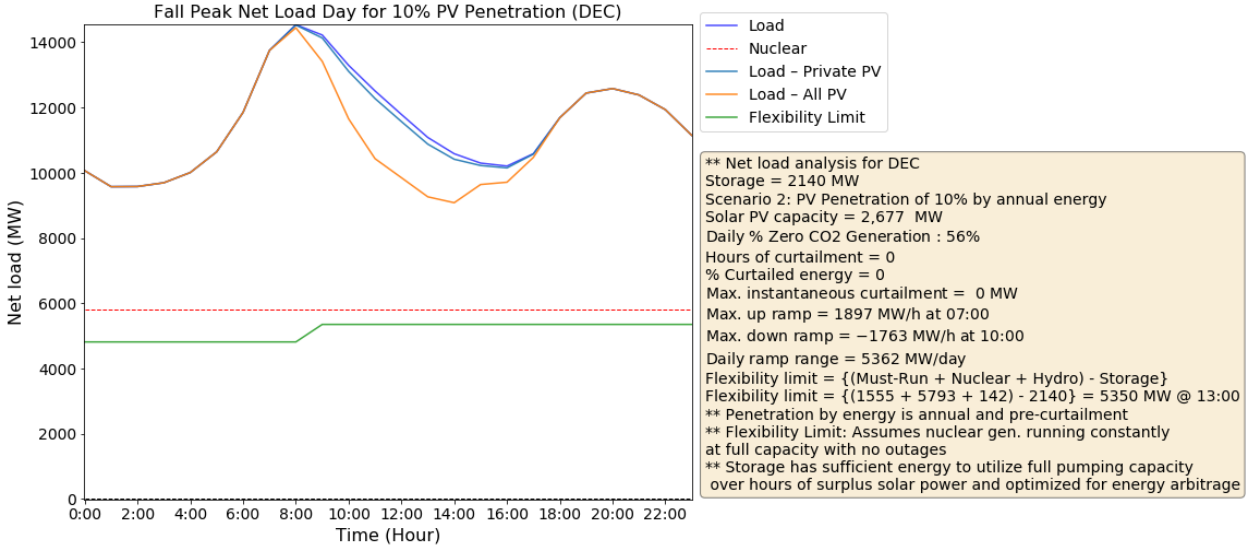


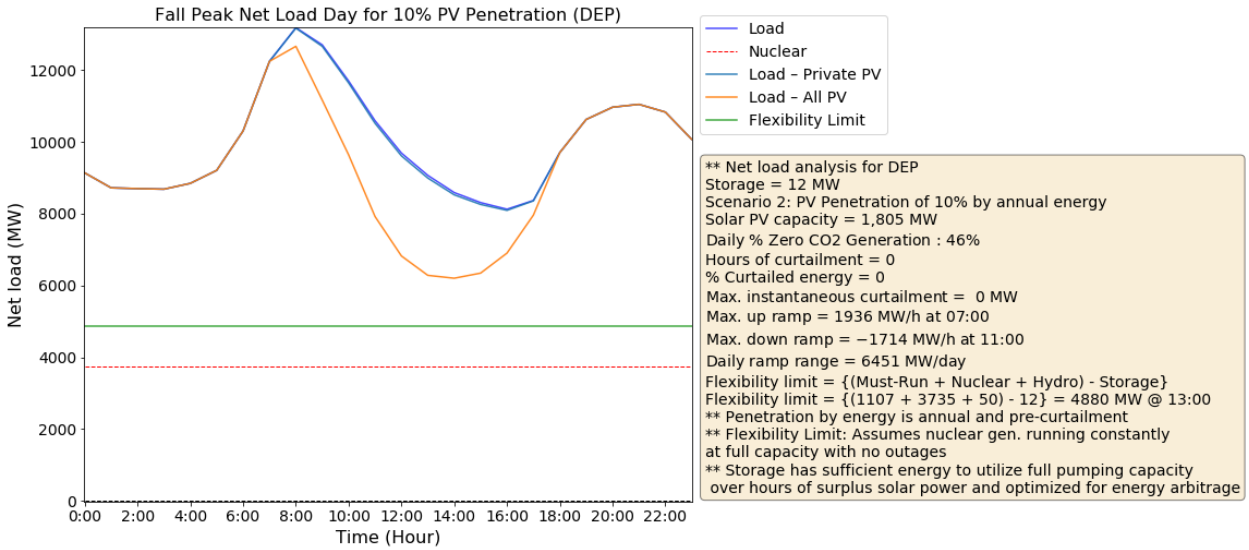
** Net load analysis for DEP
Storage = 12 MW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 1,805 MW
Daily % Zero CO2 Generation : 42%
Hours of curtailment = 0
% Curtailed energy = 0
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1502 MW/h at 07:00
Max. down ramp = −798 MW/h at 09:00
Daily ramp range = 3687 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1107 + 3735 + 120) - 12} = 4950 MW @ 13:00
** 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

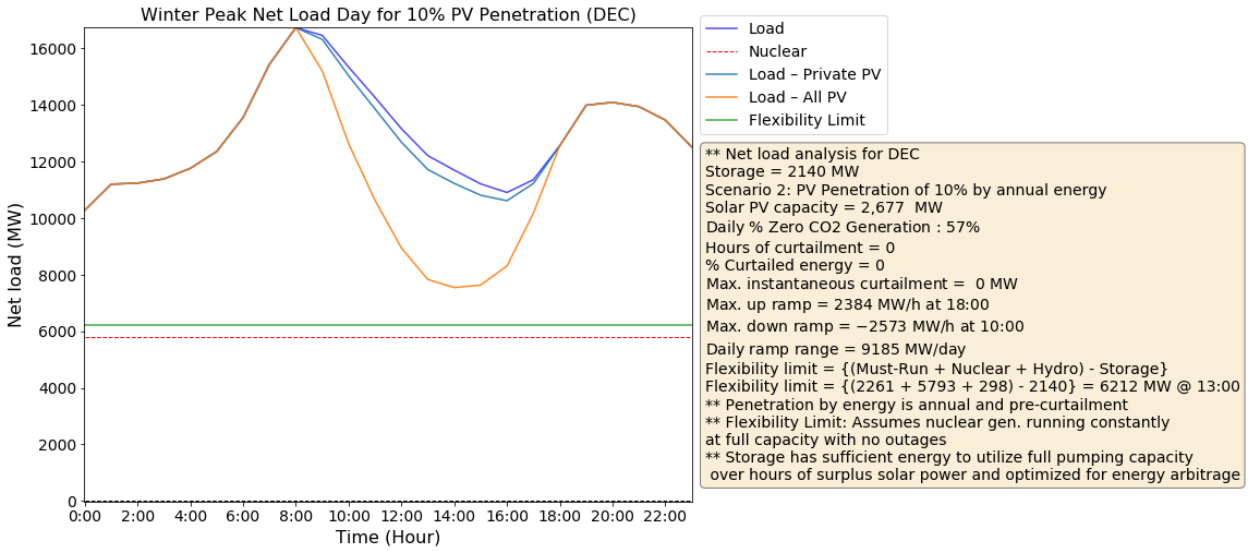


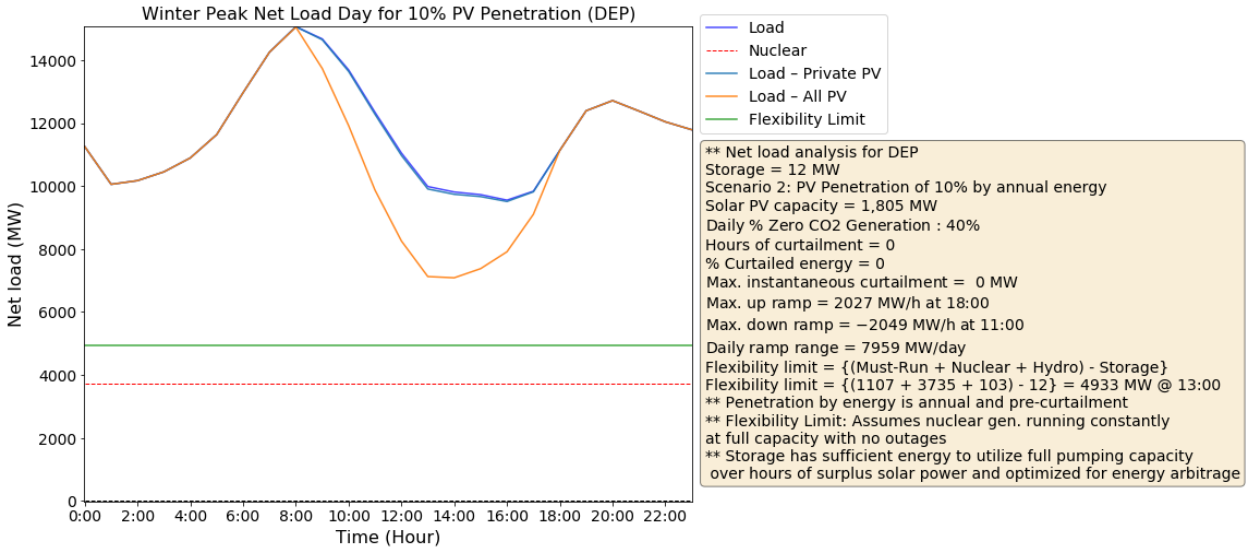
** Net load analysis for DEC
Storage = 2140 MW
Scenario 2: PV Penetration of 10% by annual energy
Solar PV capacity = 2,677 MW
Daily % Zero CO2 Generation : 58%
Hours of curtailment = 0
% Curtailed energy = 0
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1118 MW/h at 14:00
Max. down ramp = −1331 MW/h at 23:00
Daily ramp range = 6852 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2261 + 5793 + 130) - 2140} = 6044 MW @ 13:00
** 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



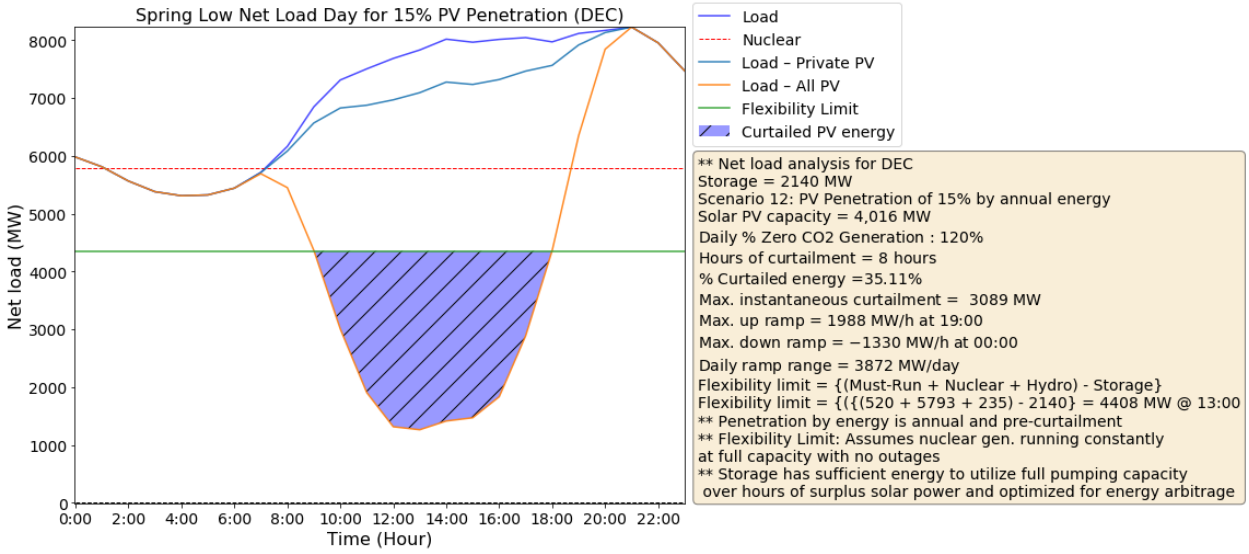


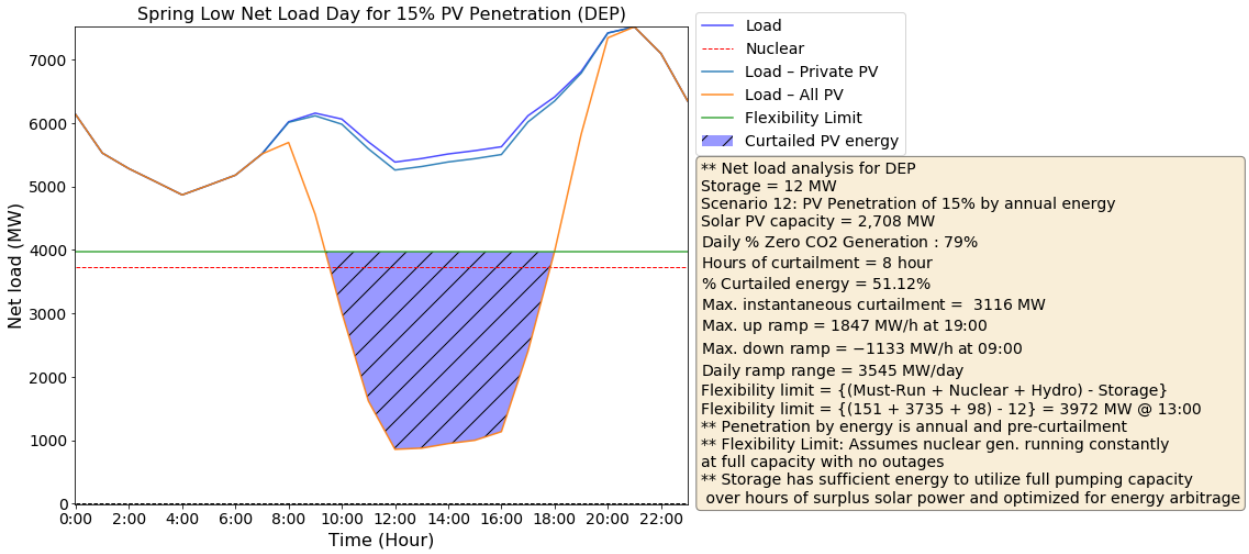


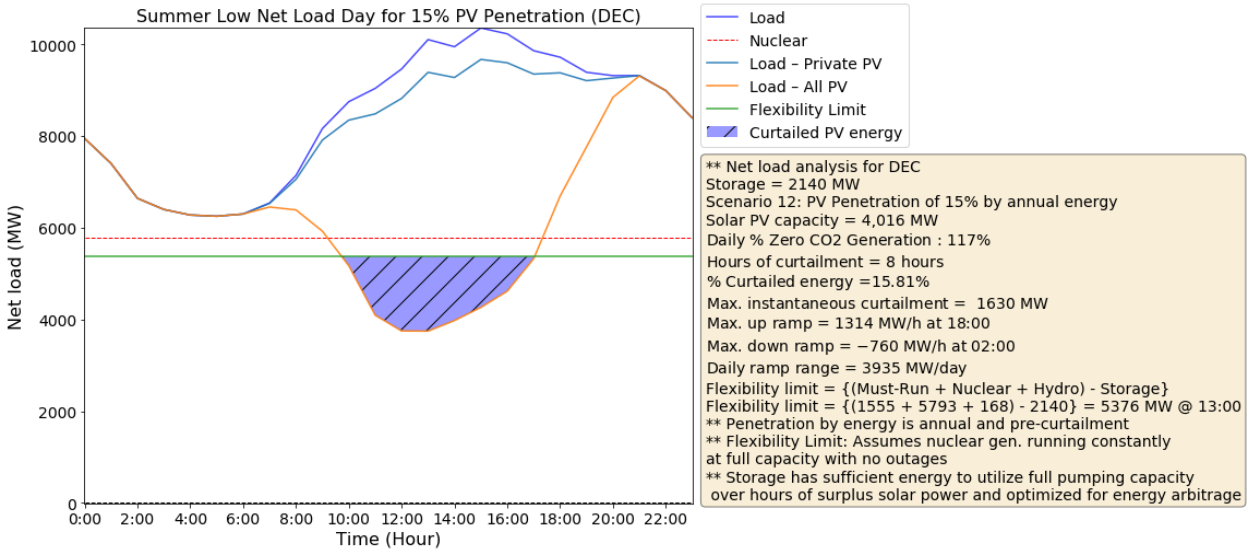


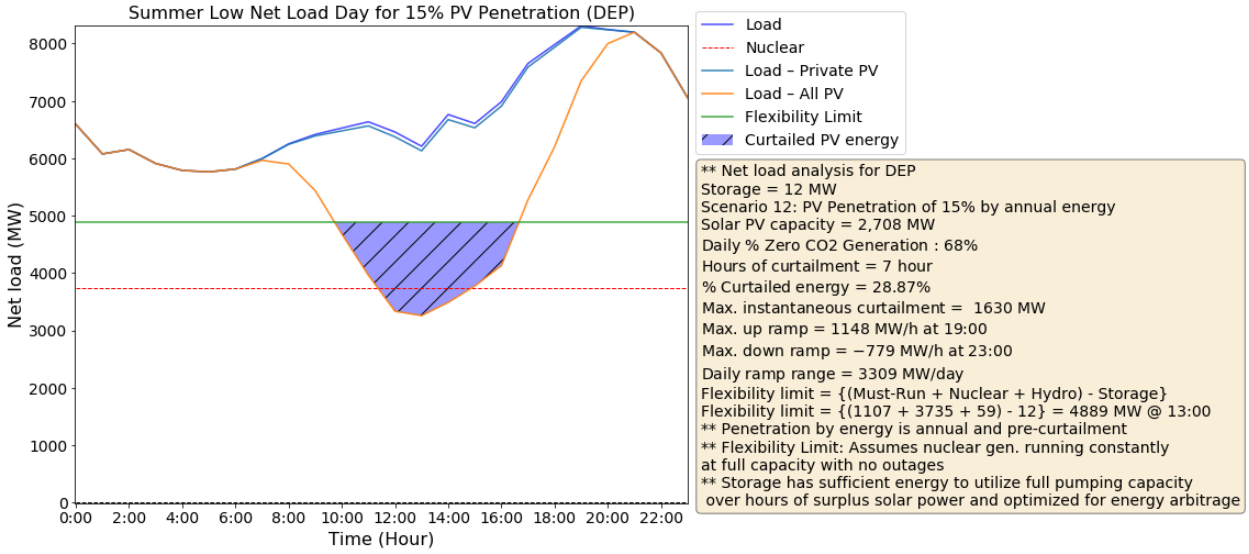


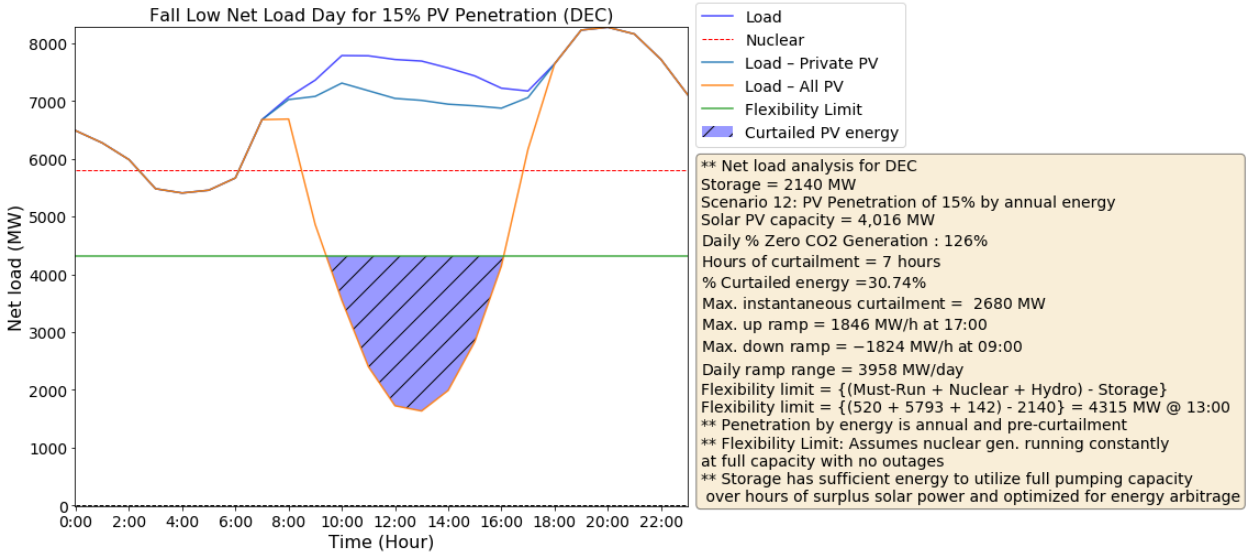
Seasonal Low Net Load Days: 15% PV Penetration

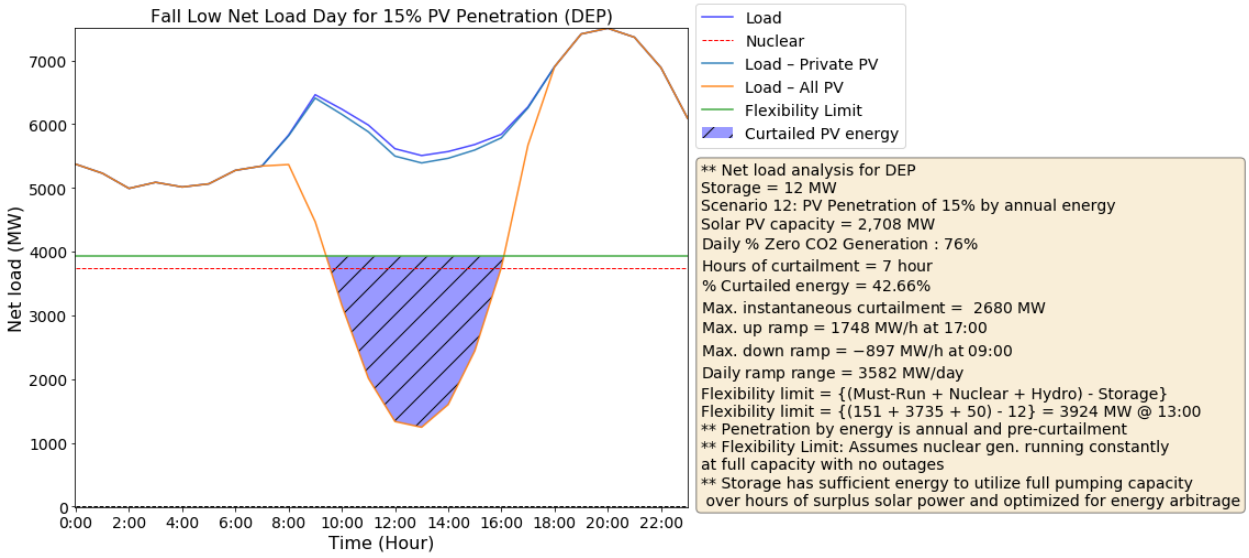


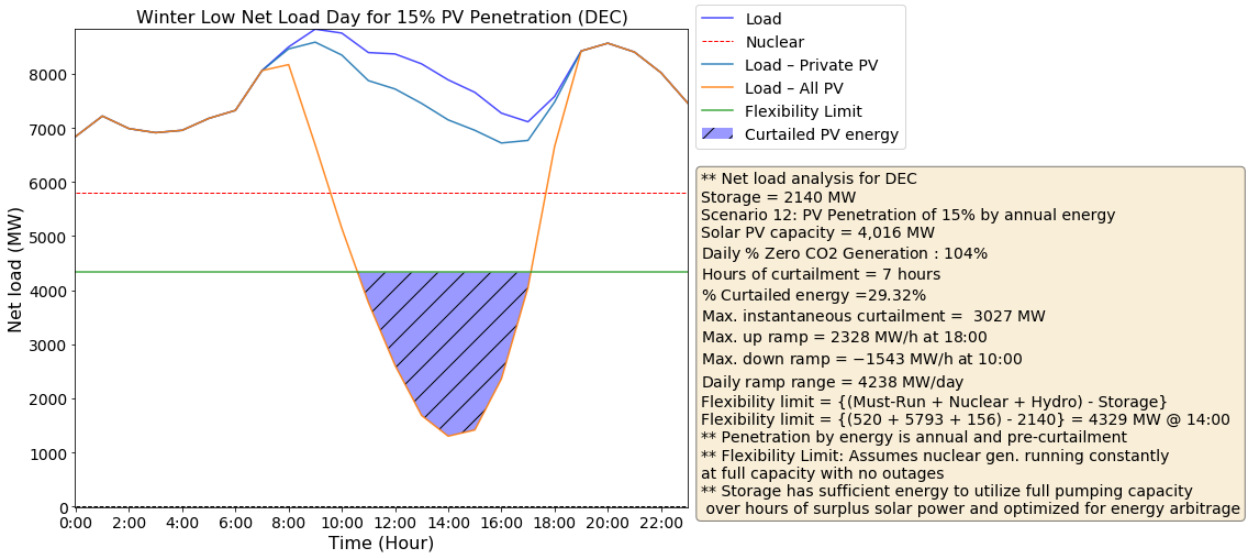


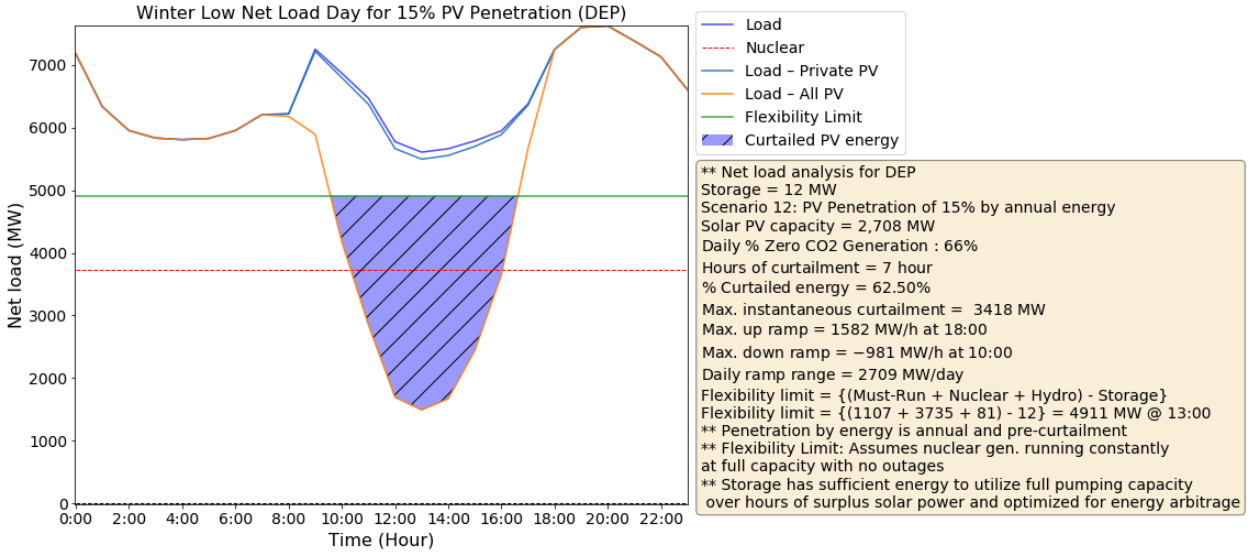




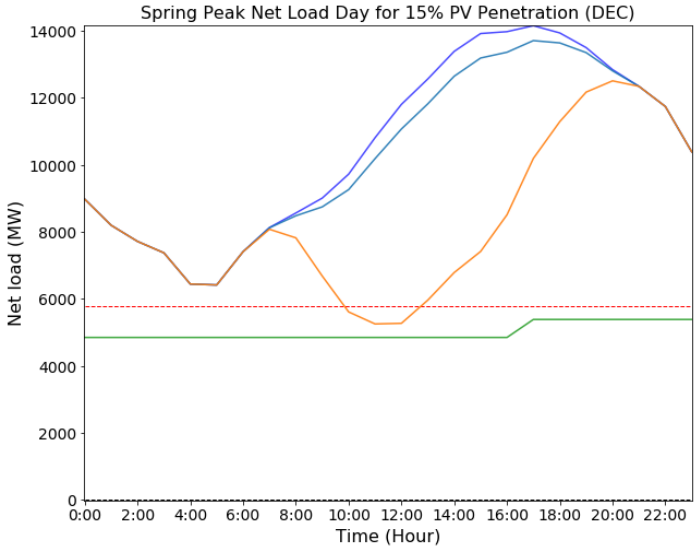




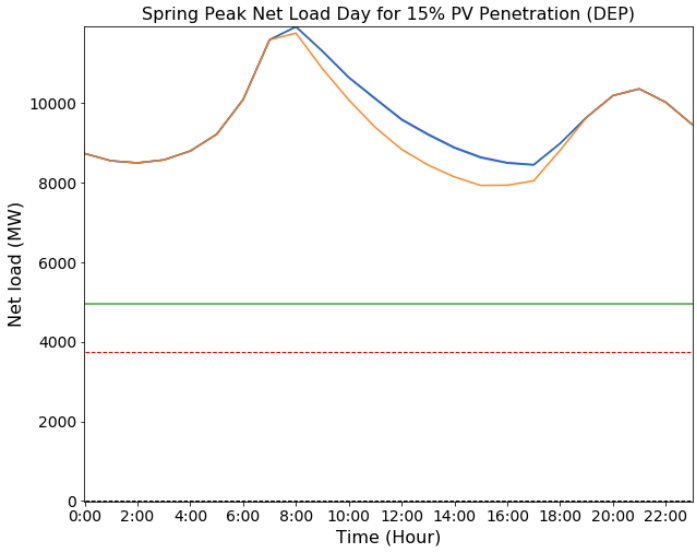




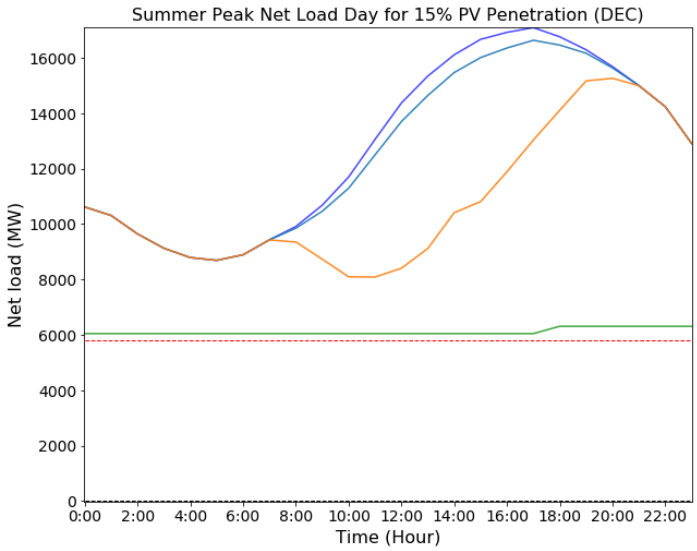
Seasonal Peak Net Load Days: 15% PV Penetration



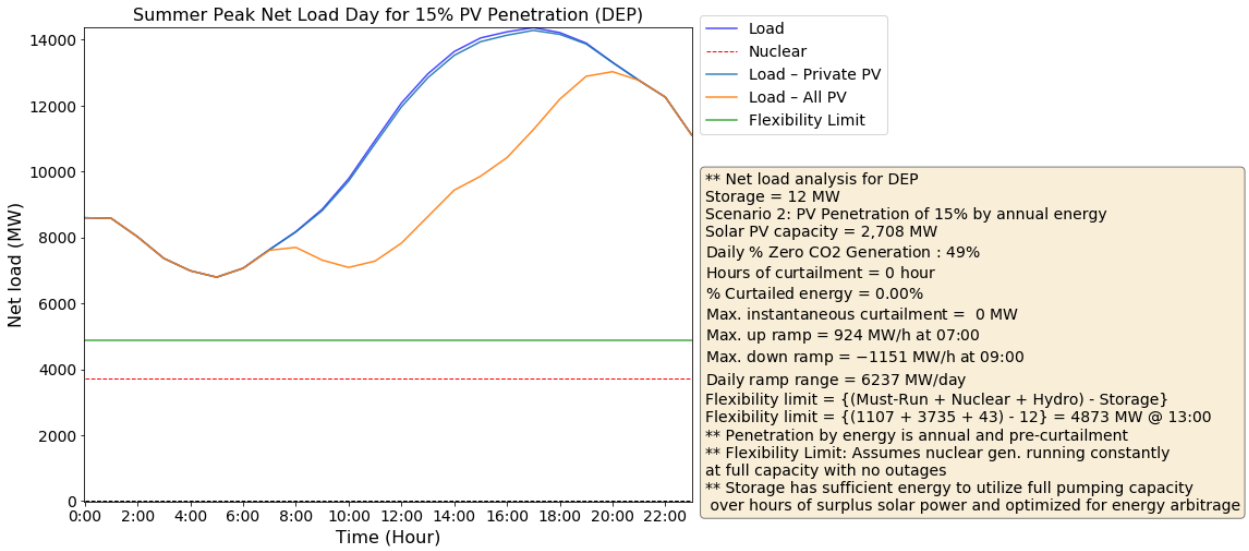
** Net load analysis for DEC
Storage = 2140 MW
Scenario 2: PV Penetration of 15% by annual energy
Solar PV capacity = 4,016 MW
Daily % Zero CO2 Generation : 90%
Hours of curtailment = 0%
% Curtailed energy = 0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1683 MW/h at 17:00
Max. down ramp = −1355 MW/h at 23:00
Daily ramp range = 7660 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1018 + 5793 + 180) - 2140} = 4851 MW @ 13:00
** 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

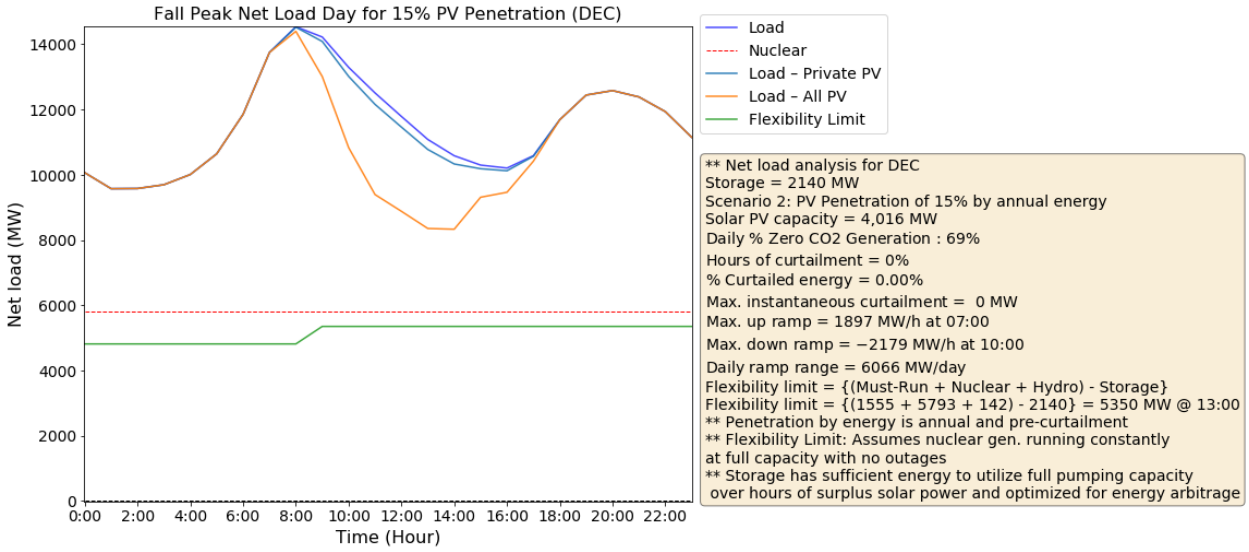


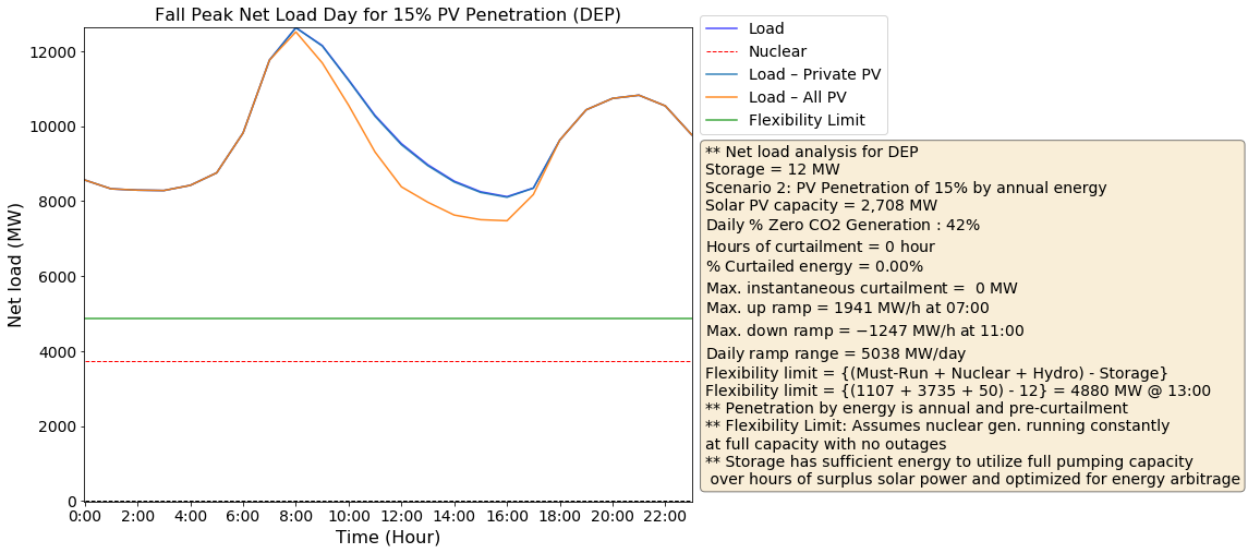
** Net load analysis for DEP
Storage = 12 MW
Scenario 2: PV Penetration of 15% by annual energy
Solar PV capacity = 2,708 MW
Daily % Zero CO2 Generation : 43%
Hours of curtailment = 0 hour
% Curtailed energy = 0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1502 MW/h at 07:00
Max. down ramp = −892 MW/h at 09:00
Daily ramp range = 3826 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(1107 + 3735 + 120) - 12} = 4950 MW @ 13:00
** 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

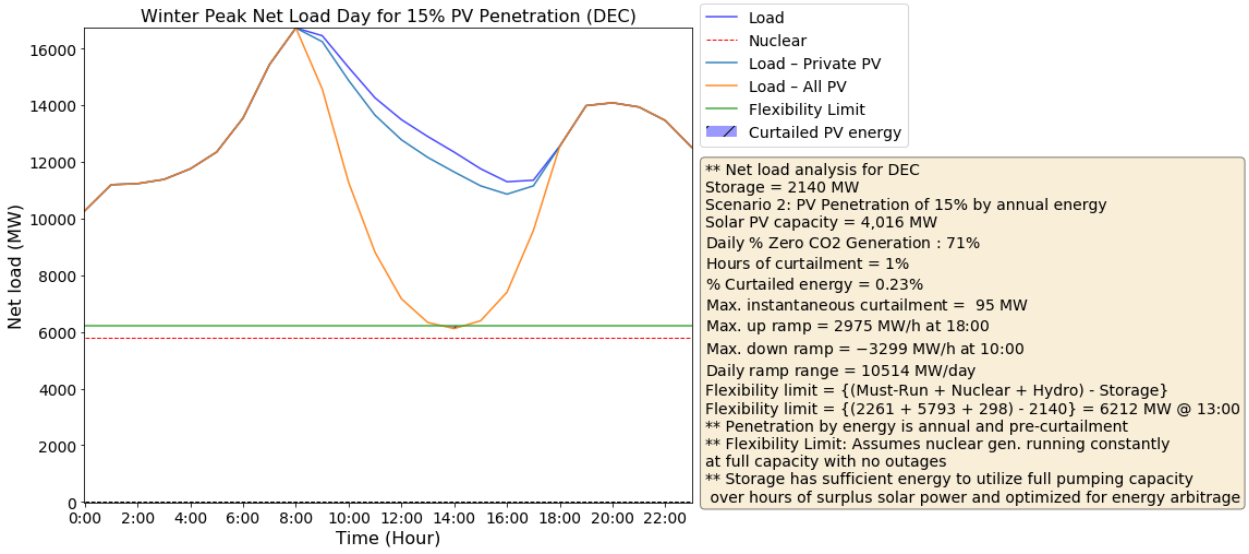


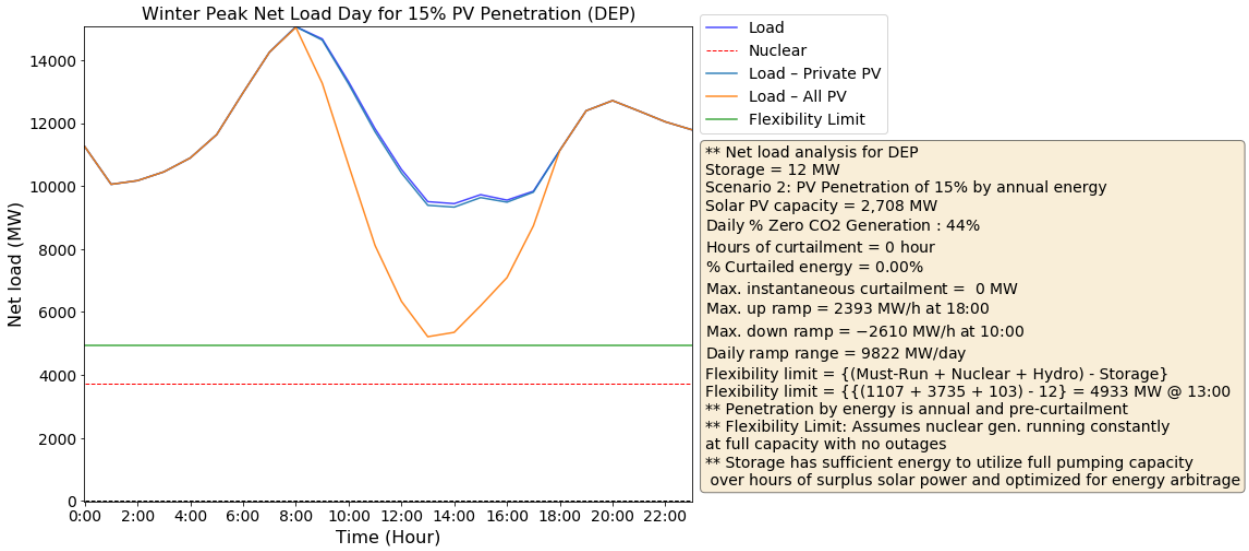
** Net load analysis for DEC
Storage = 2140 MW
Scenario 2: PV Penetration of 15% by annual energy
Solar PV capacity = 4,016 MW
Daily % Zero CO2 Generation : 75%
Hours of curtailment = 0%
% Curtailed energy = 0.00%
Max. instantaneous curtailment = 0 MW
Max. up ramp = 1294 MW/h at 14:00
Max. down ramp = −1331 MW/h at 23:00
Daily ramp range = 7173 MW/day
Flexibility limit = {(Must-Run + Nuclear + Hydro) - Storage}
Flexibility limit = {(2261 + 5793 + 130) - 2140} = 6044 MW @ 13:00
** 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











A.5 Geospatial Analysis

Several maps were produced for the purpose of visualizing available solar and wind resource in North & South Carolina, and show the *typical* exclusions applied in our technical potential analysis. The technical potential shows a broad overview of technically developable resources. This type of analysis does not take into account economic or market factors.

The technical potential analysis uses time-series data to calculate potential system generation across multiple years or weather data. This type of analysis can be useful for narrowing down places for further exploration for development.

Capacity Factors

Capacity factors were produced for photovoltaic (PV) and wind generating systems using the System Advisor Model (SAM) (Freeman et al., 2018). Input resource time-series data for calculating capacity factors include the National Solar Radiation Database (NSRDB) (Sengupta et al., 2018) for PV systems, and the Wind Integration National Dataset (WIND) Toolkit (Draxl, Clifton, Hodge, & McCaa, 2015) for wind systems. The capacity factors produced reflect the multi-year mean capacity factors across all available resource years. For the NSRDB, this encompasses the years 1998-2017 inclusive, for the WIND Toolkit, this covers years 2007-2013 inclusive.

The system configurations used in this analysis are described below:

PV

Array Type	1-Axis Tracking
Azimuth	180 Degrees (South)
Tilt	0 Degrees
Module Type	Standard
Inverter Efficiency	96%
DC/AC Ratio	1.3
Losses	14.07%

Wind

	Land-Based	Offshore
Hub Height	80m	100m
Wind Shear Coefficient	0.143	0.143
Rotor Diameter	92m / 108m / 117m	155m
Wind Turbulence Coefficient	0.10	0.10
Losses	15%	15%
Availability	98%	98%

Rotor diameter and power curves for land-based turbines depends on multi-year mean wind speed using the logic below:

- ws* <= 5.5 m/s: 117m Rotor Diameter
- 5.5 m/s < ws <= 10 m/s: 108m Rotor Diameter
- ws > 10 m/s: 92m Rotor Diameter

*ws = wind speed (m/s)

Exclusions

In order to determine locations for further investigation of new PV or wind development, assumptions are made based on land categories and use-type to exclude locations from consideration. The exclusions used in this analysis may be adjusted and new data used in the future to account for more locally-sourced data or other assumptions that aren't considered at this time.

PV

The land exclusions used for PV include the following:

Slope > 5%
Urban Areas
Water and Wetlands
Parks and Landmarks
National Parks and Other Environmentally or Culturally Sensitive Areas

Wind

The land exclusions used for wind analysis include the following:

Slope > 20%
Urban Areas
Water and Wetlands
Forests
National Parks and Other Environmentally or Culturally Sensitive Areas

Maps

The results of the Technical Potential analysis are visualized in maps and web application layers. The descriptions of the maps can be found below. Due to their large size, they have been sent to Duke in a separate file.

1. Duke GHI-01.jpg: Multi-year mean Global Horizontal Irradiance (GHI) from the NSRDB.
2. Duke GHI with Exclusions-01.jpg: Multi-year mean GHI from the NSRDB with excluded areas removed using the PV exclusion logic listed above.
3. Duke PV CF-01.jpg: Multi-year mean capacity factors using the PV system configurations listed above.
4. Duke PV with Exclusions-01.jpg: Multi-year mean capacity factors using the PV system configurations listed above and excluded areas removed using the PV exclusion logic listed above.
5. Duke Wind Speed 80-01.jpg: Multi-year mean wind speed from the WIND Toolkit.
6. Duke Wind Speed 80 with Exclusions-01.jpg: Multi-year mean wind speed from the WIND Toolkit with excluded areas removed using the wind exclusion logic listed above.
7. Duke Wind CF-01.jpg: Multi-year mean capacity factors using the wind system configurations listed above.
8. Duke Wind CF with Exclusions-01.jpg: Multi-year mean capacity factors using the wind system configurations listed above with excluded areas removed using the wind exclusion logic listed above.

Carbon-free resource integration study

Bri-Mathias Hodge

Scott Haase

National Renewable Energy Laboratory (NREL)

Jennings Exhibit No. 16
Docket No. E-7, Sub 1229

Scope of work – Phase 1

Net Load Analysis

- Analyzed the impacts of integrating differing amounts of new solar photovoltaic (PV) power into Duke Energy's Carolinas service territory, comparing estimated hourly solar, wind, load, and system minimum generation time series for 12 different scenarios

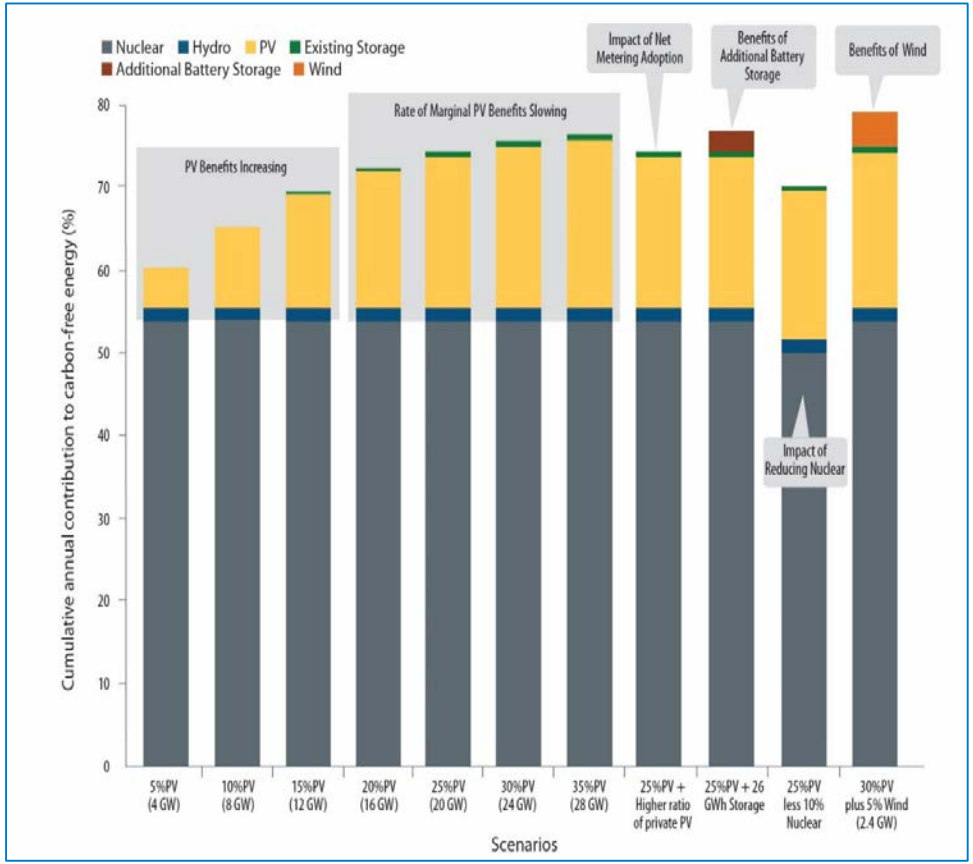
Phase 1 Scope

- Quantified the amount of carbon-free electricity
- Estimated curtailment, ramping, and system flexibility limits
- Evaluated shifts in daily and seasonal net load timing, supply and demand challenges

Phase 1 Did Not Consider

- Unit commitment and economic dispatch
- System stability analysis, e.g. voltage/frequency/transient analysis
- Cost or transmission impacts

Summary of scenarios



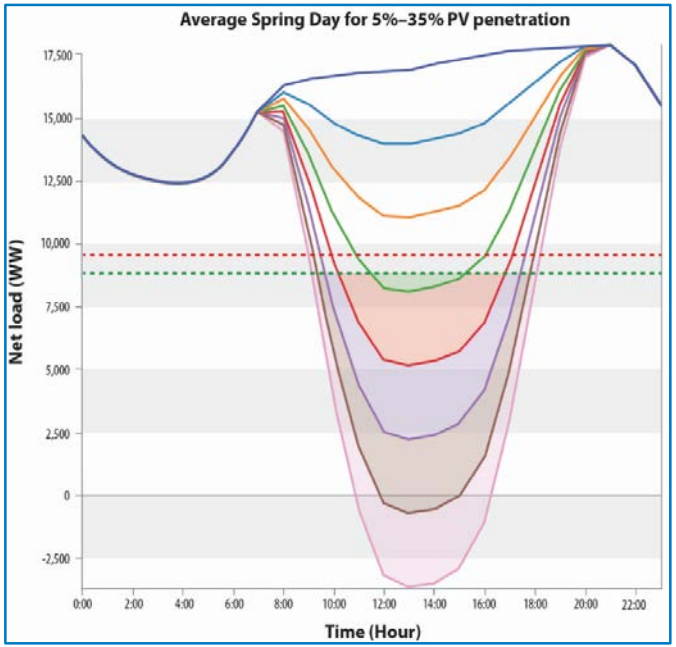
Key Findings:

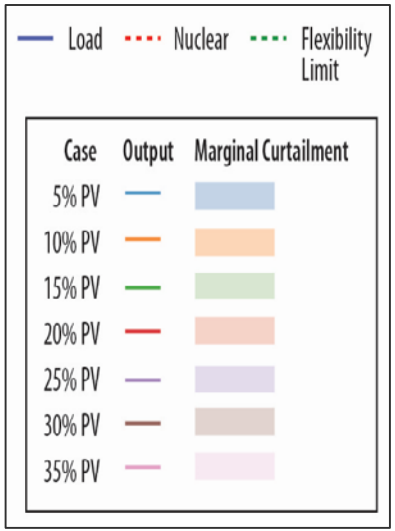
- Net load analysis highlights challenges and opportunities with integrating solar PV
- Average annual % of load met by carbon-free generation ranges from 60-79%
- Nuclear remains greatest contributor to carbon-free energy
- Above 15% solar PV, required curtailment grows
- The highest share of carbon-free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

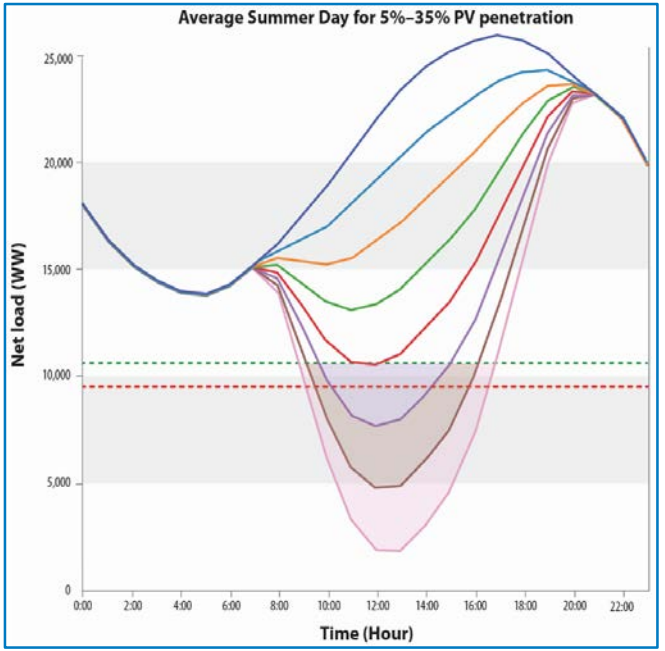
Scenarios

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 zero-carbon generation, %	60.4	65.5	69.7	72.5	74.4	75.6	76.5







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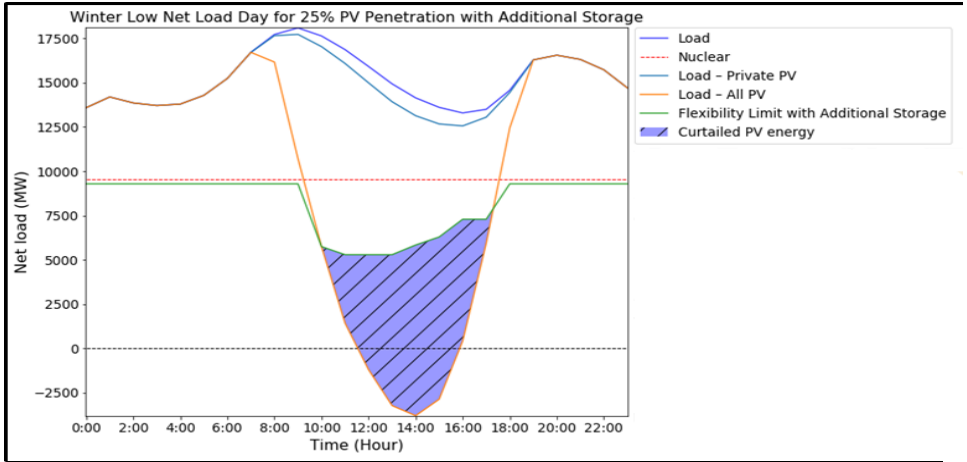
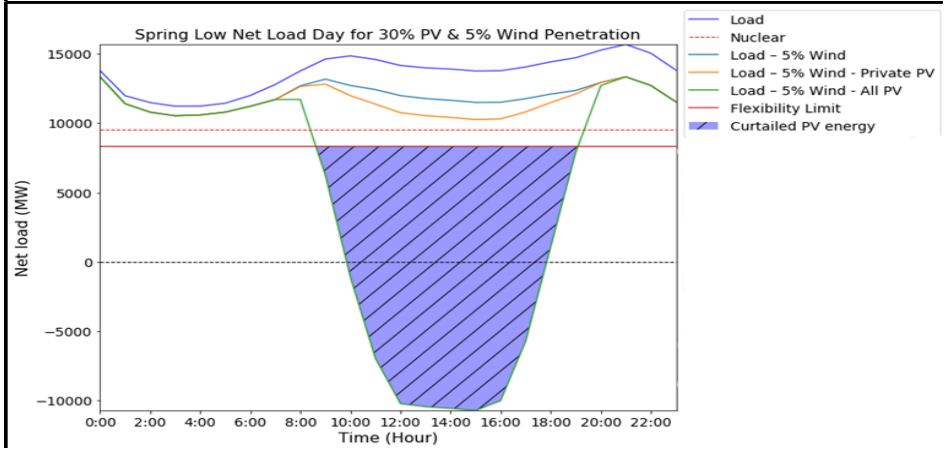
Storage, nuclear and wind scenarios





Key Findings:

Storage deployment (26,000 MWh)*

- Solar curtailment reduces from 27% to 15%
- Zero-carbon contribution rises from 76% to 78%

Nuclear

- The nuclear retirement scenario reduces the solar curtailment from 27% to 22%, but also reduces carbon-free generation from 74% to 70%

Wind

- Carbon free generation increases from 77% to 79% with 5% wind + 30% solar, as opposed to 35% solar case due to reduced curtailment

**Estimated cost for 26,000 MWh of storage based on current market prices is approximately $8-12 Billion*

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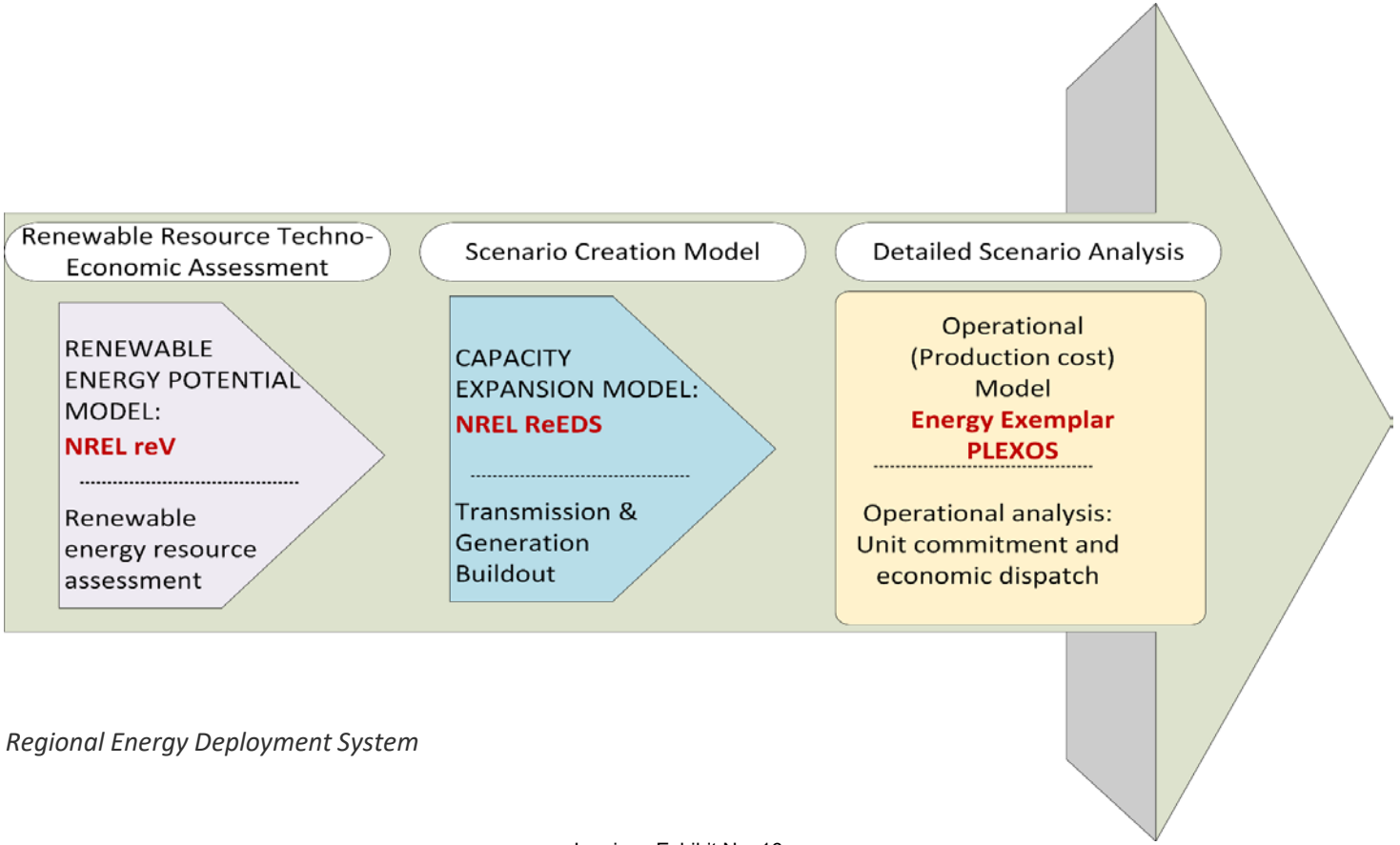
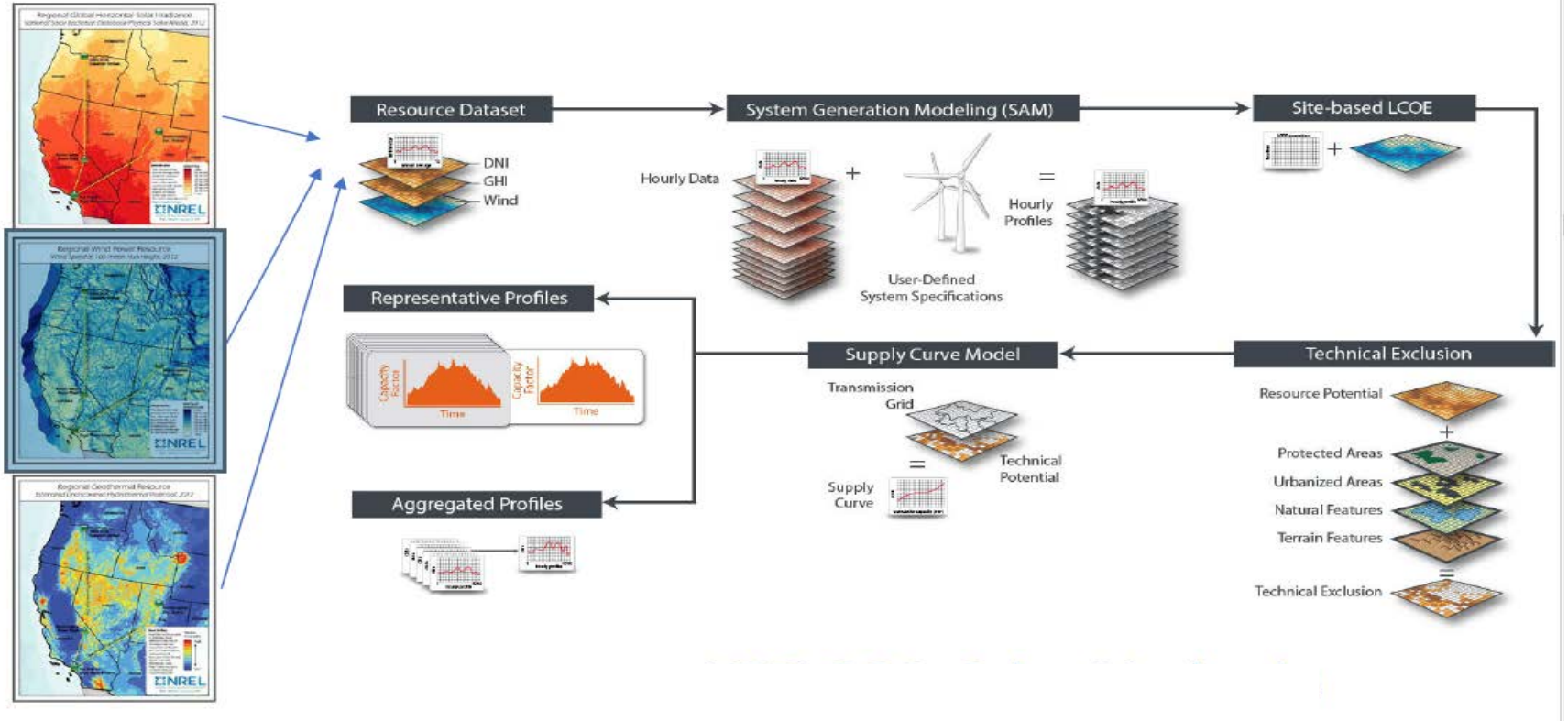
Carbon-Free Resource Integration Study – Phase 2



**ReEDS: Regional Energy Deployment System*

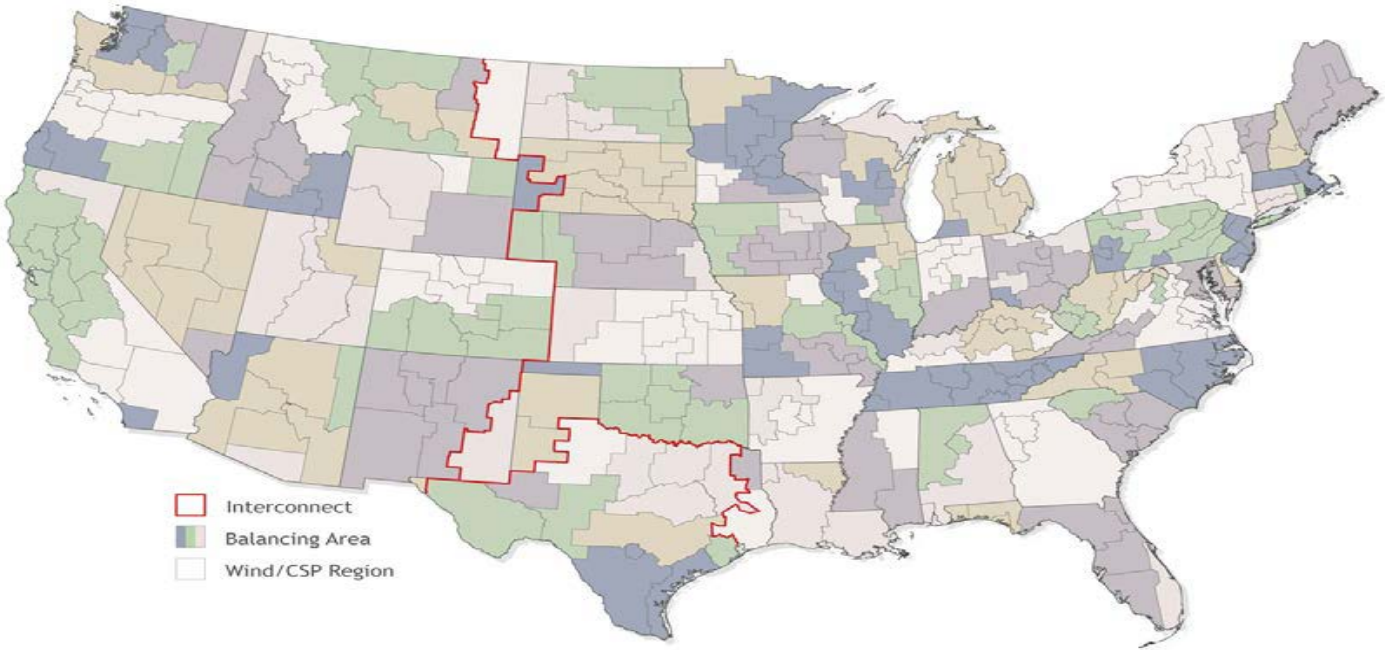
Renewable Energy Potential Model – NREL reV

- 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



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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

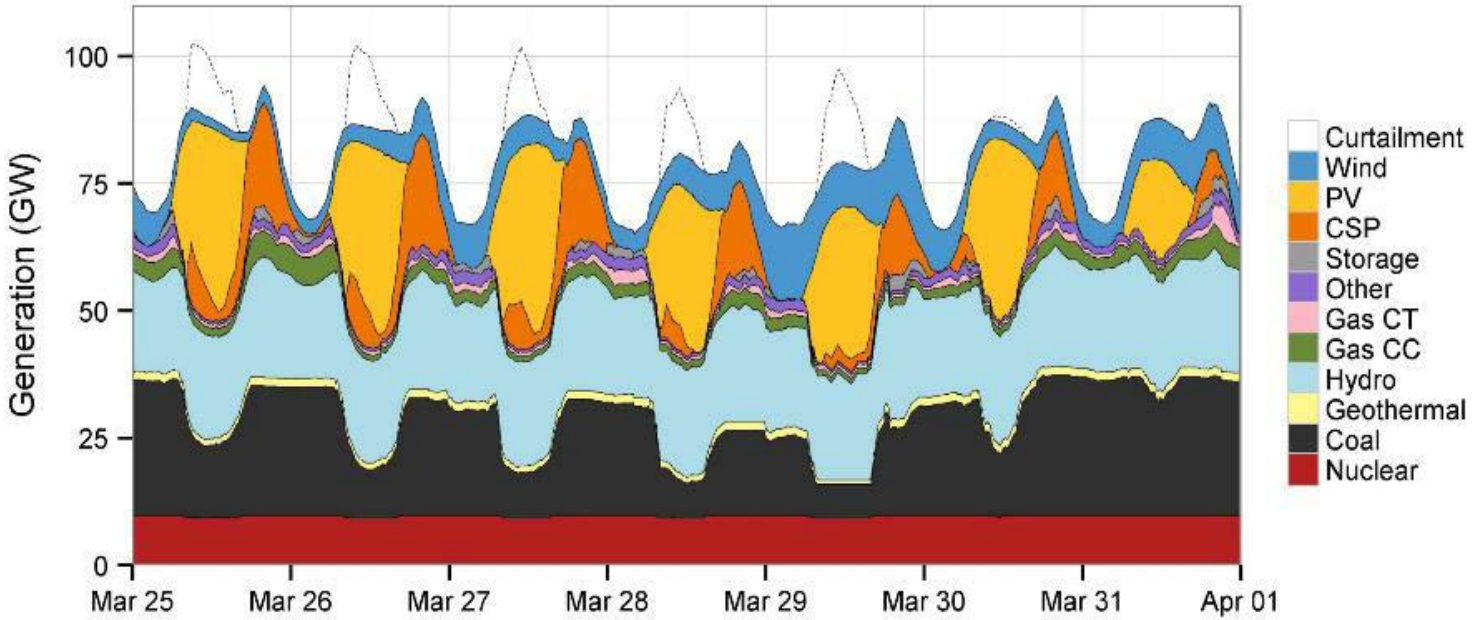
Combinations
- Low/High NG Price with
  - Low/High RE Cost
  - Low/High Geo Cost
  - Low/High CSP Cost
  - Low/High Hydro Cost
  - Low/High Offshore Wind Cost

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



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Docket No. E-7, Sub 1229

Jennings Exhibit No. 17
Docket No. E-7, Sub 1229

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

Bri-Mathias Hodge, Scott Haase (NREL)
Ken Jennings (Duke Energy)

January 17th, 2020

Agenda

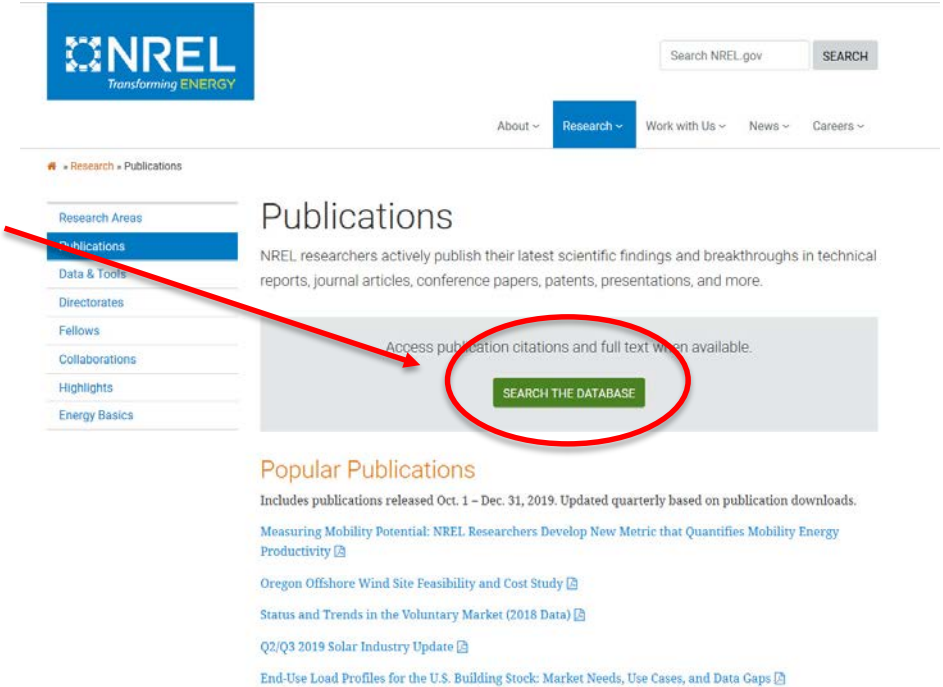
- **Webinar Welcome and Instructions** – Terri Edwards, Duke Energy
- **Study Purpose and Background** – Ken Jennings, Duke Energy
- **Integration with Clean Energy Plan** – Tim Profeta, Nicholas Institute
- **NREL Phase 1 Analysis** – Scott Haase and Bri-Mathias Hodge, NREL
- **Next Steps, Wrap Up**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

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
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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

Advanced Computer Science, Visualization, and Data

Crosscutting

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.

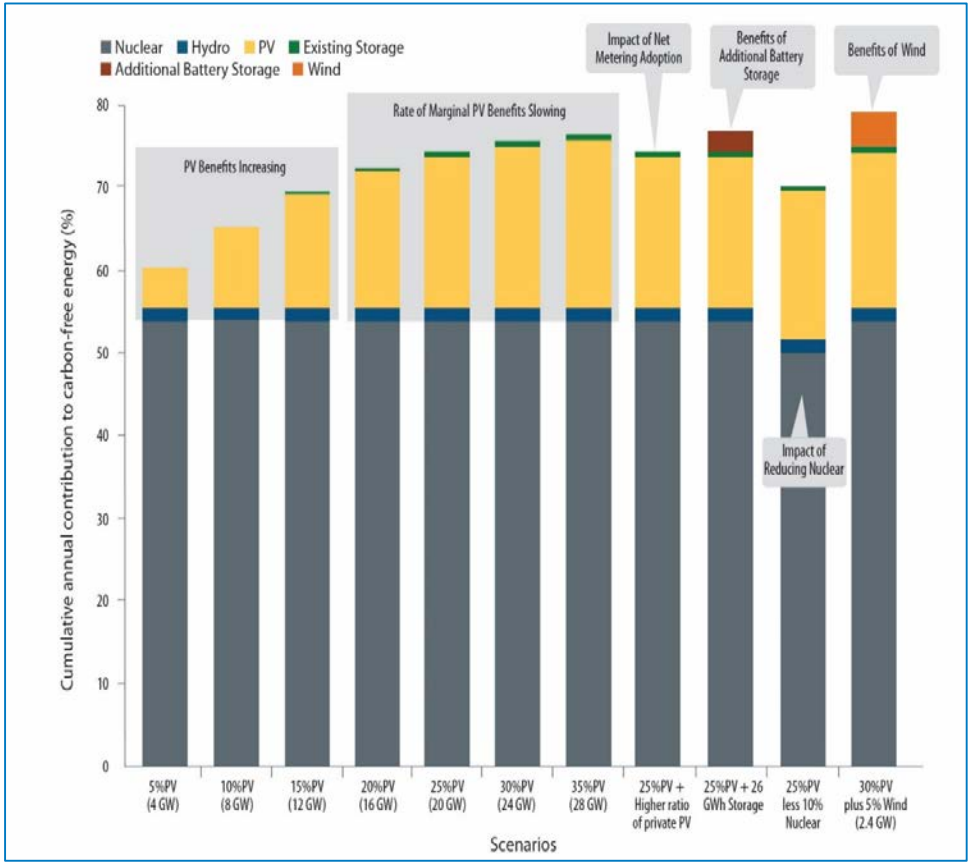
Geospatial Analysis Maps with Interactive Web App

- 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.

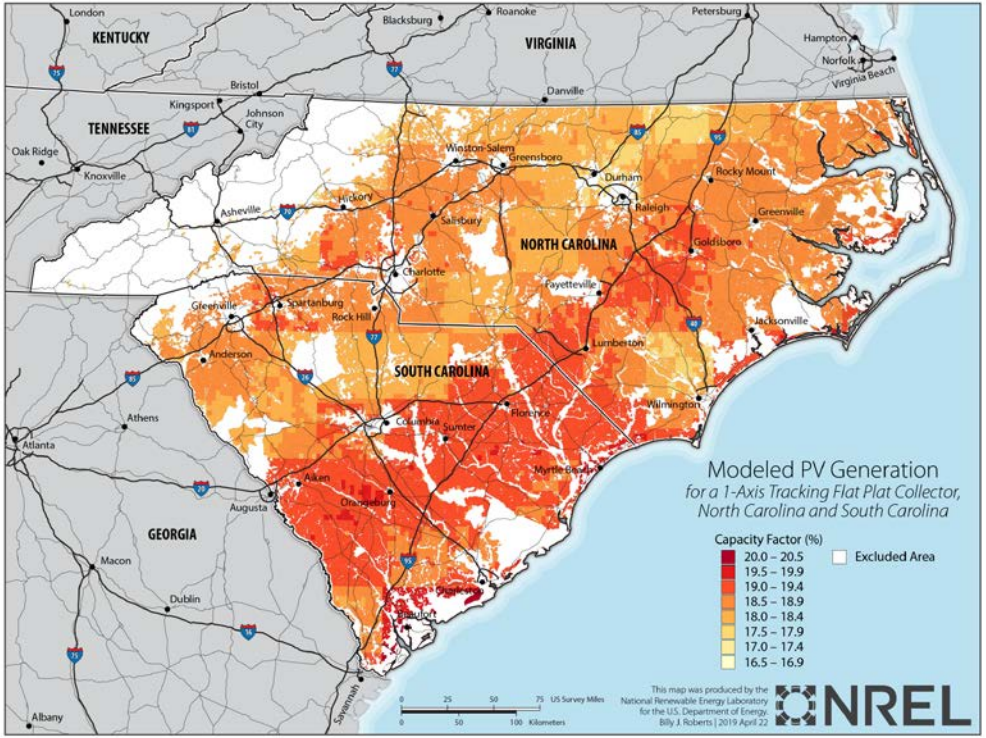
Summary of scenarios



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…

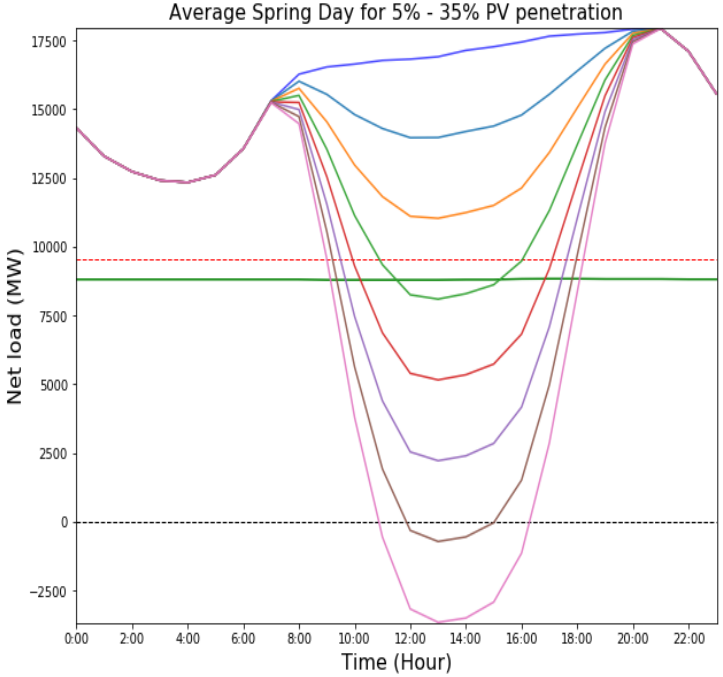
Definitions

- 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

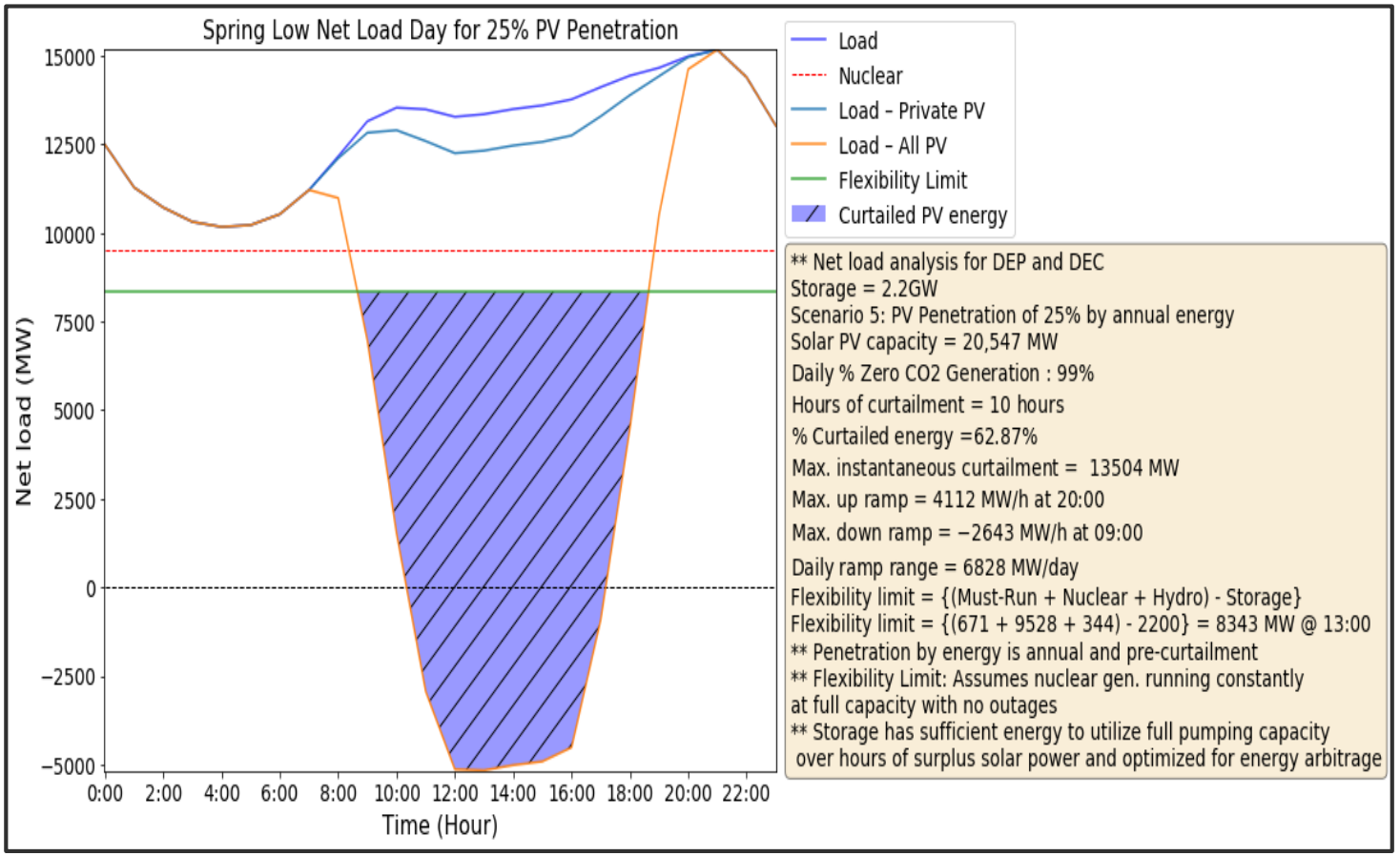
Annual Economic Indicators



** 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

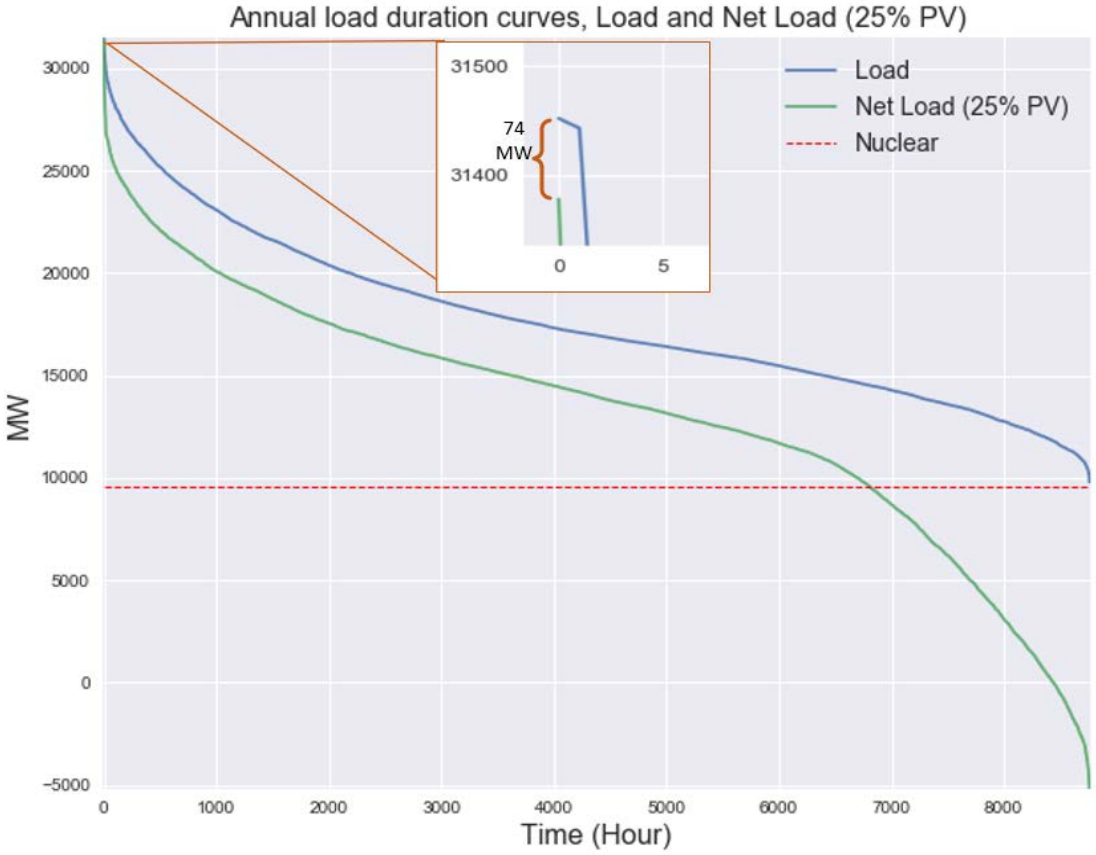
Here we show spring, as it is the highest curtailment season

Peak Load Day for 25% PV Penetration



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

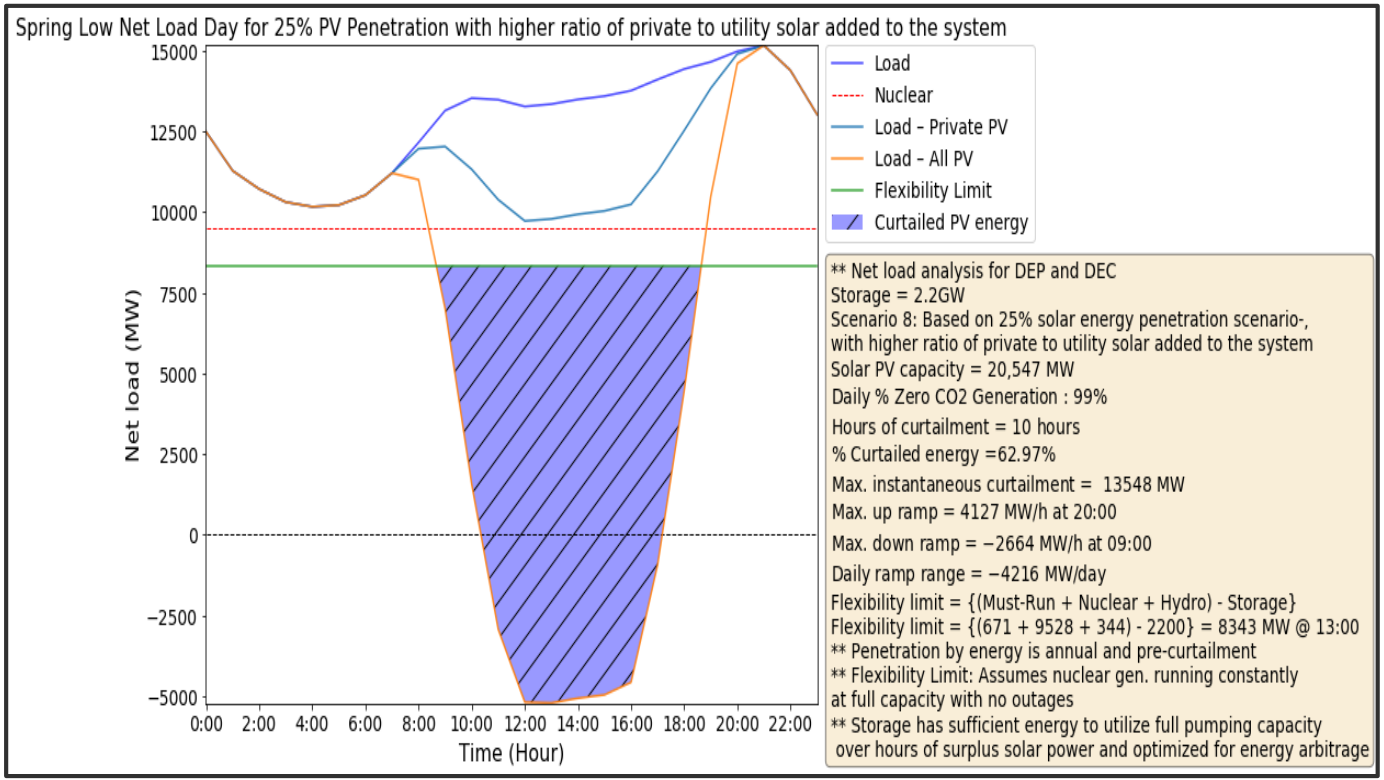
Load Duration Curves for the Existing Load and Projected 25% PV Penetration Case



With the addition of 25% PV penetration:

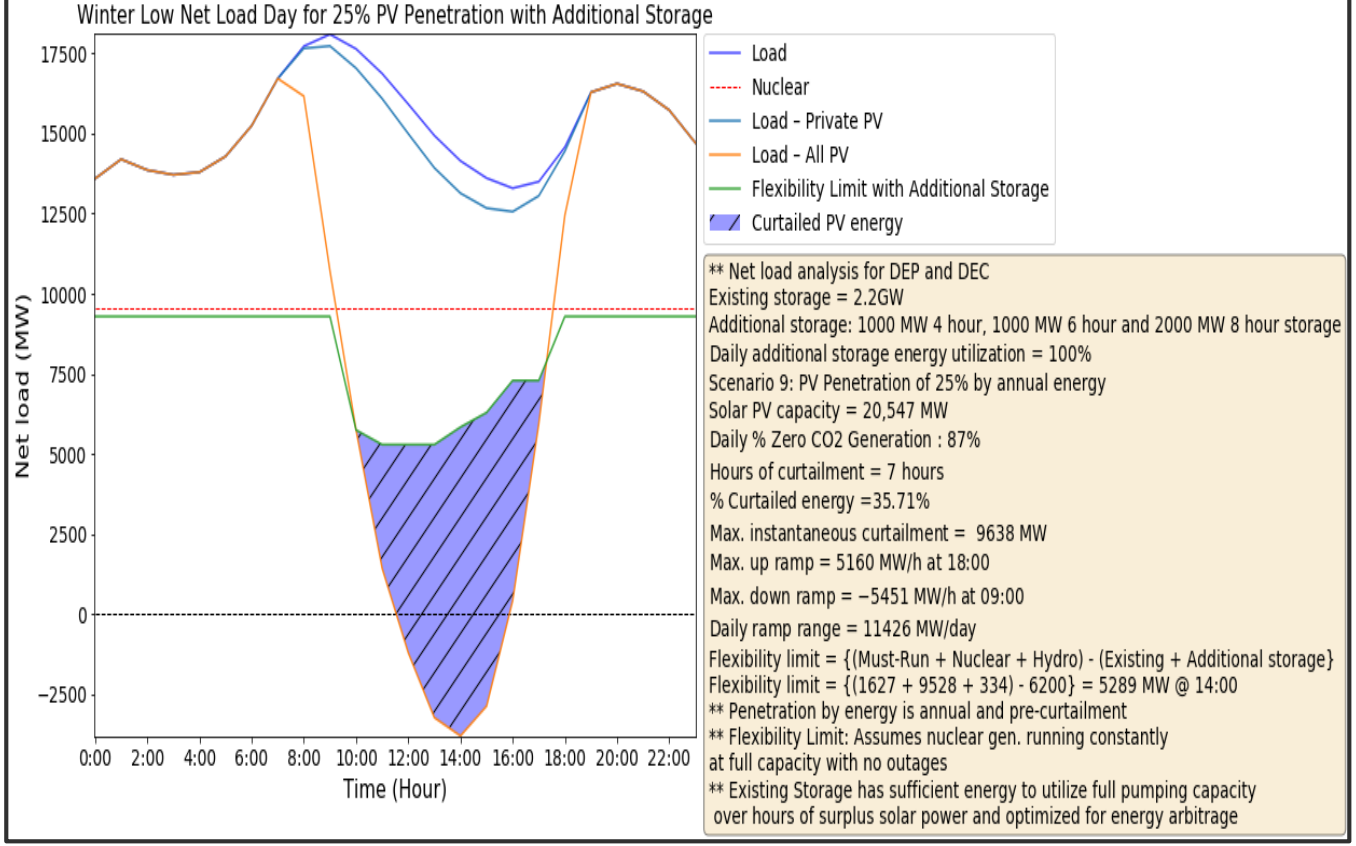
- Peak load is reduced
- Annual minimum load drops below the nuclear output

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

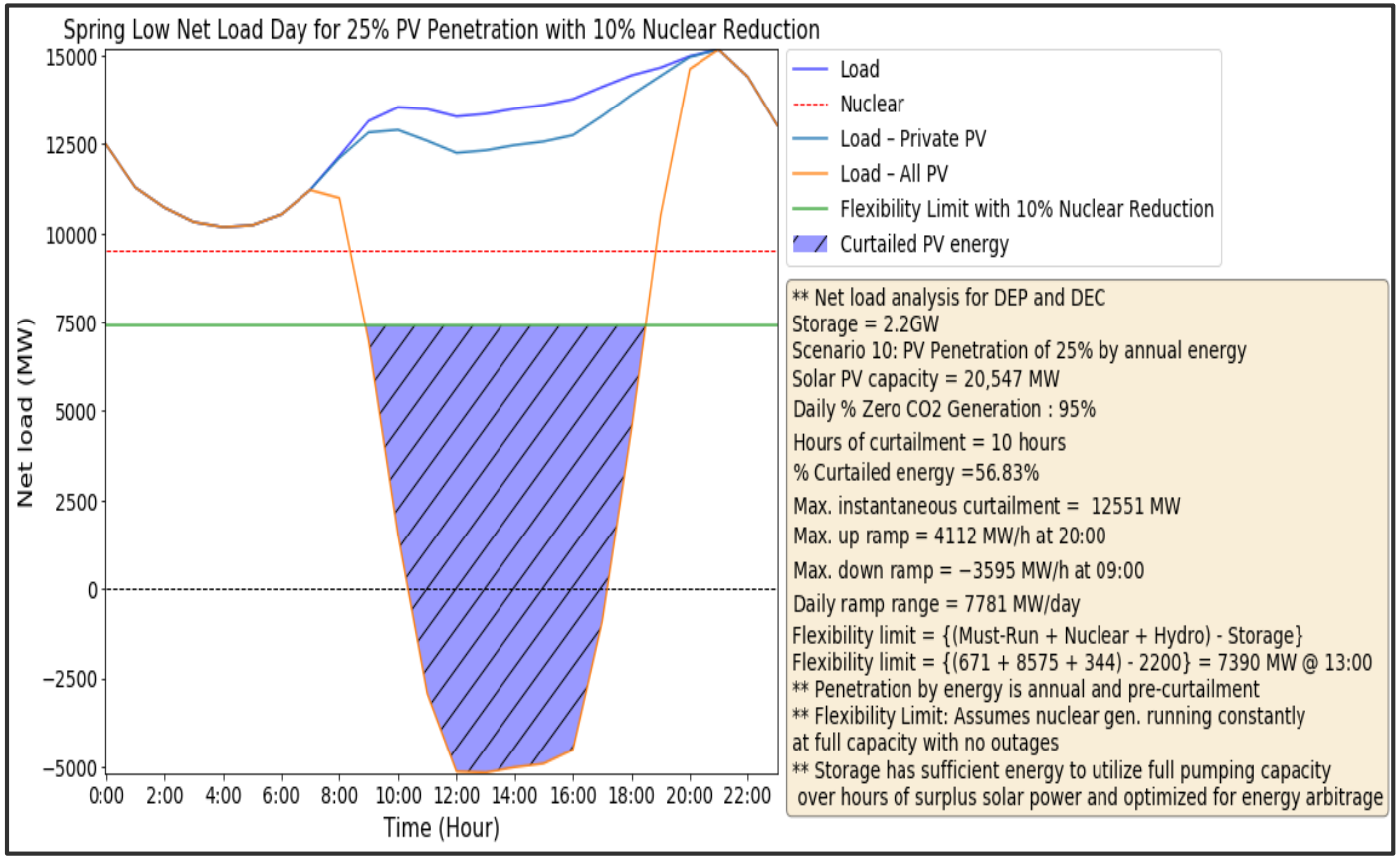


- Starts with the 25% PV penetration base case
- 1,000 MW of 4-hour, 1,000 MW of 6-hour and 2,000 MW of 8-hour (26,000 MWh)
- Annual contribution of this addition storage amounts to 3.7% of annual load
- Renewable energy is stored and released the same day with 80% round-trip efficiency

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

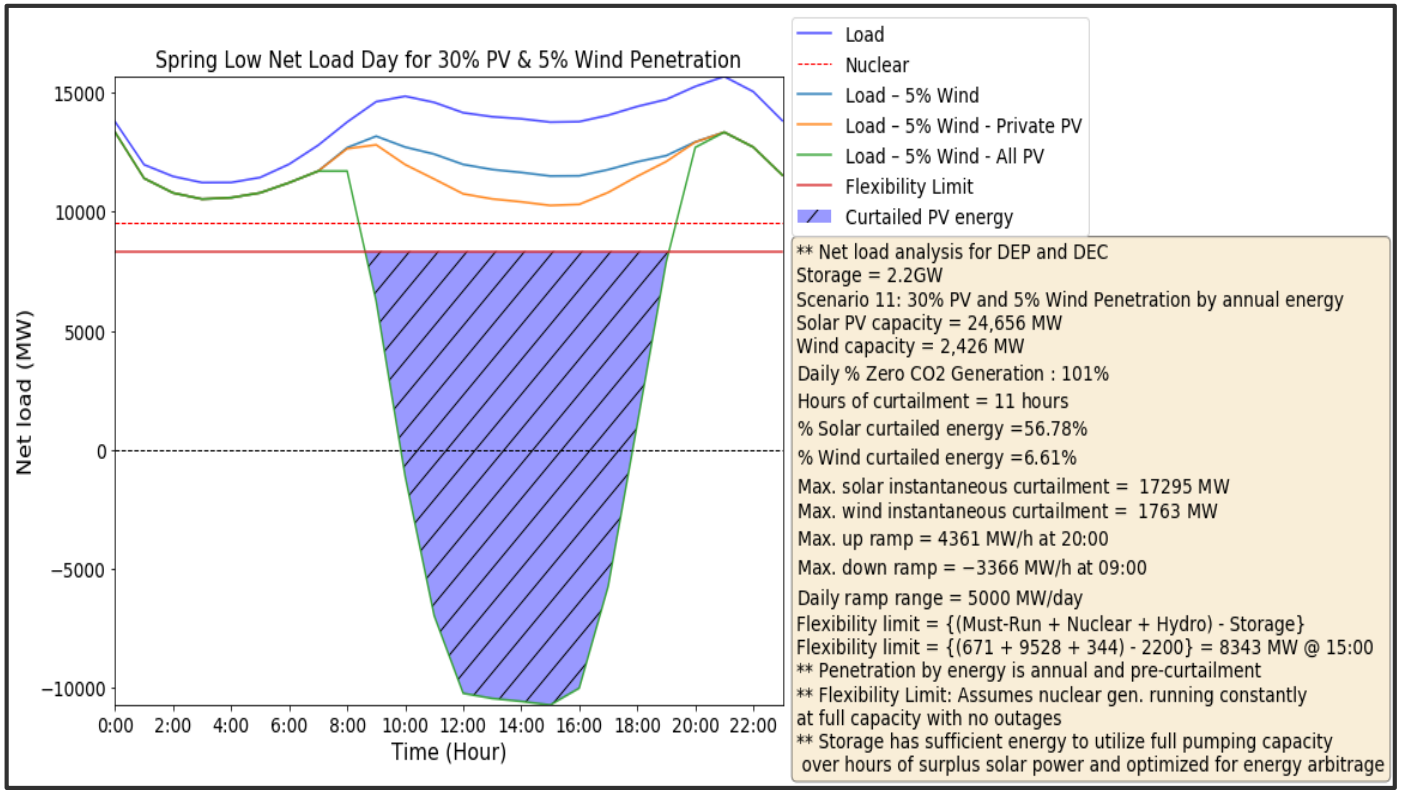


- Based on 25% PV penetration case, 10% of nuclear power is retired and assumed replaced with flexible thermal generation

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



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

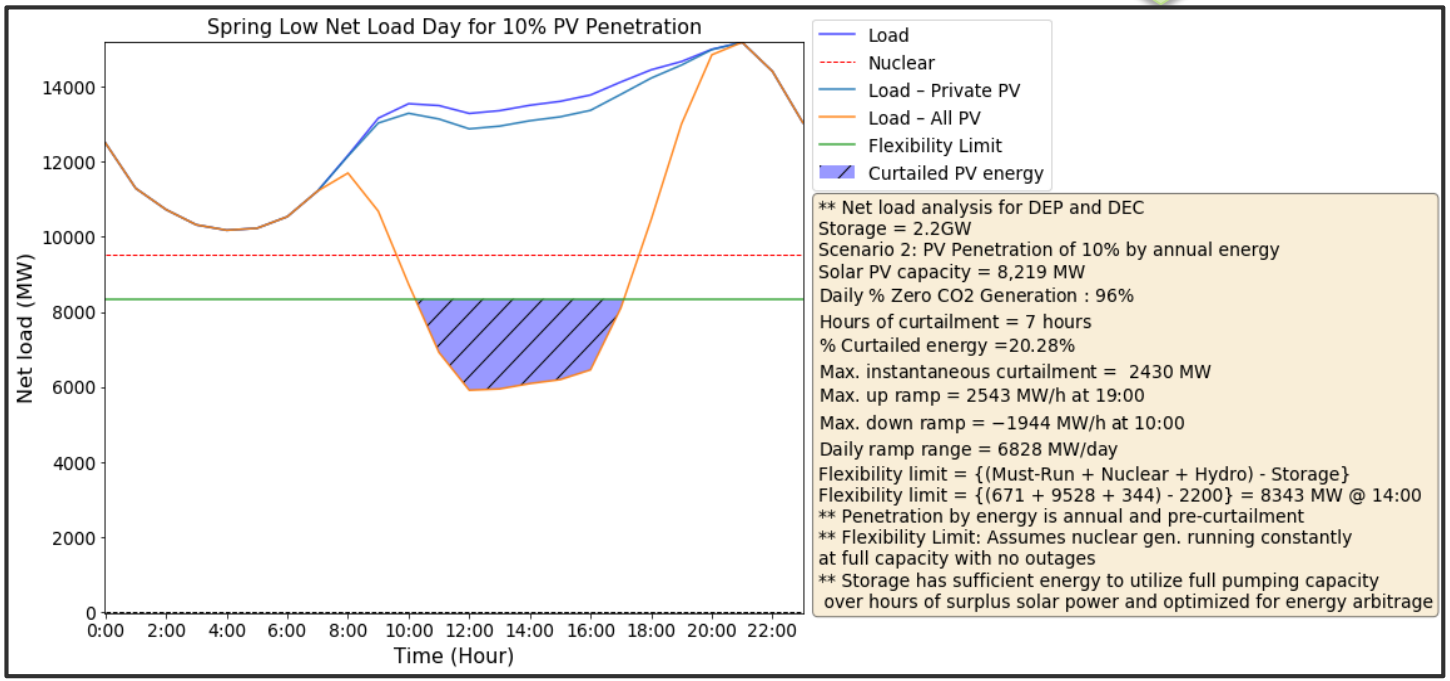
Compared to the 35% PV penetration case:

- 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



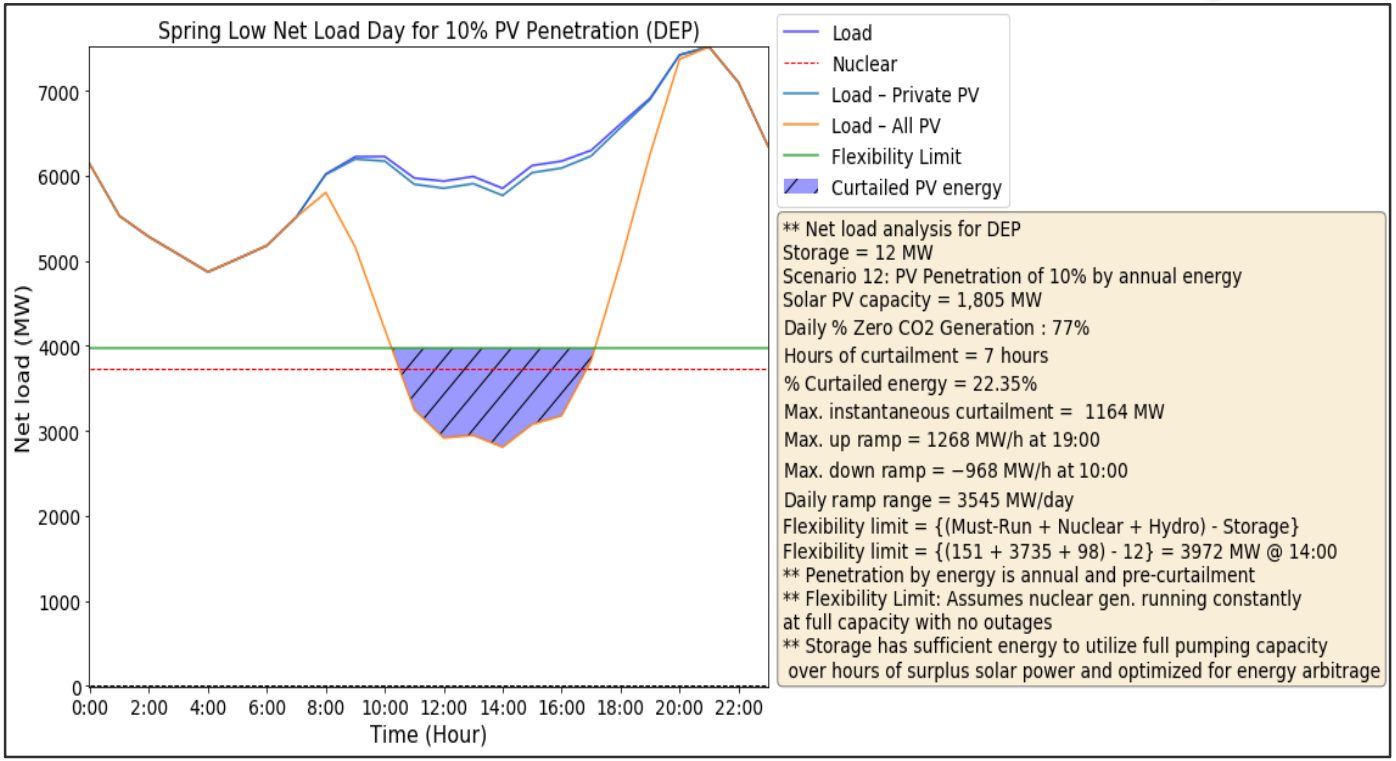
10% PV penetration is the lowest PV penetration scenario where curtailment occurs and the day pictured here has the highest curtailment at 20.28%.

- 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

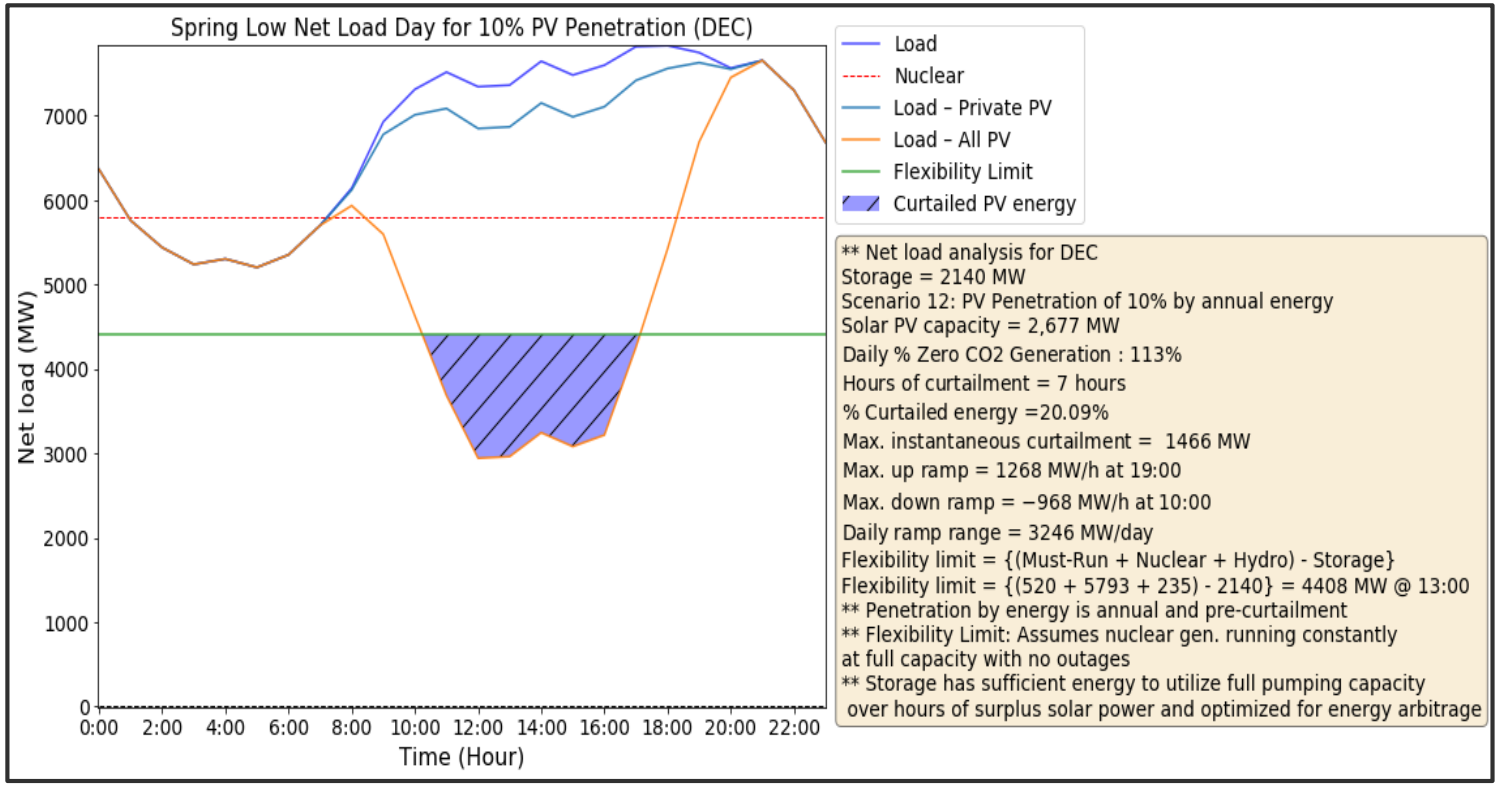


- Curtailed energy = 22.35%

Scenario 12:

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

Chart
DEC after interconnection



Curtailed energy = 20.09%

Scenario 12:

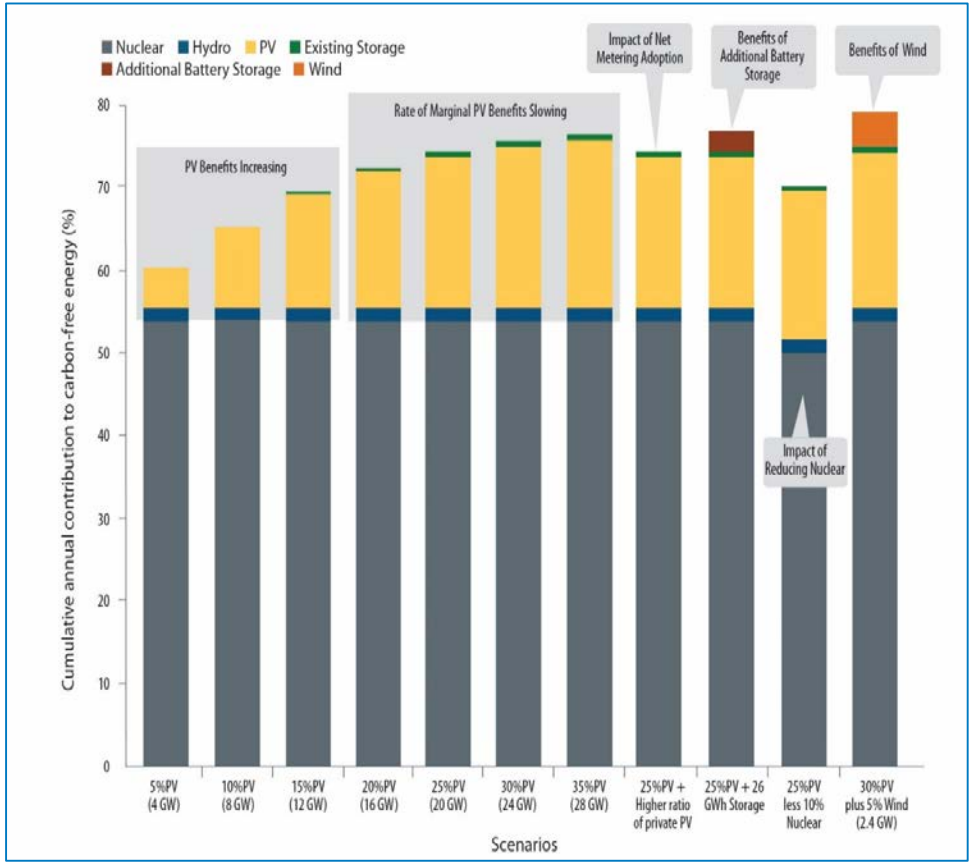
DEC and DEP Modeled as Individual Balancing Authorities with a Limited Interconnection

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

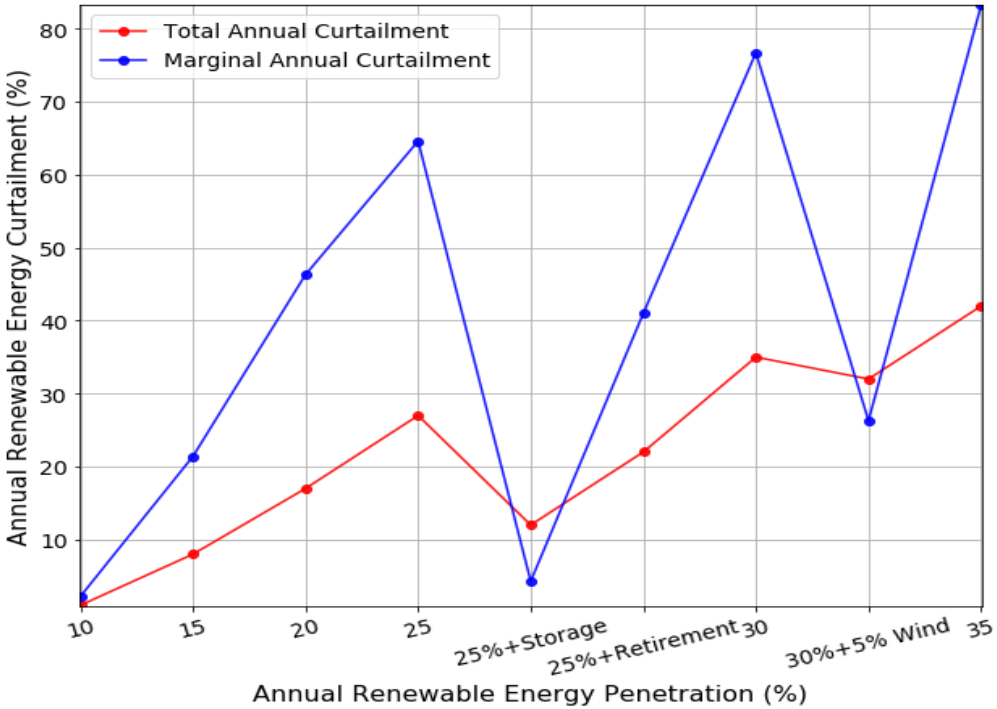
Annual Summary of Flexibility Metrics

Annual Flexibility Indicators

Scenario	5%	10%	15%	20%	25%	30%	35%	High DPV	Storage	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

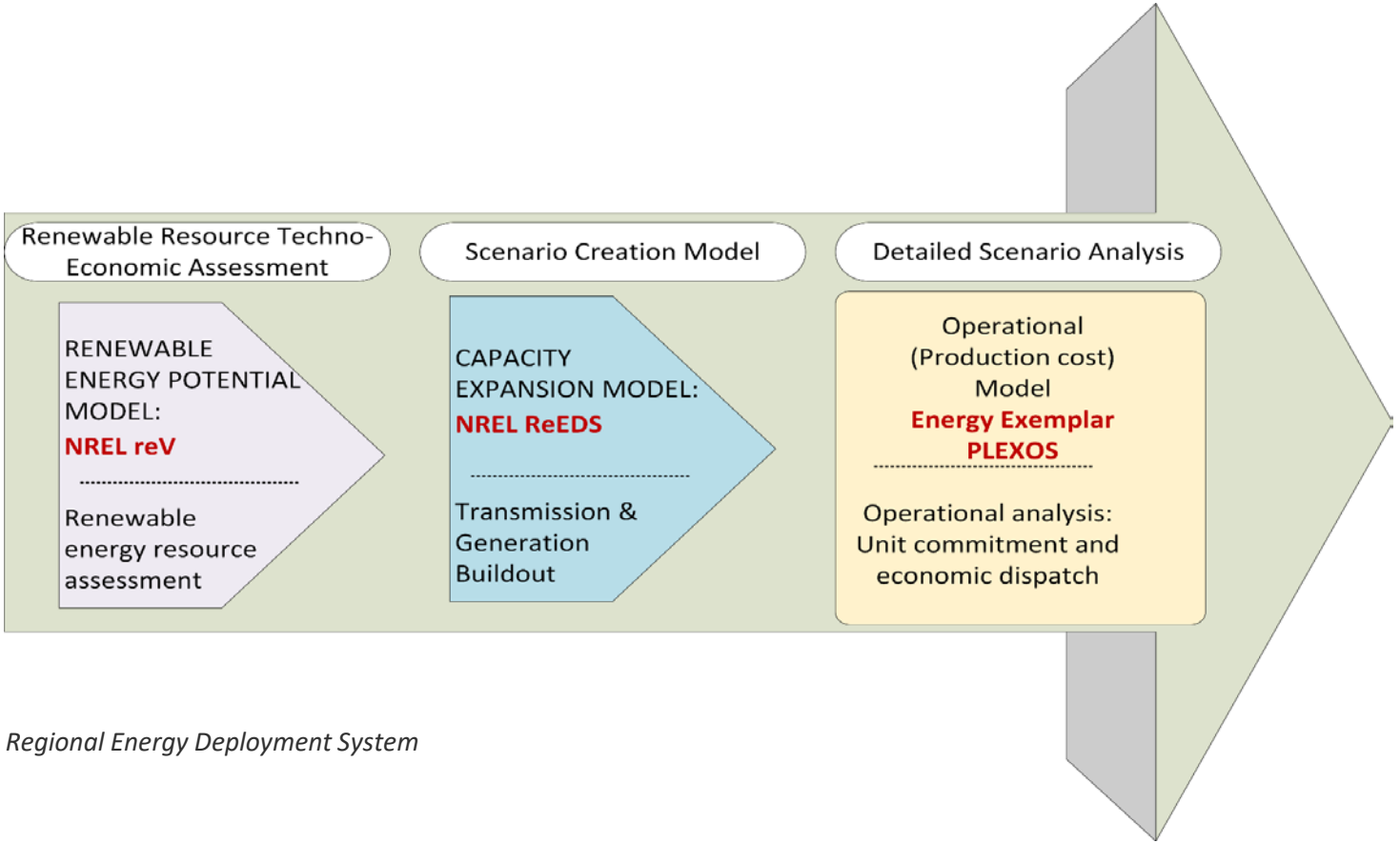
- Maximum instantaneous curtailment occurs in winter for penetrations up to and including 20% and then occurs in spring
- All maximum ramps happen in winter
- Transmission and nuclear retirement are both challenges with increasing PV penetration

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

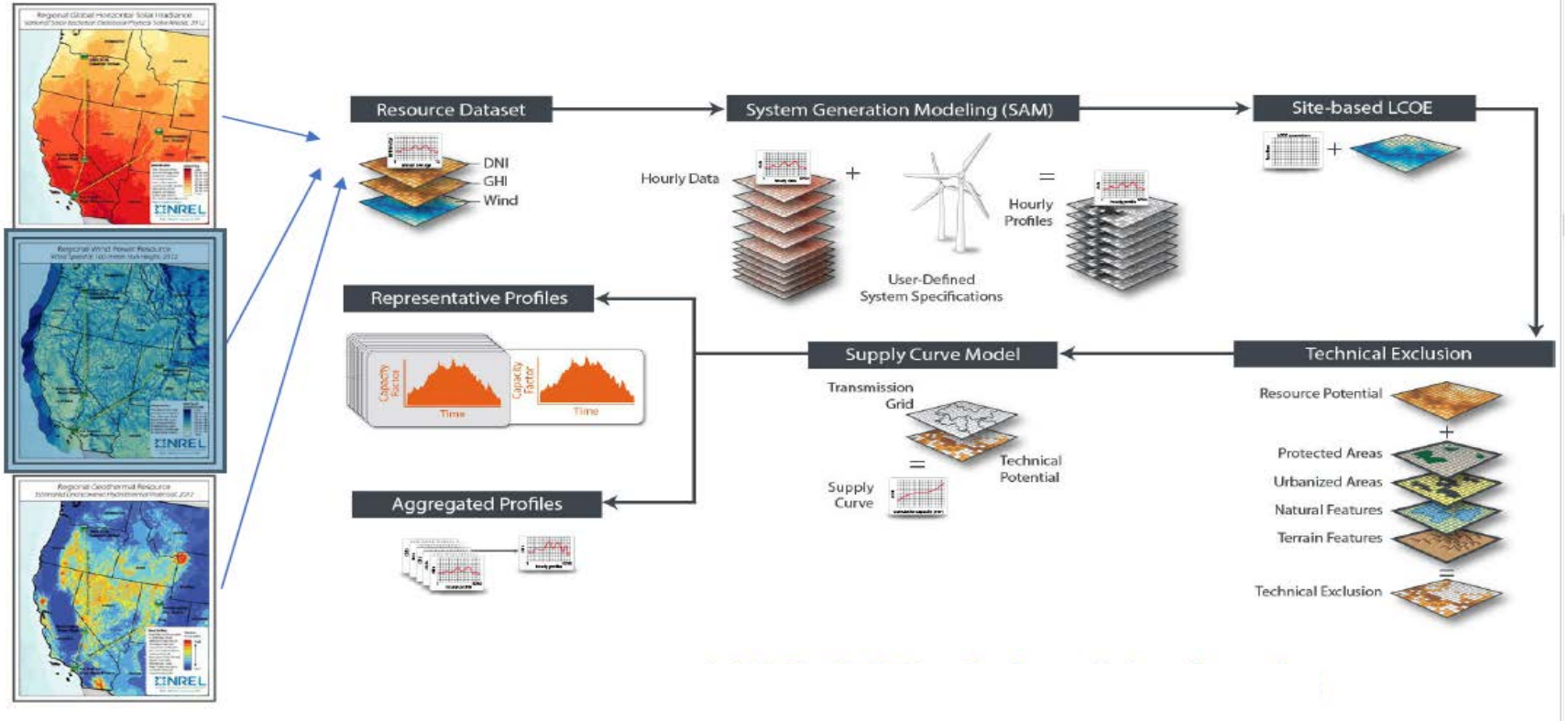
Carbon-Free Resource Integration Study – Phase 2



**ReEDS: Regional Energy Deployment System*

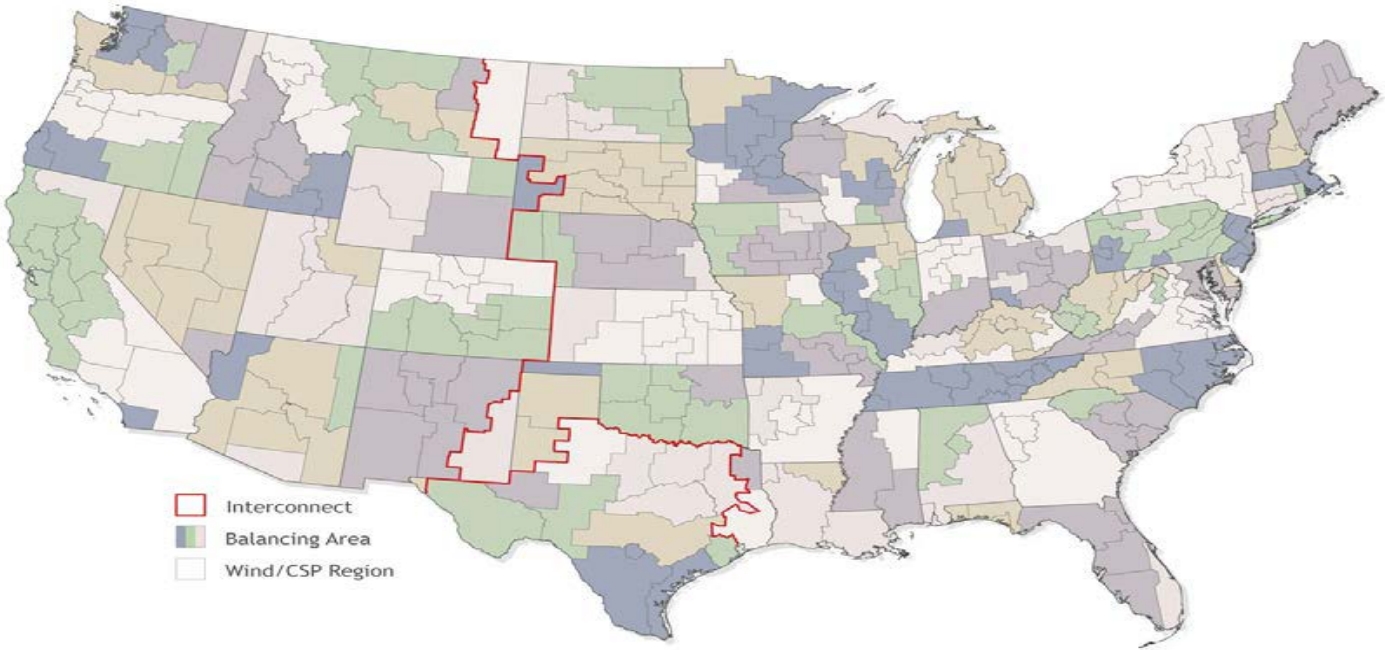
Renewable Energy Potential Model – NREL reV

- 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

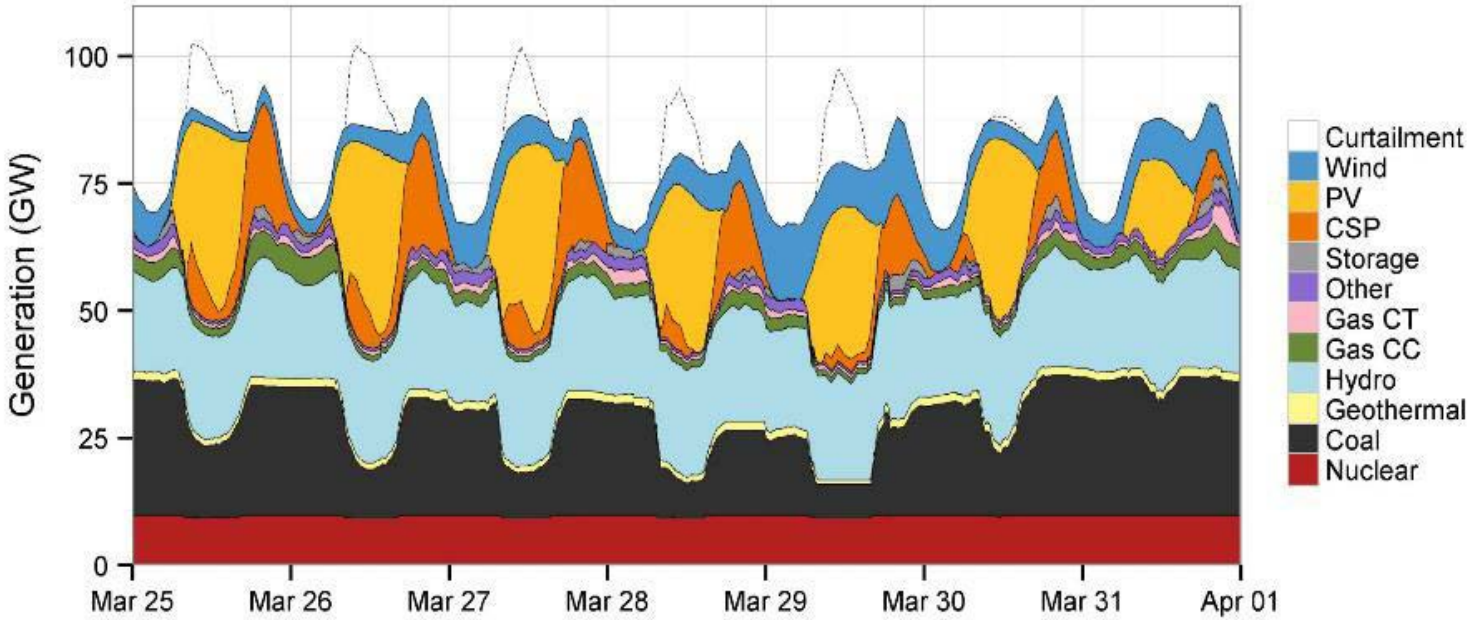
Combinations
- Low/High NG Price with
  - Low/High RE Cost
  - Low/High Geo Cost
  - Low/High CSP Cost
  - Low/High Hydro Cost
  - Low/High Offshore Wind Cost

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?

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

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

JENNINGS CONFIDENTIAL EXHIBIT NO. 18

DOCKET NO. E-7, SUB 1229

CONFIDENTIAL – FILED UNDER SEAL

JENNINGS CONFIDENTIAL EXHIBIT NO. 19

DOCKET NO. E-7, SUB 1229

CONFIDENTIAL – FILED UNDER SEAL

JENNINGS CONFIDENTIAL EXHIBIT NO. 20

DOCKET NO. E-7, SUB 1229

CONFIDENTIAL – FILED UNDER SEAL