Impacts of Renewable Generation on Fossil Fuel Unit Cycling: Costs and Emissions

Clean Energy Regulatory Forum: Preliminary Background Paper

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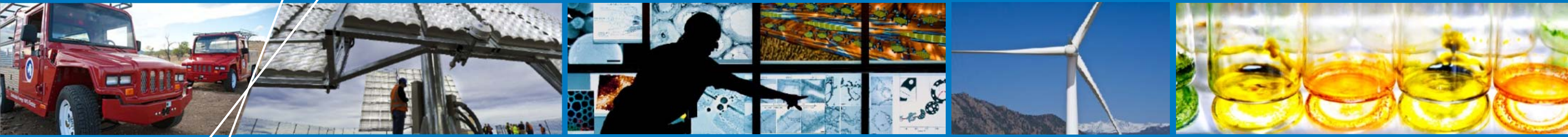
Overview

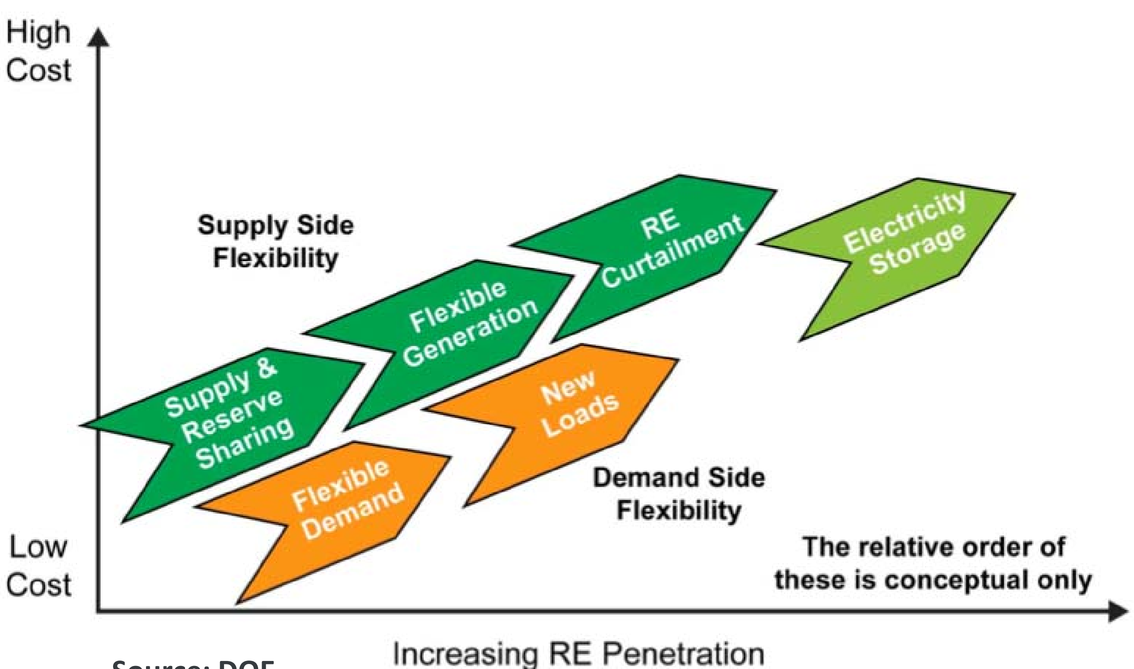
- Why are we concerned about cycling of conventional generators?
- How much does cycling cost?
- Cycling impacts on the value of renewables to the grid
- How does cycling impact emissions?
- Cycling impacts on the emission benefits of renewables.



Lessons from Western Wind and Solar Integration Study (Phase 1)

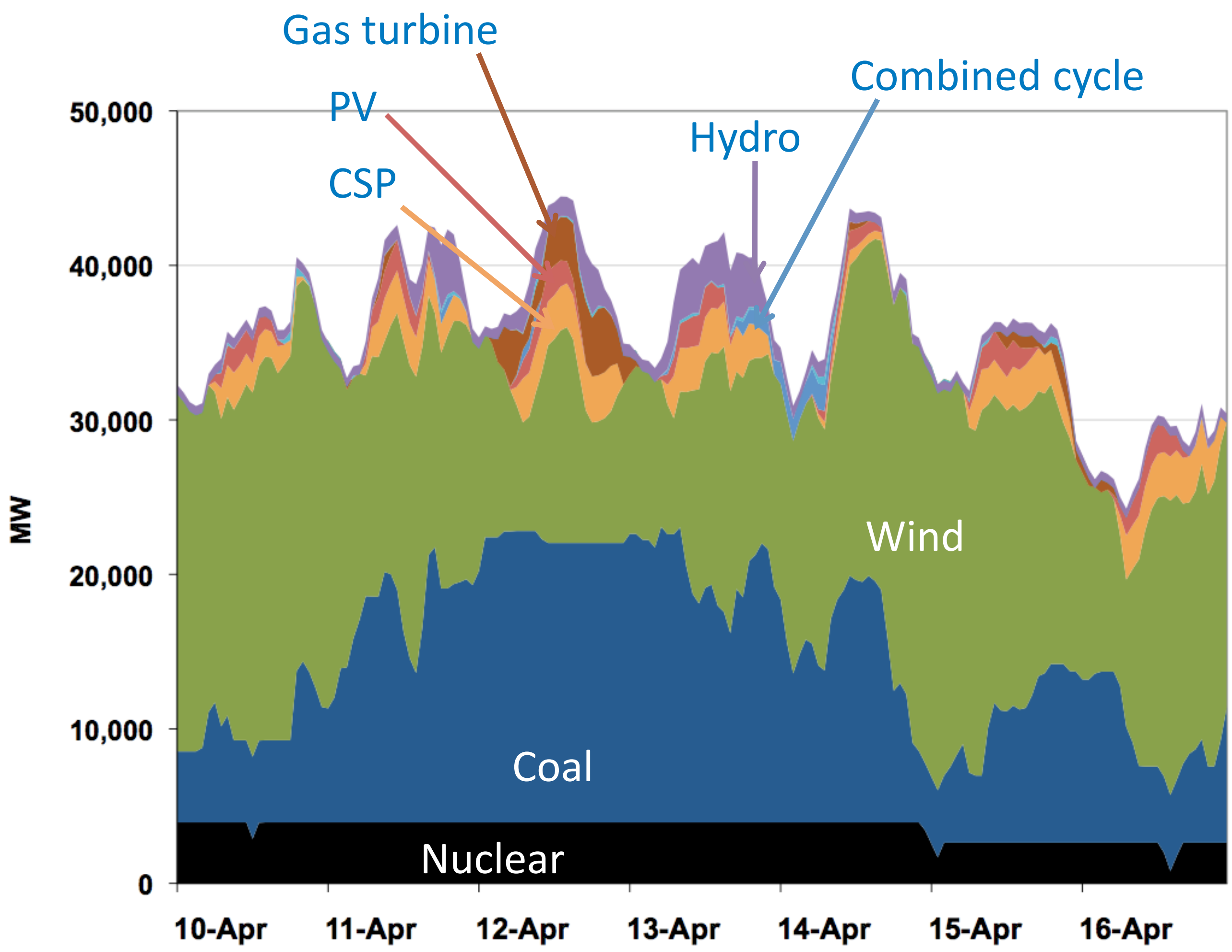
WestConnect: Operationally Feasible to Accommodate 30% Wind and 5% Solar – Conditions Apply

- Substantially increase balancing area cooperation
- Increase use of sub-hourly scheduling
- Increase utilization of transmission
- Enable coordinated commitment and dispatch over wider regions
- Use forecasts optimally in operations
- Increase flexibility of dispatchable generation (e.g. thermal units, storage)
- Commit additional operating reserves as appropriate
- Implement/expand demand response programs
- Require wind to provide down reserves.



Source: DOE

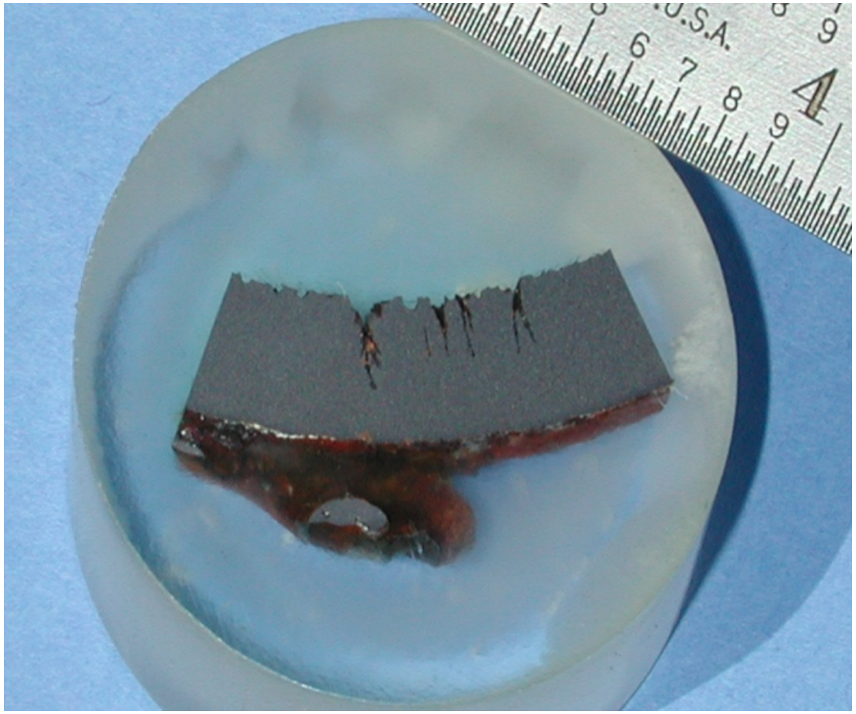
What Happens to Emissions and Wear and Tear Costs?



Source: Western Wind and Solar Integration Study, 2010.

Adding wind and solar generation leads to more startups and ramping at existing thermal units, especially coal.

Boiler Corrosion Fatigue

Source: Steve Lefton, Intertek APTECH, with permission.

Startups and ramping can lead to fatigue on various parts of a generator due to thermal stresses (temperature change).

Lessons from Previous Studies

- **Renewable penetration leads to increased cycling (off/on) and load following (varying levels of output) operation at fossil-fueled units**
- **Cycling and load following can lead to increases in operation and maintenance costs due to fatigue on parts**
  - How does this affect the cost of integrating renewables?
  - How does this affect the emissions impact of integrating renewables?

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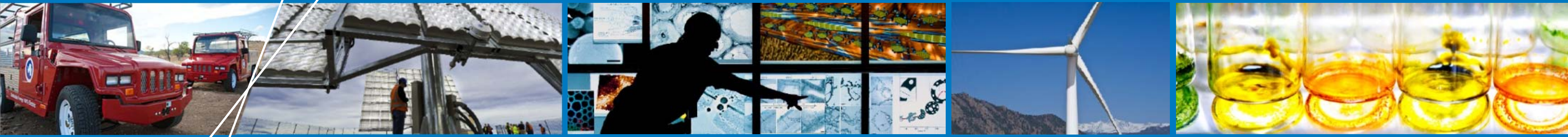


How Much Does Cycling Cost?

Cycling Cost Estimates

- **This section is based on work done by Intertek APTECH**
- **Cycling (on/off) and ramping generators leads to temperature changes that can cause materials to crack and fail**
- **APTECH estimates the cost of these repairs per cycle or ramp**
  - Including cold, warm, hot starts, and load following (ramping).

APTECH Methods to Estimate Cycling Costs

- APTECH has analyzed over 400 units worldwide to estimate impacts of cycling
- 170 units met criteria for inclusion in database to estimate typical costs
  - U.S. units, recently analyzed with newest methods.

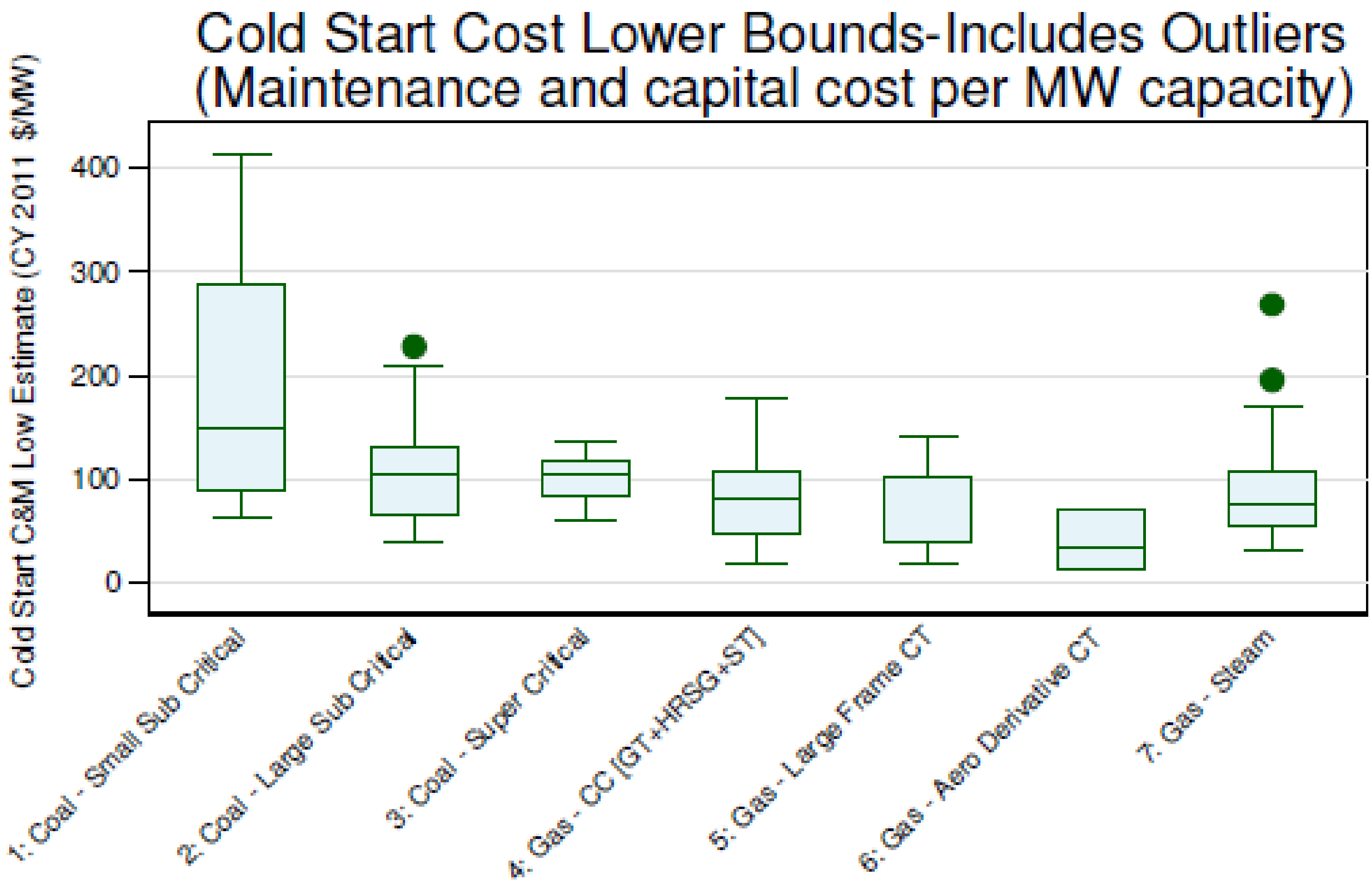
Top-down

- Regression analysis
- Filter all maintenance costs for potential cycling-related repairs
- Include all historical cycling information and maintenance cost timing.

Bottom-up

- Detailed analysis of 7-10 years of work orders
- Specific analysis of all major plant components
- Operator interviews
- Used to confirm top-down analysis.

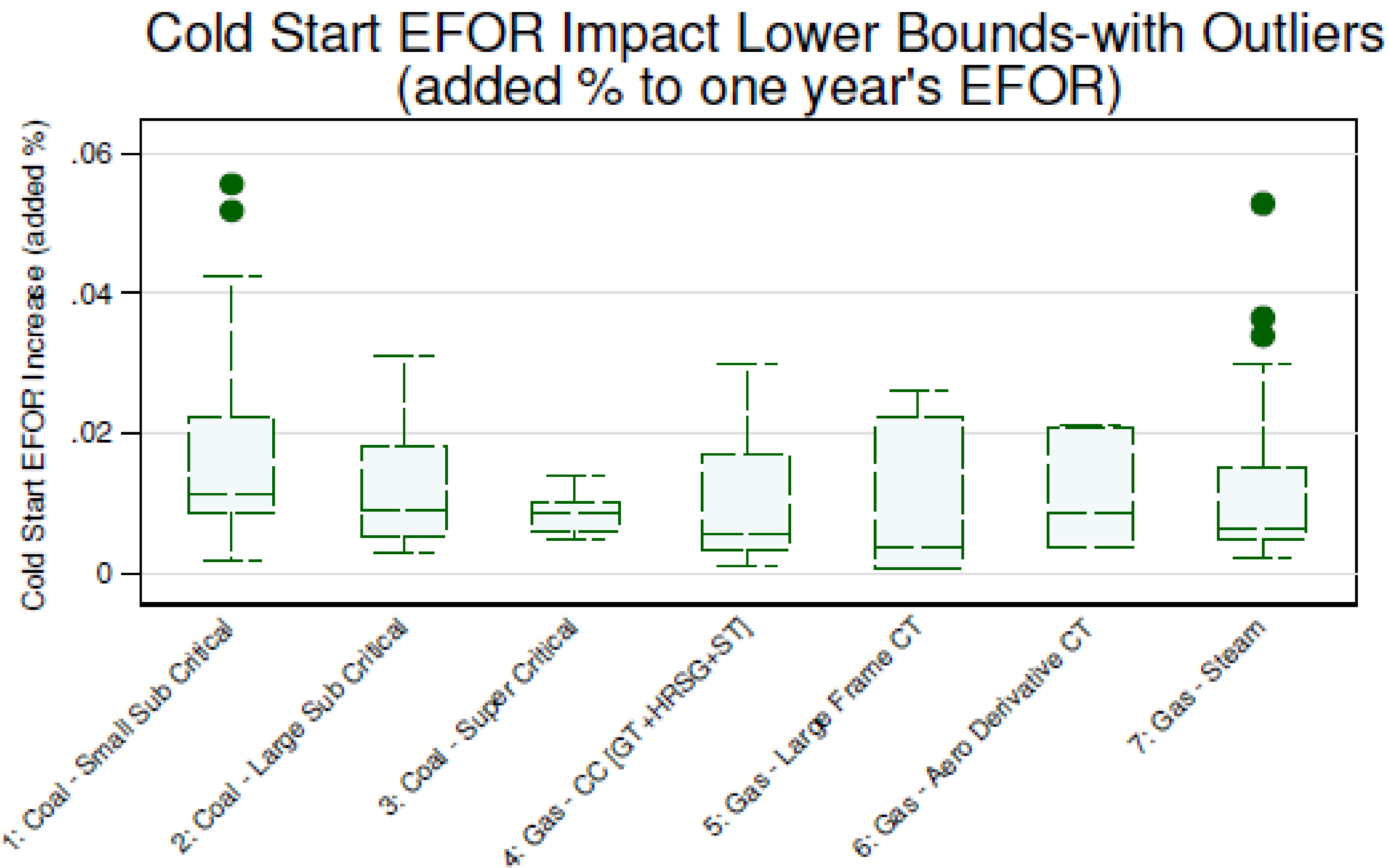
Cold Start Costs (Per MW Capacity)



Coal start costs are highest, but gas startup costs still significant.

Kumar et al, “Power Plant Cycling Costs”, Intertek/APTECH report #AES 12047831-2-1

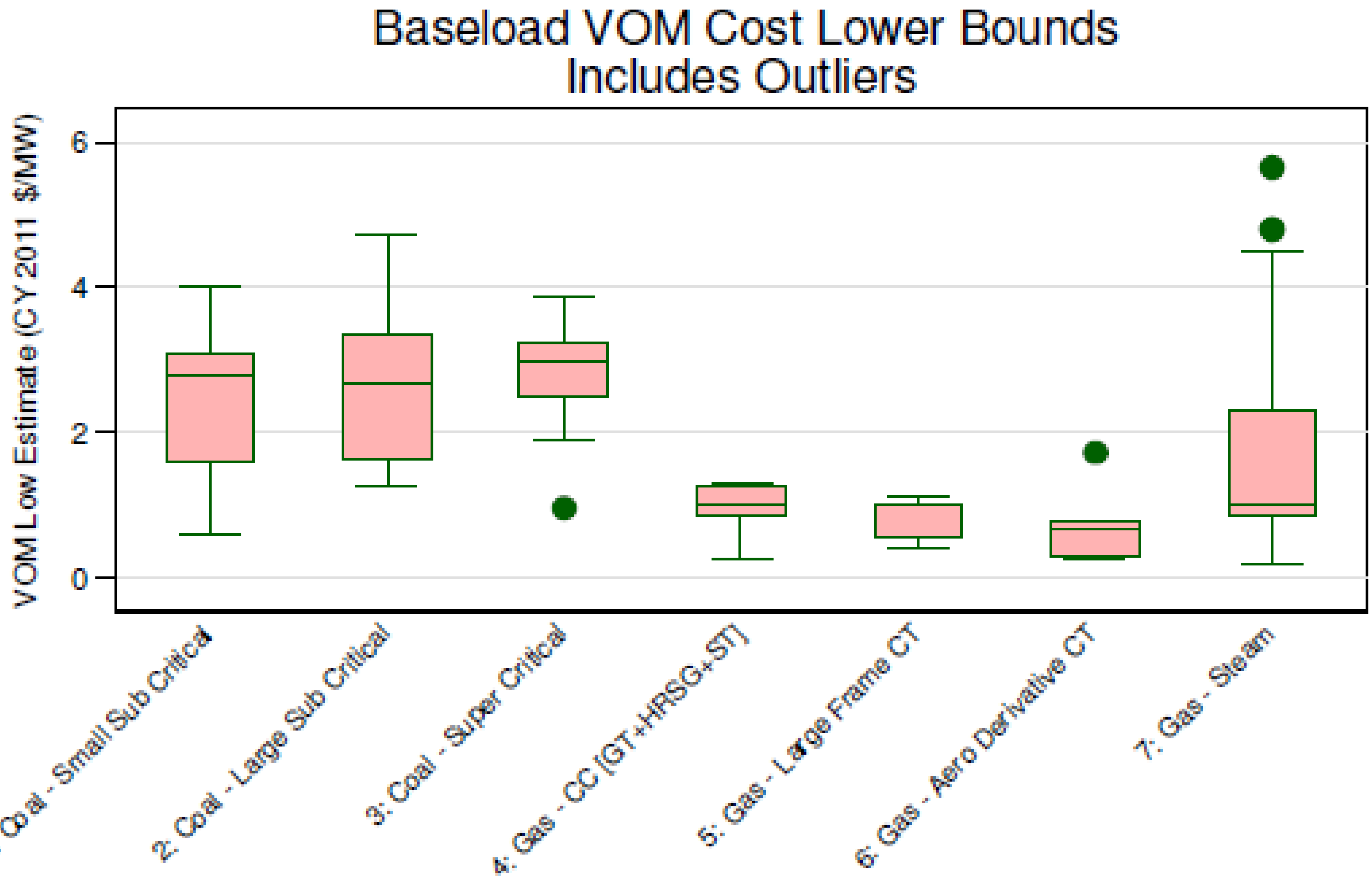
Cold Start-Forced Outage Rate Impacts



Fatigue caused by startups leads to more unplanned unit outages.

Kumar et al, “Power Plant Cycling Costs”, Intertek/APTECH report #AES 12047831-2-1

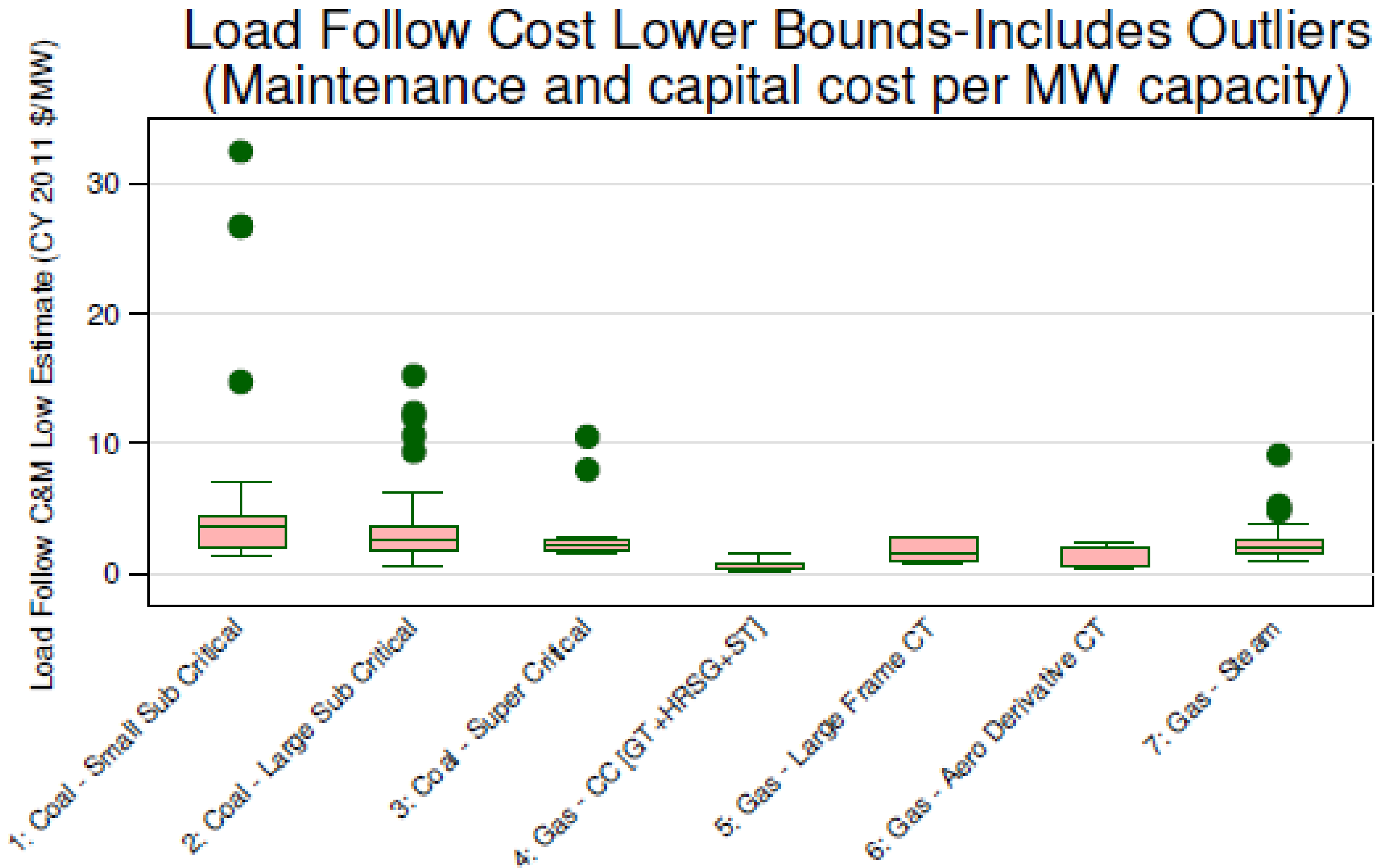
Baseload Operation and Maintenance Costs



Baseload (not considering cycling) O&M is higher for coal units.

Kumar et al, “Power Plant Cycling Costs”, Intertek/APTECH report #AES 12047831-2-1

Load Following (Ramping) Costs



Load following costs are much lower than startup costs, but they happen more frequently.

Kumar et al, "Power Plant Cycling Costs", Intertek/APTECH report #AES 12047831-2-1

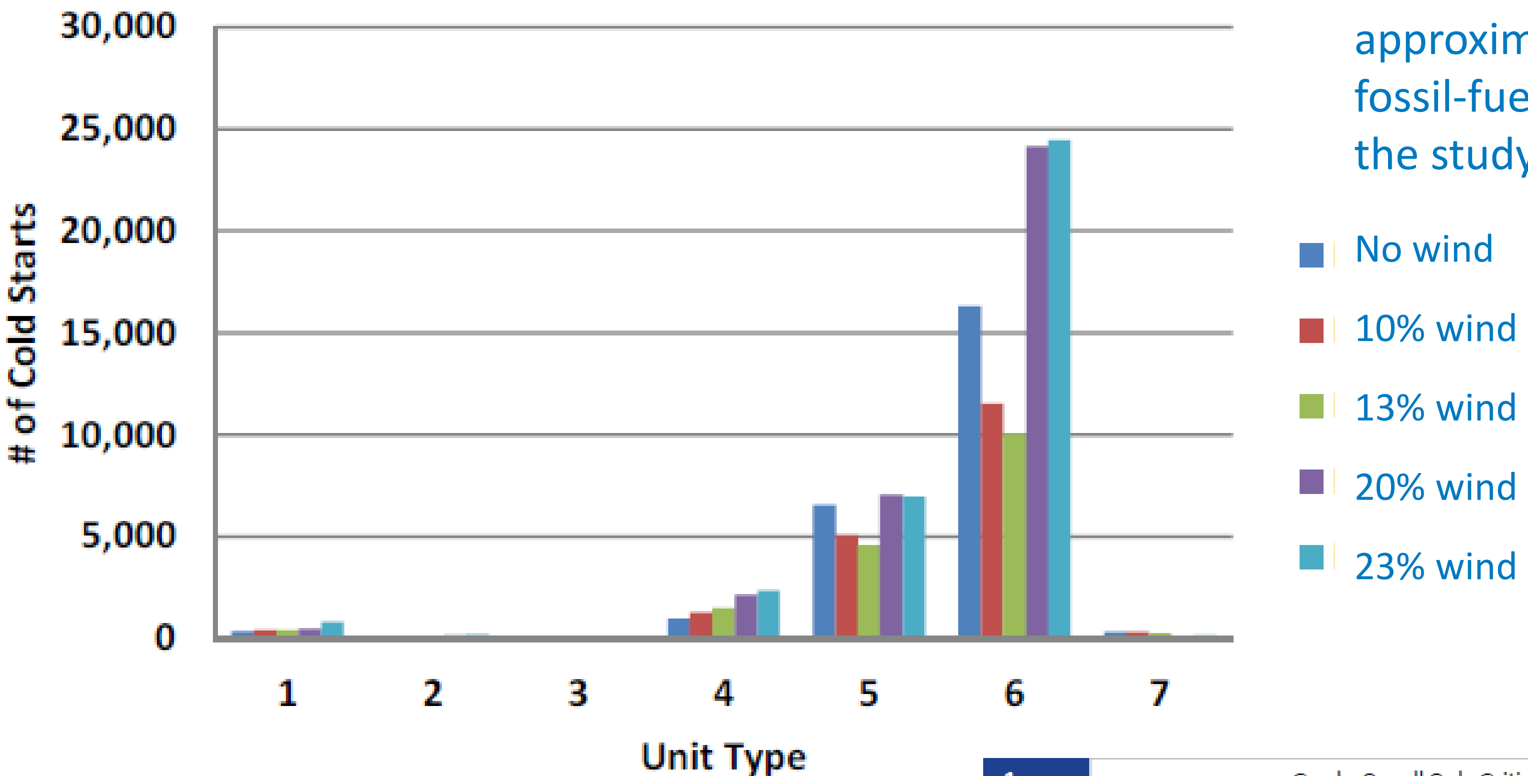
Re-analysis of Western Wind and Solar Integration Study Phase 1 Results – Cycling Impacts on the Value of Renewables to the Grid

Cost of Cycling in Renewable Scenarios

- GE re-analyzed the dispatch results of the Western Wind and Solar Integration Study (WWSIS)
- APTECH startup and load follow cost estimates were added to the original cost estimates
- Value of renewable energy was re-calculated.

Number of Cold Starts Per Year

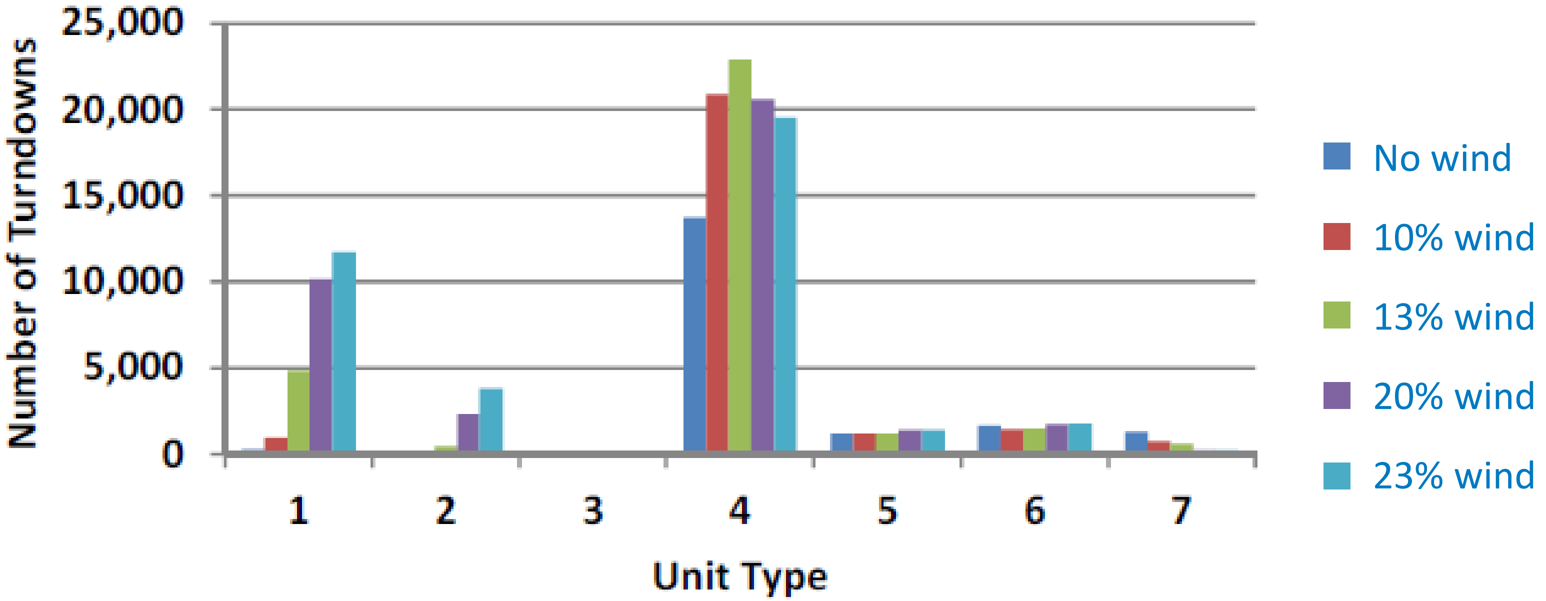
There are approximately 1,000 fossil-fueled units in the study area.



Cold starts of coal units go up significantly, but the total number of cold starts of coal units is still small.

1	Coal - Small Sub Critical
2	Coal - Large Sub Critical
3	Coal - Super Critical
4	Gas - CC
5	Gas - Large Frame CT
6	Gas - Aero Derivative CT
7	Gas - Steam

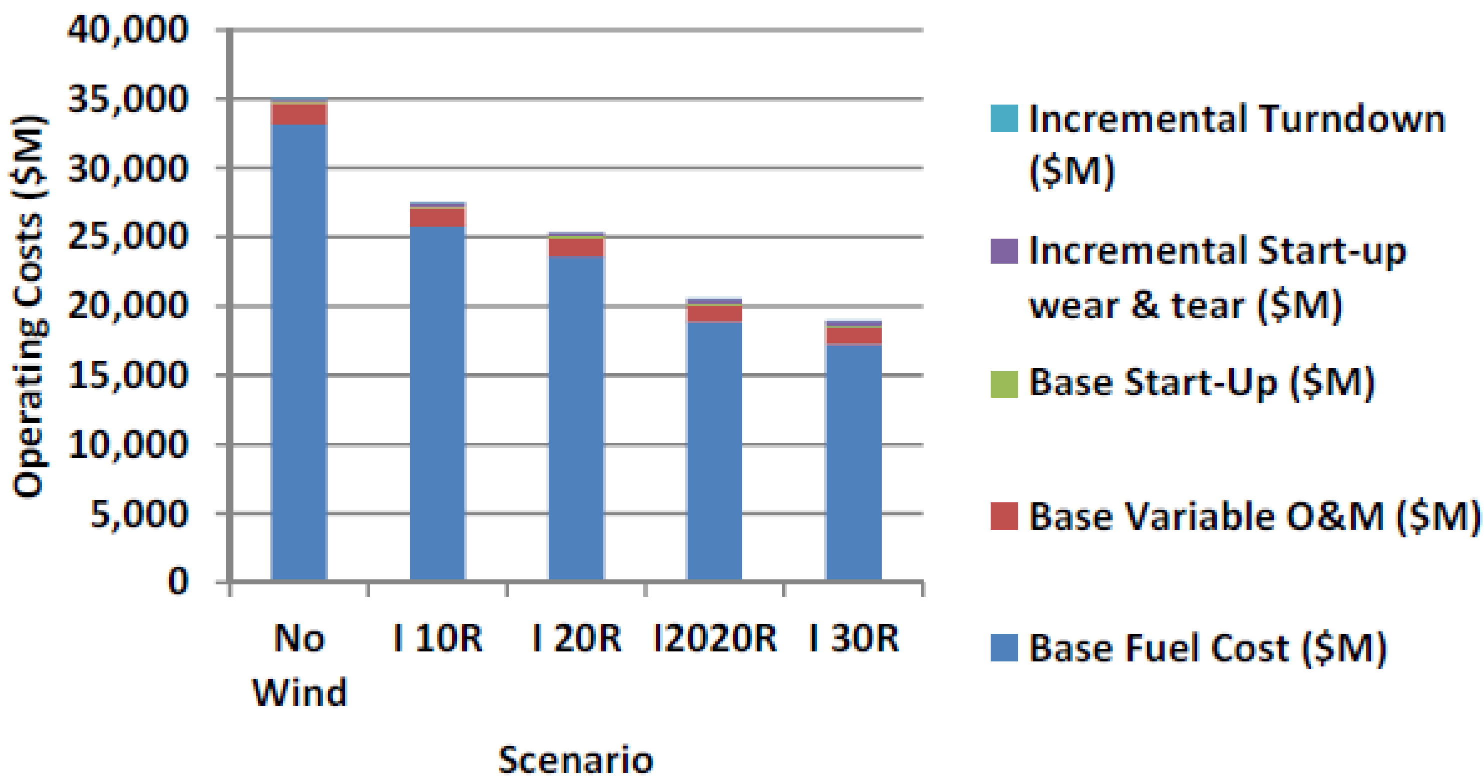
Number of Ramping Events



Ramping of coal units goes up significantly while there is little change for gas units.

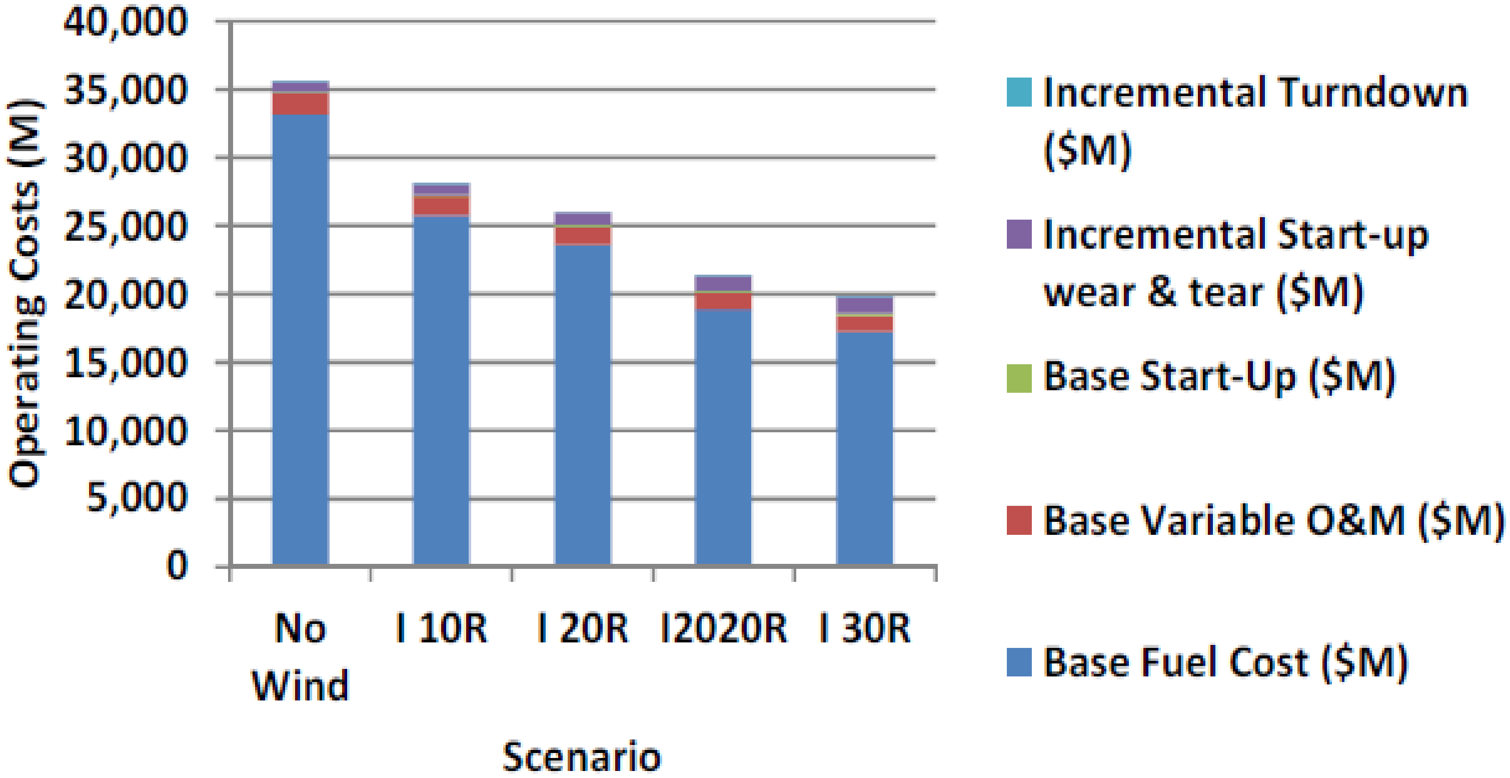
1	Coal - Small Sub Critical
2	Coal - Large Sub Critical
3	Coal - Super Critical
4	Gas - CC
5	Gas - Large Frame CT
6	Gas - Aero Derivative CT
7	Gas - Steam

Operating Costs – Lower Bound Cycling Cost



Additional startup costs make up a very small portion of total costs (mostly fuel).

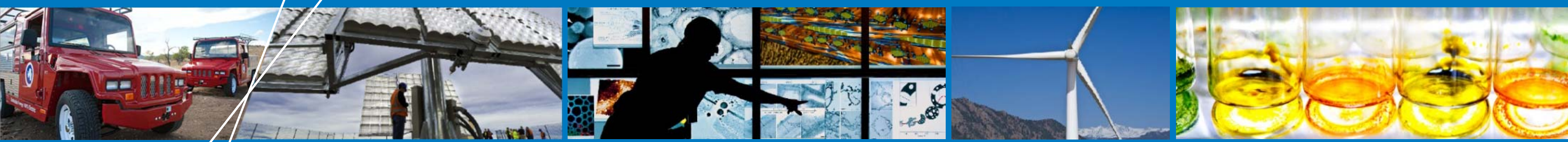
Operating Costs – Upper Bound Cycling Cost



Even in the upper bound case (detailed cost inputs are confidential), additional startup costs are a small fraction of total costs.

Conclusions

- **WWSIS1 found value of wind to be ~$85/MWh**
  - Highly sensitive to gas price assumptions
- **Lower bound cycling cost estimates would reduce that value by 0.1% to 0.7%**
- **Upper bound cycling cost estimates (not shown in this presentation and covered by NDA) would reduce that value by 0.6% to 2.4%**
- **Value of wind and solar is reduced by $0.06 to $2.00/MWh, depending on assumptions.**



How Does Cycling Impact Emissions?

Estimating Cycling Impacts on Emissions

- **NREL analyzed historical data from ~95% of fossil-fueled generation in the U.S.**
- **Estimates were made for emissions (CO_2, NO_x, SO_2) impacts due to:**
  - Part-load operation (operating significantly below rated capacity)
  - Startups (cycling off/on)
  - Load following/ramping (changing generation levels).

Wind Impacts on Emissions

- **Previous studies:**
  - Hypothesized that emission reductions from wind are not as high as expected due to unit cycling
  - Some evidence exists, but no studies have modeled system from generator properties through dispatch.
- **Western Wind and Solar Integration Study (WWSIS) (Phase 2 Plan):**
  - Understand interaction between wind/solar penetration and thermal unit cycling
  - Step-by-step approach to emissions
    - Gather unit-specific data on emissions
    - Characterize impacts of part-load operation, ramping, startups on existing fossil-fueled generators
    - Include these properties in unit commitment and dispatch modeling.

EPA Continuous Emission Monitors (CEMs)

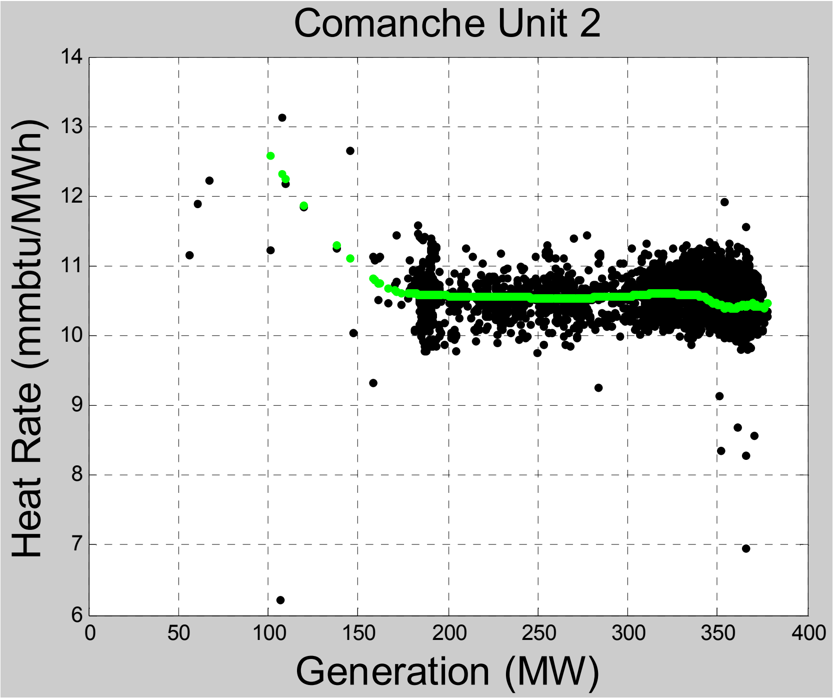
- **Hourly emission measurements on almost all fossil fuel units in the U.S.**

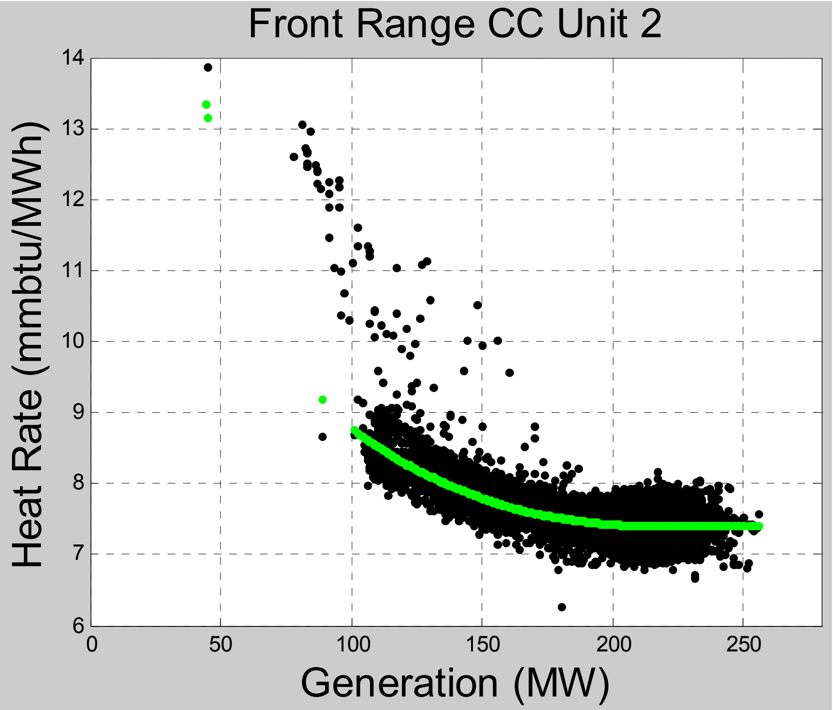
- **Use CEM data to find unit-specific data**
  - Heat rate (and CO_2 emissions) as a function of generation
  - Emissions (NO_x, SO_2) as a function of generation

- **Data from year 2008.**

Heat Rate and Emission Curves

- **Local linear fit for every unit**
- **Eliminate units with obviously clustered data caused by:**
  - Installation of pollution control equipment during year
  - Part-time operation of pollution control equipment
  - Combined cycle units in various modes of operation.

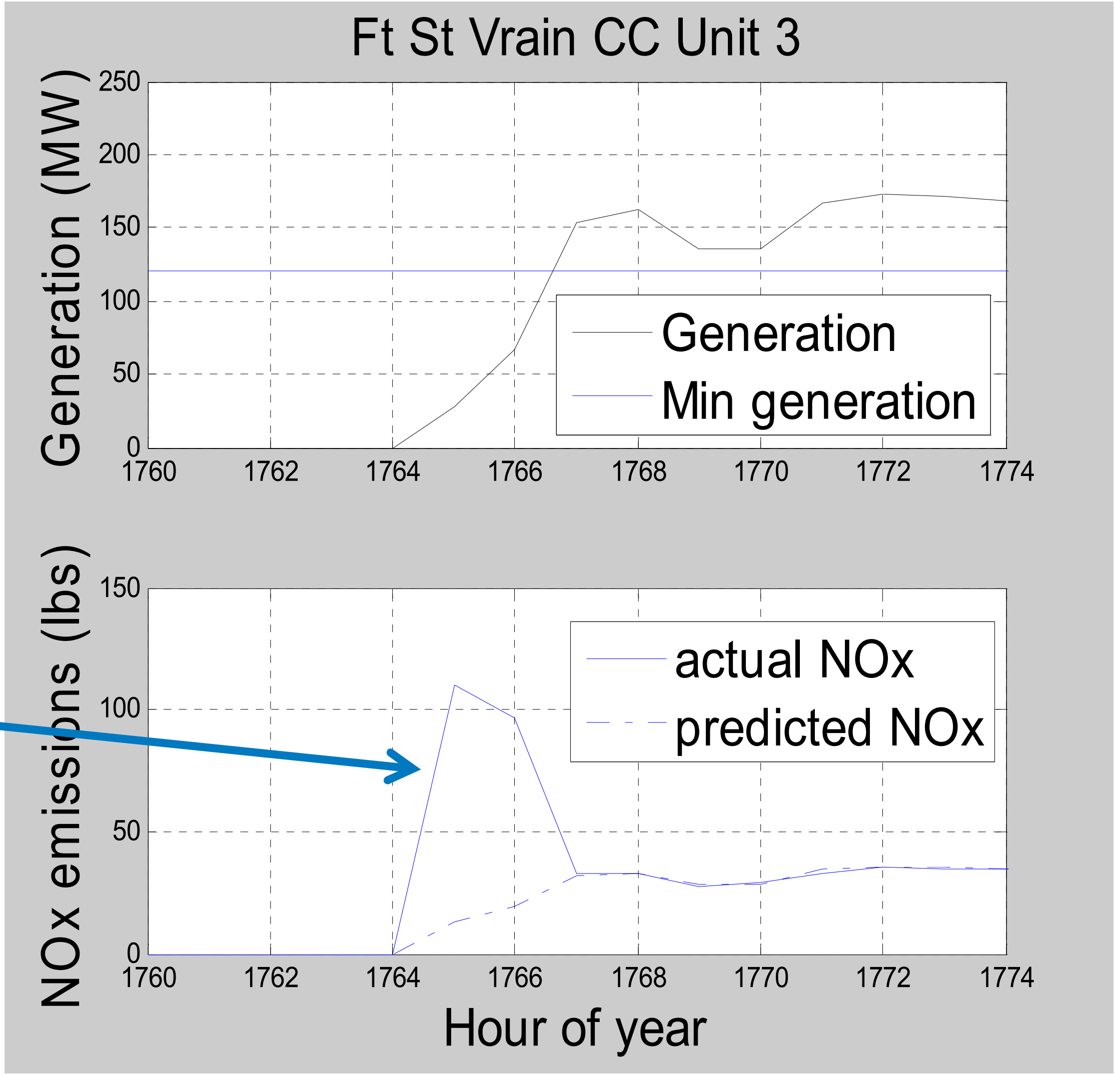




EPA Continuous Emissions Monitor data, 2008

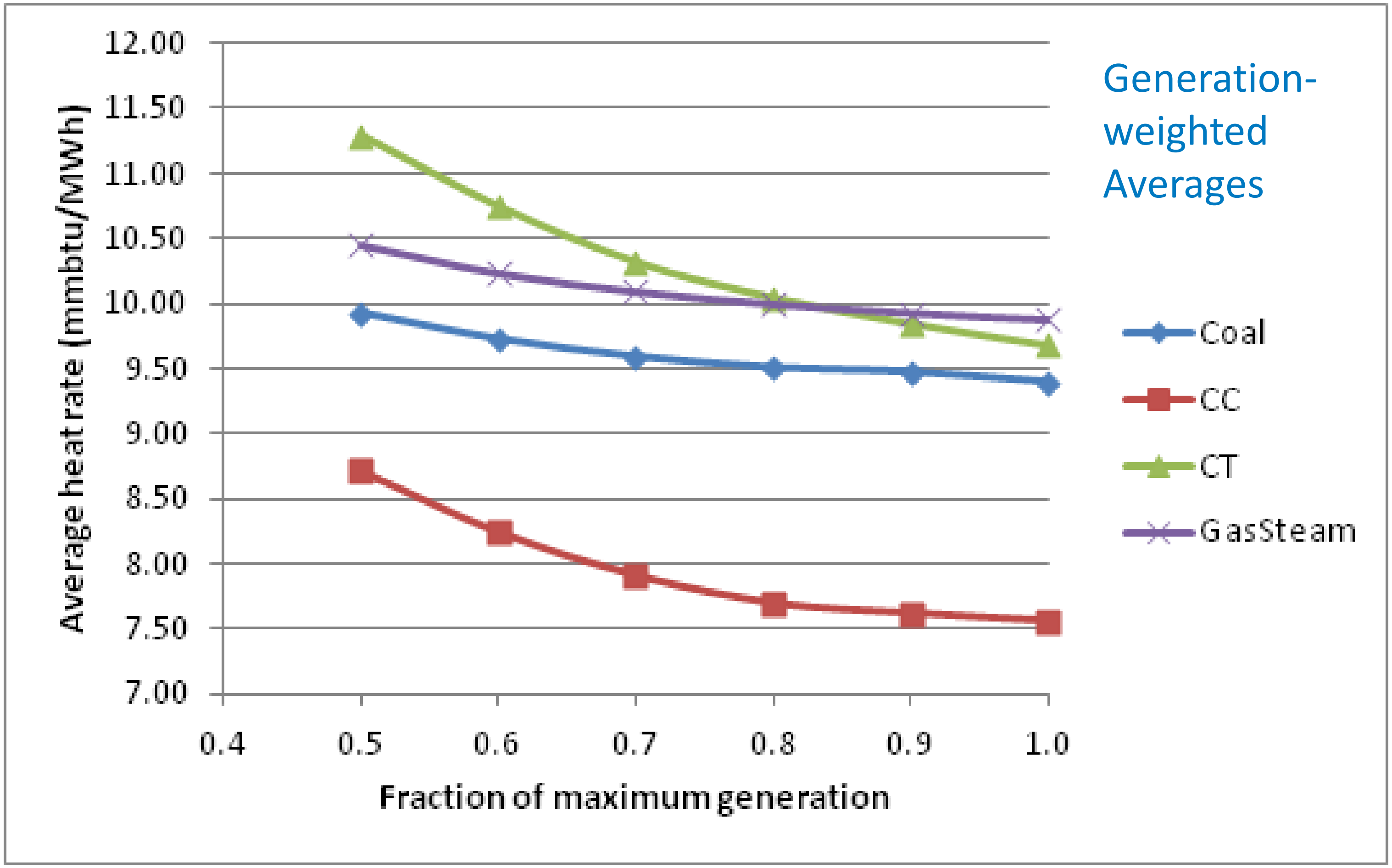
Startup Emissions

- **Add up residuals from all hours prior to and following a startup until unit reaches its minimum generation level**
- **Integral between the predicted and actual NO_x curves**
- **Ramping emissions quantified in similar manner.**



EPA Continuous Emissions Monitor data, 2008

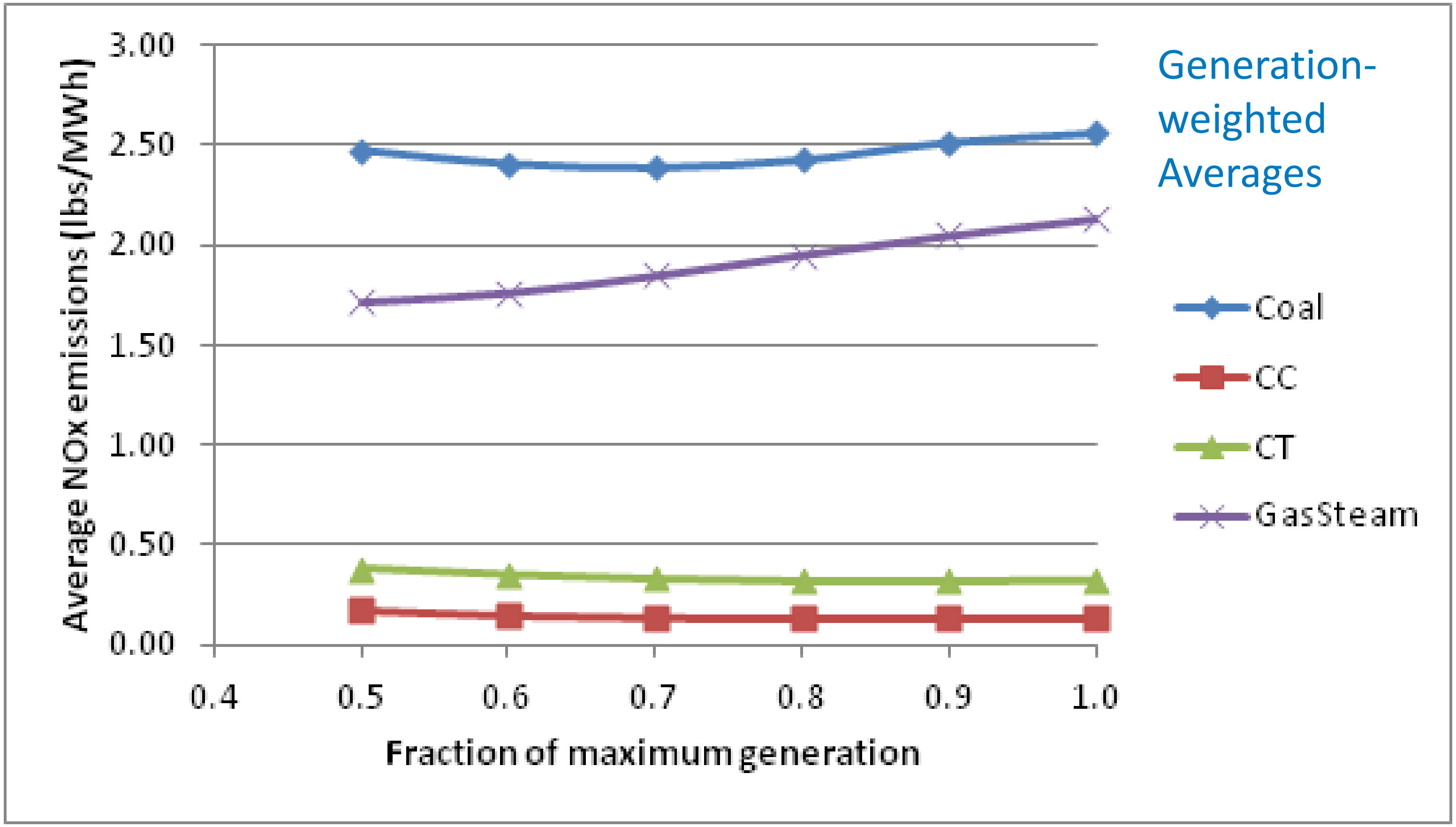
Results (Heat Input or CO_2)



Percentage increase in heat rate at 50% of capacity.

Coal	Gas CC	Gas CT	Gas steam
6%	15%	17%	6%

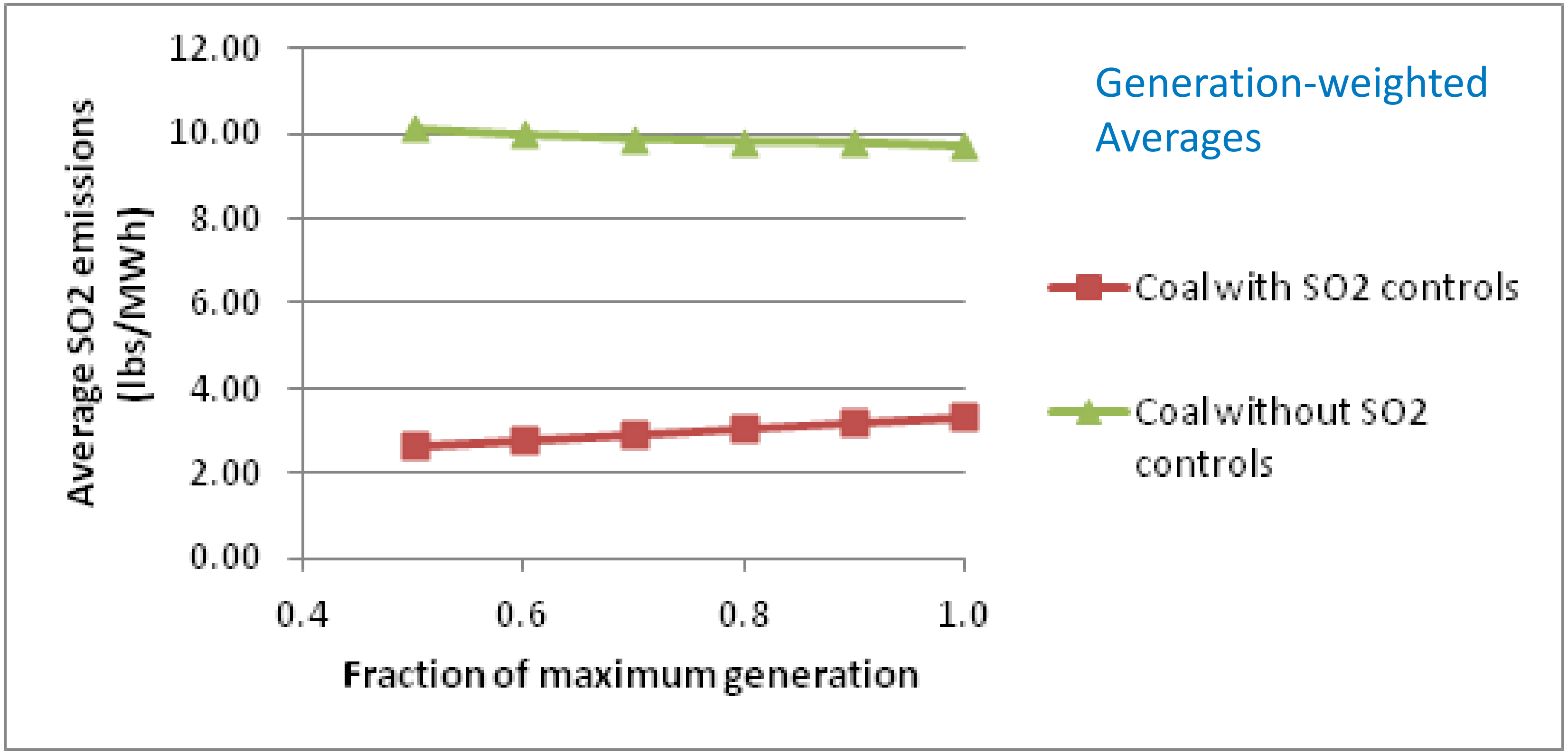
Results (NO_x)



Percentage increase in NO_x/MWh at 50% of capacity.

Coal	Gas CC	Gas CT	Gas steam
-3%	29%	16%	-19%

Results (SO_2)



Percentage increase in SO_2 emission/MWh at 50% of capacity.

Coal (controlled)	Coal (uncontrolled)
-20%	4%

Startups and Ramping

Startups

	CO_2	NO_x	SO_2
Coal	1.2	1.0	0.8
Gas CC	0.3	6.1	n/a
Gas CT	0.4	1.8	n/a
Gas steam	0.9	0.0	n/a

Ramping

	CO_2	NO_x	SO_2
Coal	0.03	0.08	0.07
Gas CC	0.01	0.08	n/a
Gas CT	0.01	0.01	n/a
Gas steam	0.01	0.08	n/a

Startup and ramping emission penalty listed in hours of equivalent full-load operation. Coal units emit less NO_x during startup relative to full-load operation. Ramping leads to far less emissions compared to startups, but occurs more often.

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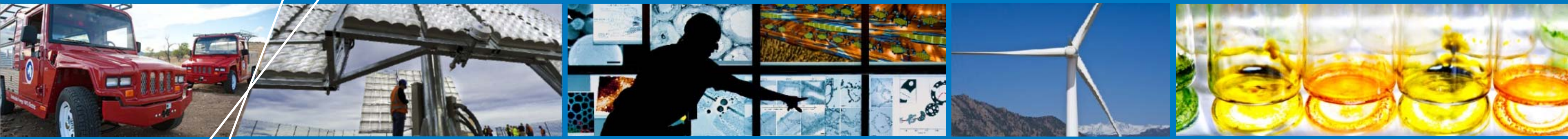


Re-analysis of Western Wind and Solar Integration Study Phase 1 Results – Cycling Impacts on the Emission Benefits of Renewables

Emission Impact of Cycling with Renewables

- **NREL re-analyzed the dispatch results of the Western Wind and Solar Integration Study (WWSIS)**
- **Startup, part-load, and ramping emission estimates were added**
- **Emissions avoided by wind and solar generation were estimated**
    - Effects of part-load operation, startups, and ramping were separated.

WWSIS Re-analysis

- **WWSIS1 was re-analyzed for startup, ramping, and part-loading emissions of NO_x and CO_2**
  - Original dispatch used.
- **Generic emission rates (specific to WECC) applied by category to previously modeled dispatch**
  - Slightly different than the U.S. averages shown here – coal plants emit more and gas plants emit less in WECC
  - Coal part-load NO_x emissions benefit bigger in WECC.

WWSIS Re-analysis

- Numbers are avoided emissions per MWh displaced generation
- Numbers with +/- are changes to original numbers due to cycling, part-loading, and ramping
- Numbers in parentheses are changes in percentage terms.

	NO_x benefit of renewables (lbs/MWh)	CO_2 benefit of renewables (tons/MWh)
Assuming flat emission curves	0.422	0.499
+Considering part-load emission rates	+0.031 (+7.3%)	-0.006 (-1.3%)
+Considering startup emissions	-0.006 (-1.3%)	-0.001 (-0.3%)
+Considering ramping emissions	-0.011 (-2.7%)	-0.001 (-0.2%)
Total	0.436 (+3.3%)	0.490 (-1.7%)

Conclusions and Future Work

- **Startups, part-load efficiencies, and ramping have a relatively small impact on total cost and emissions**
  - Compared to determining which unit is on the margin.
- **Cycling may have significant impacts at specific times or places, or for individual generators**
  - Specific generators have significantly higher cost and emission impacts from cycling and load following
  - Identifying these generators and addressing the issues could be important.
- **How does wind/solar impact emissions?**
  - Type of unit (and emissions performance of unit) on margin more important than "cycling"
  - WWSIS2 will use unit-specific data for these parameters.

WWSIS Phase 2 (Follow-up Work)

1. Obtain better data for **wear and tear costs** of fossil-fueled units due to on/off cycling and load following
2. Examine **emission impacts** of fossil-fueled units due to on/off cycling and load following
3. Optimize unit commitment and economic dispatch with these inputs and examine impact of increasing penetrations of wind and solar on thermal units
4. Examine mitigation options to reduce costs of thermal unit cycling and ramping.

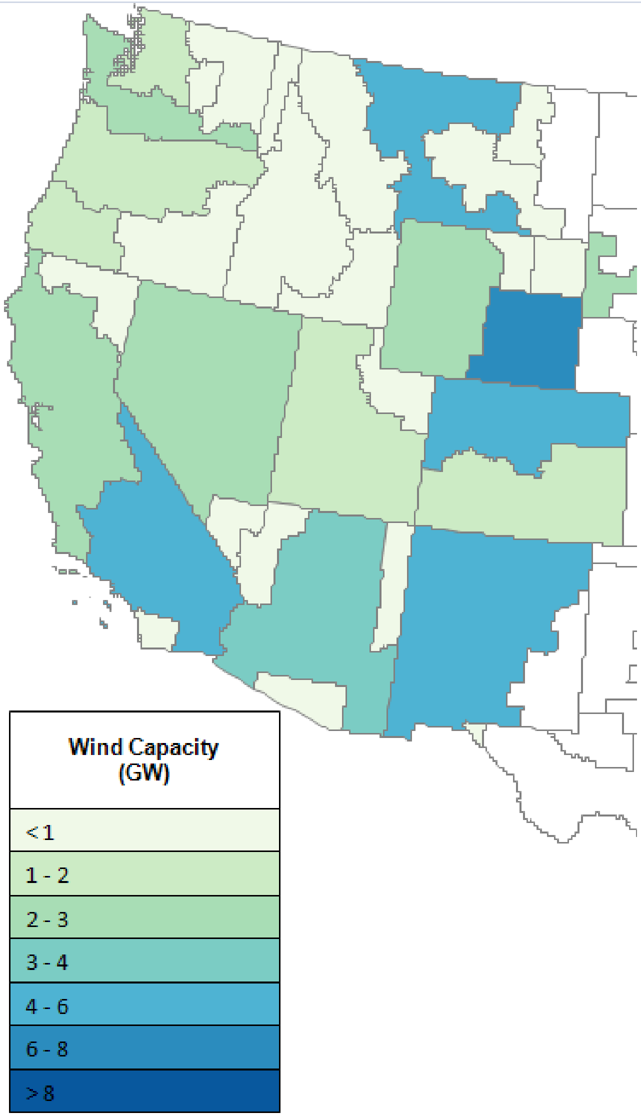
Scenarios for WWSIS2

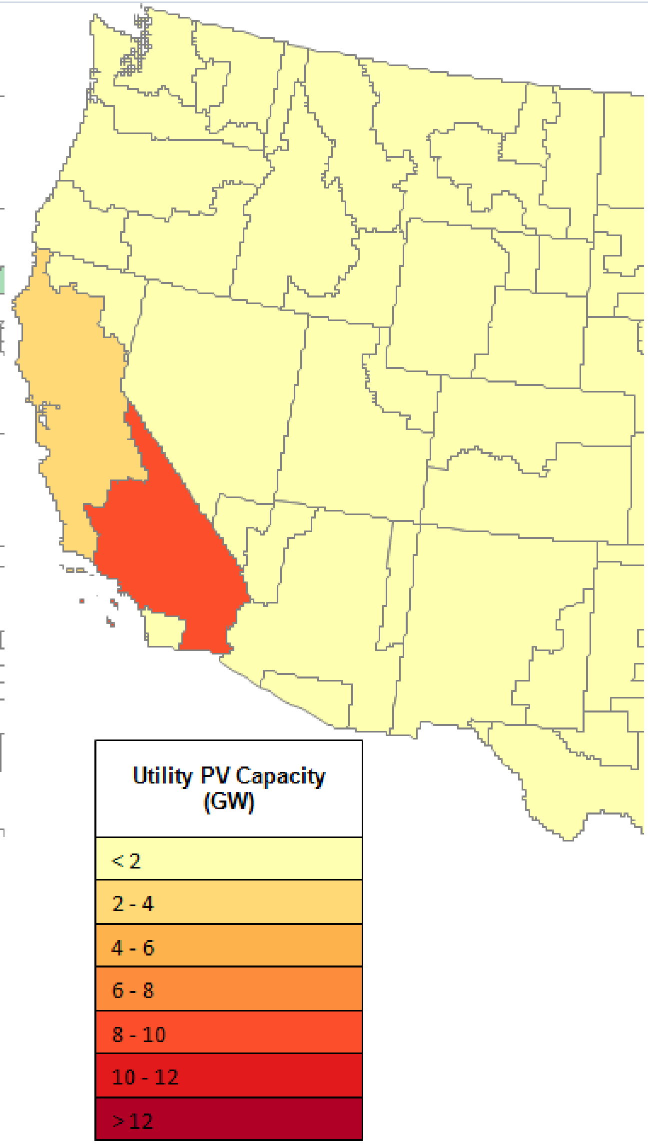
Renewable Penetration (Annual) by Energy	High Wind	High Mix	High Solar
11%	WECC TEPPC 2020 8% wind 3% solar		
33%	25% wind 8% solar	16.5% wind 16.5% solar	8% wind 25% solar

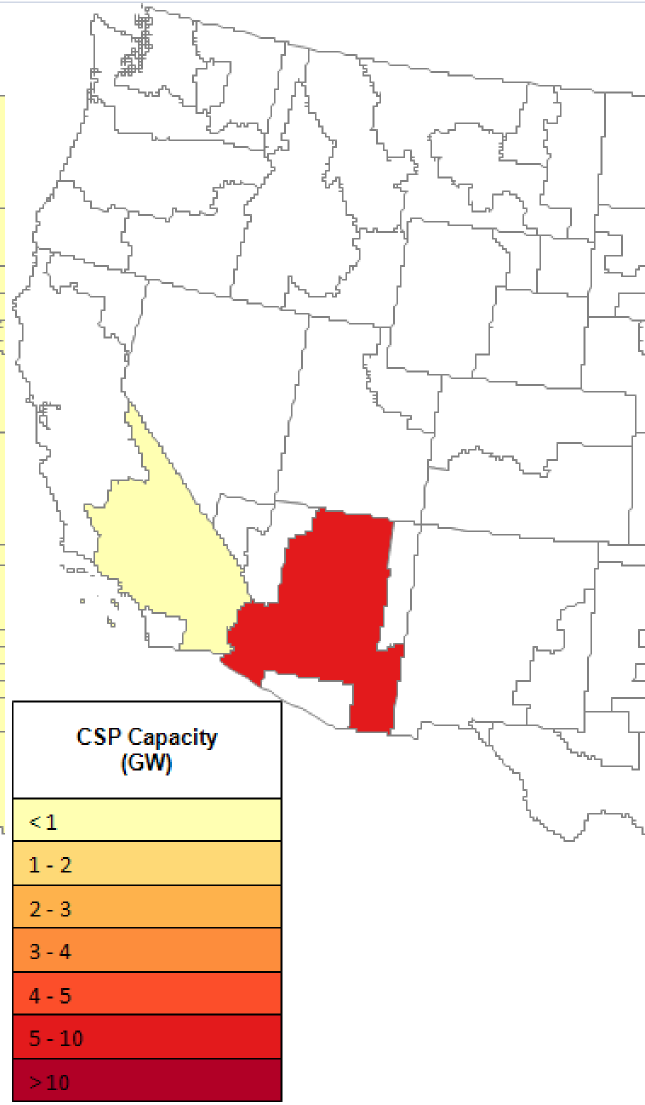
Use NREL ReEDS model to expand generation fleet subject to geographical and electric power system constraints (and select regional distribution).

- Solar consists of 40% CSP and 60% PV
- CSP has 6 hours of storage.

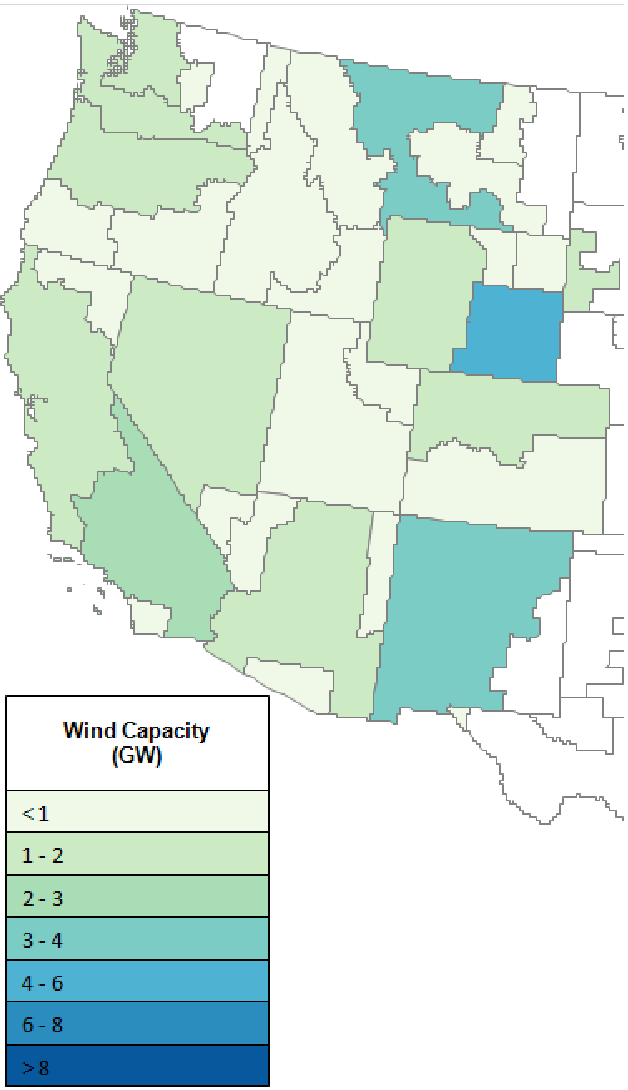
High Wind (25% Wind, 4.8% PV, 3.2% CSP)

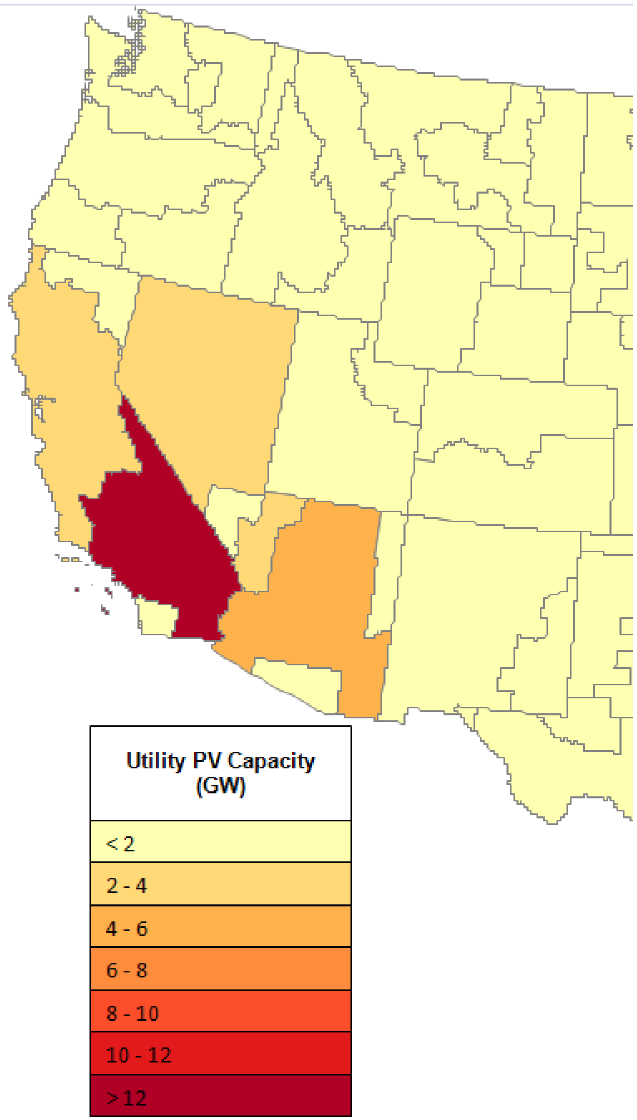


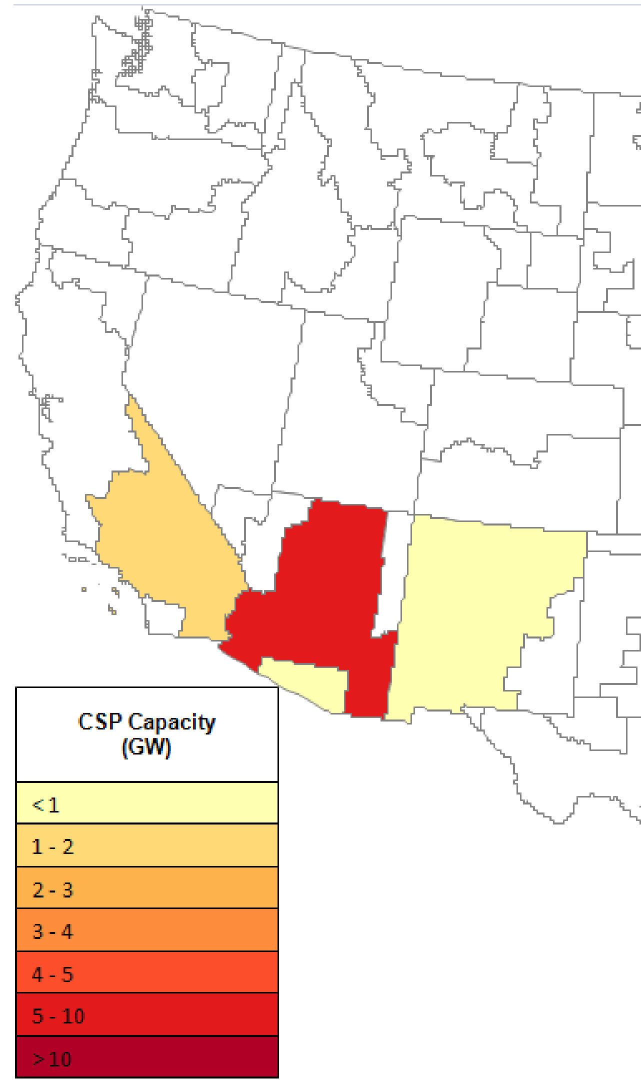




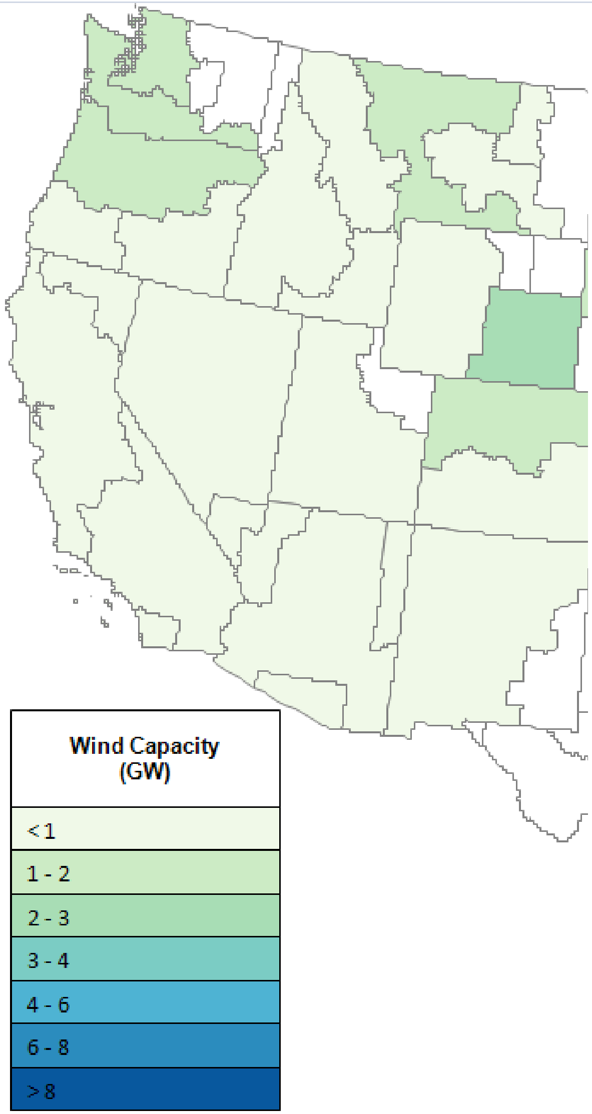
High Mix (16.5% Wind, 9.9% PV, 6.6% CSP)

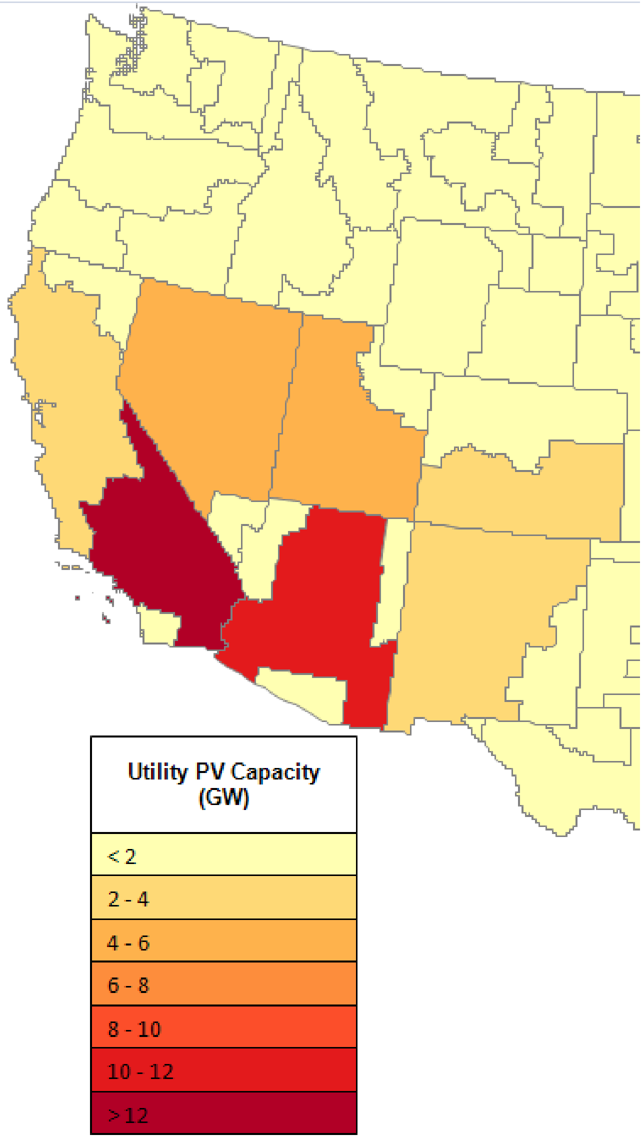


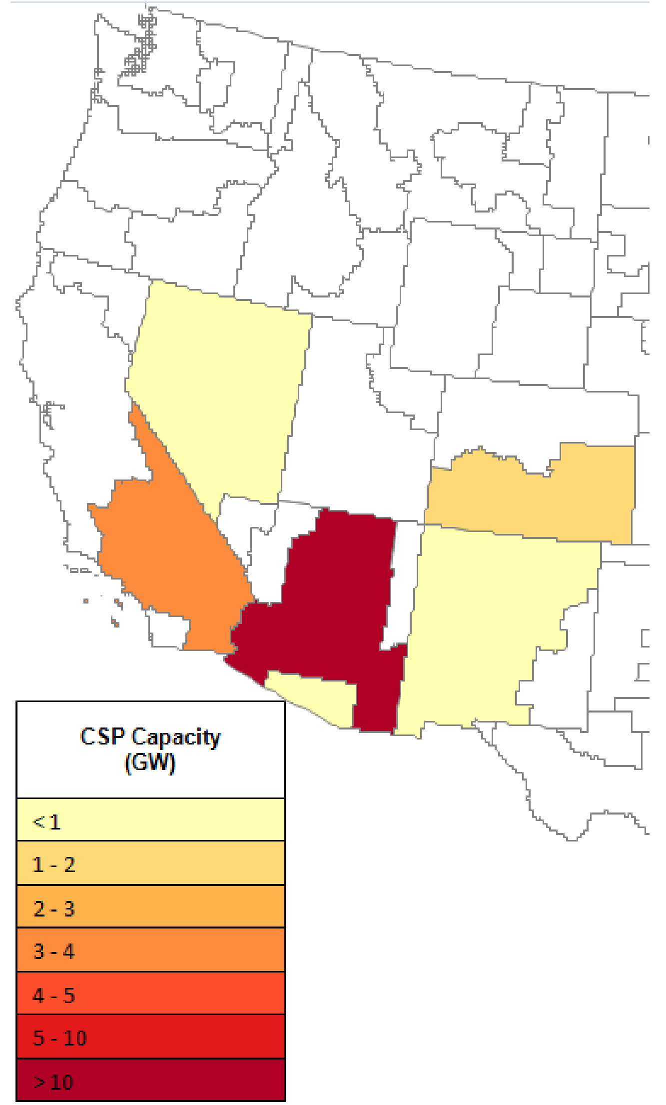




High Solar (8% Wind, 15% PV, 10% CSP)







Questions?

Follow-on questions:

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