Challenges of a Flexible Future:

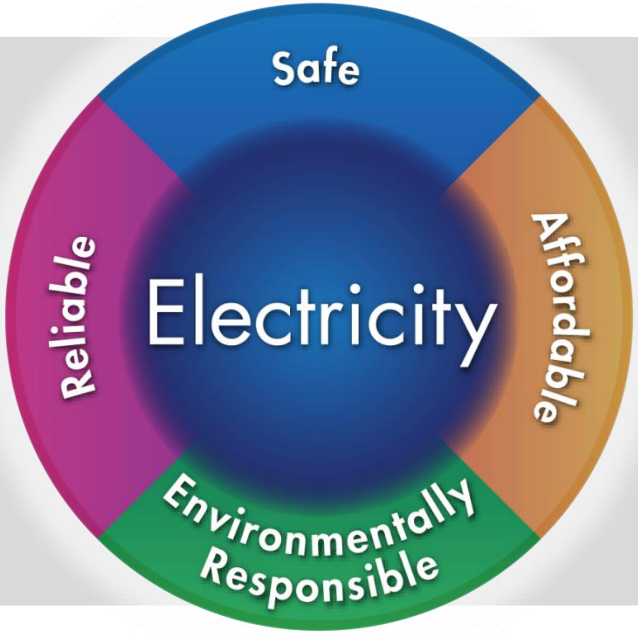
Coal Generation as a Tool for Grid Flexibility and Stability

Mike Caravaggio
Senior Program Manager
July 23, 2019

ELECTRIC POWER RESEARCH INSTITUTE

Electric Power Research Institute's Mission

Advancing ***safe***, ***reliable***, ***affordable*** and ***environmentally responsible*** electricity for society through global collaboration, thought leadership and science & technology innovation



Agenda

- Implications of non-dispatchable power and need for flexibility
  - Duck Curves & Generation Supply Curves
  - The value propositions from flexibility
- The challenge of achieving flexible generation
  - Balancing the scales
  - Achieving safe, reliable, affordable, environmentally responsible electricity
  - EPRI Collaborative R&D

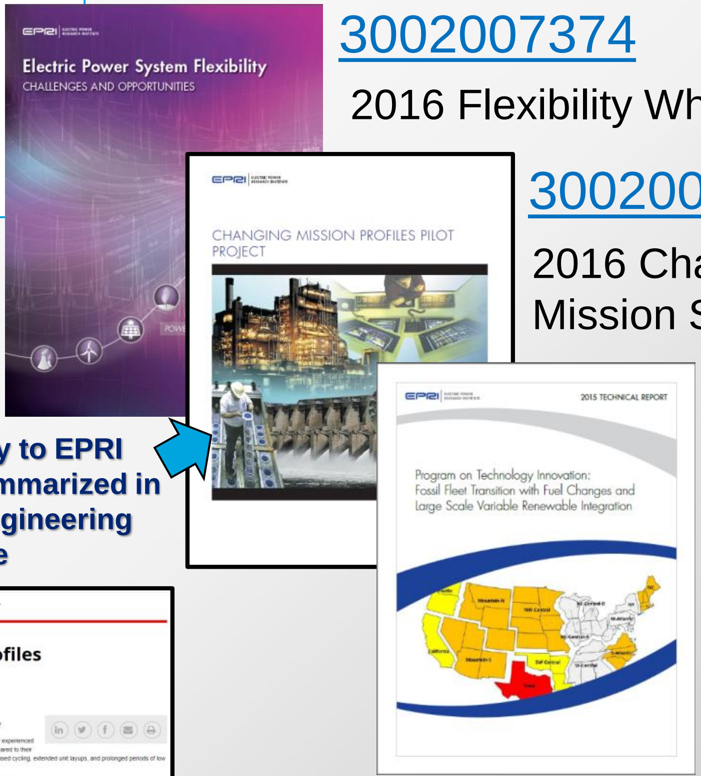
http://genstrategy.epri.com/enabling-flexible-operations-of-the-generation-fleet/

Publically available website

Publically Available Reports

>200 Reports

3002015097
2019 Description of Past EPRI Flexible Operation R&D Reports

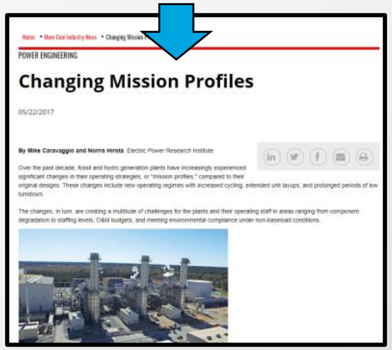


3002007374
2016 Flexibility White Paper

3002005859
2016 Changing Mission Study*

3002006517
2014 DOE Sponsored Flexibility Study

***Available only to EPRI Members but summarized in 2017 Power Engineering Article**



Power Engineering
2017 Changing Mission Summary

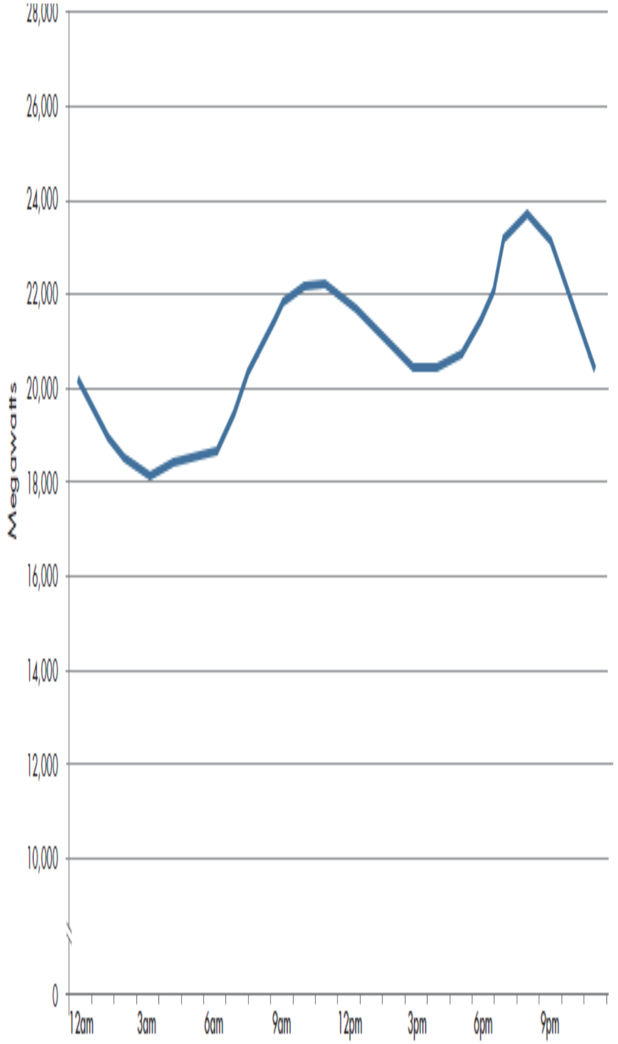
Generating Technologies

Semi-Dispatchable:
- Solar Thermal
- Nuclear
- Hydroelectric

Dispatchable:
- Coal
- Gas
- Biomass

Non-Dispatchable:
- Wind
- Solar PV

Daily Electricity Demand



Demand and Supply must balance … every second

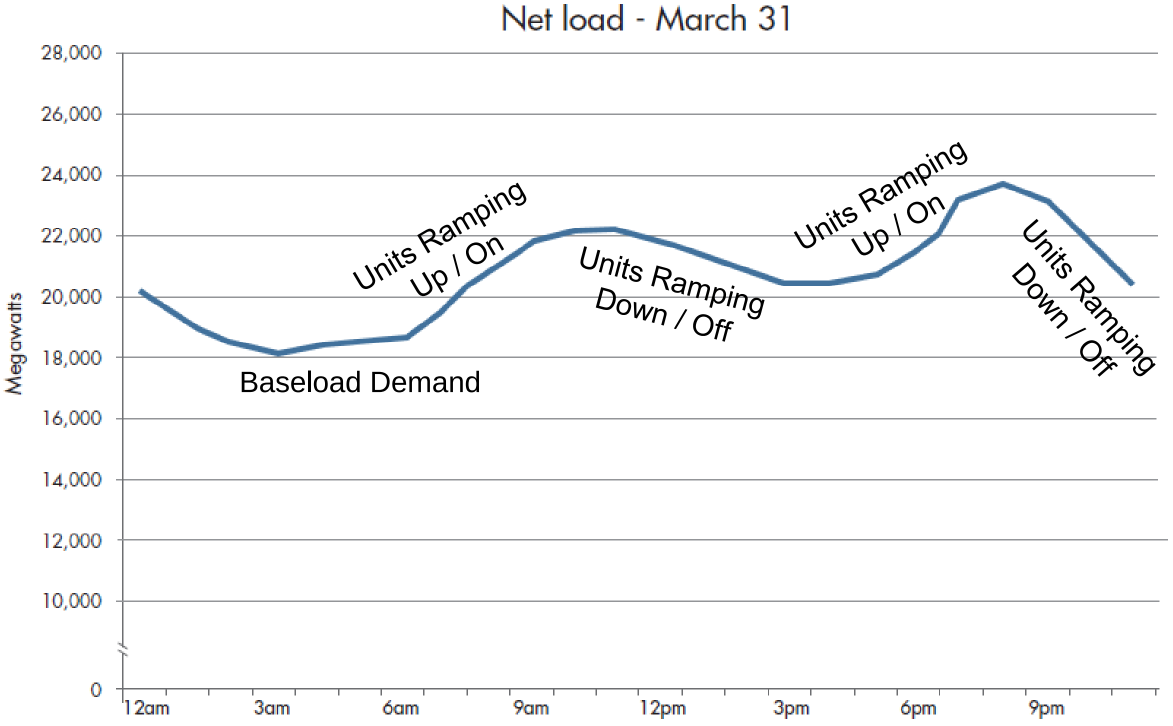
Duck Curves
California Solar Photovoltaic

http://www.caiso.com/TodaysOutlook/Pages/default.aspx

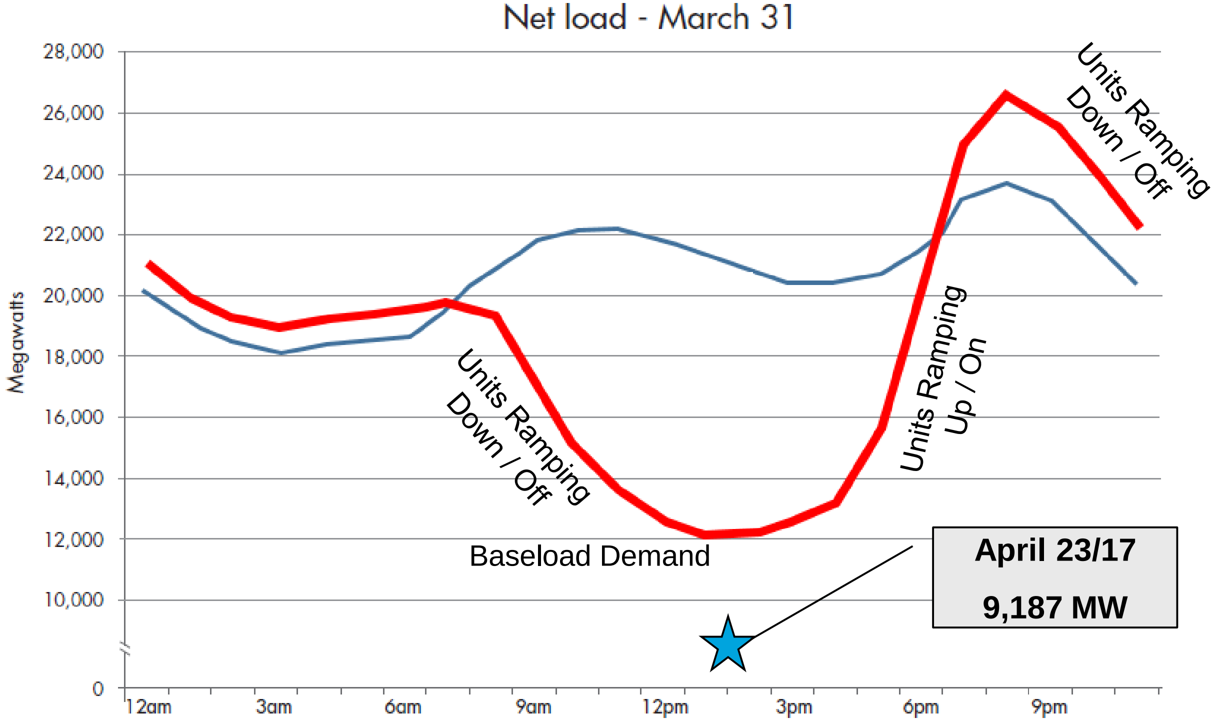
Flexibility – An Example from CAISO impact of Increasing Solar PV

Net Load: Actual Power Demand on the Grid, less the power provided by non-dispatchable generation (e.g. solar and wind)

CAISO – 2012 Actual Net Load Demand

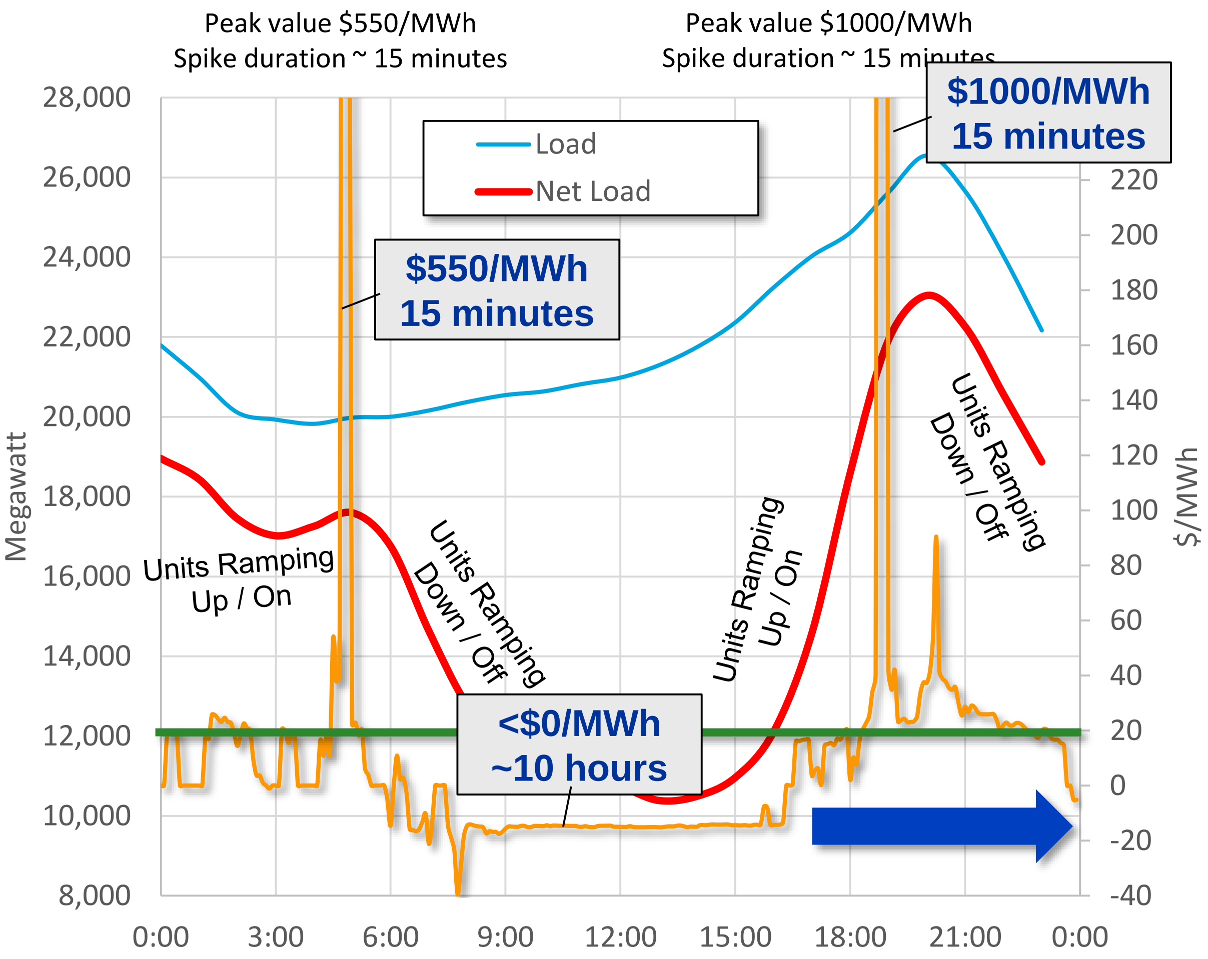


CAISO – 2020 Modeled Net Load Demand



	2012 Actual	2020 Prediction	Implication
Baseload Demand	18,000 MW	12,000 MW	Lower minimum loads, more on/off operation
Peak Ramping Rate	~1000 MW per hour	>5000 MW per hour	Faster loading/unloading, brownout/blackout risk
Peak Demand	24,000 MW	26,000 MW	More installed dispatchable capacity required
Daily Total Energy	498,000 MWh	459,000 MWh	Fewer units of production across more capacity
Peak to Base	6,000 MW	14,0000 MW	More flexible capacity required

Solar: Hourly Average Load – CAISO – April 23, 2017



Flexibility due to Solar PV

http://www.caiso.com/TodaysOutlook/Pages/default.aspx

- Daily Ramp
  - Minimum Loads, On/Off Cycling
  - Driven by low or even negative prices
  - Short duration extreme high prices
- Economic Viability Challenged
  - Increases Wear & Tear (Slopes / Min)
  - Still need dispatchable units (Max)
  - Reduced MWh by dispatchable units (Area)
  - Reduced price per MWh produce
  - Short duration high value periods of production

May 5, 2019 had a net load hour of 5,470 MW

Daily Ramping / Minimum Load / Daily On-Off Cycling

May 5, 2019

- Energy Imbalance Market
  - Significant Import to Satisfy Ramp
  - Significant Export to Manage Excess
- Dispatchability Adjacent to Non-dispatchable Market has significant arbitrage value
- Value of incremental non-dispatchable power?

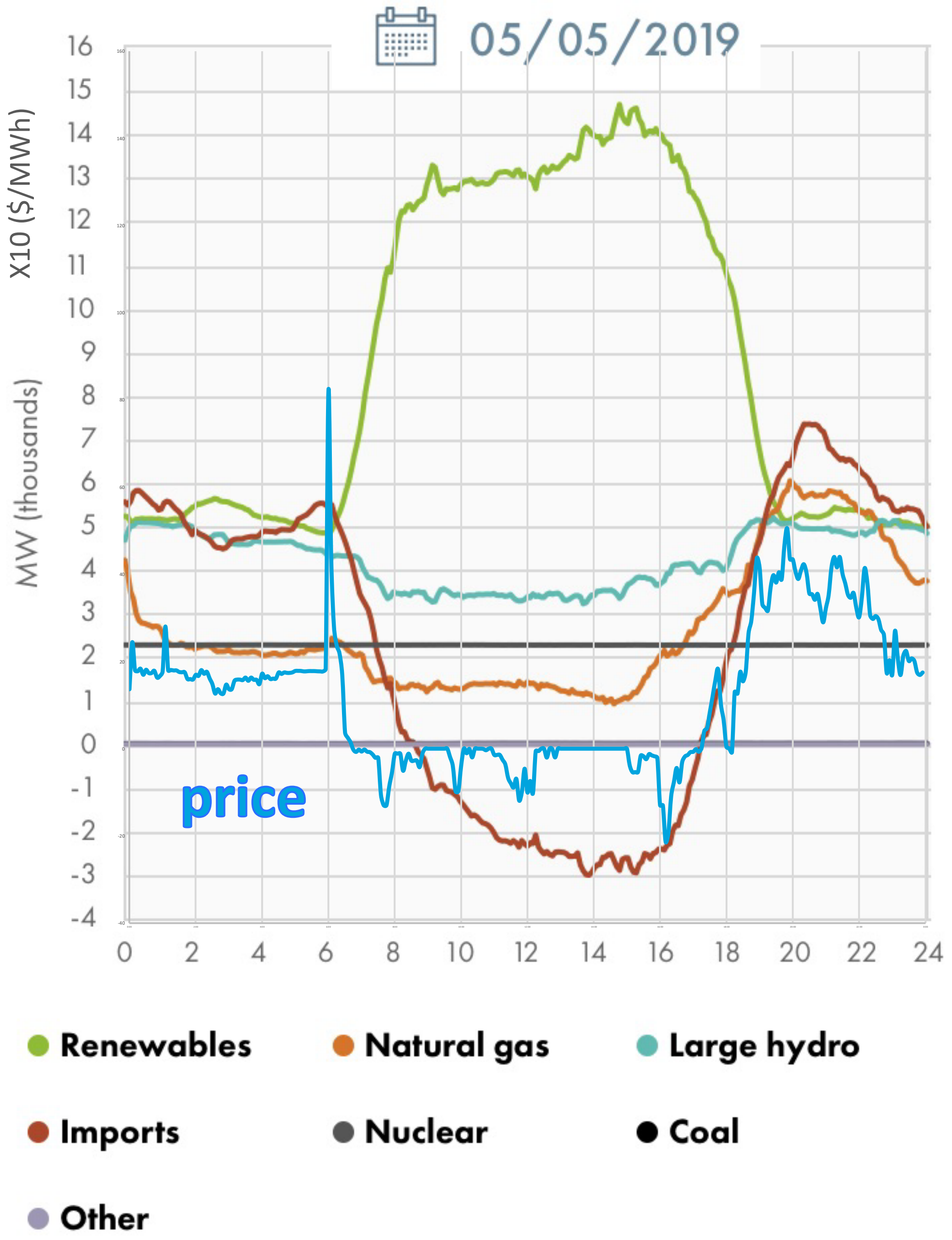
Ontario power: Why Ontario effectively paid its neighbours $214,584.24 in one weekend hour to take our power

Ontari
Sunda
see Ni

We're paying others to use our electricity - again

As most Ontarians slept on April 10, they unknowingly deposited a credit of almost $229,000 in the accounts of electricity users in Quebec, New York and Michigan.

https://communityimpact.com/austin/georgetown/city-county/2018/12/10/georgetown-will-renegotiate-renewable-contracts-after-energy-price-drop-costs-city-6-84-million/



California Capacity Contracts

- 10-20+ year agreements for replacement units
- Storage and Gas Plants

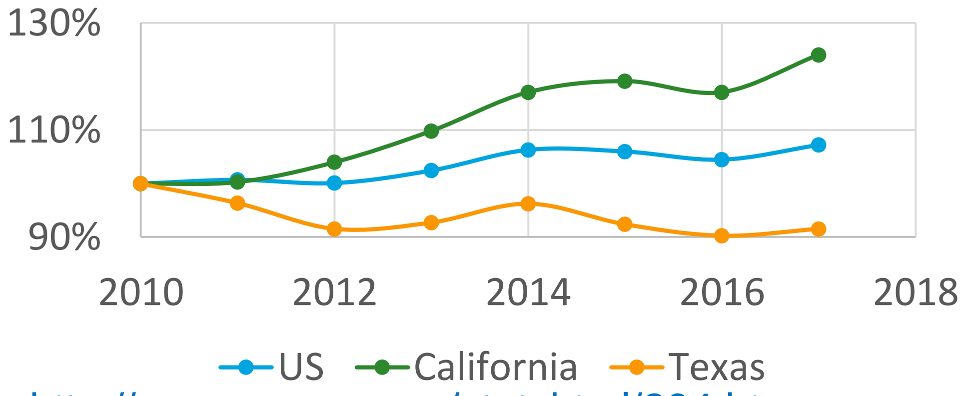
	LA Basin	Big Creek/Ventura	Bay Area	Other PG&E Area	San Diego-IV	CAISO System
Contracted Capacity (MW)	83,851	26,500	70,150	29,877	24,300	76,239
Percentage of Total Capacity in Data Set	27%	9%	23%	10%	8%	25%
Weighted Average Price ($/kW-month)	$3.48	$3.45	$2.22	$2.27	$3.18	$2.09

2017 Resource Adequacy https://www.cpuc.ca.gov/General.aspx?id=6307

TABLE 2: LARGE SCALE REPLACEMENTS FOR CAISO JURISDICTIONAL OTC UNITS AND SAN ONOFRE

Resource Name	Capacity (MW)	Location	Commercial Online Date	Contract Duration (Years)
Alamitos Energy Center	640	LA Basin	2020	20
Alamitos Energy Storage	100	LA Basin	2021	20
Barre Wellhead	98	LA Basin	2020	20
Carlsbad Energy Center	500	San Diego	2018	20
Huntington Beach Energy Center	644	LA Basin	2020	20
Pio Pico Energy Center	300	San Diego	2017	25

- At $2.20-$3.50/kW-month
- 500 MW – 12-20+Million / year



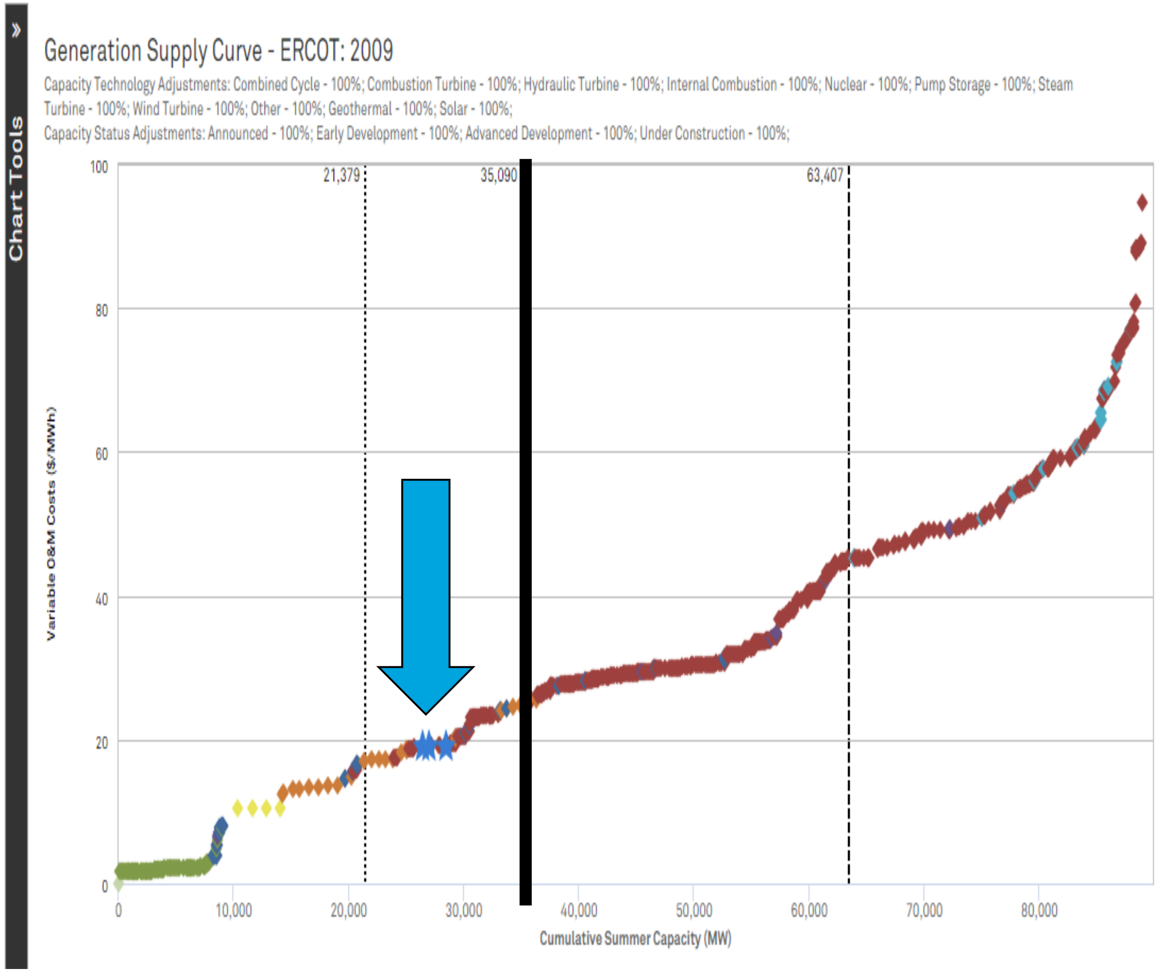
https://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442457193

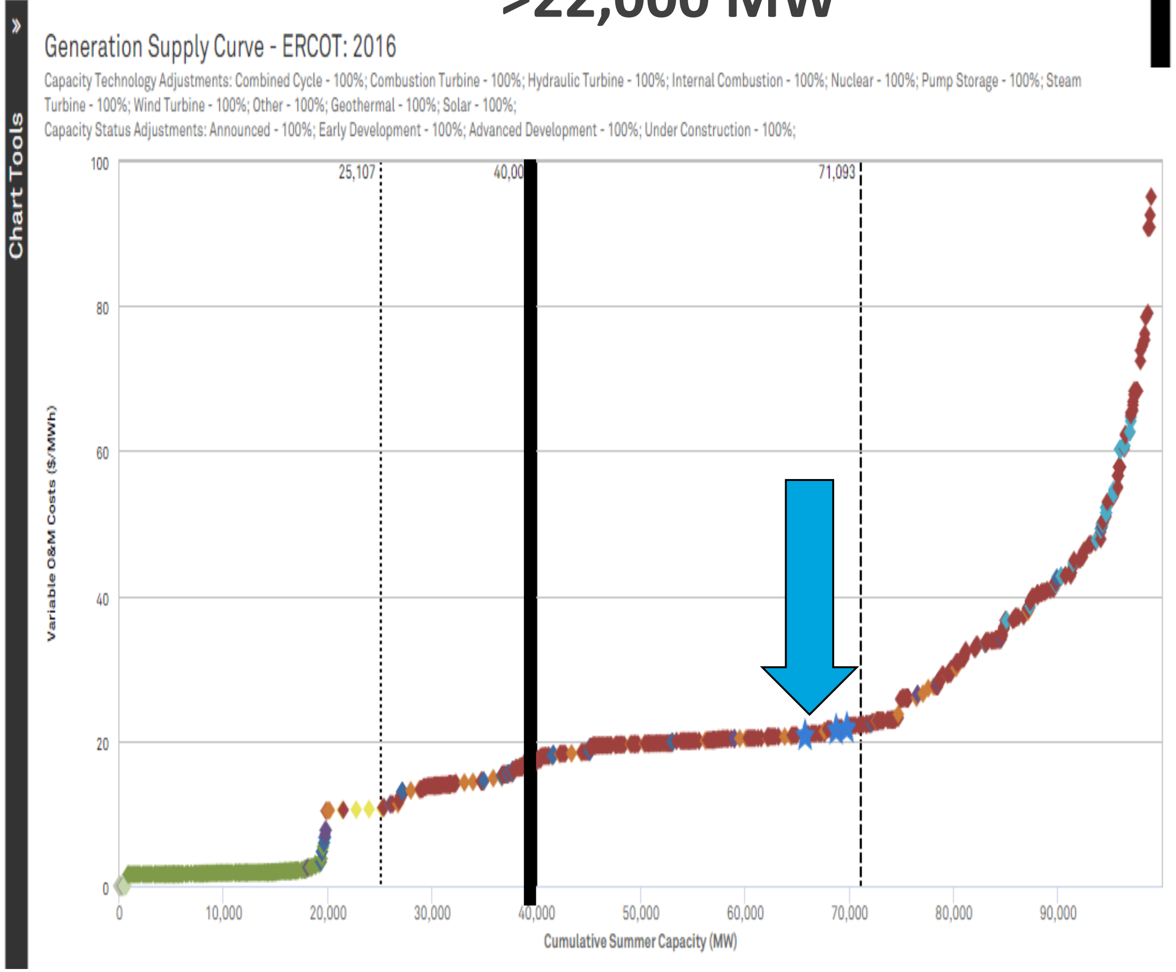
http://www.neo.ne.gov/statshtml/204.htm

Generation Supply Curve
Texas Wind

Wind Energy Growth Texas Example: Texas Generation Supply Curve 2009 / 2016

2018 Wind Capacity >22,000 MW





Solar | Wind | Other Fuel | Biomass | Coal | Water | Natural Gas | Uranium

..... Min Load ▬ Average Load - - - Peak Load

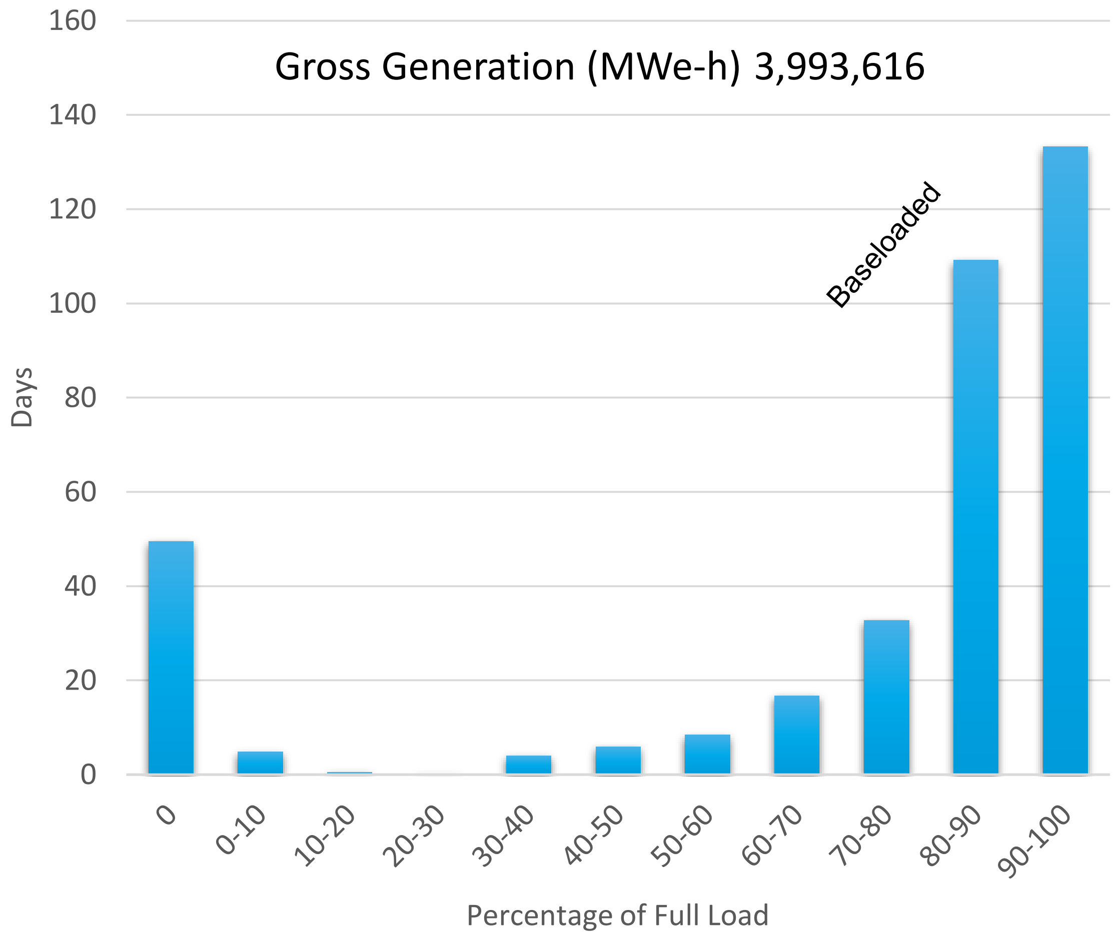
www.snl.com

Texas Coal Fired Unit

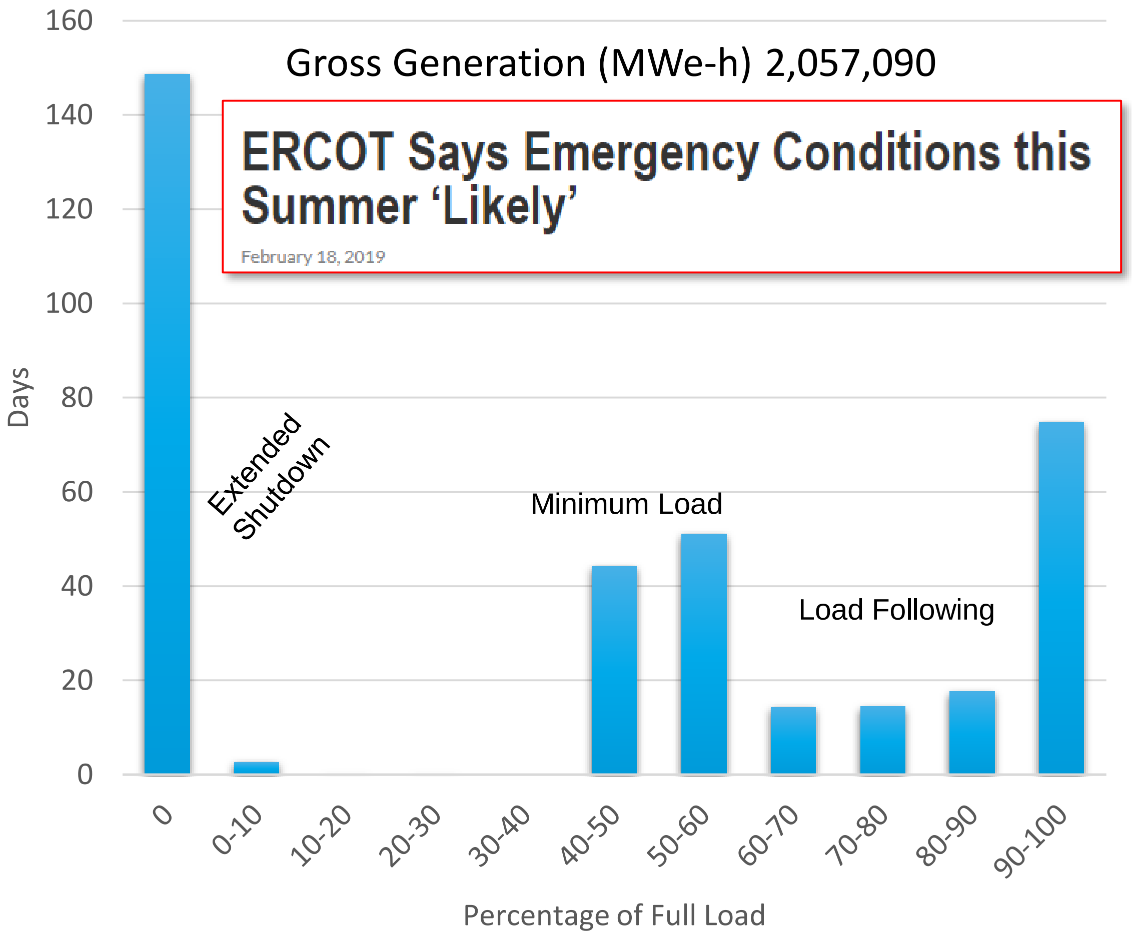

ENERGY OCT 13

Texas' largest power generator speeds up coal's decline with closure of two more plants

2002 MCR 594 MW, 71.9% CF, 83% Op. CF



2016 MCR 563 MW, 41.6% CF, 70% Op. CF



Extended Layup / Minimum Load / Load Following

Implications of Over Supply

Variable Generation Drives Fundamental Change

Rapid growth in variable generation is driving the need for a more flexible power system and for a research and development strategy to help achieve that.

In most cases, variable generation is connected to the grid, benefitting support, flexibility, and integrated with th

The New York Times

ENERGY & ENVIRONMENT

A Texas Utility Offers a Nighttime Special: Free Electricity

By CLIFFORD KRAUSS and DIANE CARDWELL NOV. 8, 2015

ERCOT Says Emergency Conditions this Summer 'Likely'

February 18, 2019

https://www.rtoinsider.com/ercot-emergency-conditions-summer-111456/

News / Queen's Park

Ontario paying for wind turbines to not produce electricity

em operator can now order wind hem not to produce electricity when it's

'Unprecedented': Energy operator in daily fight to keep lights on

By Cole Latimer

April 4, 2019 – 12.04am

Australian Energy Market Commission's (AEMC)

Report an Error | + save to mystar

Ontario power: Why Ontario effectively paid its neighbours $214,584.24 in one weekend hour to take our power

Ontario's Sunday. B see Niaga

- Payments soar 13,733% in ONE year... and £1.6million is paid out on one day alone
- Cost of paying wind farms to close is ultimately passed onto families

PER

:37 GMT, 18 January 2012

Ontarians paid $37 billion extra for electricity fro general Bonni

Markets

Ontario Fair Hydro Bonds Offer Fat Yield, Political Baggage

farms in Pacific Northwest paid to roduce

• Published March 07, 2012 • FoxNews.com 2717 715 61

Fri., July 13, 2018

Ontario's new Progressive Conservative government is pulling the plug on 758 green energy contracts in a bid to save $790 million.

► A way of sharing the cost of going green, government says

Flexibility Required to Balance Non-Dispatchable Power

Flexible Assets Within Market with high penetration of non-dispatchable generation

- Ramp down / ramp up driven by negative operating margins
  - Daily cycle for solar
  - More variation for wind
- Potential for long periods of zero output
  - Generally more prevalent with wind in shoulder months for demand
- Potential for short periods of high wholesale prices
  - Daily very short periods for solar
  - Seasonal longer periods for wind
- Reduction in production units and in average price per unit - more challenging to cover fixed costs
- Pressure on both top line revenue and bottom line net income (wear & tear / complexity cost)
  - Capacity Contracts covering fixed costs have been used for replacement of long term dispatchable assets

Flexible Asset in Neighboring Market without high penetration of non-dispatchable generation

- Opportunity to import low cost, import free, or be paid to import and then resell in own market
- Opportunity to export at high price to satisfy high ramping needs of neighboring market
  - Top line growth can balance cost pressure of flexible operation

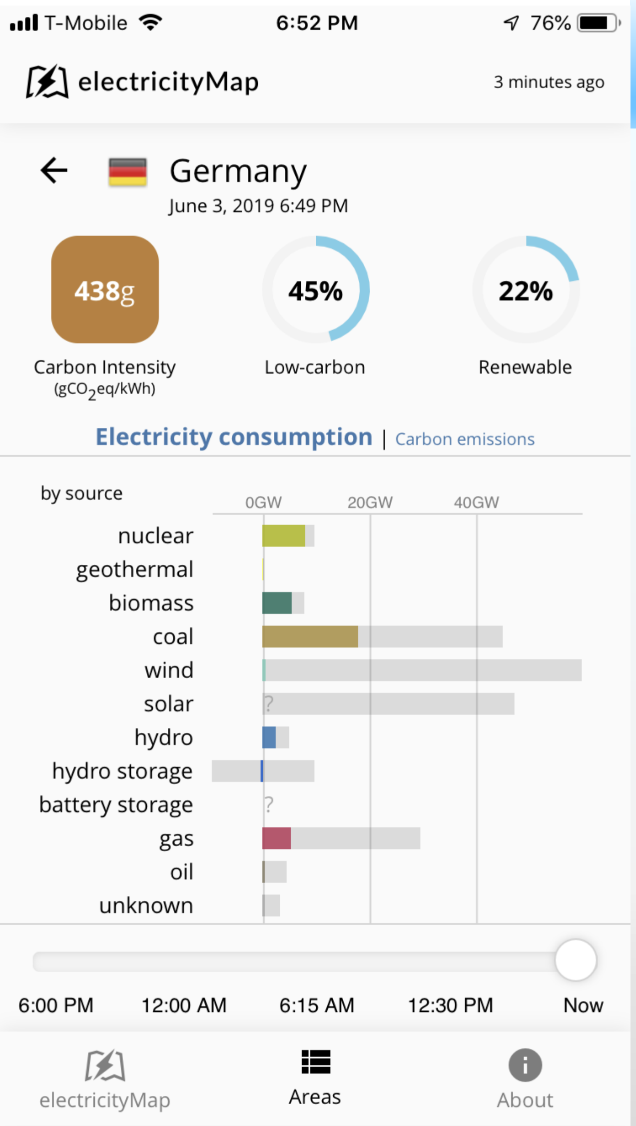
For Grid Stability – Need for Flexibility is increasing

Actual Value of Flexibility for Generating Company depends heavily on markets

What about Europe?

Energiewende

(German for energy trans



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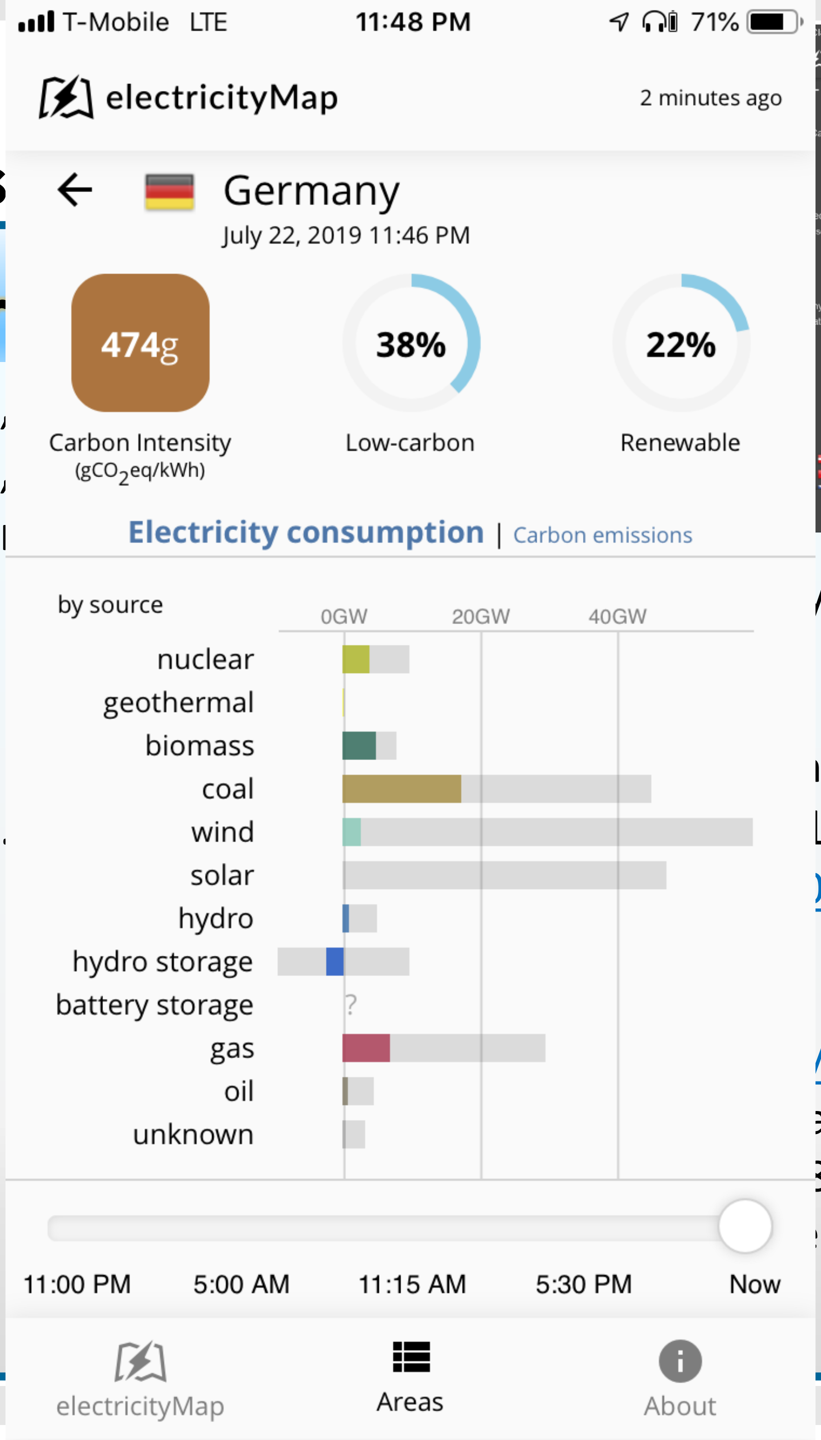
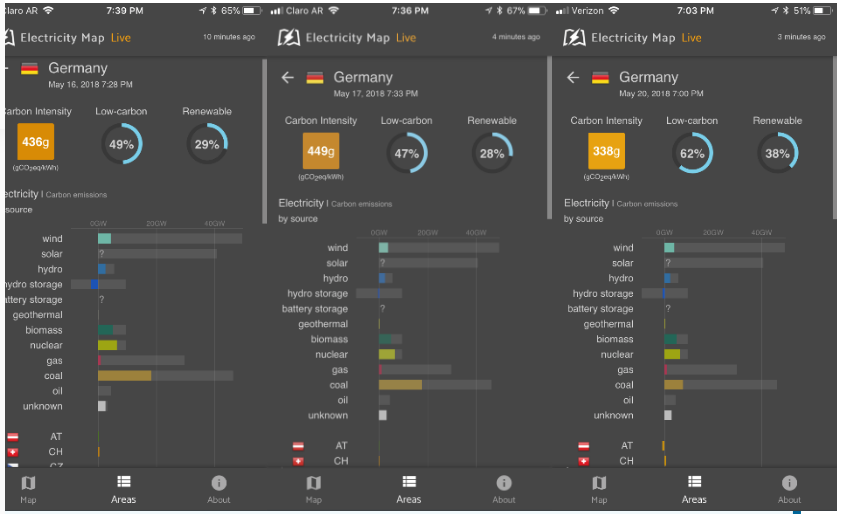




/ no significant output

and nuclear at this time

-dispatchable Generation

17

[078/electricity-prices-for-households-]

/

ation

35 Billion USD (~2.1% of GDP)

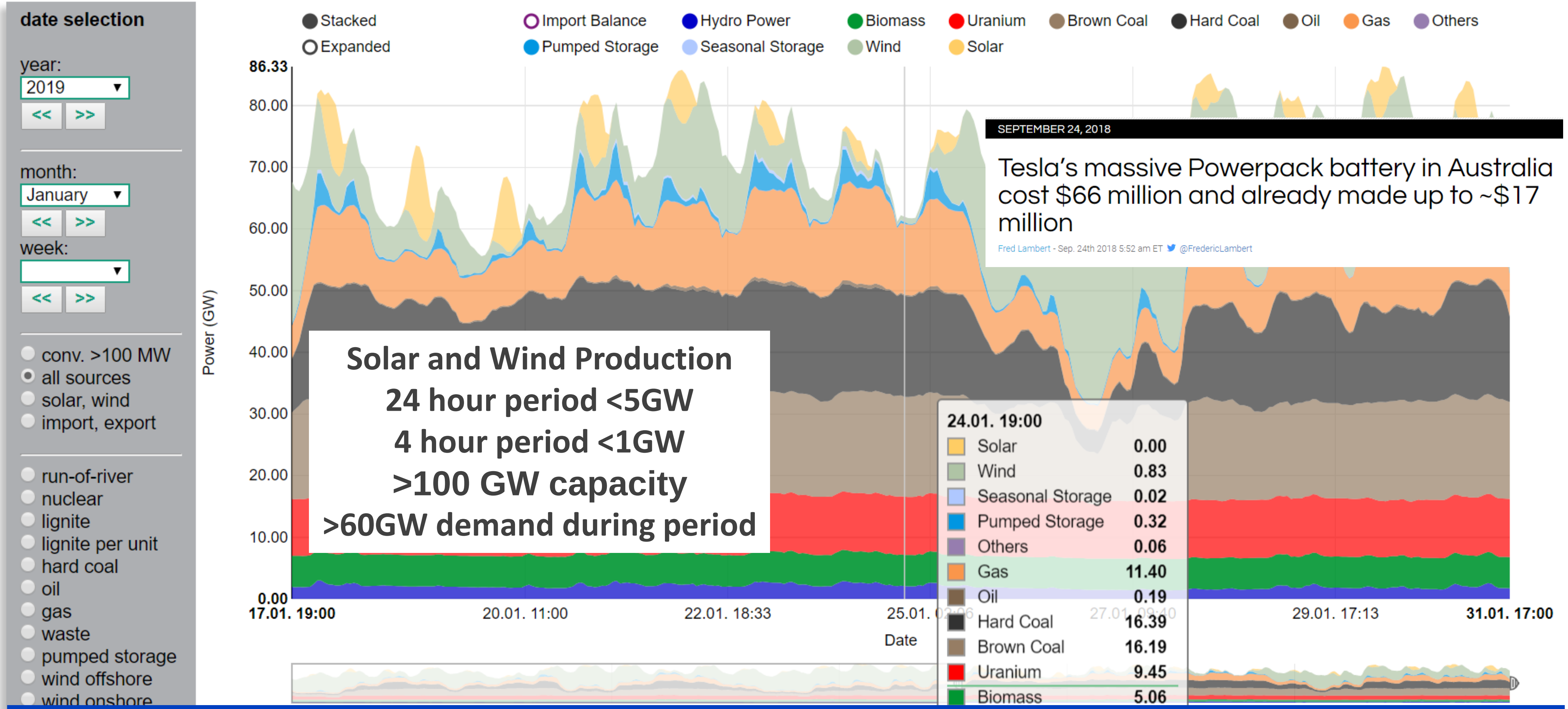
s would total

https://www.electricitymap.org

What about Storage?

Electricity production in Germany in January 2019

https://www.energy-charts.de/power.htm?source=all-sources&year=2019&month=1



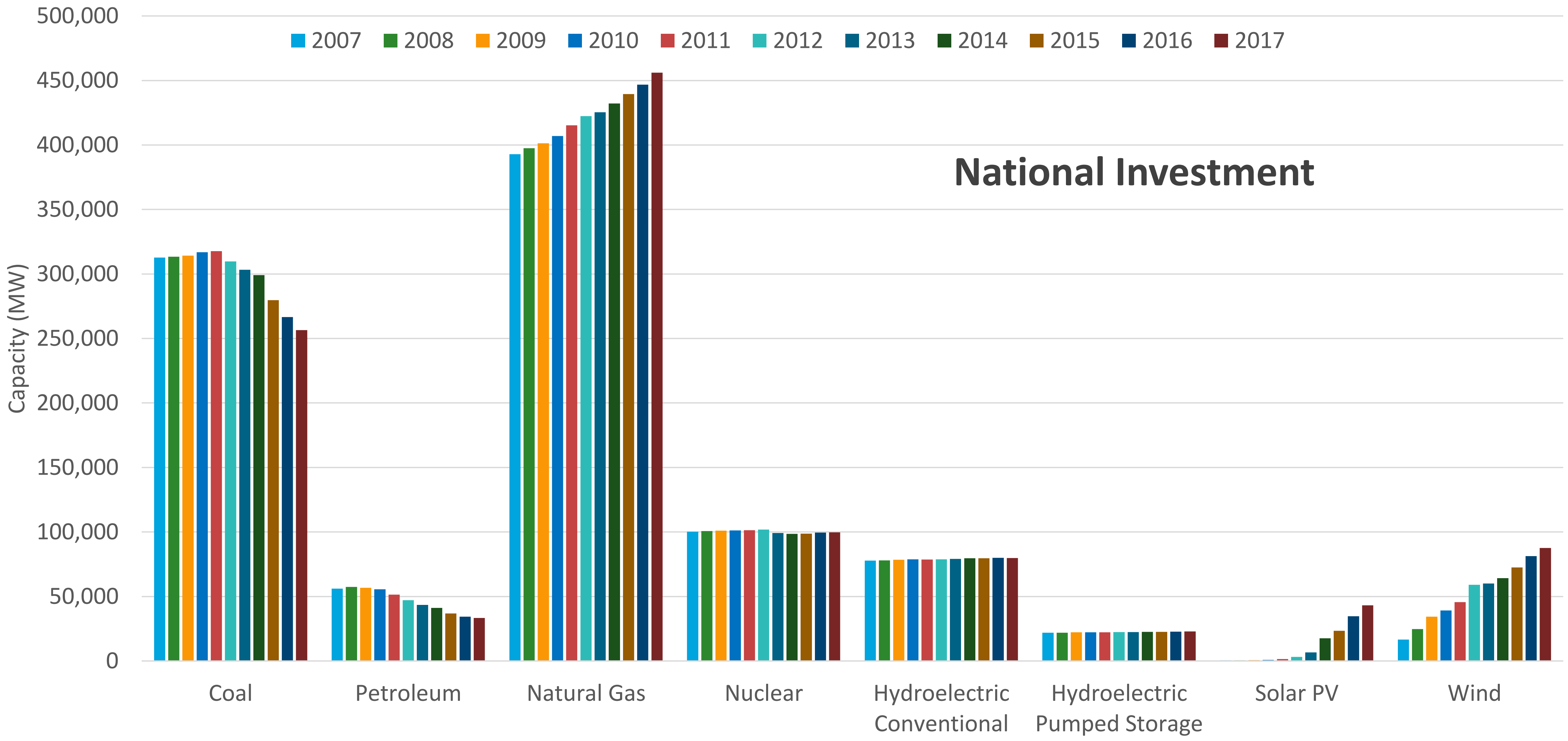
>1000 GWh of Storage needed – 10,000 100 MWh batteries

Coal Generation as a Tool for Grid Flexibility and Stability

“You can’t wipe out society and make a whole new society. You have to deal with the society that exists. But you have to figure out how you’re going to change it to something that’s better.”

Chauncey Starr, EPRI Founder

US Annual Electricity Capacity (source EIA)



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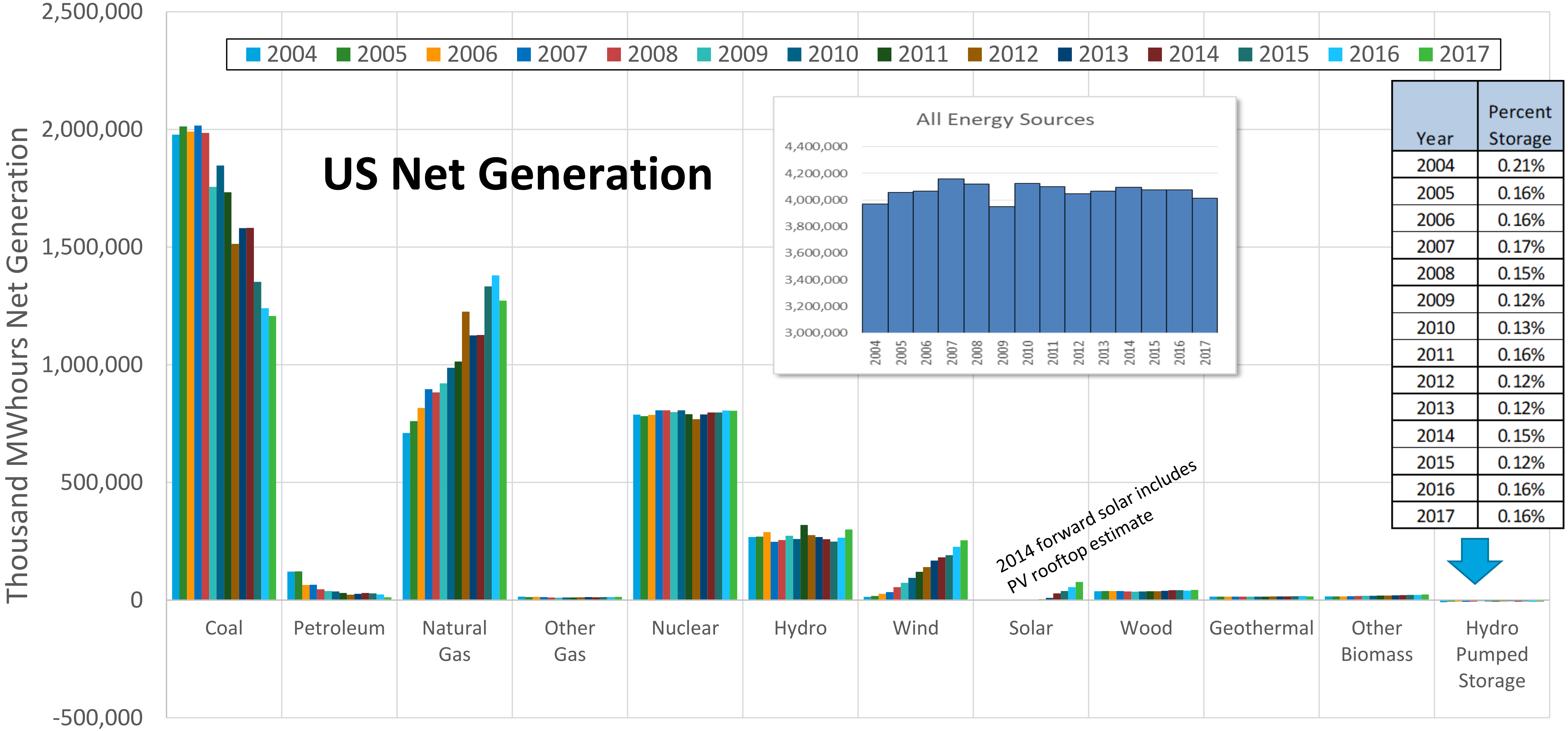
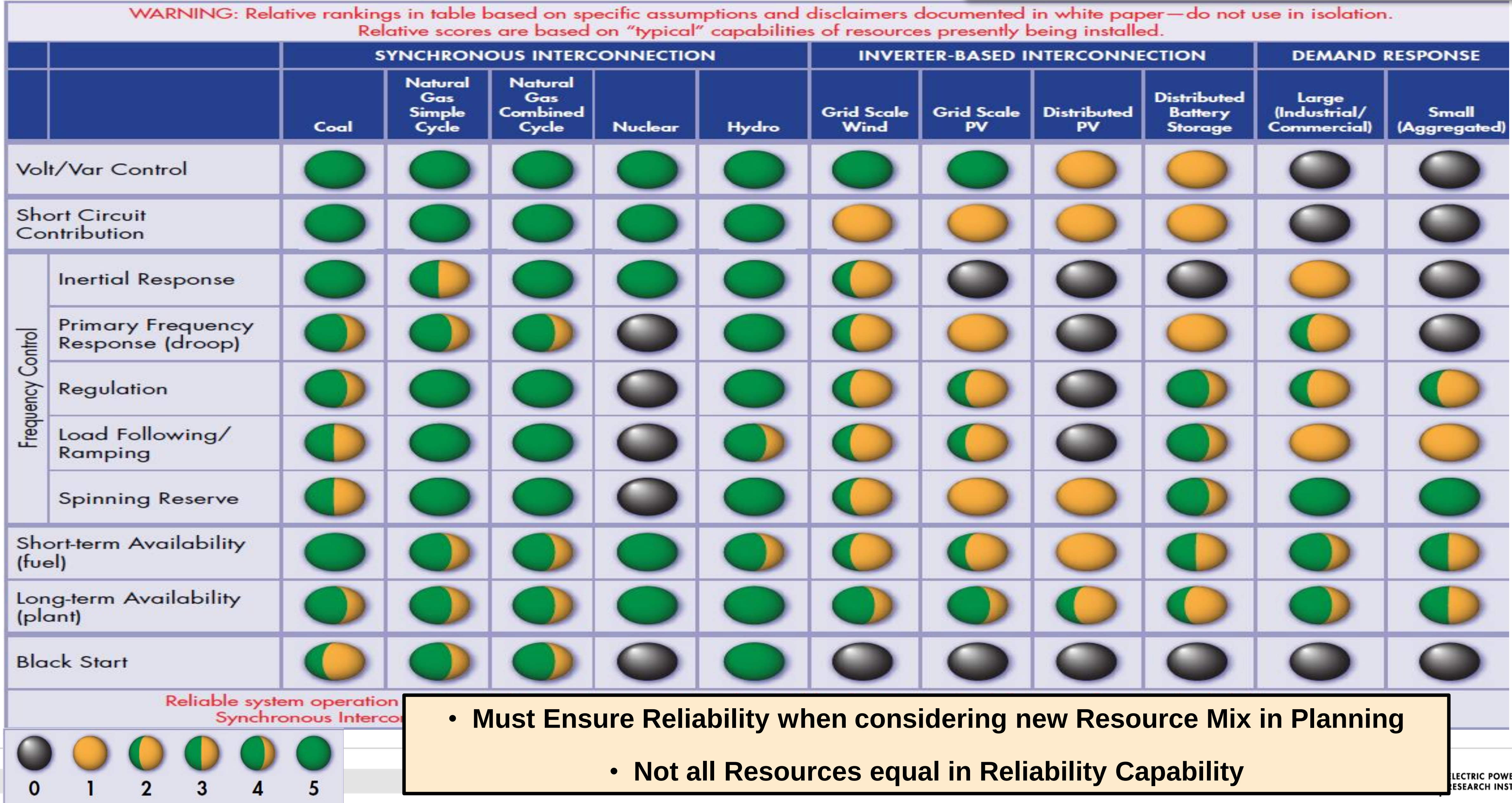


Year	Percent Storage
2004	0.21%
2005	0.16%
2006	0.16%
2007	0.17%
2008	0.15%
2009	0.12%
2010	0.13%
2011	0.16%
2012	0.12%
2013	0.12%
2014	0.15%
2015	0.12%
2016	0.16%
2017	0.16%

Resource Reliability Contributions

EPRI whitepaper (2015):
Contributions of Supply & Demand Resources to Required System Reliability Services (3002006400)



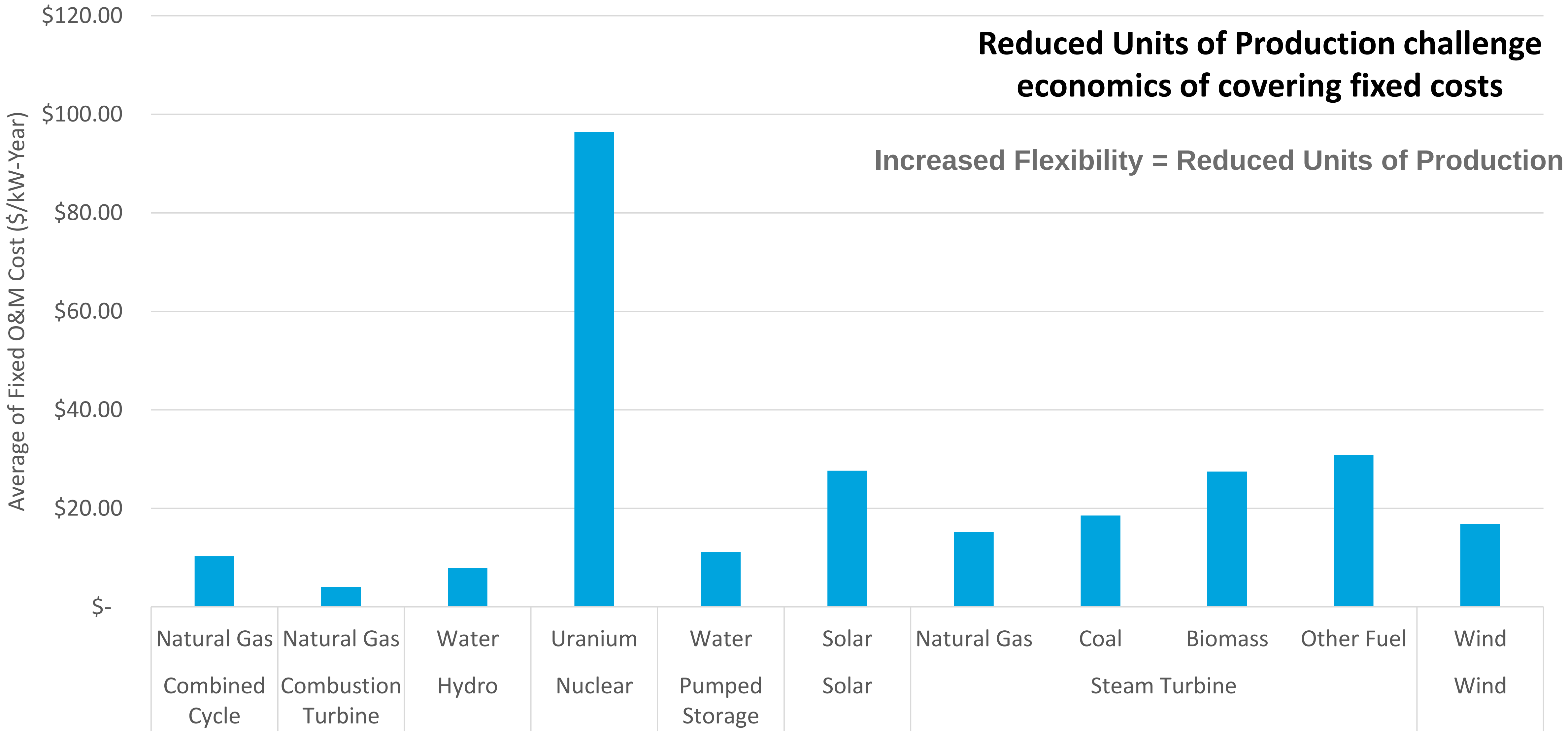
- **Must Ensure Reliability when considering new Resource Mix in Planning**
- **Not all Resources equal in Reliability Capability**

Evaluating Flexibility – Typical Capabilities

- Flexibility Parameters:
  - On/Off, Upward/Downward Ramp, Minimum Load

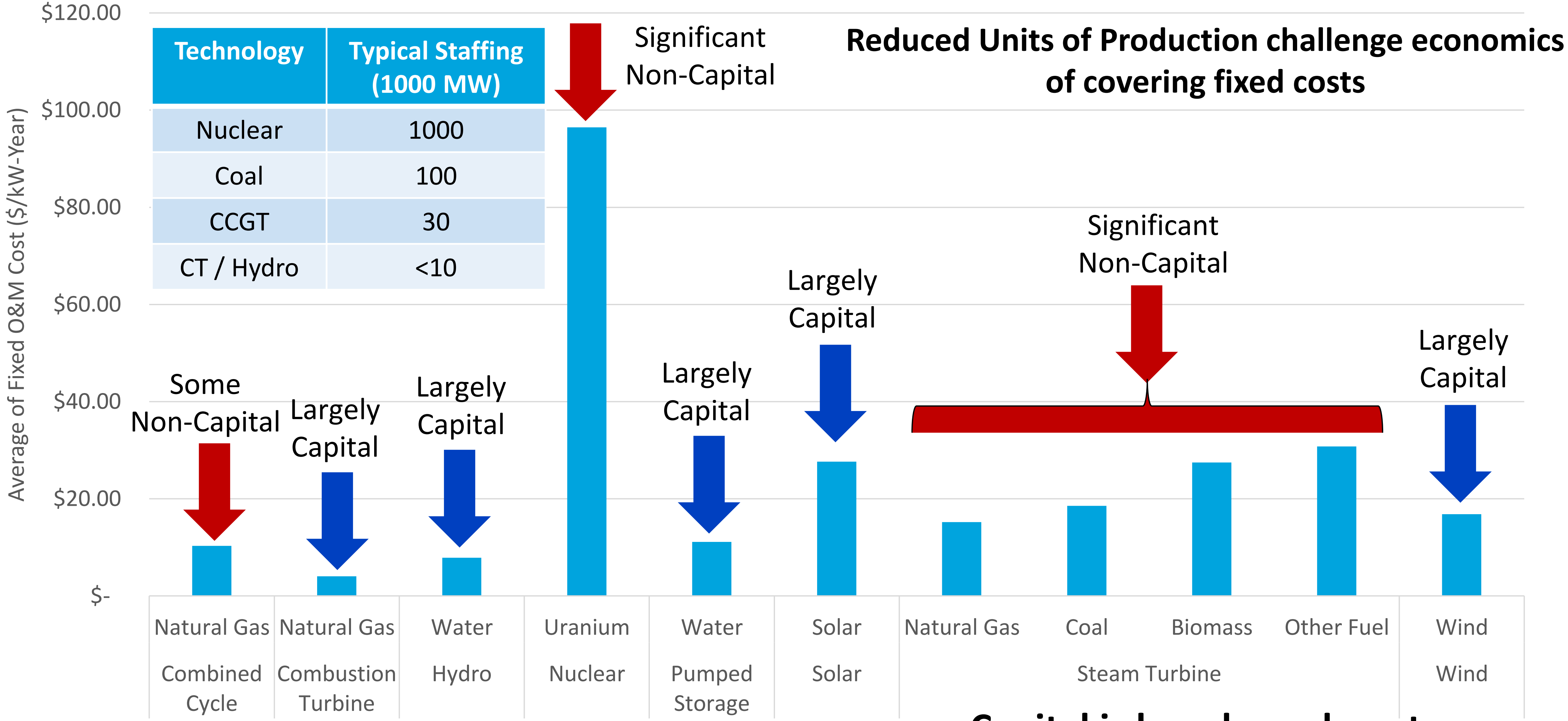
	On/Off	Ramp Rate	Minimum Load
Coal (Subcritical)	Possible 2-5h lead time (Not typically done)	0.6-4%/minute (avg. 1%)	20-55% (avg. 38%)
Coal (Supercritical) Constant Pressure	Not done	0.6-4%/minute (avg. 1%)	40-70% (avg. 52%)
Coal (Supercritical) Sliding Pressure	Possible 2-5h lead time (Not typically done)	1-8%/minute	20-40%
Gas (Supercritical) Sliding Pressure	Possible 1-4h lead time	0.6-7%/minute	10-50%
Combined Cycle	Possible 1-4h lead time	0.8-15%/minute (avg. 3%)	40-70% (1x1 ~65%, 2x1 ~55%, 3x1 ~45%)
Simple Cycle	Possible 0.1-1h lead time	7-30%/minute (avg. 14%)	35-60%
Hydroelectric	Possible,<0.1h lead time	15-25%/minute	5-6%
Reciprocating Engines	Routinely done 0.1h lead time	25%/minute	Modular
U.S. Nuclear	Not done	Not done	60-80%

Example Fixed O&M Costs



Example Fixed O&M Costs

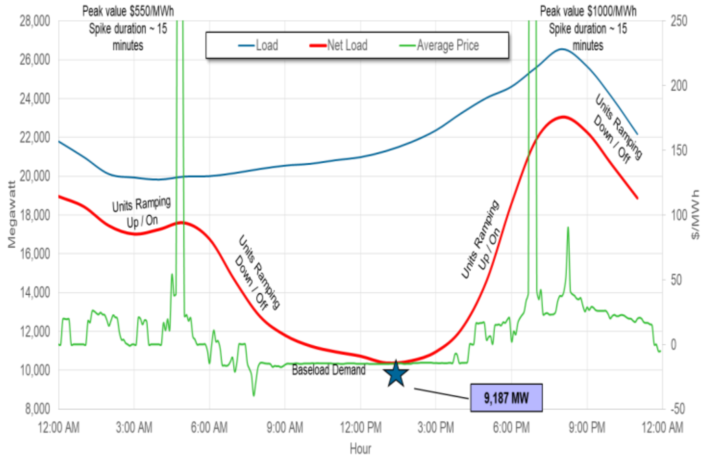
Technology	Typical Staffing (1000 MW)
Nuclear	1000
Coal	100
CCGT	30
CT / Hydro	<10

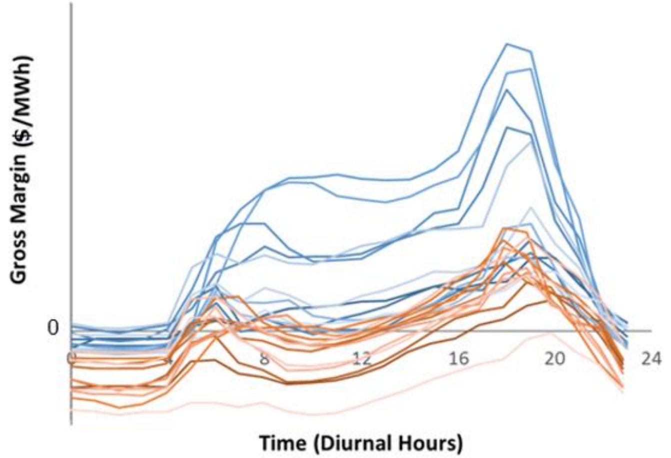


Capital is largely sunk cost

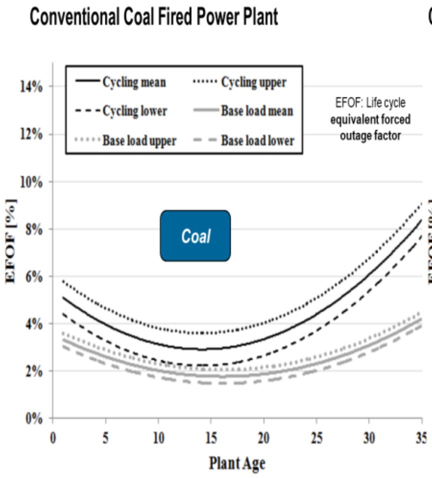
Dispatchable Asset Current State of Value and Cost

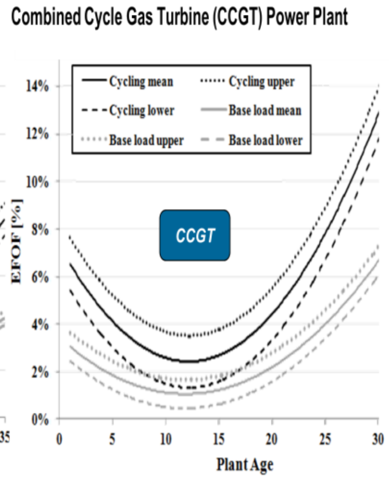
Value

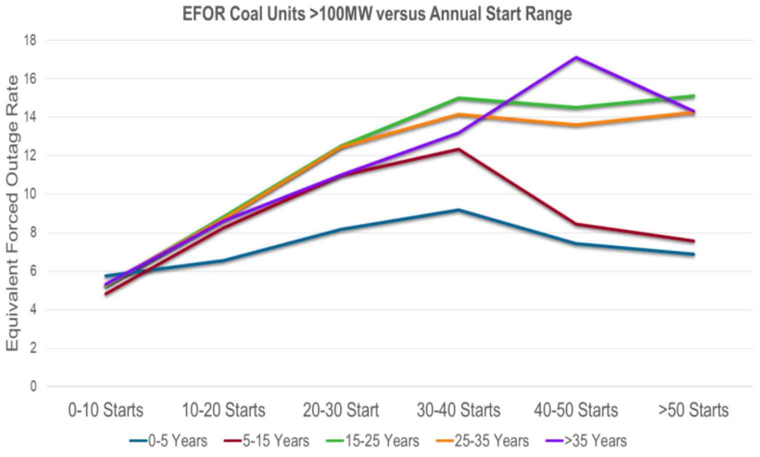




Cost



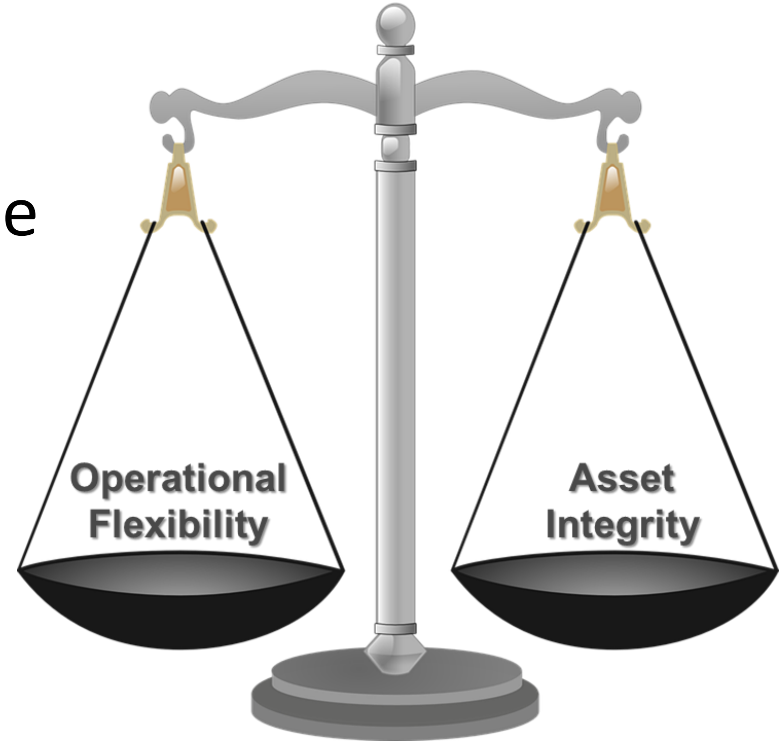




Minimize Negative Margins / Minimize Starts – Minimize Damage from Starts (Cost)

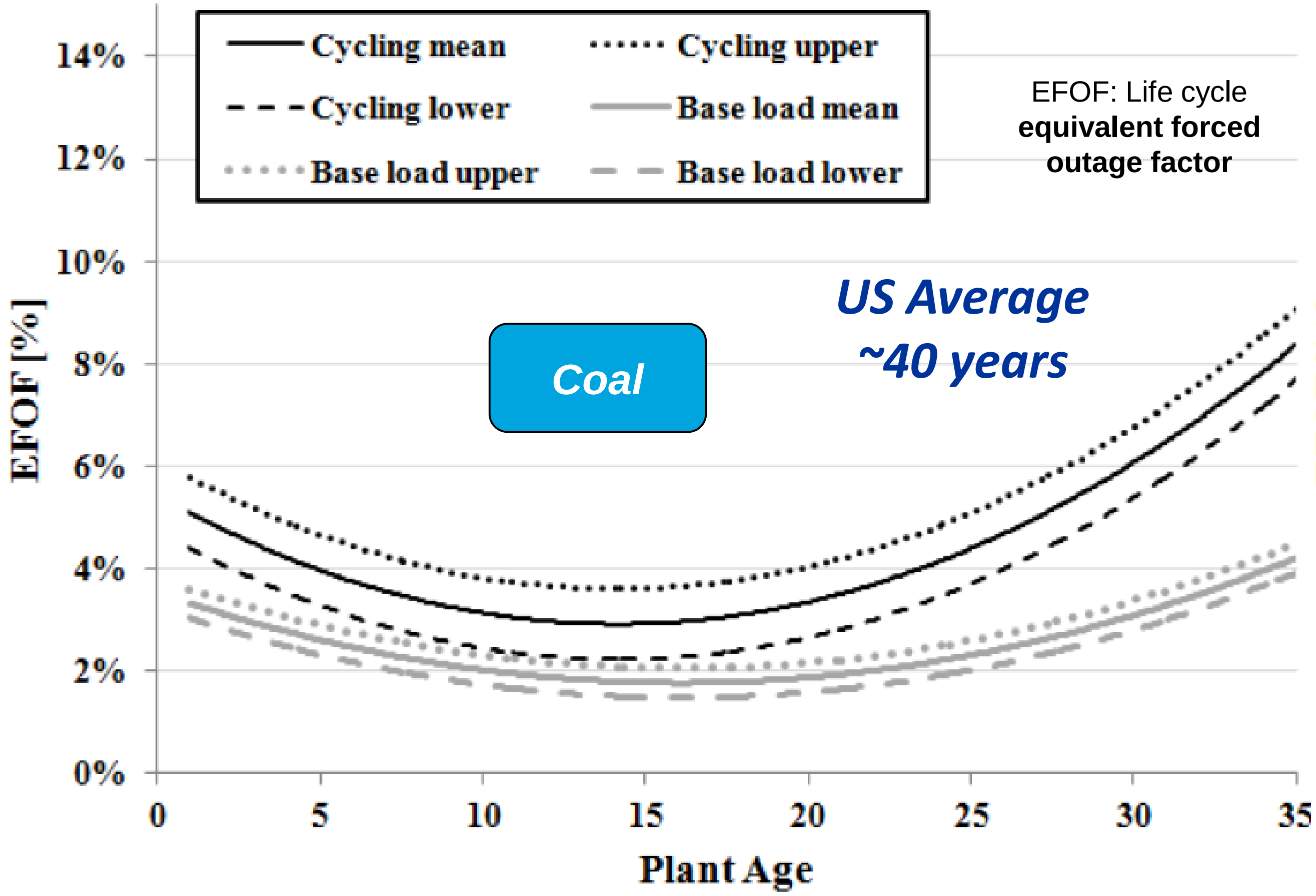
Reliable, Safe, Affordable, Environmentally Responsible Electricity

Understanding the Challenge



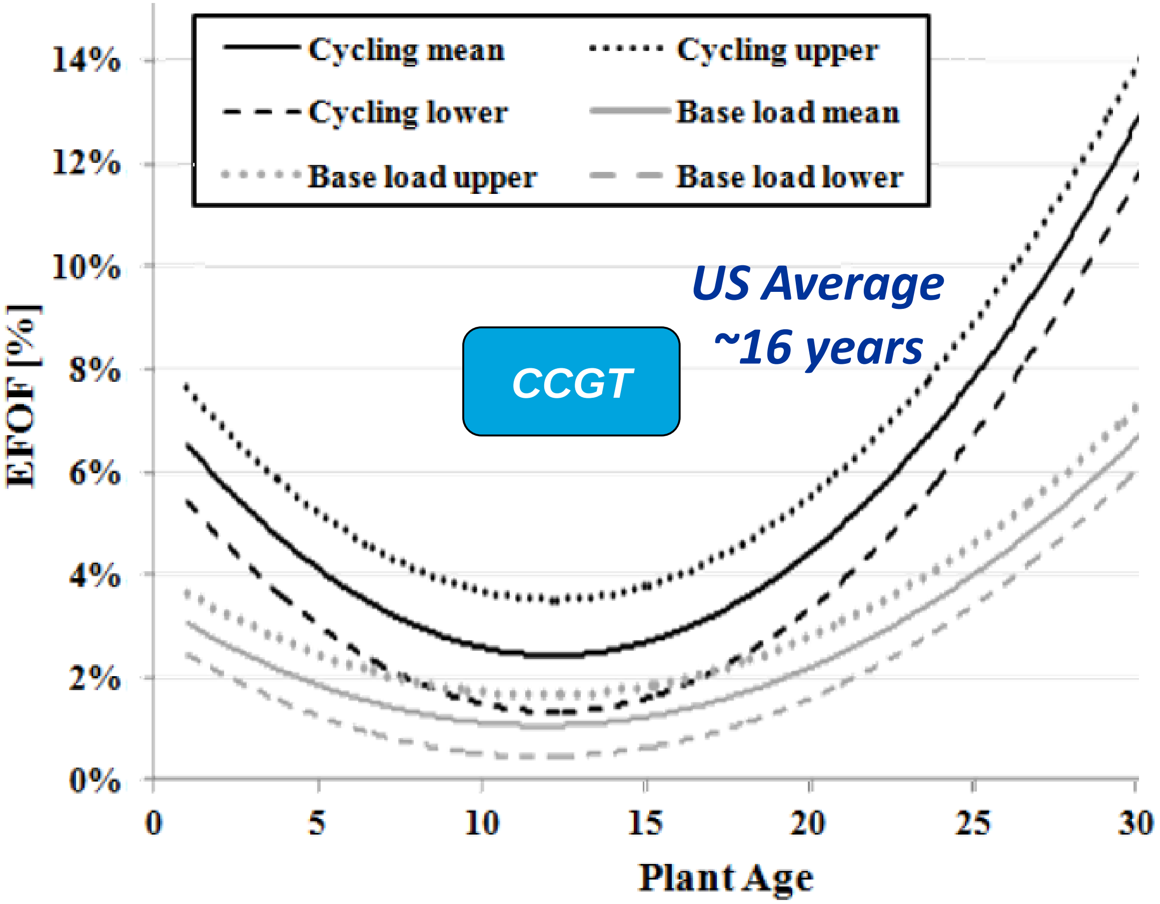
Flexibility and Overall Plant Reliability

Conventional Coal Fired Power Plant



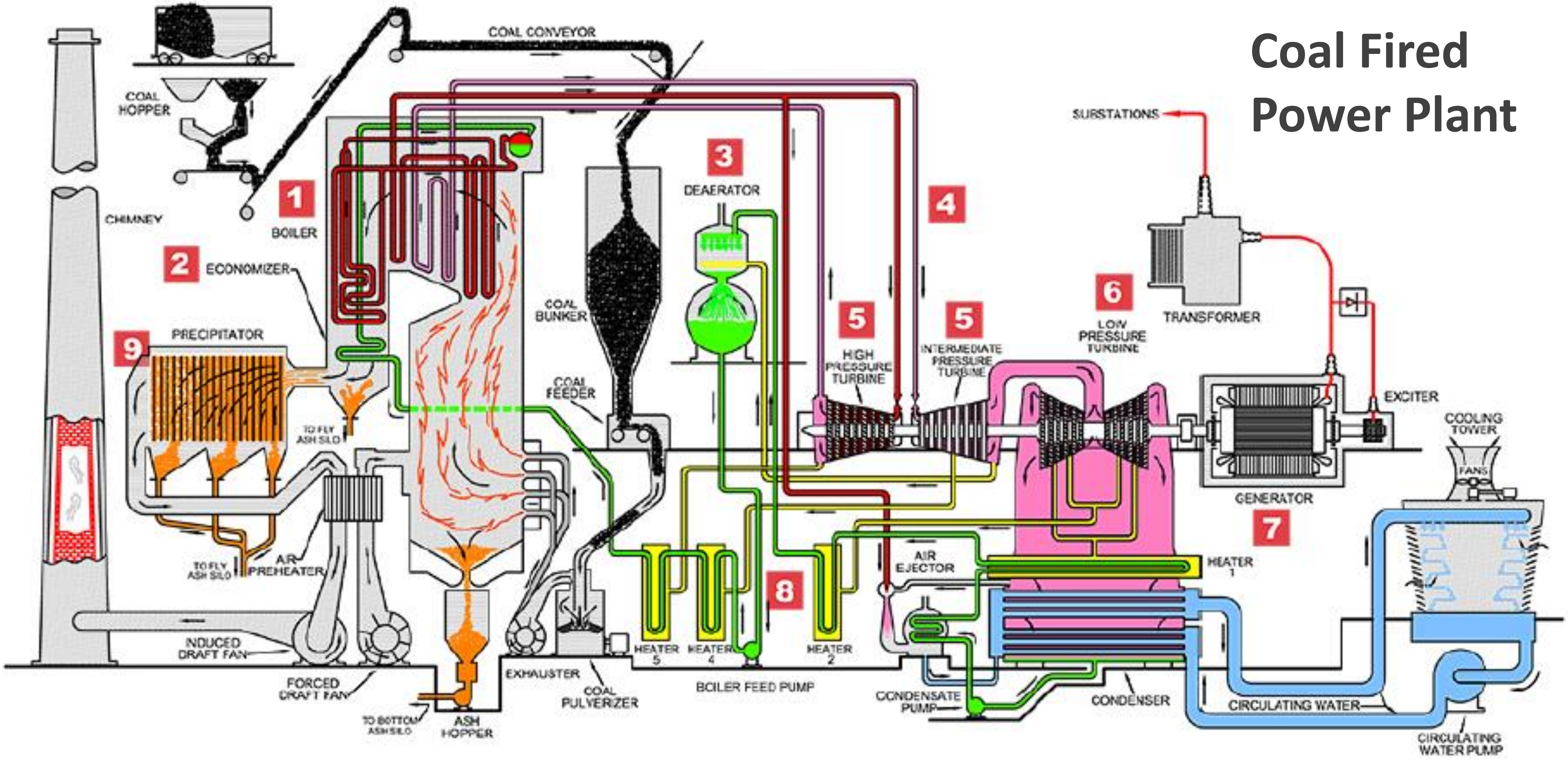
EFOF: Life cycle **equivalent forced outage factor**

Combined Cycle Gas Turbine (CCGT) Power Plant



Age and cycling (flexible operation) impacts plant reliability

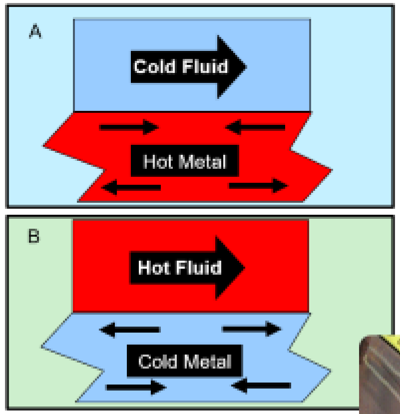
Coal Fired Power Plant

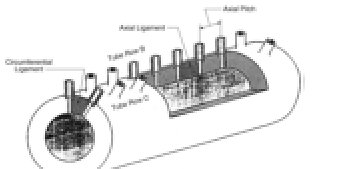


Some General Impacts of Flexible Operation

Flexible Operation: Thermal Fatigue Damage

- Predominate failure mode in boiler and turbine components subjected to:
  - Frequent starts
  - Fast ramping
  - Load following
- Caused by:
  - Temperature mismatch between steam and metal surfaces
  - High amplitude stress cycles result
  - Rapid cooling caused by liquid quenching; very high surface tensile stresses




Header with Stub Tubes

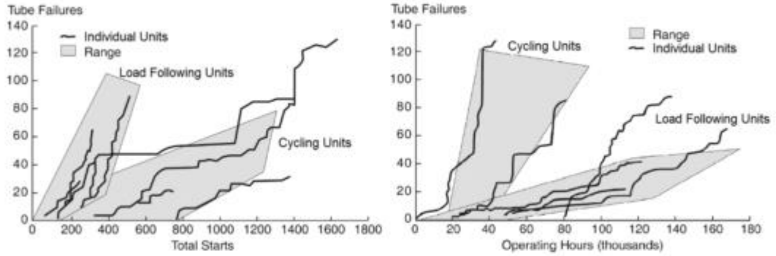

Header ID Cracking Due to Thermal Fatigue


Header Fatigue Cracking

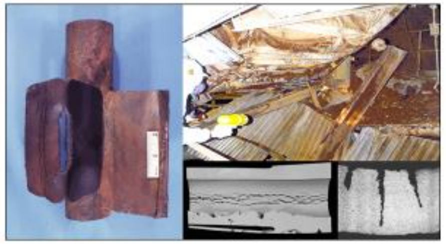

Damaged Header

Flexible Operation: Corrosion Fatigue

- On drum units, **corrosion fatigue** has been observed on the riser tubes.
- This mechanism involves **the combination of:**
  - manufacturing-induced bend stresses,
  - water chemistry fluctuations under cycling operation
  - thermal stress cycles



Corrosion Fatigue Failures have caused injuries and deaths in power plants



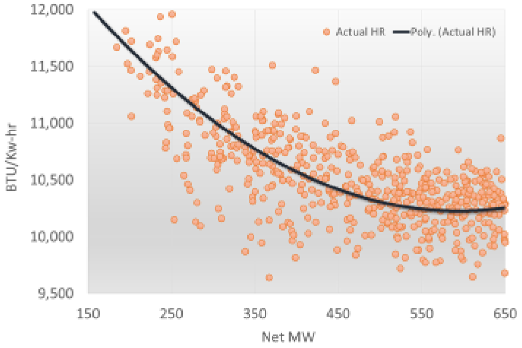
Flexibility and Plant Efficiency (Heat Rate)

Heat Rate:
Energy in Fuel / Electrical Energy to Grid

- Lower is Better (Inverse of Efficiency)
  - 100% Efficiency is 3,412 Btu/kWh
- Better Heat Rate provides:
  - Fuel Savings
  - CO_2 & Emission Reductions

  By minimizing amount of fuel burned per kWh of electricity produced
- For Existing Coal-fired Plants 10,000 is Good
- For New Combined Cycle Plants 6,500 is Good

650 MW Conventional Coal Fired Power Plant
Impact on Heat Rate operating at Part Loads (Throttling)

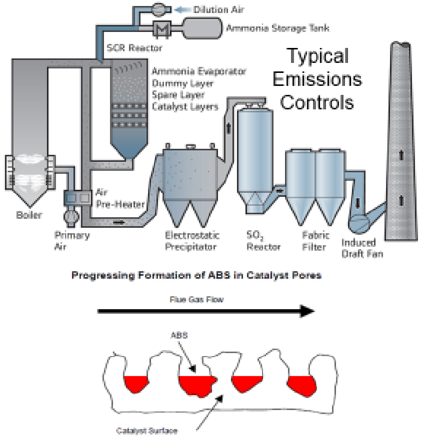


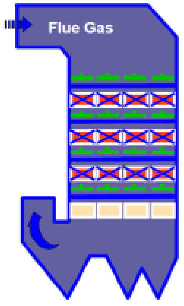
Flexible Operations and Heat Rate Technical Brief 3002013992

Flexible operation impacts significantly plant's ability to operate efficiently

Flexibility and Emission Controls: SCR (NOx Control)

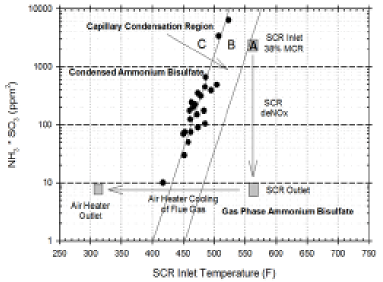
SCR = Selective Catalytic Reduction – Reduces NOx to Nitrogen and Water





SCR with Catalyst Beds

- Ammonium Bisulfate Fouling of Catalyst Surface
  - At lower loads ABS precipitates in SCR and reduces its ability to control NOx emissions

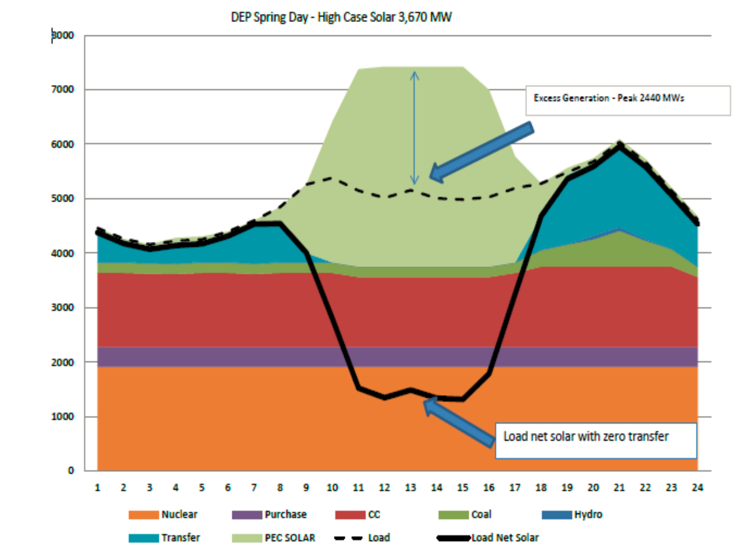


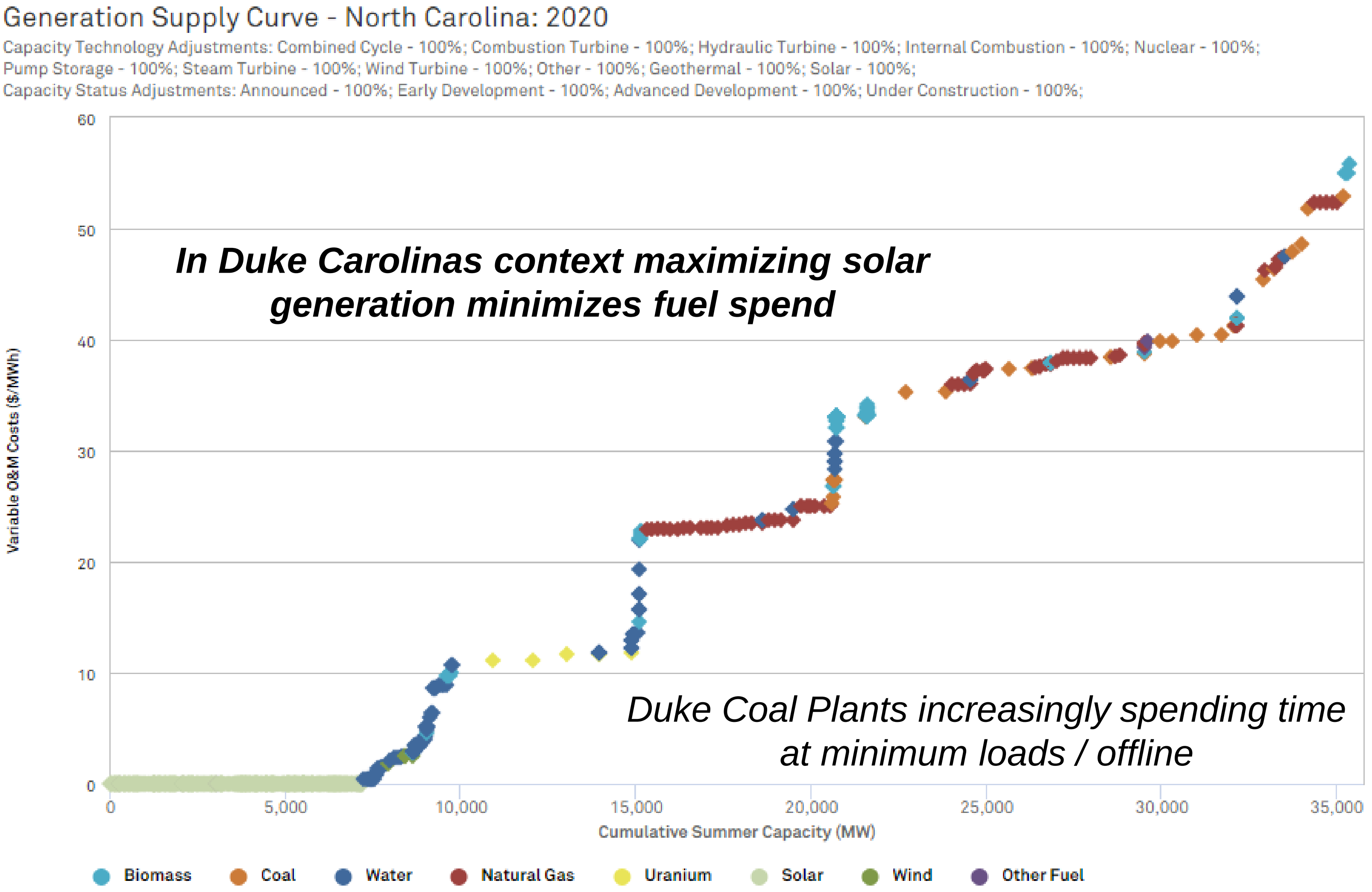
SCR Requires Minimum Temperature to Operate and Avoid Fouling

North Carolina 2017

- Coal and Gas dispatch at higher costs than solar
- Solar assets are correlated in a geographic area
- Periods of excess generation (low or negative prices)

Spring Day (4/2/2017) –Projected 2022 Solar High Case





www.snl.com

Operational Flexibility – Unit Specific

- The minimum load in 2016 at Rox 2 was 150 net MW's
- In 2017, Duke staff championed a station initiative to reduce the minimum loads on all 4 units applying EPRI R&D

Unit	Minimum Load (MW_{GROSS})	Percentage of Rated Load
1	57.3	14.0
2	103.4	15.7
3	167.1	22.4
4	270.9	36.4

- The tangible benefits to Roxboro and the fleet to reducing min load include
  - Reduced hot/warm/cold cycling impacts on equipment (unit stay on vs cycling off)
  - Eliminate the cost of oil for another start-up
  - Eliminating the cost of component lay-up
  - Spinning reserve with tremendous "up" side
  - ECC flexibility with highly variable daytime solar generation
- **Modeling shows approx. $2.5M/year system savings from the Roxboro units min load reductions**
  - These savings result from more efficient generation (gas CC) replacing the reductions achieved

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SUCCESS STORY

DUKE ENERGY REDUCES MINIMUM LOAD, AVOIDS INCREASED CYCLING AND PROVIDES INCREASED OPERATIONAL FLEXIBILITY AND GRID STABILITY

Duke Energy applied EPRI research and a web-based tool to reduce the minimum load of a formerly baseloaded plant, thereby allowing the units to remain on line more often at the reduced loads and prevent as many unit cycles. The load reduction allowed the utility to maintain the plant as a flexible, dispatchable, efficient member of its generation fleet.

NEED FOR REDUCTION OF MINIMUM LOADS

In recent years, with the increasing load from renewables, stricter environmental regulations on coal-fired stations, and cheaper natural gas prices, the operation of coal-fired power plants has changed significantly. Baseload coal-fired power plants have now become cycling plants and are likely to be shut down during low load demands. One option being considered to keep units on line during the low demand periods is to run units at minimum loads for extended periods. These new minimum loads are being investigated to avoid the costly shutdowns and the additional wear-and-tear on plant equipment.

Turndown is almost always the better option for matching generation to reduced demand. When larger units can turn down, the benefits to the fleet as a whole are substantial by reducing the need to take other generation assets offline.

However, because most coal-fired plants were not designed for long operating periods at minimum load, reducing the minimum sustainable load on a plant is proving to be a challenge for many facilities. Reduction in load requires operating below design flow rates, temperatures, and pressures, and many units do not have procedures for such operation.

SYSTEMATIC APPROACH TO REDUCING MINIMUM LOAD

Several years ago, to address this industry issue, EPRI conducted research to develop a systematic approach to reducing a plant's minimum sustainable load. As part of this research, EPRI conducted several case studies in which the reduction of minimum load was successfully achieved. The lessons learned from these case studies were used to document a systematic approach to achieving this goal and are summarized in an EPRI report titled *Systematic Approach to Reducing Minimum Load* (3002002835).

The research showed that the critical portion of such an approach is to understand the system interactions and operating practices of each specific unit. The study developed a matrix/fault tree approach to troubleshooting and testing new minimum load operation. The matrix identifies potential roadblocks that may be encountered on various unit

Duke Energy's Roxboro Steam Electric Plant

"This effort shows how the innovation of highly engaged employees can help to solve real world problems. The team saw an opportunity for our Roxboro location to fill the gap and create an innovative and untapped energy profile. This effort will be a benefit to our employees and our customers."

– JASON HAYNES
Roxboro Steam Electric Plant Manager
Duke Energy

Asset Integrity Risk Matrix – Minimum Load / Extended Layup

	Probability	Minimal	Moderate	Significant	Severe	Critical
5	Critical [>15%]			49		9
4	Severe [<15%]			13, 51, 56, 58	42,45	
3	Significant [<10%]				3,5,46	
2	Moderate [<5%]					
1	Minimal [<2%]					
	Impact	1	2	3	4	5

Enterprise Risk Assessment

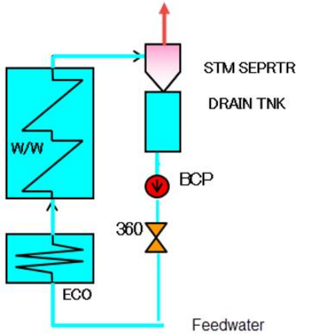
- Financial ≥$50M: No — Calculated
- Reputational: Assessing ← Select

Order	Risk ID	Risk Short Name	Probability		Impact		Total
1	9	[redacted]	5		5		25
2	45	[redacted]	4		4		16
3	42	[redacted]	4		4		16
4	49	[redacted]	5		3		15
5	5	[redacted]	3		4		12
6	13	[redacted]	4		3		12
7	46	[redacted]	3		4		12
8	51	[redacted]	4		3		12
9	56	[redacted]	4		3		12
10	3	[redacted]	3		4		12
11	58	[redacted]	4		3		12

Examples of Incidents – Significant Unanticipated Costs

Supercritical Coal Plant – Mission Minimum Load

- Two Supercritical Units
  - Each about 12,000+ hours at minimum load (accumulated over about 8 years)
  - Minimum load below the critical point (go into subcritical mode on flash tank)
  - Over 6 month period extensive bull nose failures experienced – failure mechanism long term overheat, also indications of some short term overheat damage
  - Contributing cause appears to be departure from nucleate boiling while operating below the critical point
  - Immediate fix, raise minimum load
  - Intermediate actions, partial nose replacement (**Several Million USD to replace**)
    - Cost excludes reliability (loss revenue) and immediate repair costs for prior tube leaks
  - 5 years earlier chemical cleans had been done on units to address heavy deposits

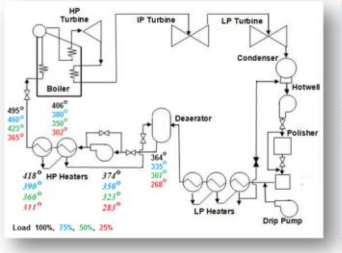


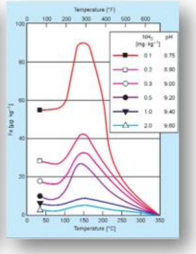
Significant Costs of flexible operation can be latent, not manifesting into immediate issues

100 MW Subcritical Unit – Frequent BFP Starts

- 1960's Subcritical Drum-Type Wall-Fired (Reheat)
- Significant failure occurred:
- Unit came on line at 22:05 hrs.
  - At 7:35 hrs. the following morning the unit was almost to full operating pressure of 1800psi
    - A loud explosion was heard outside the north wall of the control room
    - It caused the control room and annex to shake
    - And the plant to fill with steam.
  - Lead operator started to de-load unit but the boiler tripped on low drum level tripping the unit.
  - All DCS communication was lost on the control room screens, just the graphics remained
- Root cause found the damage to be Flow Accelerated Corrosion (FAC) – plant did have an FAC inspection program
- No Injuries

Low load feedwater pipe, located on the 2nd floor





Critical to understand how changing modes of operation impact on our units

150 MW Natural Circulation Subcritical Unit Minimum Load

- 1950's vintage roof fired subcritical unit.150 MW operating at 2100 psi drum pressure – suffered extensive hydrogen damage in waterwall tubing found (discovered after rearwall tube leak developed):
  - 40 dutchman installed on furnace rear wall.
  - Most dutchman installed at elevation 514 ft.
  - Dutchman were up to 11 ft in length
- Unit Details:
  - Manufacturer minimum load is 85 MW
  - AVT-R & Caustic Treatment
  - Unit had a previous history of underdeposit corrosion tube failures; but prior to incident had no failures for 10 years
  - 3 years prior to tube leak entire rearwall had been borescoped
  - No indication of operating with condenser leaks.
  - No chemical events since last chemical cleaning (3 years prior to tube leak)

Historically limited hours at <25% Full load (just startup / shutdown periods)

2 years before failure >800 hours at <25% Full load

Year before failure >1000 hours at <25% Full load

A complete circulation model was developed:
At <25% load a steam blanket developed on the rear wall tubes. This steam blanket hindered heat transfer and caused elevated heat fluxes in this area which was sufficient in creating a long term departure from nucleate boiling (DNB)

The presence of localized DNB conditions (steam film) triggers localized hydrogen damage.

Raised Minimum Load and Adjusted low load operation based on findings

Operation outside of acceptable range not immediately obvious, latent damage causes re-evaluation of capabilities

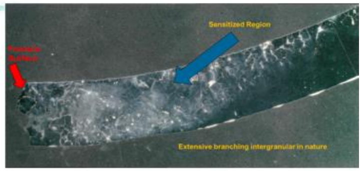
Minimum Loads

- Major Failures
  - Extensive repairs (millions)
  - Extensive loss of generation
- In two cases needed to re-rate the minimum load upwards

Examples of Incidents – Significant Unanticipated Costs

~700 MW Supercritical Unit - Shutdown

- Tube failure occurred during a startup following a 4 month outage
- One section from circuit 1 from the cold reheat loop was removed after failure for analysis
  - Tube was 304 H stainless steel
  - Stress Corrosion Cracking identified
  - Extensive intergranular branching
  - Circuit compromised
- Root cause identified:
  - Salt Contamination present in Reheater
  - Inadequate Layup procedures
  - Susceptible Material (304 H)
- Plant adopting more protective layup procedures (impacts on time required to return unit to service)

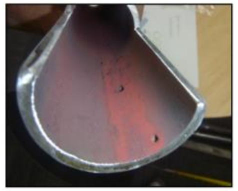


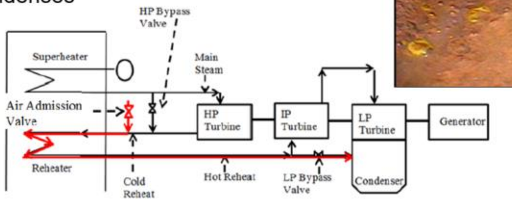
Longer term unit will replace the susceptible 304 H with 347 H which is less susceptible to sensitization

Due to susceptible material in location where offline corrosion is likely need to reduce flexibility to preserve asset

Supercritical Coal Plant – Extended Shutdown

- One Supercritical Unit
  - ~8,000 hours of shutdown
  - On most extended shutdowns forced cooling was performed
  - For non-forced cooled shutdowns unit relied on vacuum 'drying' of reheater (lowers dewpoint but not capable to reduce offline relative humidity, i.e. removes some water and reduces the temperature at which moisture condenses but not low enough to prevent condensation)
  - Reheater tube leaks due to pitting, extensive damage found in the horizontal reheat sections as part of root cause on primary failure
  - Horizontal Reheater Replacement estimated at **Several Million USD**
    - Cost excludes reliability (loss revenue) and immediate repair costs





Value of Proper Lay-up is little for a baseloaded power plant – but there will be a tipping point

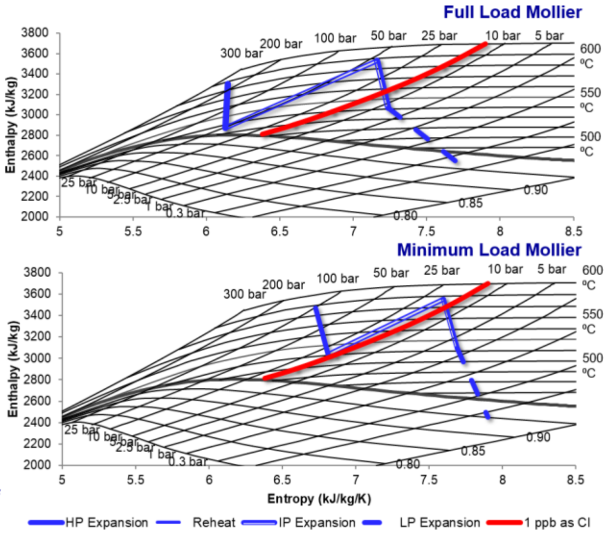
Layup

- Major Failures
  - Extensive repairs (millions)
  - Extensive loss of generation
- Inadequate protection due to needing to remain 'available'

700 MW Supercritical Units Minimum Load - Shutdown

- Unit 'A' and Unit 'B' LP Turbine installed in early 2000s
- Unit 'A' and 'B' are once through supercriticals (~700MW each) on oxygenated treatment with full flow powdex condensate polishers
  - During first Unit 'A' planned turbine inspection outage after LP install (~10years operation), cracking was found on more than 90% of the last stage (L-0) buckets.
  - Based on these discoveries Unit 'B' was subsequently removed from service and the last stage buckets were inspected.
  - The buckets were found to have similar cracking (however it was less severe)
  - Laboratories' findings determined the cracking mechanism to be Stress Corrosion Cracking (SCC).
- Low level contamination identified as root cause combined with increased low load operation / unprotected shutdown
  - Cation Conductivity 0.13-0.16 uS/cm for days

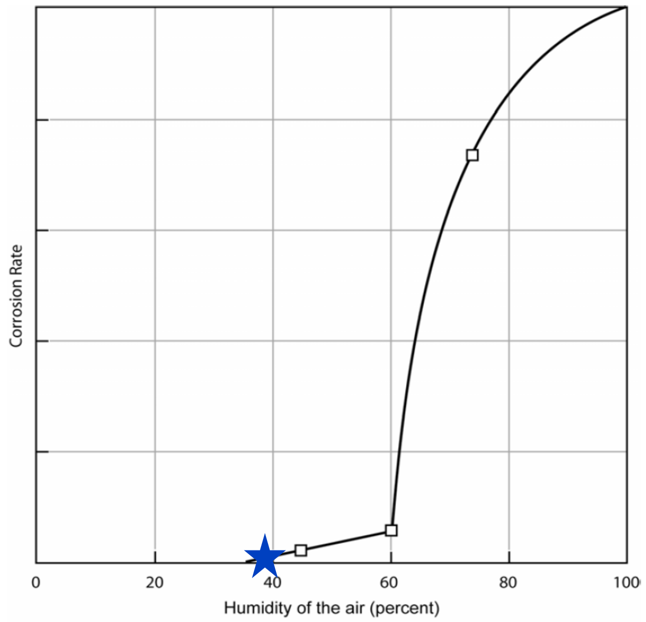
Whenever a once through unit has a cation conductivity greater than 0.06µS/cm at the effluent of the polisher plant staff need to confirm the cause



Steam Purity Requirements Increase with lower load Operation!

Offline Protection

- Attached are 60 kW heaters installed in LP Turbines
- Removed the duct from access door and lay the relative humidity (RH) wand inside the hood approximately 3 ft away from L-0 buckets.
- RH reading was 39% after it had been in the hood for about 7-8 minutes and was still dropping



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Modes of Flexible Operation

Meeting the Challenge &

Value of Collaboration

EPRI's Mission Profile Working Group

16 Organization in Supplemental Project

Launched Summer 2015

Developed flexops.epri.com mapping issues and solutions associated with flexible operation for power plant systems and assets

Flexibility and Overall Plant Reliability

Major Damage Mechanisms during Flexible Operation

EPRI TR-109470

Mechanism	Affected components
Creep-fatigue	SH/RH tubing, MS/RH piping, turbine casings, steam chests, valves, HP/IP rotors
Creep cavitation	High temp. headers, MS/RH piping welds, HP/IP rotors
Corrosion-fatigue	Waterwalls, low-temp. header welds/ligaments, MS/RH piping welds, HP steam turbine blades, deaerators
Stress corrosion cracking	LP turbine rotors, generator retaining rings, condenser, deaerators
Flow-assisted corrosion	Steam piping, FW heater drains, turbine casings,
Thermal fatigue	Economize inlet, high temp. header welds/ligaments, feedwater heaters, turbine valves
Deposition	Generator cooling system, turbine steampath, condener, air preheater
Quenching	Heat recovery steam generators, pumps, piping
Corrosion	Waterwalls, SH/RH tubes, generator cooling sys., fans, feedwater heaters, air heaters
Erosion-corrosion	Economizer inlet, fans
Wear	Generator stator, pipe hangers, condenser tube supports, feedwater heater tube supports
Fretting	Generator retaining rings, control stage blading, generator rotor wedges
High-cycle fatigue	LP turbine rotor, turbine blades, generator field, fans, pumps, feedwater heaters
Low-cycle fatigue	Turbine casings, steam chests, valves, LP turbine rotors, generator fields, generator retaining rings, generator stator, HP/IP turbine rotors, fans, pumps
Erosion	Waterwalls, turbine casings, steam chests, stop valves, turbine blades, condensers, feedwater heaters, deaerators
Pitting	Generator retaining rings, LP turbine rotor, LP turbine blades
Differential growth	generator cooling system, turbine rotor/casing
Distortion	fans, turbine casings, air heaters
Cavitation fatigue	pumps, valves
Insulation fatigue	motor windings, generator windings

Mechanisms are well understood – applying cost effective solutions is the central challenge

Where EPRI is working on FlexOps

Program	Title	Flex %
63	Boiler Life and Availability Improvement Program	35%
64	Boiler and Turbine Steam and Cycle Chemistry	50%
65	Steam Turbines-Generators and Auxiliary Systems	15%
66	Fossil Fleet for Tomorrow	5%
68	Instrumentation, Controls and Automation	65%
69	Maintenance Management and Technology	50%
71	Combustion and Coal Quality Impacts	25%
75	Integrated Environmental Controls	25%
77	Continuous Emissions Monitoring	30%
79	Combined Cycle Turbomachinery	20%
87	Fossil Materials and Repair	50%
88	Combined Cycle HRSG and Balance of Plant	35%
104	Balance of Plant Equipment	30%
108	Operations Management and Technology	50%
185	Water Management Technology	10%
193	Renewable Generation	5%
194	Heat Rate Improvement	15%
PS173C	Strategic and Flexible Planning	50%
41.11.01	Flexible Operation Program	100%
49	Coal Comb. Products	10%
59	Multimedia Toxics Characterization	50%
78	CCP Use	25%

Base Programs

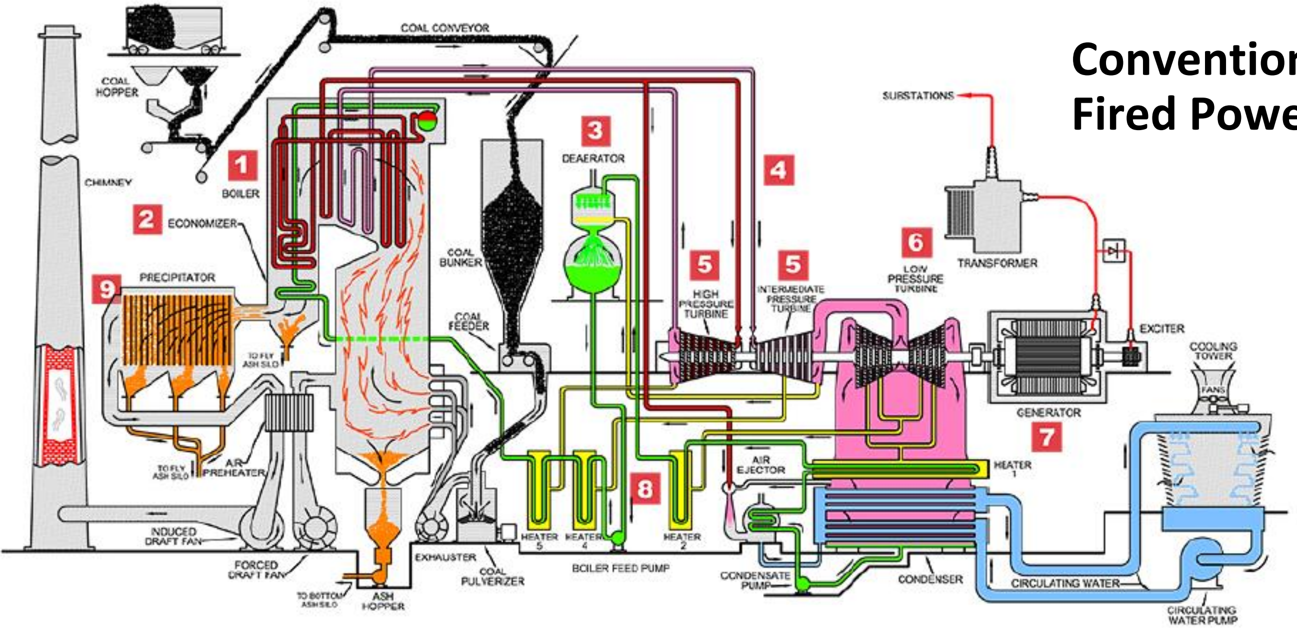
Supplementals

Supp. Project	Title	Flex %
1-108819	Superheater Outlet Header	25%
1-108396	Load Changes and Flexible Operation	100%
1-110953	**PSET_P64_Supp** Cycle Chemistry Alarms	50%
1-106718	Flash Dry Draining Sub-critical Drum	100%
1-110888	Use of SFRA to Detect Generator Rotor	100%
1-110176	TG Maintenance Intervals	50%
1-107227	**PSET_T-G** Torsional Vibration Monitoring	50%
1-109619	ComTest Phase 2 Supplemental	10%
1-110503	Concrete Thermal Energy Storage	100%
1-109252	**RICE Interest Group**	100%
1-107916	PSET_P68 Supp I4Gen	50%
1-108361	Simplified Analytical Technique for EMSA	25%
1-072390	**PSET_P69 Supp** Maintenance Case Studies	50%
1-110321	Approach for Sustainable Dynamic Combustion Optimization	100%
1-108442	Demo of Combustion Diagnostics & Optimizer for Emissions&Performance	75%
1-109567	Artificial Intelligence Application for Air Quality Control Systems	50%
1-109264	Unit Specific Predictive Model for Toxics Control	50%
1-108636	Portable Electrostatic Precipitator (ESP) Test Facility	50%
1-106768	Evaluation of Reduced-Load SCR Operation	100%
1-108203	Characterization of Stack Particulate Matter	100%
1-072056	Combustor Dynamics Monitoring for Improved Gas Turbine Reliability	25%
1-066745	Gas Turbine Rotor Life	25%
1-064708	Reducing Life Cycle Costs for Gas Turbine Hot Section Components	25%
1-106527	Application of Well Eng'd Weld Repairs for Grade 91 & other CSEF Steels	50%
1-070753	Optimizing Heat Recovery Steam Generator Drains	100%
1-109979	HRSG Spray Valve Detection	50%
1-107140	**Mission Profile Working Group**	**100%**
1-071860	**PSET_108 Supp Operational Flexibility Implementation: Case Studies**	**100%**
1-111161	**Operational Flexibility Workshop**	**100%**
1-072777	**Flexible Operation of Hydropower Assets**	**100%**
1-072366	**PSET_P69 Supp** SmartM&D	50%
1-109443	Assessment of Hydrated Lime Injection Upstream	50%
	Various One-off Supplementals applying Base Program R&D	

Selection of Base Funded Flexibility Projects 2018

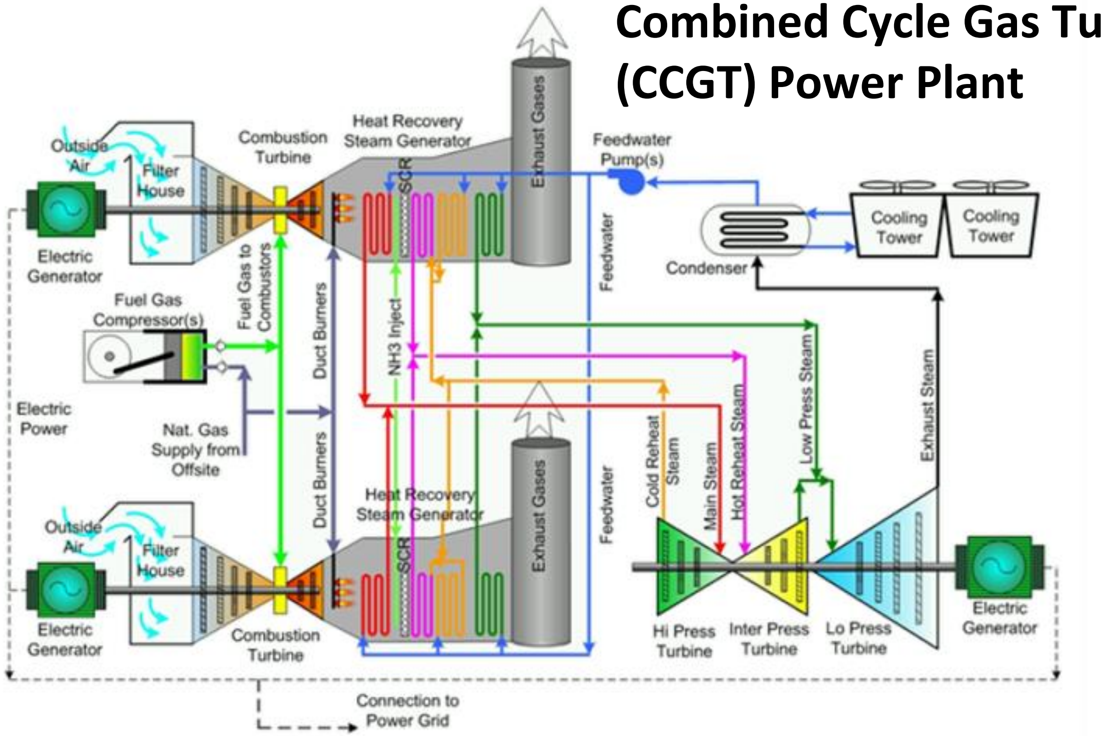
Flexible Operations Handbooks - Volume Three, Steam Touched Components 3002010385	63 Base
Film Forming Product and Filming Amine Guidelines (pending should be complete Q1) – 3002013952	64 Base
Phase Transition Zone Chemistry and Filming Products 3002008132	64 Base
Filming Products and Corrosion Fatigue 3002013955	64 Base
Outage Intervals for Generators used in Flexible Operations 3002013652	65 Base
Steam Turbine Low Load Operation – 2018 Update (pending should be complete Q1) - 3002013589	65 Base
Energy Storage Database (ESD) - 3002013709	66 Base
Non-Battery Bulk Energy Storage - 3002013535	66 Base
Demonstration - Steam Temperature Control Strategies for Combined Cycle Units - 3002013414	68 Base
Process-Control Strategies for Low-Load Operation - 3002014391	68 Base
Pulverizer Performance Studies: Survey Results - 3002013002	71 Base
Studies on Coal and Natural Gas Cofiring: Simulation of Tangentially-Fired Furnace Cofiring Strategies - 3002013004	71 Base
FGD Operations Under Extended Minimum Low-Load Conditions - 3002013046	75 Base
Fuel Quality and Combustion Impacts on Emissions - 3002013044	75 Base
Advanced Combined-Cycle Plant Design and Construction - 3002011990	79/88 Base
Life Management of 9%Cr Steels: Evaluation of Metallurgical Risk Factors in Grade 91 Steel Parent Material - 3002009678	87 Base
Guideline of Forced Cooling for Flexible Operation - 3002013943	88 Base
Acoustic Emission Attemperator Monitoring Systems: Insights Gained from Three Site Applications - 3002014348	88/68 Base
Study and Report on CT Purge Credits (pending should be complete Q1) – 3002013538	88 Base
Ramp Rate Optimization Guide – 3002012797	108 Base
Flexible Operations and Heat Rate – 3002013992	194 Base

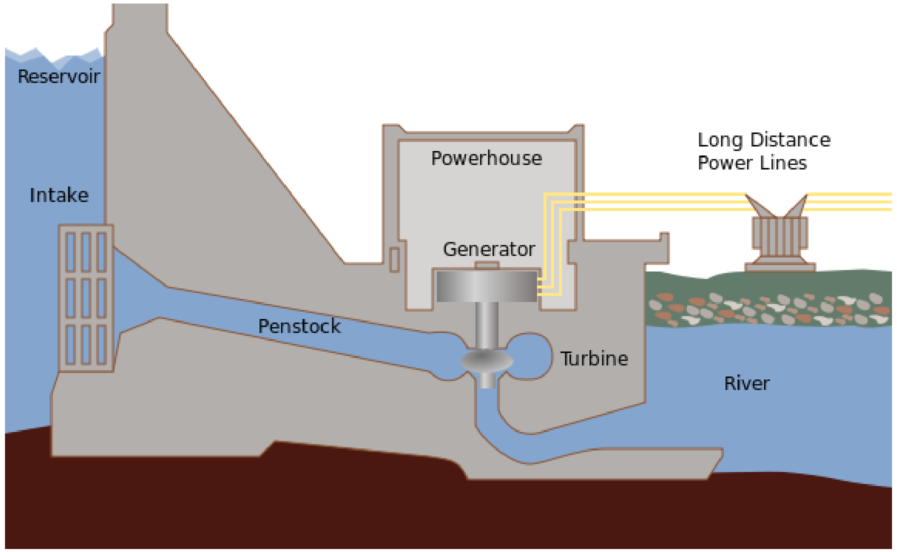
Primary Generation Plants capable of Flexible Operation



Conventional Coal Fired Power Plant

Combined Cycle Gas Turbine (CCGT) Power Plant



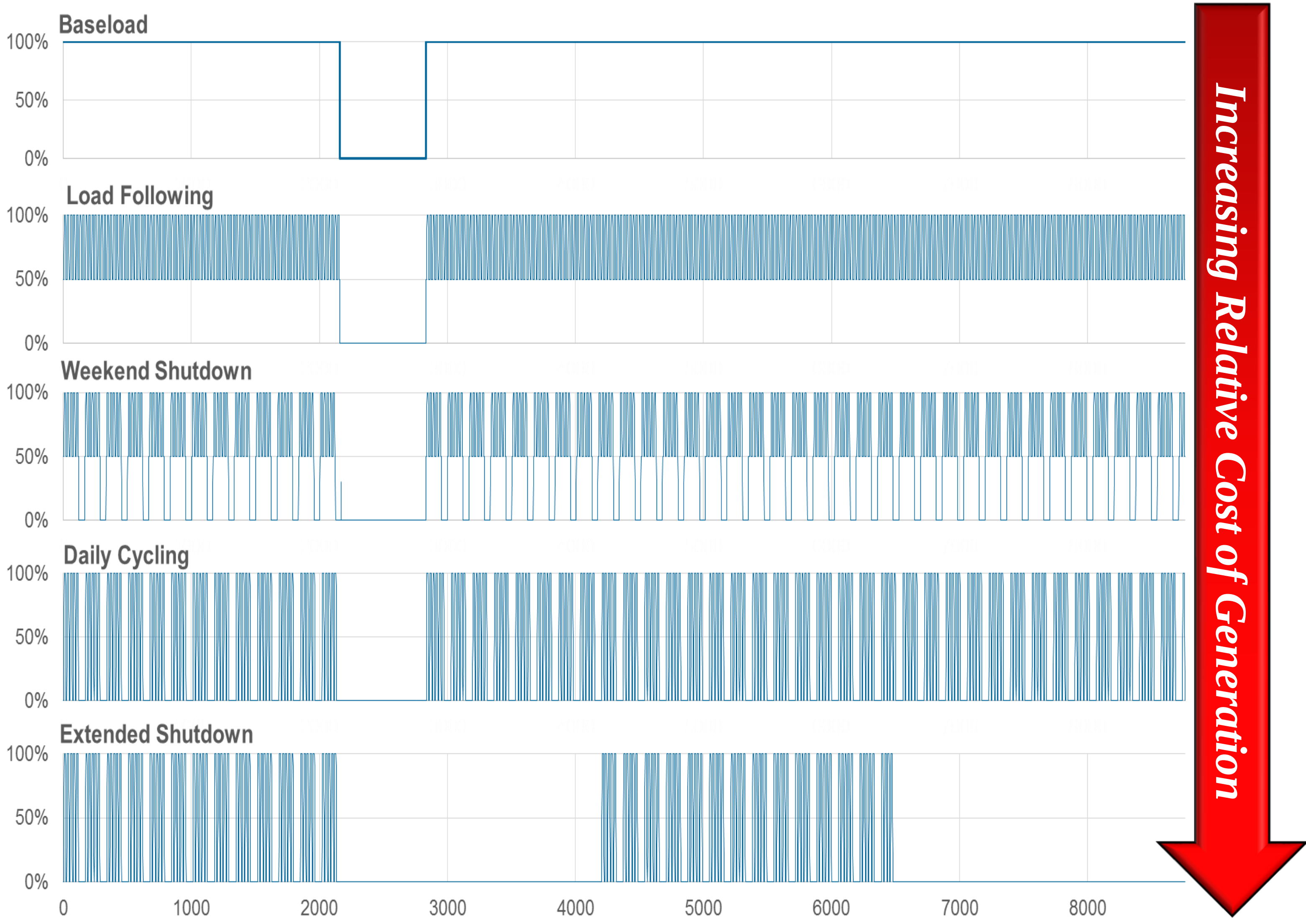


Hydroelectric Dam Power Plant

- U.S. Nuclear Power Plants have generally only been considered as baseload providers, however some plants have begun to enter into limited flexible operation modes

Example Relative Operating Statistics (Coal Plants)

	Load Changes	Starts	Capacity Factor
Baseload	4	1	92%
Load Following	2024	1	70%
Weekend Cycling	1646	49	51%
Daily Cycling	2178	242	41%
Extended Shutdown	1206	134	23%



More Starts / Load Changes, More Wear and Tear, less Capacity Factor less Energy (less $/MWh)

Spectrum of Flexible Operation

Increasing Relative Cost of Generation

Operating Mode

Baseload	Load Following	Cycling (Weekend)	Cycling (Two-Shift)	Extended Shutdowns (week / month / season)
Maximum Load Operational Reliability Cost	Maximum Load Minimum Load Ramp Rate Operating Reliability Cost	Start Reliability Minimum Load Ramp Rate Operating Reliability Cost	Start Reliability Startup Speed Minimum Load Ramp Rate Operating Reliability Cost	Minimum Load Preservation of Equipment Availability of Equipment (Startup Speed) Cost

Defining Characteristics

Economic Viability

Lower Minimum Load

Fuel Changes (Lower-Cost Fuels)

Energy Market | **Balancing Markets** | **Capacity Market**

Externalities significantly impacting costs / operation includes fuel prices, changing regulations

Retrofits for flexibility are possible but economics can be challenging (especially for ramp rate)

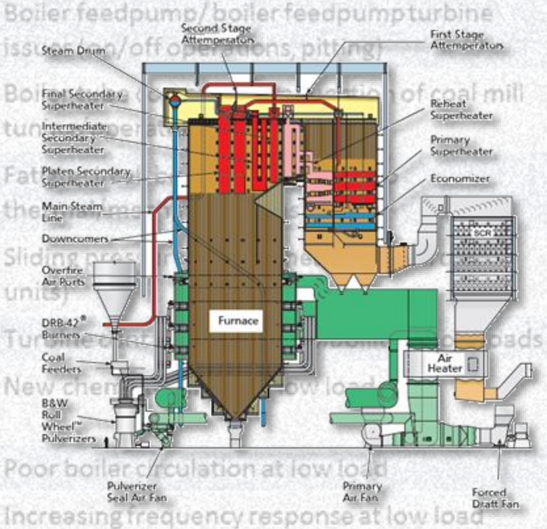
Mission Profiles Working Group - Key Issue Areas

Consensus of Subject Matter Experts (EPRI & Utility)

flexops.epri.com

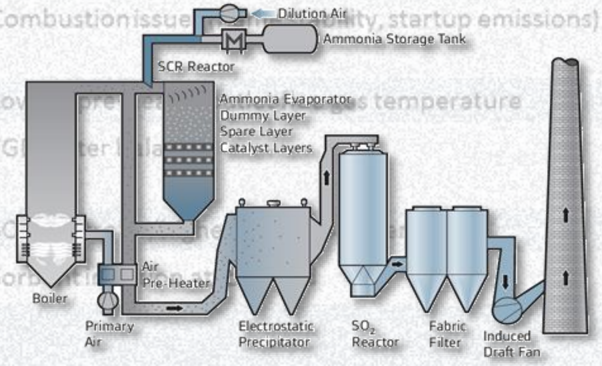
Boiler and Chemistry

- Boiler feedpump/boiler feedpump turbine iss… …/off operations, pitting)
- Boi… …tion of coal mill tur… …pera…
- Fat… the…
- Sliding pres… units)
- Tu… …oads
- New chem… …ow load
- Poor boiler circulation at low load
- Increasing frequency response at low load
- Cree… fatigue vs. design for baseload opera…s
- Eco… header cracking
- Fi… effectiveness for layup
- W…
- Flow…
- Corr…



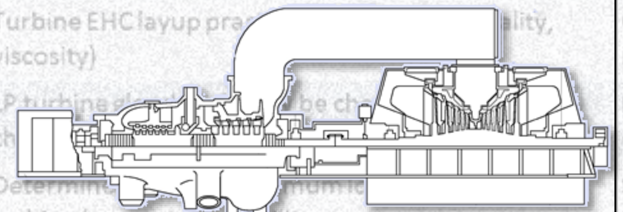
Combustion & Environmental Controls

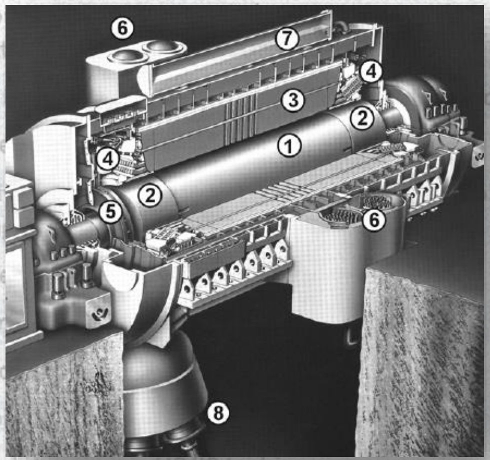
- FGD chemistry & wastewater treatment
- Fireside corrosion (coal quality, staging)
- SCR operations at low load
- Combustion issue… …ality, startup emissions)
- Low… …s temperature
- FG… …ter bala…
- SC…
- Sorb…



Turbine - Generator

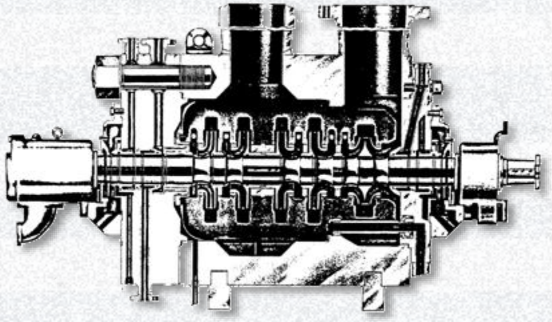
- Generator issues: service life consumption, winding fatigue
- Turbine EHC layup pra… …lity, viscosity)
- LP turbine… …be ch… ch…
- Determin… …turbine/generator re…ility
- Boiler/turbine controls tuning at low load
- LP turb… ineffe…
- Higher…
- Turbin…
- Excess… last sta…
- Turbine…
- Wider…
- Rotor,…
- LP turb…
- Thermal stresses on HP/IP turbines
- Auxiliary turbine casing warmers
- Impact of cycling on generator core integrity





O&M and Balance of Plant

- BFP flow stability at low loads
- Coal m… reliabi…
- Layup… duratio… …up
- Sliding…
- Fluctu…
- Feedwater heater and turbine drain management



Issues by systems are impacted by the specific mode of operation in unique ways

Steam & Water Chemistry Issues in Various Operating

Operating Mode	Chemistry Issues	
Load Following	• Feedwater chemistry control • Dissolved oxygen in condensate • Sampling issues	• Phosphate Hideout • Carryover (level control) • Corrosion Product Monitoring
Cycling (weekend off)	• Reheater pitting • Chemistry on startup	• General Steam Path pitting • Carryover (swell)
Cycling (two-shifting)	• Boiler chemistry control • Carryover Issues	• **Feedwater chemistry control** • Carbon dioxide ingress
Extended Layup	• **Turbine Pitting (leading to Stress Corrosion Cracking or Corrosion Fatigue)** • Chemistry System return to service	• Oxygen pitting boiler tubing • Water Treatment Layup • Instrumentation layup
Sustained Minimum Load	• **Increased steam path deposition** • FAC in economizers / IP Evaporator • FAC in BFP recirculation lines • Steaming in Economizer (two-phase FAC)	• DNB and Hydrogen Damage • High level of attemperatoring sprays • Sampling / Monitoring • Air-inleakage control

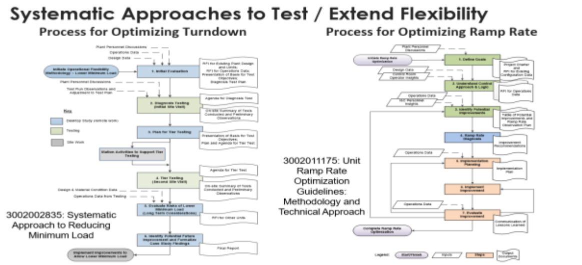
Cycle Chemistry Guidance for Combined Cycle/Heat Recovery Steam Generators Under Flexible Operation. 3002007938.

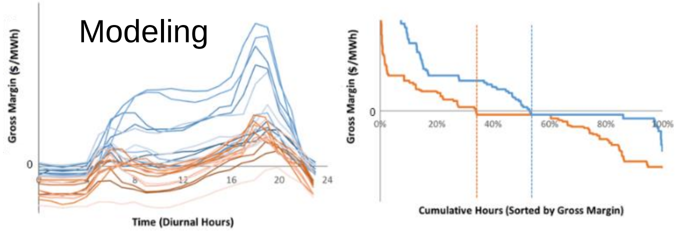
Efforts to address Flexibility Challenges

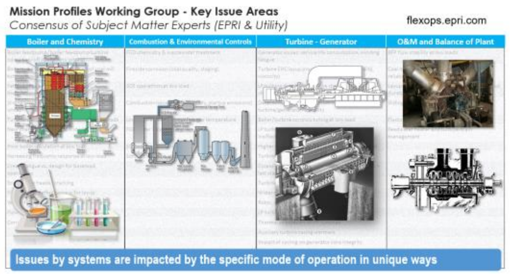
Overcoming the Challenge

Comprehensive Approach to Flexible Operations

- A comprehensive approach to assessing future flexible operations needs and responding to those needs in a manner that is economically and technically sustainable entails several steps:
  1. Assessment of current fleet characteristics and capabilities.
  2. Assessment of future levels of increased flexible operations, including assessment of transmission network capabilities to move power regionally.
  3. Assessment of technical issues and potential solutions/workarounds for specific generation unit types associated with different specific flexible operations modes.
  4. Incorporation of flexible operations criteria in future generation planning.
  5. Development of unit-specific transition plans depending on the expected future operational mode(s) for the unit, addressing operational & maintenance strategies, staffing needs, and procedural needs.







RICE Interest Group
New CCGT Plant Development Group

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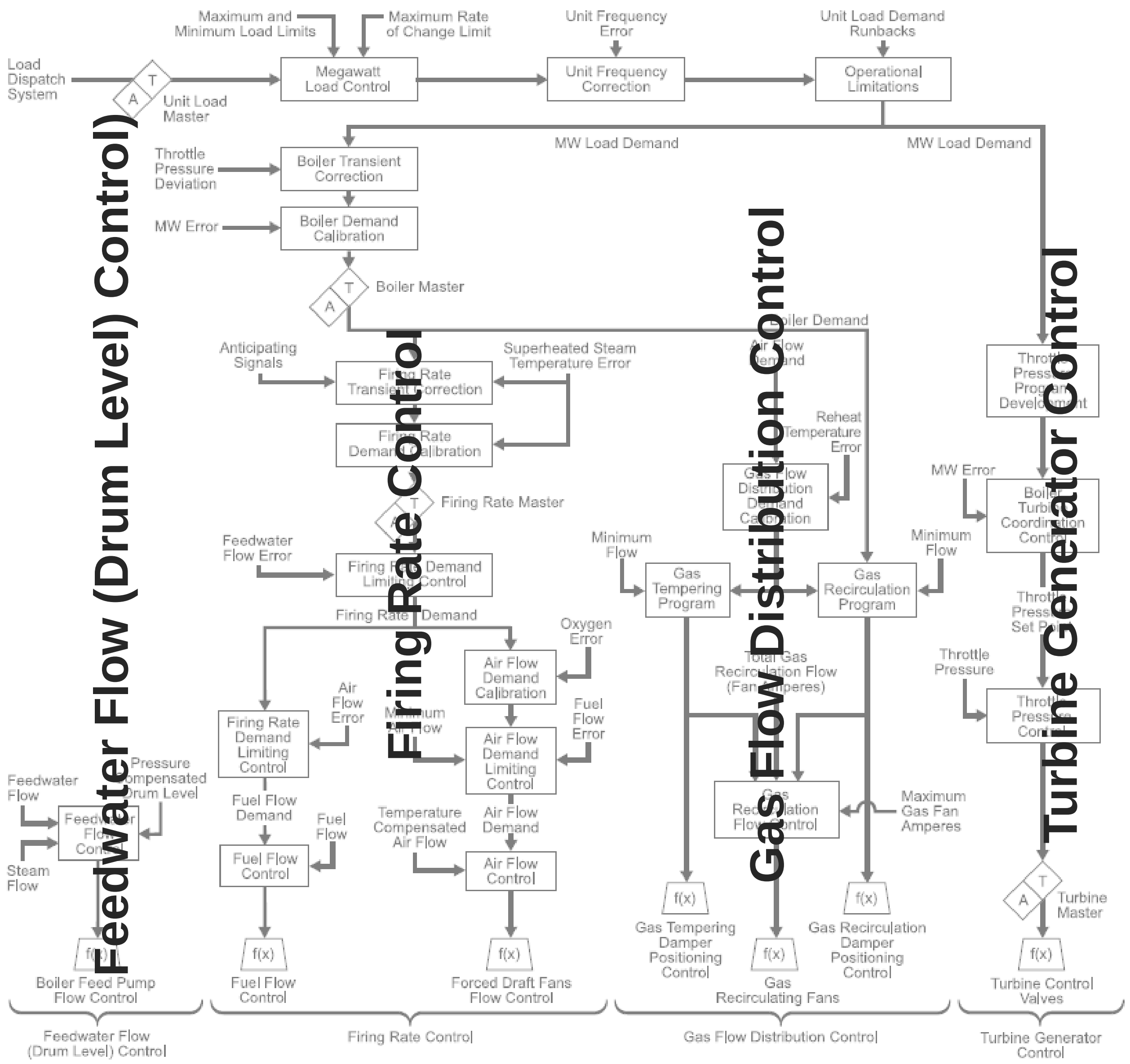
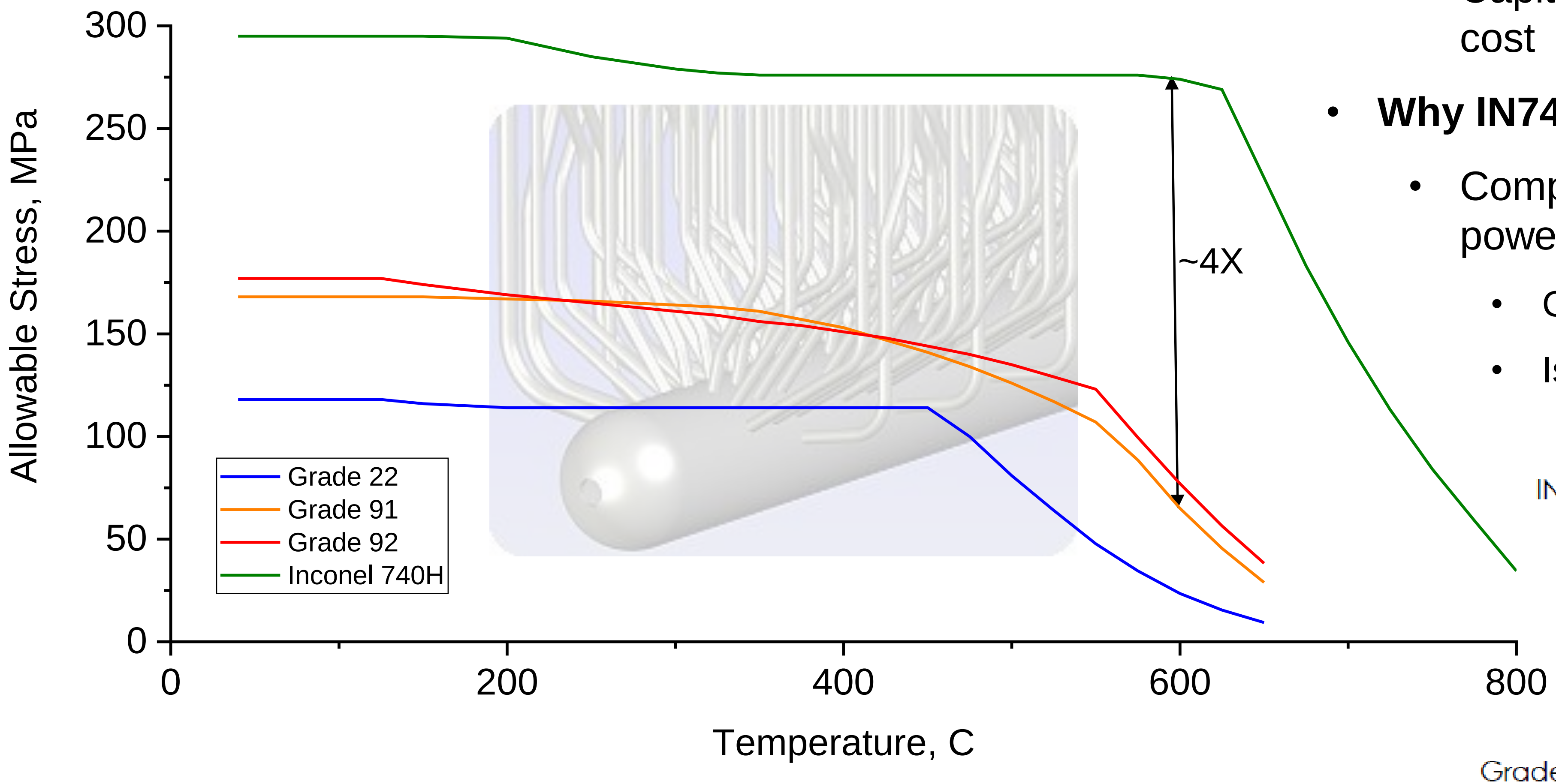
Coal Plant Ramp Rates

- Usually limited by:
  - Allowable stresses in thick wall components
    - Requires capital expenditure / unit redesign
  - Fuel Quality
    - Generally less costly coals are poorer quality
  - Controls (e.g. time lag between coal milling and turbine response)
    - Normal approach for improving ramp rates
    - May incorporate capital expenditures

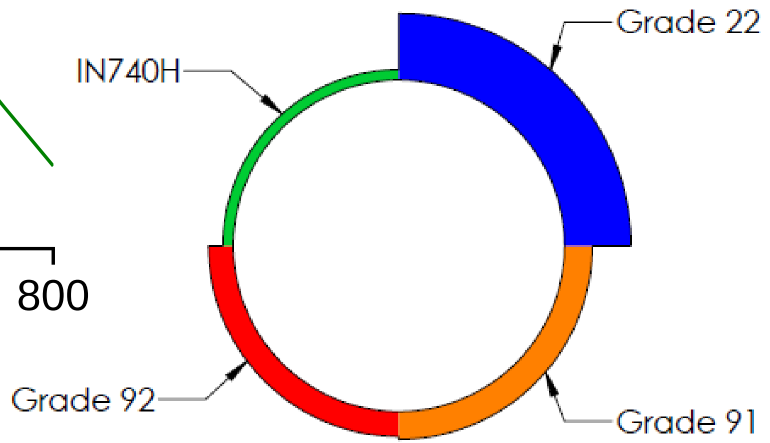


Integrated Controls (B&W Steam 42nd Edition)

Superheater Outlet Headers



- **Why Retrofit?**
  - Capital cost versus maintenance cost
- **Why IN740H?**
  - Compared to traditional ferritic power plant steels, IN740H:
    - Can be made significantly thinner
    - Is in the time dependent regime



Using this material allows for thinner components more tolerant of thermal cycling

Energy Storage Can Reduce the Need for Flexibility

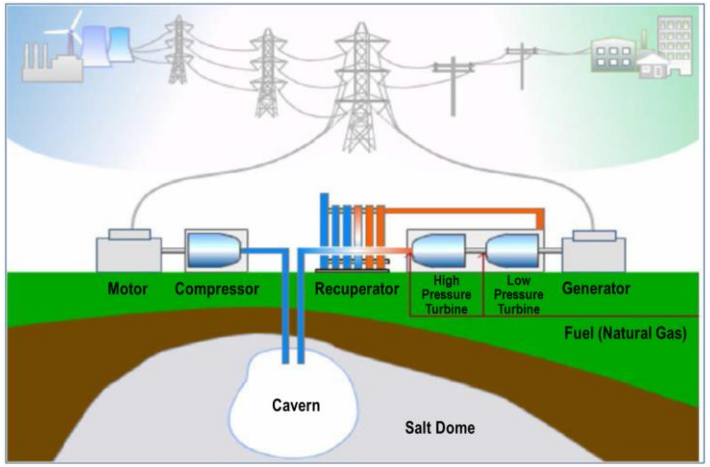
- If instead of operating flexibly, fossil plants run at full load and store energy when it makes sense:
  - Fossil plants export power when it is profitable as before
  - Fossil plants operate during low/negative pricing periods without exporting power and store it instead
  - Battery technology can be used; however, the cost of storage for batteries can be high at **$385–490/kWh** installed today*

*LAZARD Levelized Cost of Storage – Version 3 November 2017

Non-battery bulk energy storage can deliver lower cost options

Non-Battery Energy Storage Technologies

- Pumped Hydropower
  - Represents 95% of capacity today
- Compressed Air Energy Storage
  - Only two plants globally
- Liquid Air Energy Storage (LAES)
  - Demonstration stage
- Thermal Energy Storage (TES)
  - Pilot stage



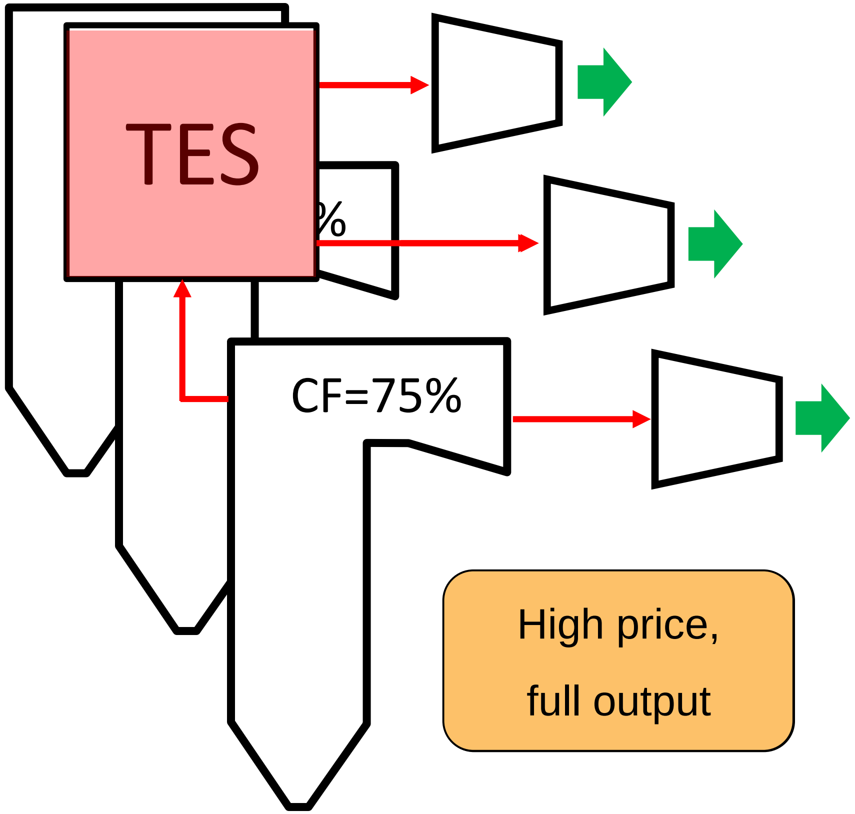
Compressed Air Energy Storage

2-MWe LAES Demonstration (Highview Power)

Thermal energy is 4 times cheaper than batteries

Thermal Energy Storage (TES)

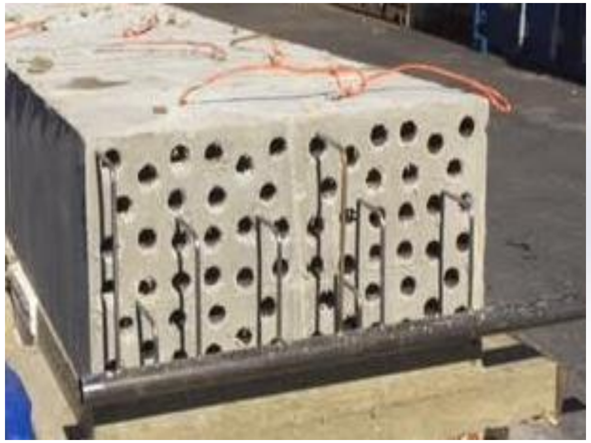
- By providing steam to TES when prices are low, the unit remains operational, avoiding shutdowns and ramping
- When prices increase, unit AND the TES units provide steam to the turbine-generators
- All three units generate power when needed

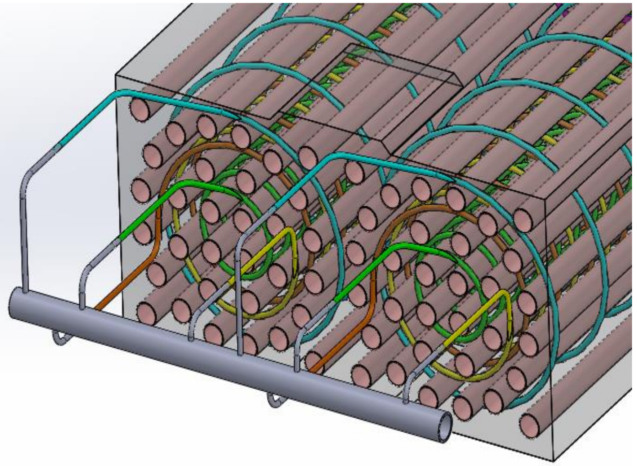


TES Example: Concrete Thermal Energy Storage

Bright Energy

- Solid 'thermocline' structure used to store thermal energy
- Low-cost material **$67/tonne**
- Modular system (12.5 m), small footprint

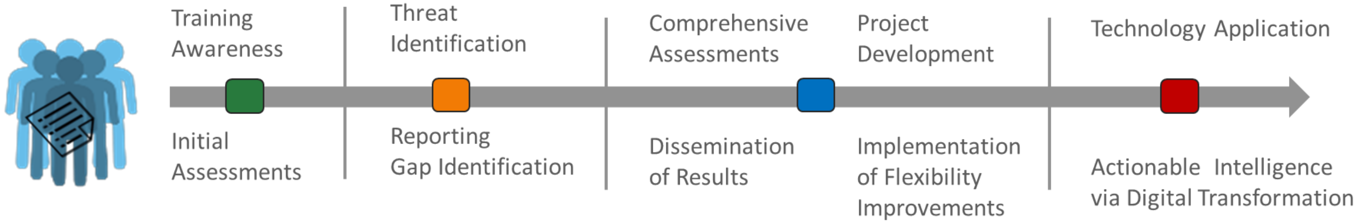




- Steam tubes embedded into concrete blocks – conductive heat transfer
- EPRI project is developing a field test at an operating coal power plant

Images courtesy of Bright Energy Storage Technologies

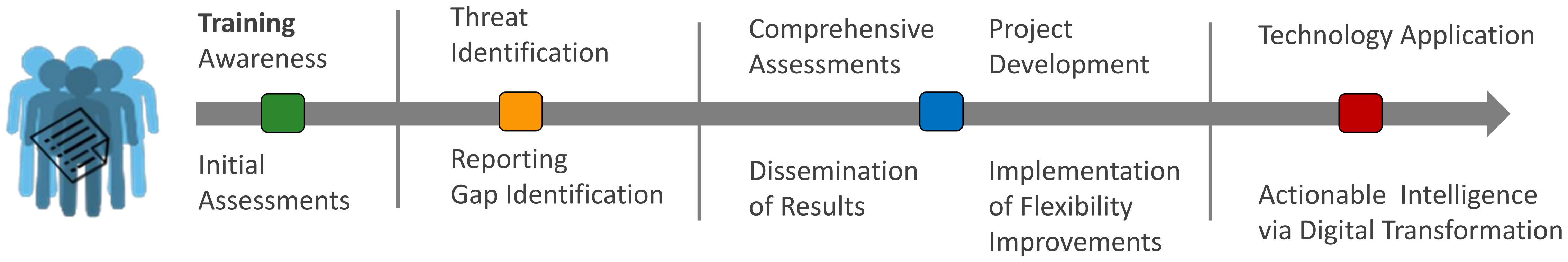
FlexOps Management



- General Awareness, Initial Endeavors
  - Tools for Managing Flexible Operation of Power Plants – Supplemental
    - flexops.epri.com
    - Annual Flexibility Conference (Inaugurated in2018)
    - Periodic update meetings / webcasts
- Deeper level initial flexibility engagement
  - 2 day Flexibility Workshop Supplemental
- Operational Flexibility Case Studies Supplementals
  - Specific projects to extend capabilities of a current unit
- Flexibility Assessments

Vision – *The Flexible Future*

Adapting to change demands enhanced plant defense strategies that utilize systematic processes. Flexibility is complex and strategic countermeasures to protect assets undergoing the new operating regimes.



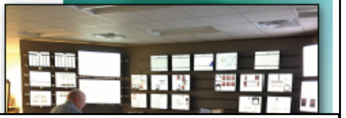
Managing fleet flexibility requires the inclusion of both quantitative and qualitative actions that drive awareness, apply best practices, encourages benchmarking and most importantly, integrates modifications and defense strategies to protect assets.

Many Flexible Operation Related Success Stories

- http://genstrategy.epri.com/enabling-flexible-operations-of-the-generation-fleet/

EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

Research Helps TVA Increase Operational Flexibility and Turndown Potential of Base-load Plants



EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

Southern Company Develops Plans for Preservation of Plant Equipment during Shutdown and Layup

EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

FirstEnergy Demonstrates Methodology for Implementing Expanded SCR Operation at Reduced Loads

FirstEnergy demonstrated a methodology for cost-effectively operating selective catalytic reduction (SCR) technology for control of nitrogen oxides (NOx) over extended periods of reduced plant load. The demonstration contributed to the validation of an EPRI methodology for better evaluating SCR operating limits and documented acceptable reduced-load SCR performance.

SCR Operation at Reduced Load

In general, operating plants at reduced load is more prevalent today than previously due to increasing levels of flexible operations. A key challenge of this trend involves its effects on environmental control equipment, including SCR systems. Currently deployed on 260 U.S. coal-fired units, SCRs are designed to operate within a specific temperature range and usually are one of the prime factors limiting a unit's low-load capability. Low-load operation, which results in lower SCR inlet temperatures, can affect the process chemistry, which is designed to operate within a specific temperature range.

SCR systems reduce NOx emissions by injecting ammonia into the flue gas stream prior to passing through a catalyst reactor. Flue gas temperatures must be at or above a minimum operating temperature (MOT), defined by catalyst vendors to achieve required levels of NOx reduction and avoid ammonia slip, which is ammonia passing through unreacted. The temperature limit

Typical supercritical boiler and selective catalyst reduction (SCR) system

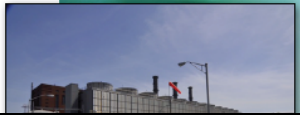
"With the need for operational flexibility in response to continued challenging market conditions, this project allowed us to successfully match

EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

Enel Increases Operational Flexibility of Its Combined-Cycle Gas Turbines by Reducing Hot Startup Times

EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

Oglethorpe Power, PSEG Power Install Ultrasonic Flow Meter Technology for Condensate Detection in HRSGs



EPRI | ELECTRIC POWER RESEARCH INSTITUTE — *Success Story*

Three Utilities Demonstrate Promising Alternative Layup Technique

As part of an EPRI project, FirstEnergy, Louisville Gas and Electric and Kentucky Utilities (LG&E and KU), and Consumers Energy conducted a series of trials of a new film-forming amine as an alternative layup technique for protecting tubing, piping, and equipment in the water/steam cycle of power plants. The chemical treatment offers utilities a simple method for chemical layup that can be applied to provide cycle chemistry component protection with minimal capital expense.

Improving Layup Practices

U.S. fossil plants face special challenges in providing equipment protection during plant layups. An increasing number of units are experiencing short-term outages, due to age and cycling, as well as reduced or seasonal dispatch demands. At the start of layups, the duration is not always clear; short-term layups can quickly become long-term layups, with different requirements. Another issue is that layup techniques often require the capital purchase of equipment and/or additional operating/maintenance expenses.

Water beads on the surface of a condenser after application of the filming amine

"After application of the filming amine to the feedwater system, we measured a dramatic

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SUCCESS STORY

PSEG FINDS OPTIMUM MIX OF AMINES FOR CORROSION PROTECTION OF HRSG COMPONENTS

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SUCCESS STORY

ENEL GLOBAL THERMAL GENERATION USES CREEP-FATIGUEPRO TO MONITOR BOILER LIFE

The international utility Enel employed EPRI's Creep-FatiguePro™ (CFPro) software to monitor accumulation of creep and fatigue damage at several locations in its coal-fired As Pontes Power Station in Galicia, Spain. The software helped the utility to track the level of damage occurring, to understand the direct effects on the plant of operational changes, and to plan remedial actions.

MONITORING CREEP AND FATIGUE WITH INCREASED CYCLING

Extensive cycling of coal-fired power plants due to variable generation and power market requirements results in accumulation of fatigue and creep damage at a faster rate than with baseload operation. The more rapid accumulation of damage requires earlier remedial action (e.g., repair, replacement) than would otherwise be necessary.

In Spain and Italy, coal-fired power plants are required to cycle extensively and operate relatively infrequently due to the power market and the extensive base of renewable energy that dispatches first. This cyclic (start-stop) operation can result in accumulation of fatigue damage, particularly in thick-walled components such as high-temperature headers that experience the greatest thermal transients. In addition, components exposed to high temperature and pressure experience creep damage over time.

Tracking the accumulation of fatigue and creep in these components is a critical element of an overall strategy to manage the life of boiler components.

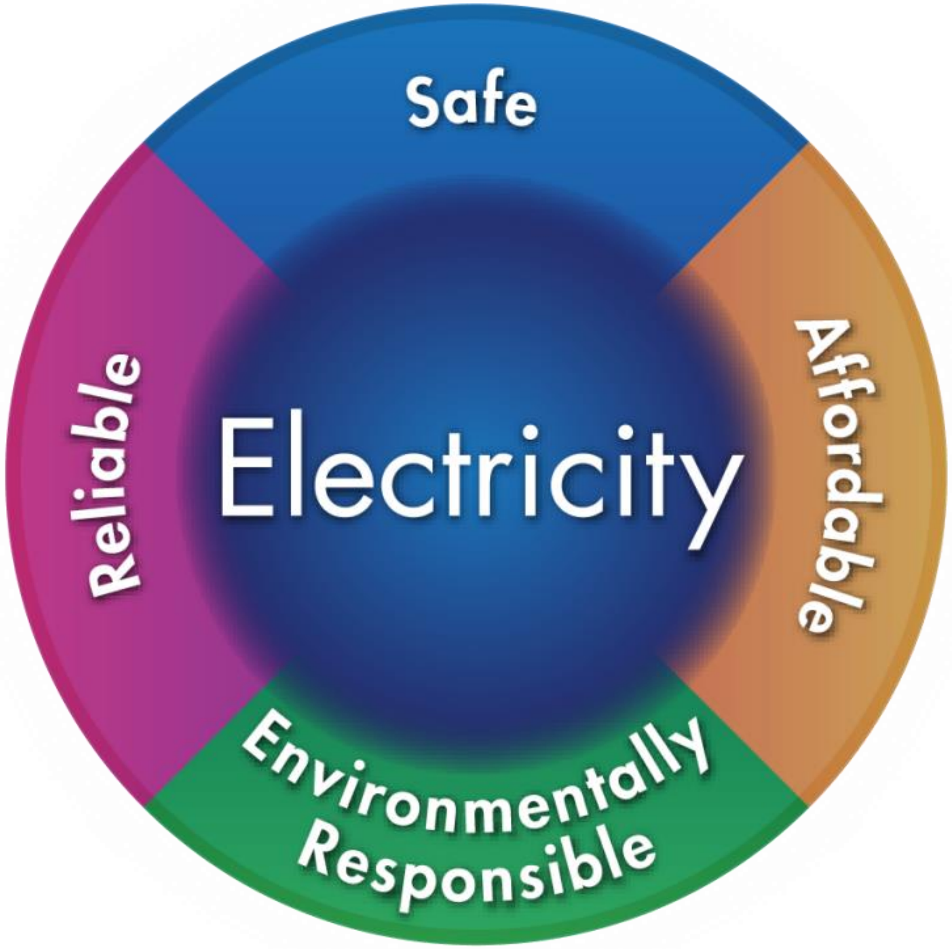
As Pontes Power Station

"The main innova[…] this project was to […] and apply a new an[…] ventional methodol[…] known problem. Th[…] onstration carried o[…] EPRI at As Pontes u[…] Pro, allowed us to i[…] our technical know[…]

The Future of Electricity

Transitioning Electricity Generation

- Understand Our Goals
  - Reduced carbon intensity?
  - Increased renewable generation?
  - Other?
- Make best use of our National Investment and future investments towards our goals
  - Optimizing use of existing flexible dispatchable generation is key when adding non-dispatchable generation

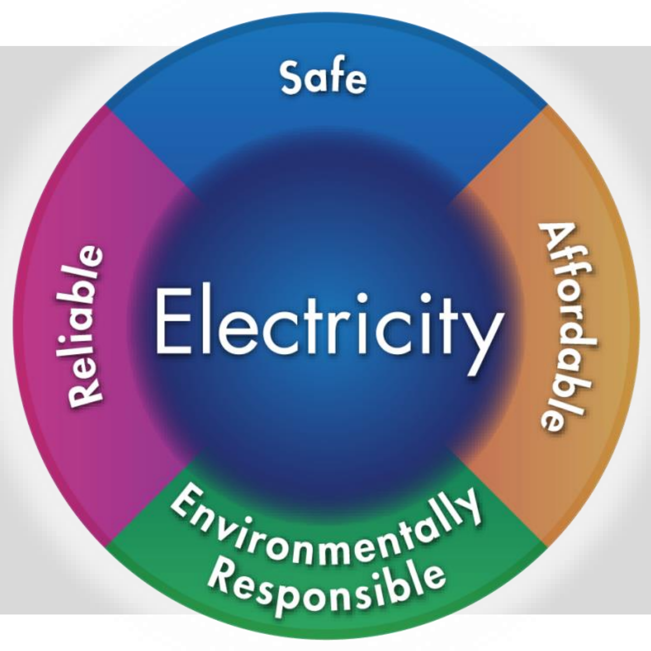


Together...Shaping the Future of Electricity

Conclusions

Advancing ***safe***, ***reliable***, ***affordable*** and ***environmentally responsible*** electricity for society through global collaboration, thought leadership and science & technology innovation

Clear Understanding of our Goals



Make best use of our national investment towards achieving our goals

CAISO Monthly Reports:

http://www.caiso.com/Documents/MonthlyRenewablesPerformanceReport-Jan2019.html

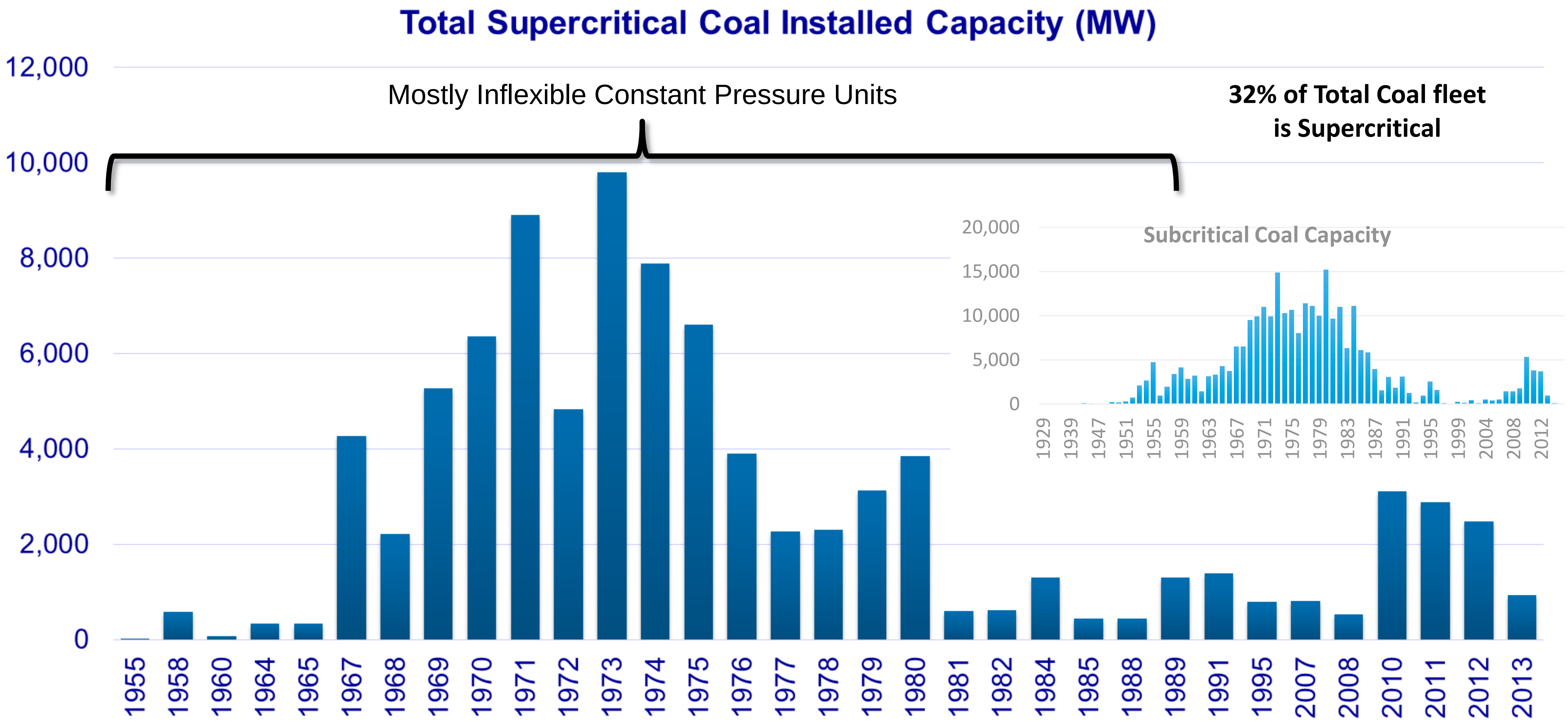
Jan. 2019 | Summary | Net Load | Pricing | VER Curtailment | Reliability Metrics

Summary

19.54% Jan Average Renewable Serving Load	**19.54%** Year to Date Average Renewable Serving Load	**73.95%** Max 5 min. Renewable Serving Load All-time	**3.406TWh** Jan Metered Renewable Generation
8876.7MW Jan Max Solar Production	**8876.7MW** Year to Date Max Solar Production	**10740MW** All-time Max Solar Production	**12314MWh** Jan Solar Energy Curtailed
4708MW Jan Max Wind Production	**4708MW** Year to Date Max Wind Production	**5193MW** All-time Max Wind Production	**449.4MWh** Jan Wind Energy Curtailed
15617MW/3hr Jan Max 3 Hour Net Load Ramp	**0.6751%** Percent of 5-min Intervals with Negative Prices	**137.4%** Jan Average Control Performance Standard (CPS1)	**12763.4MWh** Jan Wind and Solar Energy Curtailed

https://www.bbc.com/news/business-40434392

US Coal Fired Power Plant Fleet (EIA)



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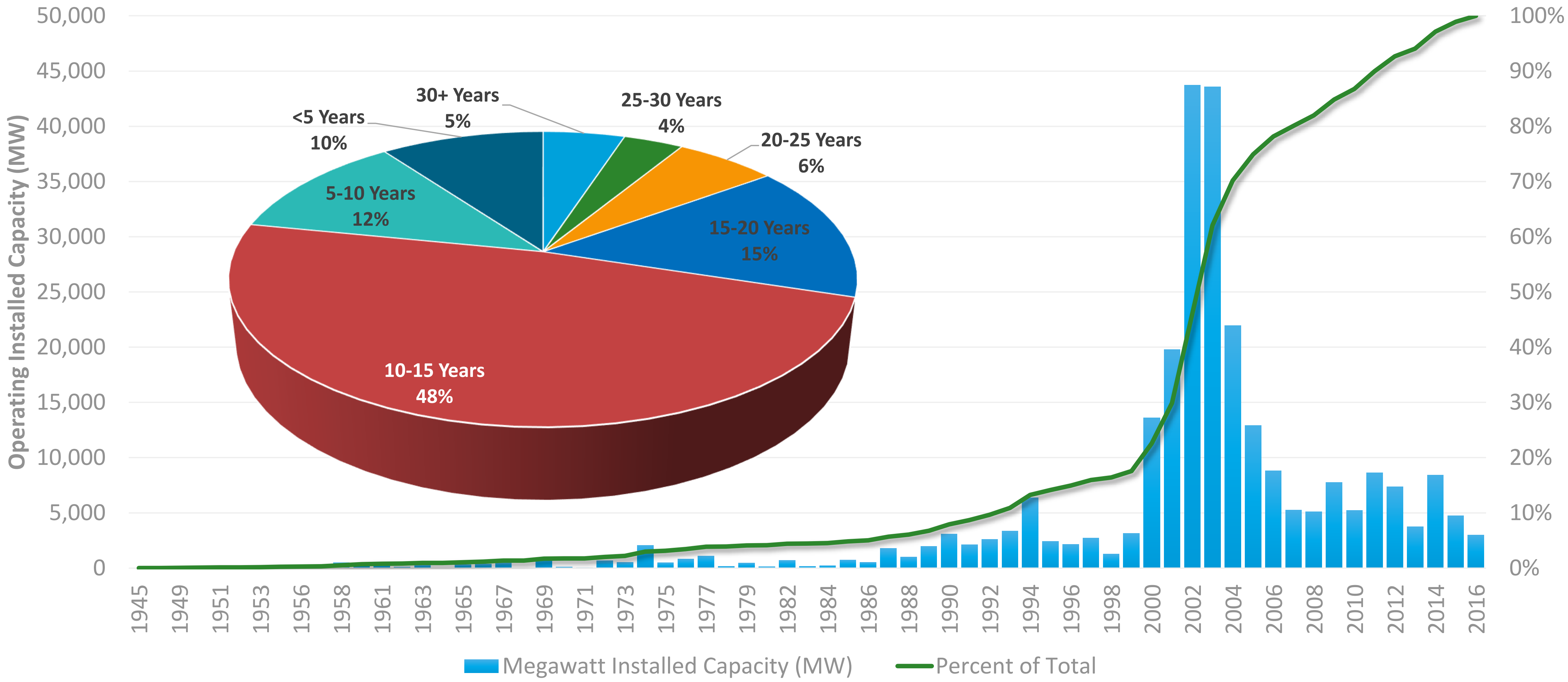
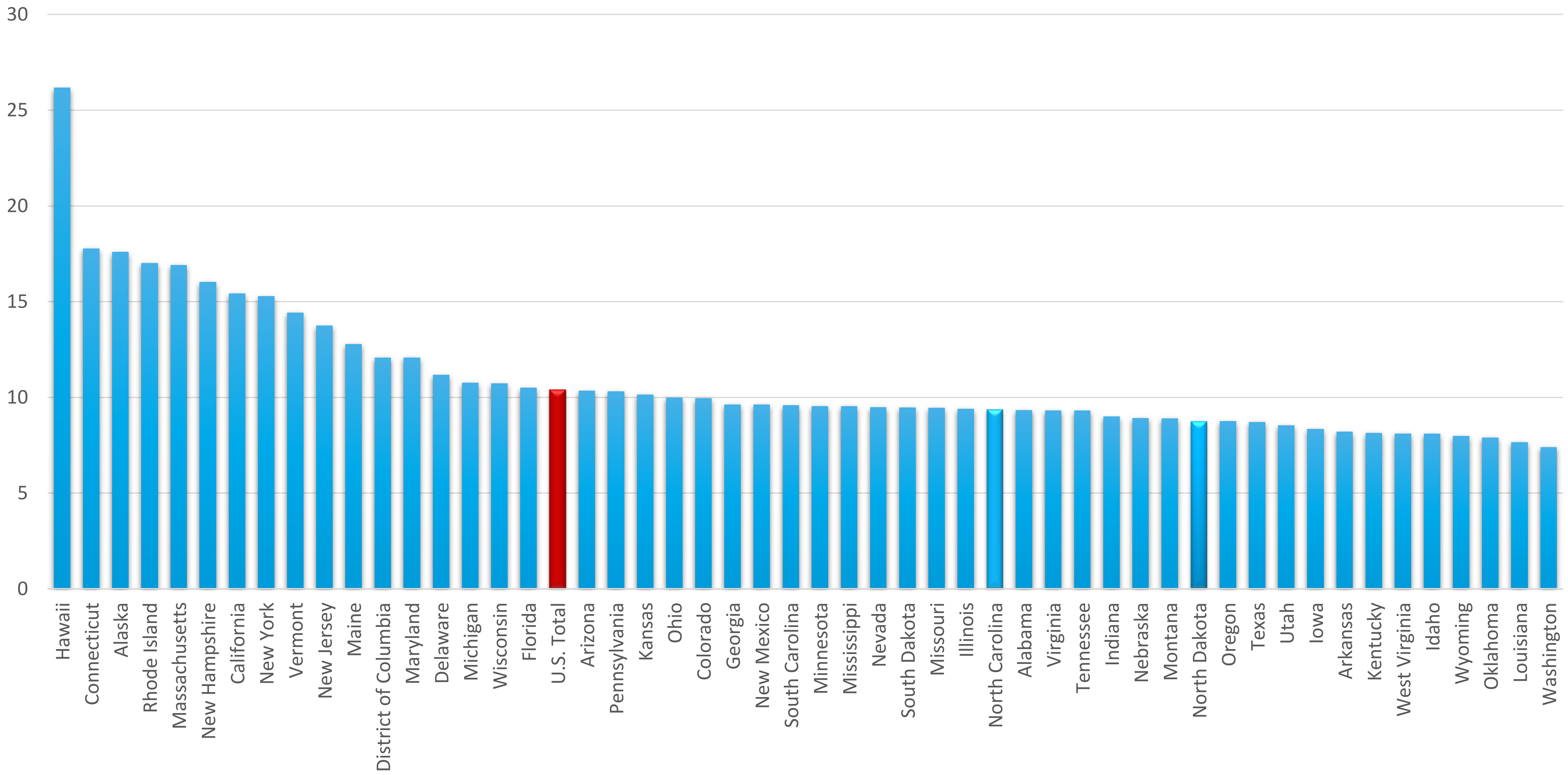
U.S. Installed Combined Cycle Capacity



Age and cycling (flexible operation) impacts plant reliability - US Fleet Relatively Young

Average retail price (cents/kWh)

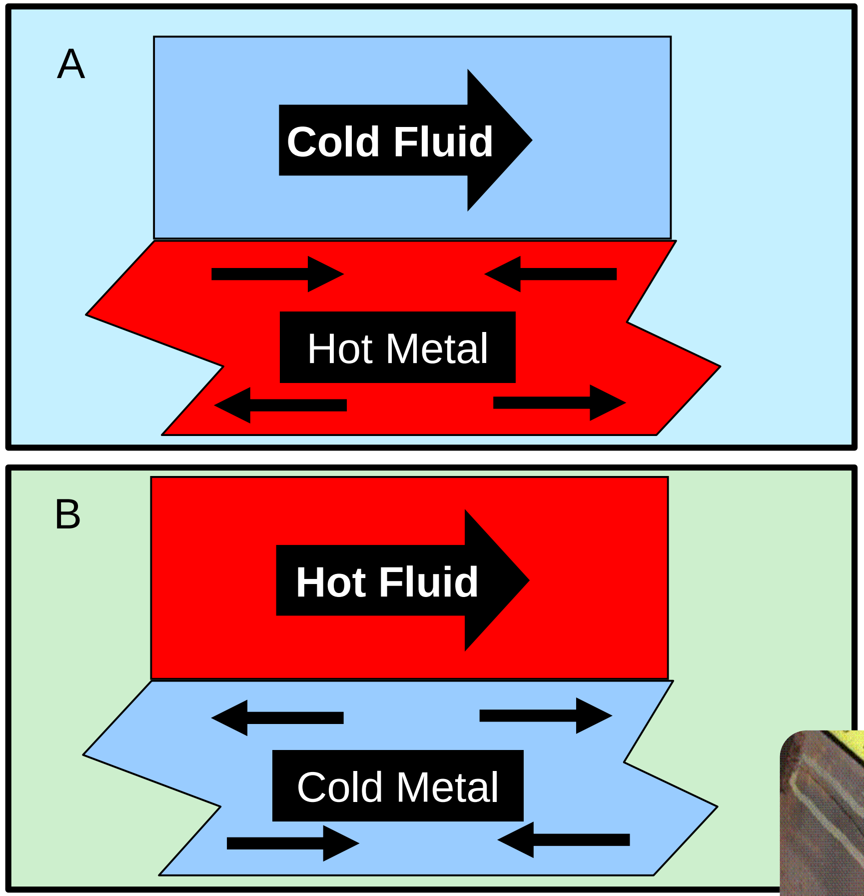


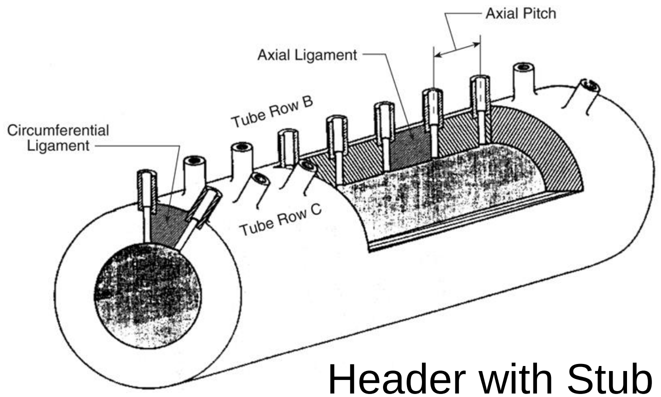
2018 Flexibility Related Generation Supplementals

Load Changes and Flexible Operations in Supercritical Boilers	**63**
Superheater Outlet Header: Validation of Fitness for Service Methodologies	63
Flash Dry Draining Sub-critical Drum Units	64
Application of Turbine Shaft Monitoring to Detect Blade Vibrations	65
Turbine Generator Maintenance Intervals: Industry Trends and Practice	65
Reciprocating Internal Combustion Engines (RICE) Interest Group	**66**
Advancing Concrete Thermal Energy Storage (TES)	66
Approach for Sustainable Dynamic Combustion Optimization	71
Evaluation of Reduced-Load SCR Operation	**75**
Optimizing Heat Recovery Steam Generator Drains (ending)	**88**
Mission Profile Working Group (ending)	**108**
Operational Flexibility Implementation: Case Studies	**108**
Flexible Operation of Hydropower Assets	**193**
Several other one-offs	

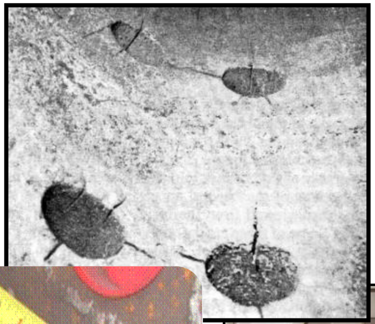
Flexible Operation: Thermal Fatigue Damage

- Predominate failure mode in boiler and turbine components subjected to:
  - Frequent starts
  - Fast ramping
  - Load following
- Caused by:
  - Temperature mismatch between steam and metal surfaces
  - High amplitude stress cycles result
  - Rapid cooling caused by liquid quenching; very high surface tensile stresses





Header with Stub Tubes



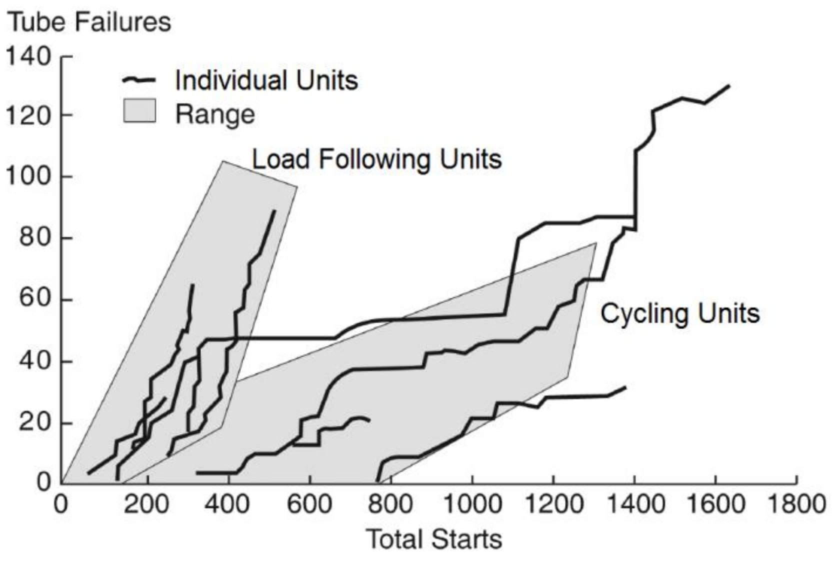
Header ID Cracking Due to Thermal Fatigue

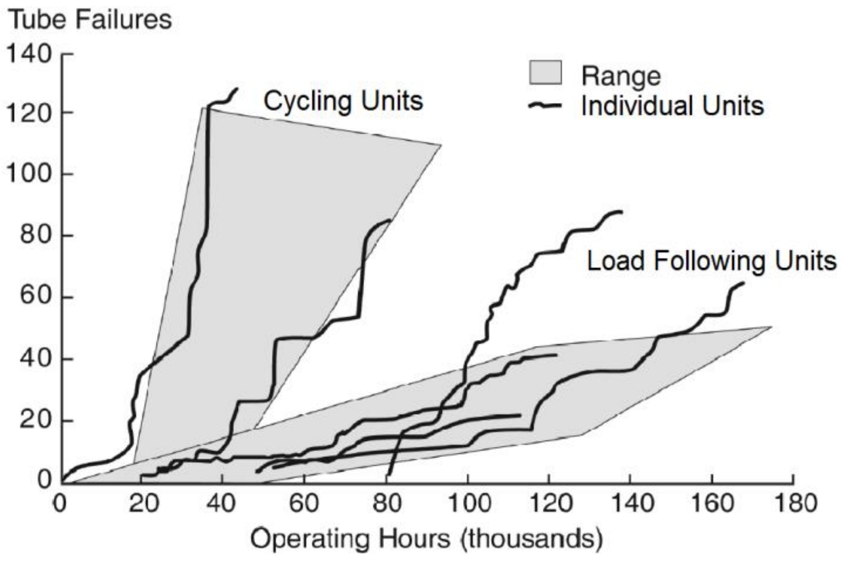
Header Fatigue Cracking

Damaged Header

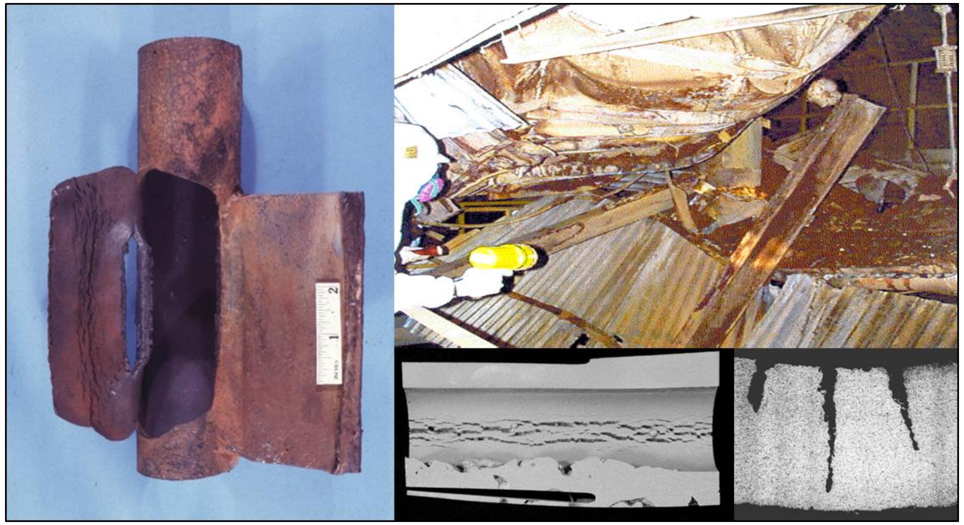
Flexible Operation: Corrosion Fatigue

- On drum units, **corrosion fatigue** has been observed on the riser tubes.
- This mechanism involves **the combination of:**
  - manufacturing-induced bend stresses,
  - water chemistry fluctuations under cycling operation
  - thermal stress cycles



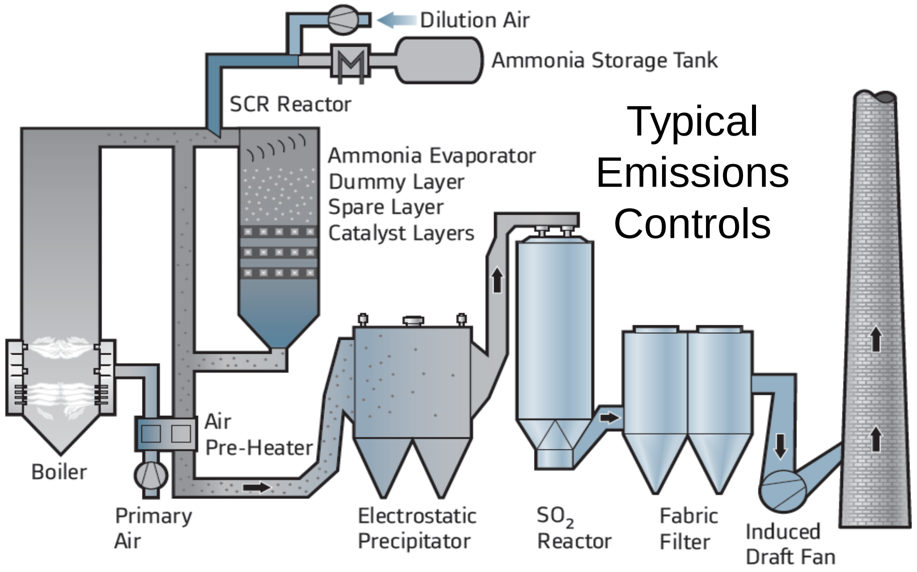


Corrosion Fatigue Failures have caused injuries and deaths in power plants

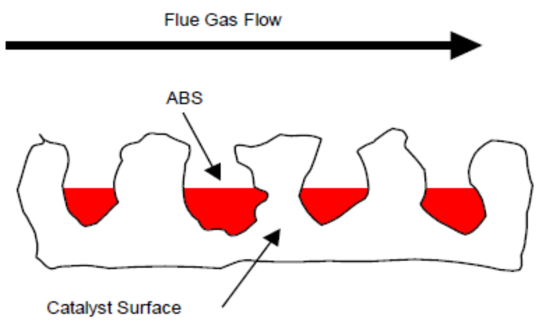


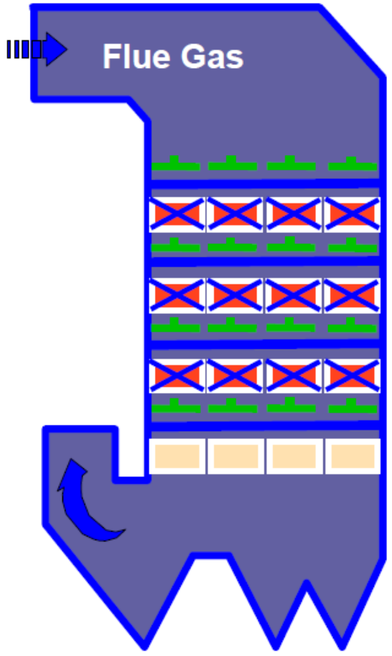
Flexibility and Emission Controls: SCR (NOx Control)

SCR = Selective Catalytic Reduction – Reduces NOx to Nitrogen and Water



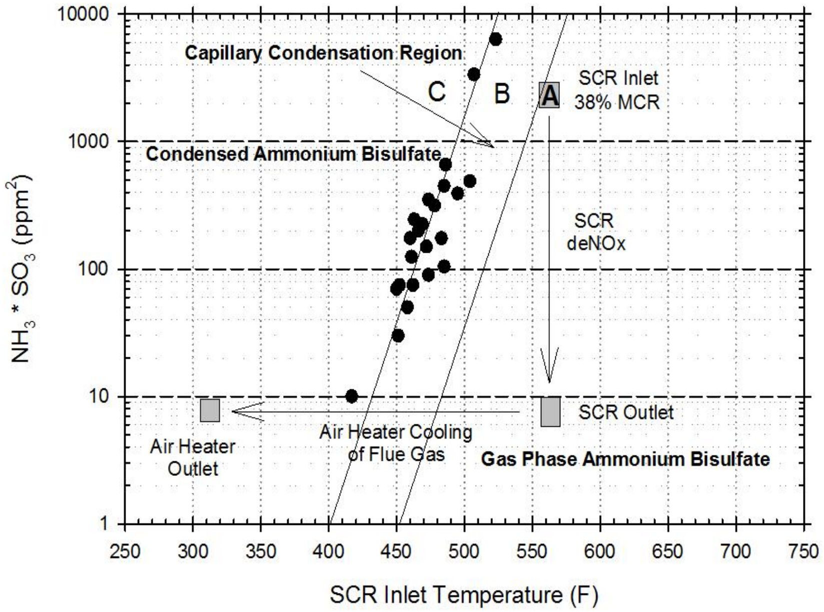
Progressing Formation of ABS in Catalyst Pores





SCR with Catalyst Beds

- Ammonium Bisulfate Fouling of Catalyst Surface
  - At lower loads ABS precipitates in SCR and reduces its ability to control NOx emissions



SCR Requires Minimum Temperature to Operate and Avoid Fouling

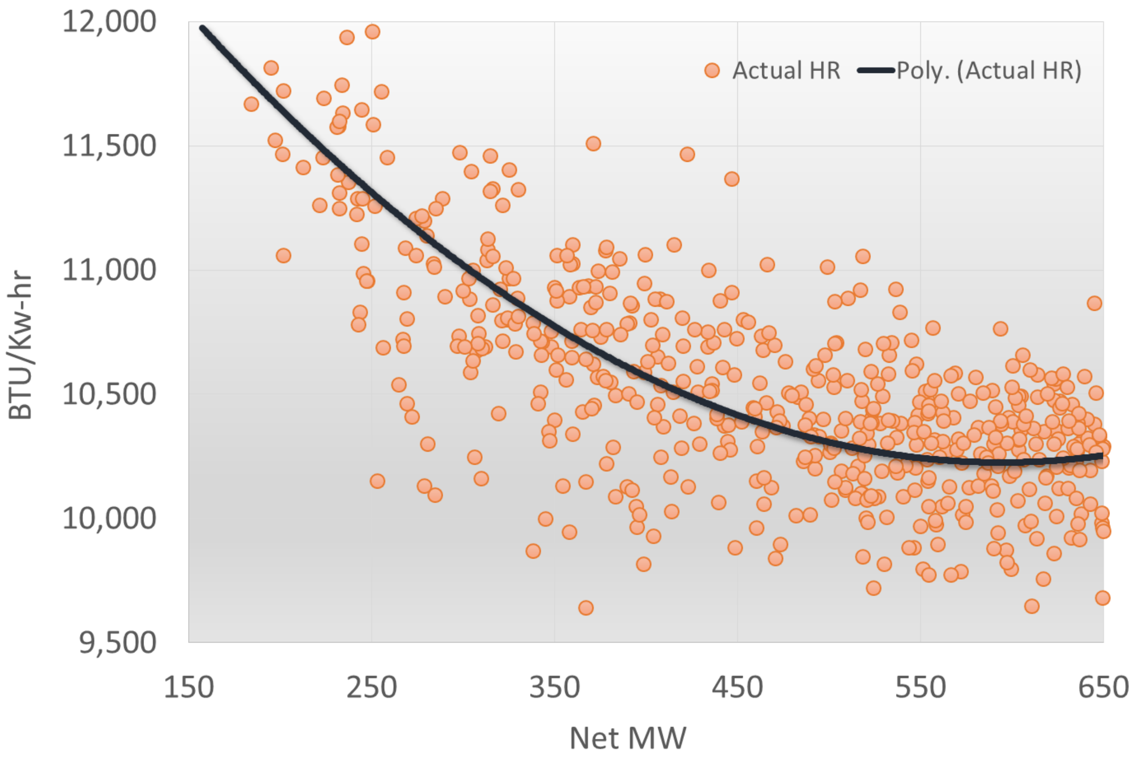
Flexibility and Plant Efficiency (Heat Rate)

Heat Rate:
Energy in Fuel / Electrical Energy to Grid

- Lower is Better (Inverse of Efficiency)
  - 100% Efficiency is 3,412 Btu/kWh
- Better Heat Rate provides:
  - Fuel Savings
  - CO_2 & Emission Reductions

  By minimizing amount of fuel burned per kWh of electricity produced
- For Existing Coal-fired Plants 10,000 is Good
- For New Combined Cycle Plants 6,500 is Good

650 MW Conventional Coal Fired Power Plant
Impact on Heat Rate operating at Part Loads (Throttling)



Flexible Operations and Heat Rate Technical Brief 3002013992

Flexible operation impacts significantly plant's ability to operate efficiently