THE ROLE FOR BASELOAD GENERATORS IN OPTIMIZED ELECTRIC POWER SYSTEMS

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OVERVIEW

- We see plentiful, low-cost natural gas as potentially fueling a spiral, i.e., a dynamic process, by which NGCC capacity is dispatched ahead of higher heat rate coal units, increasing their load following and accelerating their retirement.
- The dynamic process continues as the retiring coal units are likely replaced with more NGCC, which likely bumps more coal units down the loading order with increased cycling and earlier retirement.
- This is an expensive process because of the increased need for investment in replacement capacity, and likely incremental gas price increases (unless gas supply were perfectly inelastic forever)
- It also “locks in” large amounts of new NGCC capacity which would likely delay the adoption of advanced, low-carbon generation technologies
- And classic externalities seem to apply

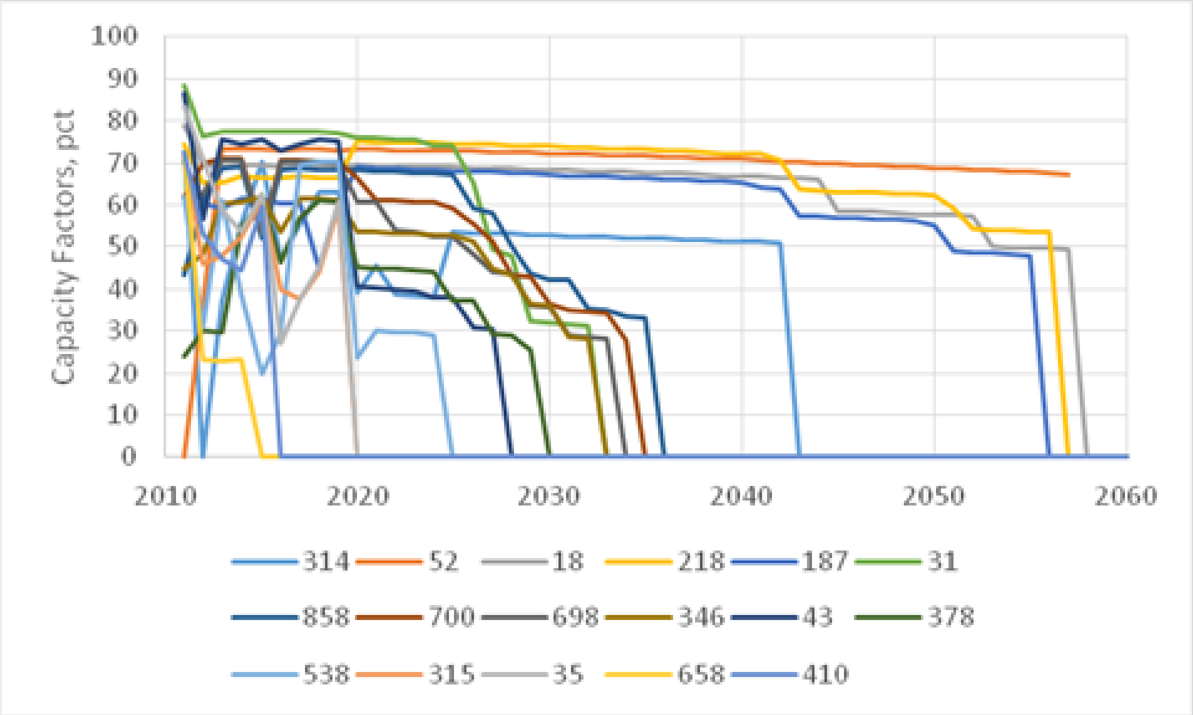
GENERATING UNIT CYCLING IS SENSITIVE TO GAS PRICE AND CARBON PRICE

The variable cost curve is relatively flat, implying that small changes in gas prices or CO_2 prices would have large effects on shifting generation from coal units to NGCC units, resulting in increased cycling of the coal units.

This knife-edge response, combined with historic power plant operating design, creates a special situation for reducing emissions compared with other sectors of the economy

SELECTED GENERATING UNIT CAPACITY FACTOR DECLINES

A sampling of individual coal unit capacity factors shows some units retiring quickly and others continuing to generate power.



WHY GENERATING UNIT CYCLING IS SENSITIVE TO GAS PRICES OR CARBON PRICE

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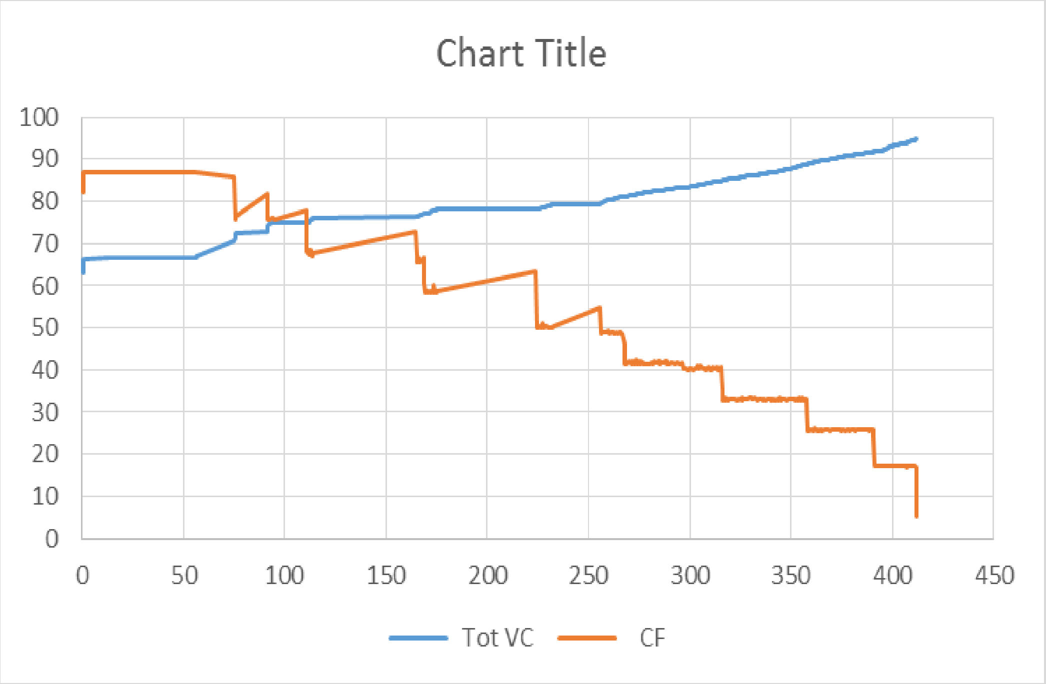

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Definition of an “Externality” based on Baumol-Oates *The Theory of Environmental Policy*, Second Edition, Cambridge University Press, 1988.

- Condition 1. An externality is present whenever some individual's (say A's) utility or production relationships include real (that is, non-monetary) variables, whose values are chosen by others (persons, corporations, governments) without particular attention to the effects on A's welfare.

- Condition 2. The decision maker, whose activity affects others' utility levels or enters their production functions, does not receive (pay) in compensation for this activity an amount equal to the value of the resulting benefits (or costs) to others." P 17.

- As a specific instance applicable to power markets, when a wind developer decides to invest, he most likely doesn't include in his accounting the resulting increased cycling damage that would occur on nuclear and coal plants. So adding this wind farm may or may not be part of a Pareto Optimal solution, and a carbon tax which is designed to correct the CO2 externally, but not the electricity generation interaction externality, may or may not be optimal in a second-best world.

- In the presence of an externality, a Pigouvian Tax on CO2, may or may not be an efficient policy instrument.

TO EXPLORE THIS ISSUE, WE COMPARE THREE SCENARIOS

- a tax on CO_2 emissions to raise revenue, but also would aggravate the cycling of coal plants and a more rapid uptake of NGCC
- a technology development and deployment (Tech D&D) effort with a delays CO2 program
- And a “lower cycling” regulatory strategy in which NGCC capacity additions are limited in favor of some new gas capacity in the form of peaking turbines, which would have less effect on baseload displacement

BACKGROUND ON AGING, CYCLING, AND LOAD FOLLOWING

Aging, cycling, and load following are not new

- Extensive literature back at least into the 1990's
- Pervasiveness of cycling and load following has grown
  - Renewable energy mandates
  - Low natural gas prices
  - Growth of NGCC capacity

- Multiple projections anticipate increasing non-dispatchable generation impacting operation of CFPP
  - EPRI, CAPUC, ERCOT, Argonne, others
  - ISO/RTO electricity market rules
  - Recent EPRI study examining ramp rates and operating modes to accommodate greater wind and solar generation capacity

The cycling damages result in

- Increased Operating and Maintenance costs,
- Lower efficiency, i.e., increased fuel consumption and emissions
- Loss of generating revenue
- Shortened remaining useful life due to accumulated damages (to be discussed further)
- Existing coal-fired power plants (CFPP) built in the 1960’s were designed for baseload (24/7) operation
- These CFPP have limited tolerance for swings in operations

TERMINOLOGY

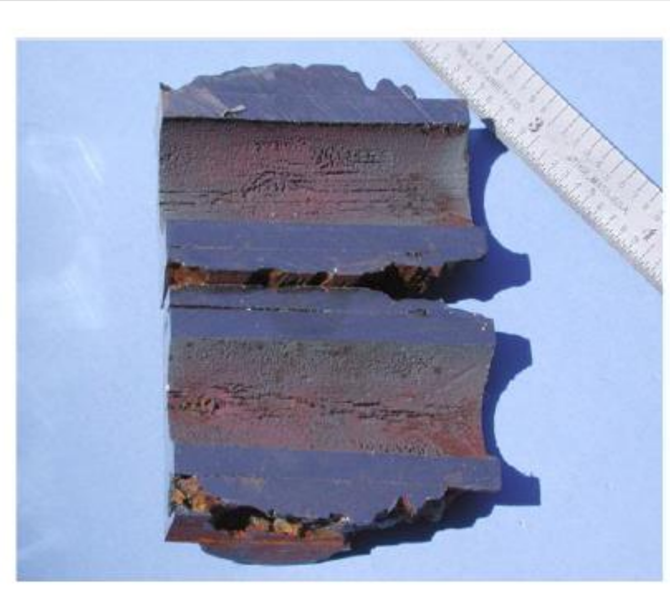
- Heat Rate
  - Btu/ kWh, operating, not test/design
- Load following
  - Operating between design (100%) and ~30%* design
- Cycling
  - Unit output to grid goes to zero
- Creep (metallurgical)
  - Time dependent deformation below tensile yield
- Fatigue (metallurgical)
  - Defect growth from cyclic changes in stress

* *Flexibility objective, generally requires some physical modifications*

KNOWN PHYSICAL PROCESSES THAT INCREASE HEAT RATE AND CAUSE FORCED OUTAGES

- Wear of seals and turbine blades
- Fouling and deposition on heat transfer surfaces and steam turbine blades
- Aging of refractories and structural shells, particularly boilers
- Component failure from corrosion, fatigue, and creep
- Interaction of fatigue and creep under cycling and temperature swings

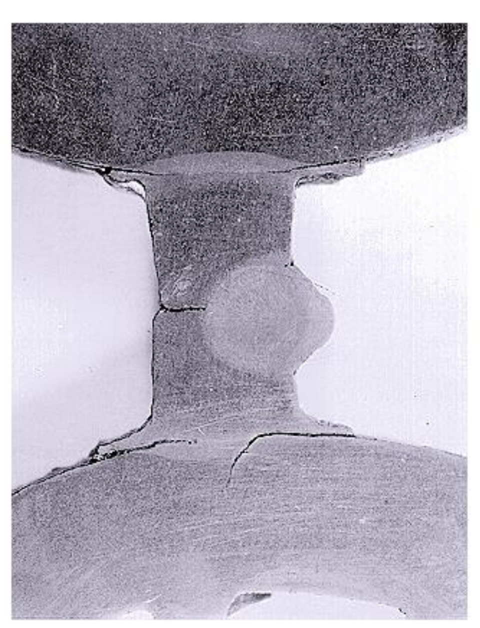
BOILER MATERIAL FAILURES



Boiler tube corrosion

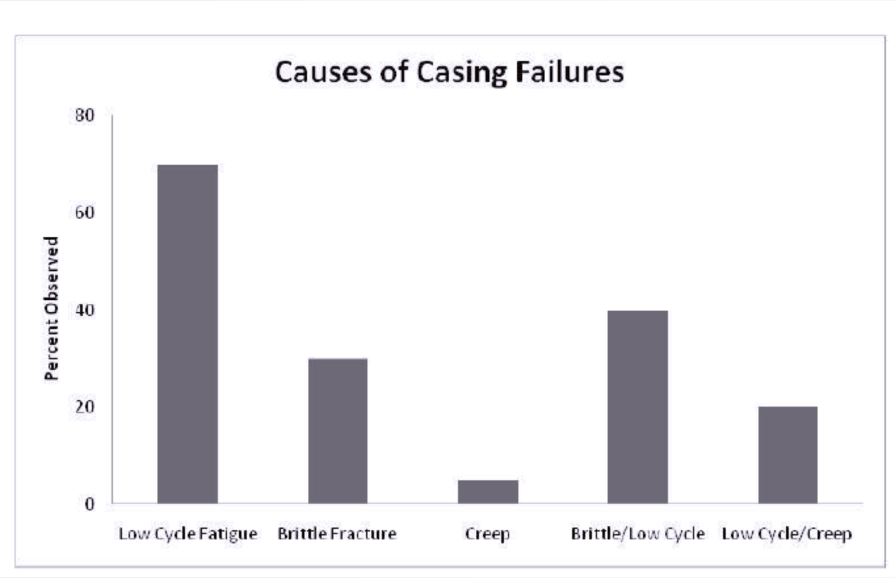
Source: Lefton, Power Plant Asset Management

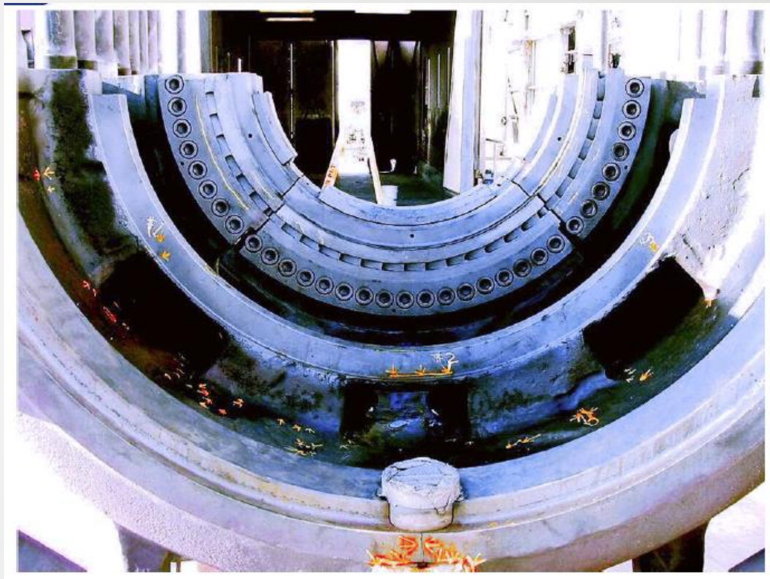
Waterwall web cracking



Superheater tube attachment fatigue cracking

STEAM TURBINE FAILURES





Source: Lefton, S., Power Plant Asset Management, Intertek AIM

OPERATING ISSUES, LOW LOAD AND CYCLING

- Configuration of coal mills, combustion air, and burners
- Balancing steam production, superheat, attemperation, reheat, boiler feedwater heating
- Maintaining NOx conversion, controlling NH3 slip, avoiding ammonium bisulfate deposits
- EPA reduction of startup, shutdown, malfunction waivers
  - EPA issued SIP revision call
  - Litigation briefs due Oct. 19, SIP revisions due Nov. 22

REVIEW PAPERS ON POWER PLANT CYCLING DAMAGES

- Donald Hanson, David Schmalzer, Christopher Nichols, Peter Balash, "The Impacts of Meeting a Tight CO_2 Performance Standard on the Electric Power Sector," *Energy Economics*, 2016; see on-line Appendix on cycling damage literature review at http://dx.doi.org/10.1016/j.eneco.2016.08.018

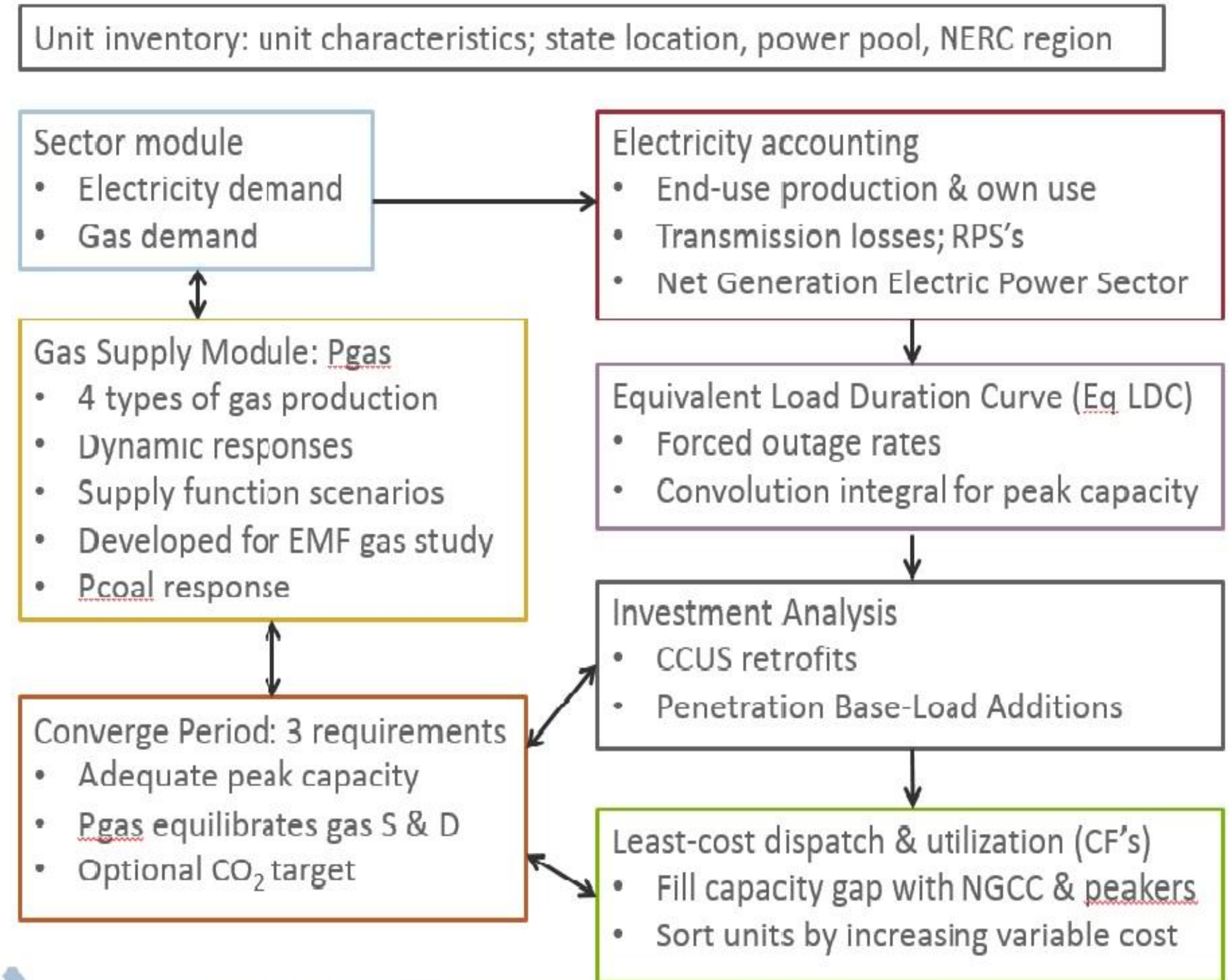
- EPRI, 2001. Damage to Power Plants due to Cycling, Report No. 1001507

- Kumar, N., P. Besuner, S. Lefton, D. Agan, and D. Hilleman, (2012), *Power Plant Cycling Costs*, Intertek AIM (formerly APTECH), Subcontract Report No. NREL/SR-5500-55433, NREL, Golden CO, July 2012.

ESIM MODEL OVERVIEW

- The electric power sector component of the AMIGA Integrated Assessment Model
- Includes a unit inventory of existing power plants
- Dispatches existing and new coal/biomass fired units, NGCC units, and advanced units with direct gas combustion and CO_2 separation against load duration curves for six U.S. regions
- Dispatch order and capacity factors based on variable cost ranking, i.e., merit order (or some alternative, potentially more efficient criterion)
- Includes cumulative cycling damages resulting from low dispatch operation
- Compares scenario costs and investment requirements
- Includes a dynamic gas supply scenario model originally calibrated to EIA NEMS runs.
  - With higher and lower gas supply curve scenario shifts
- Upgraded object-oriented computer code implementation

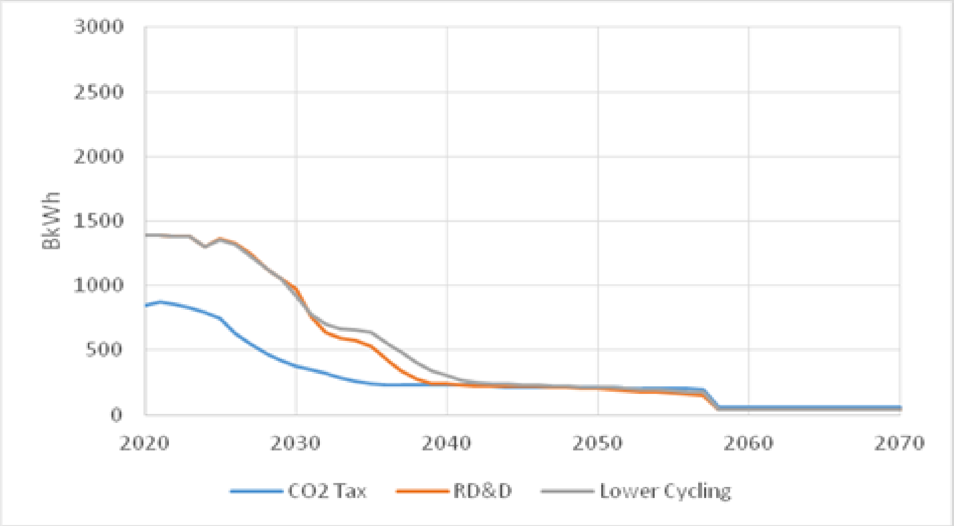
Electricity Supply and Investment Model -- **ESIM**



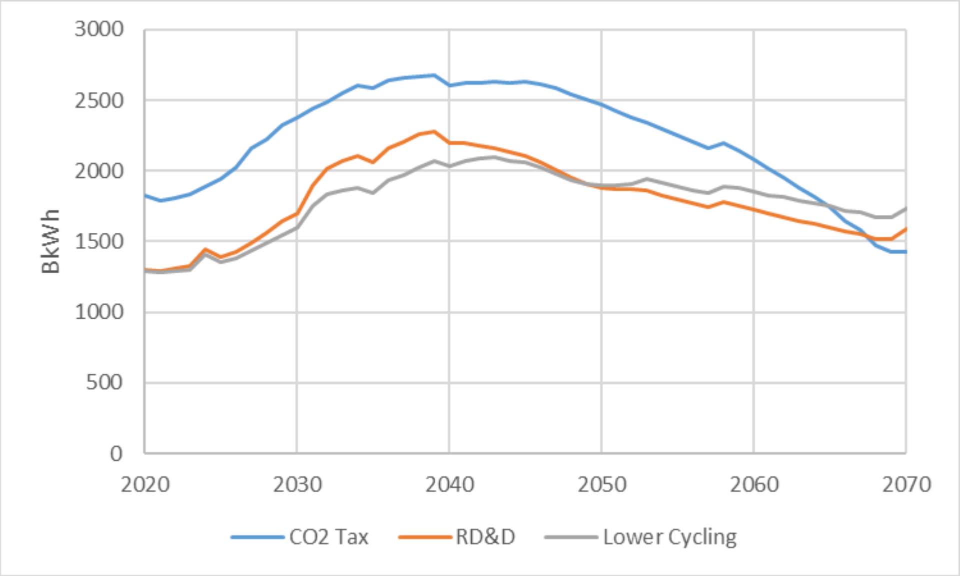
TECHNOLOGY CATEGORIES: SOME NEEDED FOR DEEP CO2 REDUCTIONS

Existing PC Units	**Biomass plus Coal**	**Mostly Gas**	**Renew w Storage**
- Pre-retrofit	- EP Sect Biomass	- NGCC	- Hydro
- Middle existing	- Ind Biomass	- Gas w CO_2 captr	- Geothermal
- Near retirement	- CFB w CCS	- Peaking turbine	- Battery Storage
- CCS retro w EOR	- Ind cofire w CCS	- Steam Gas-Oil	- Pumped storage
- CCS retrofits	- Adv Bio-process	- EP sect CHP	
- Industrial units	- Muni waste	- EP sec CHP CCS	
		-Industrial CHP	
New Coal Units	**Nuclear**	- Distributed gen	**Intermittent RE**
- SOA cap ready	- existing		- Wind
- SOA PC w CCS	- new		- Utility Solar
-Adv Coal/Bio CCS			- Distributed PV
- Co-Production			

COAL AND GAS GENERATION BY SCENARIO

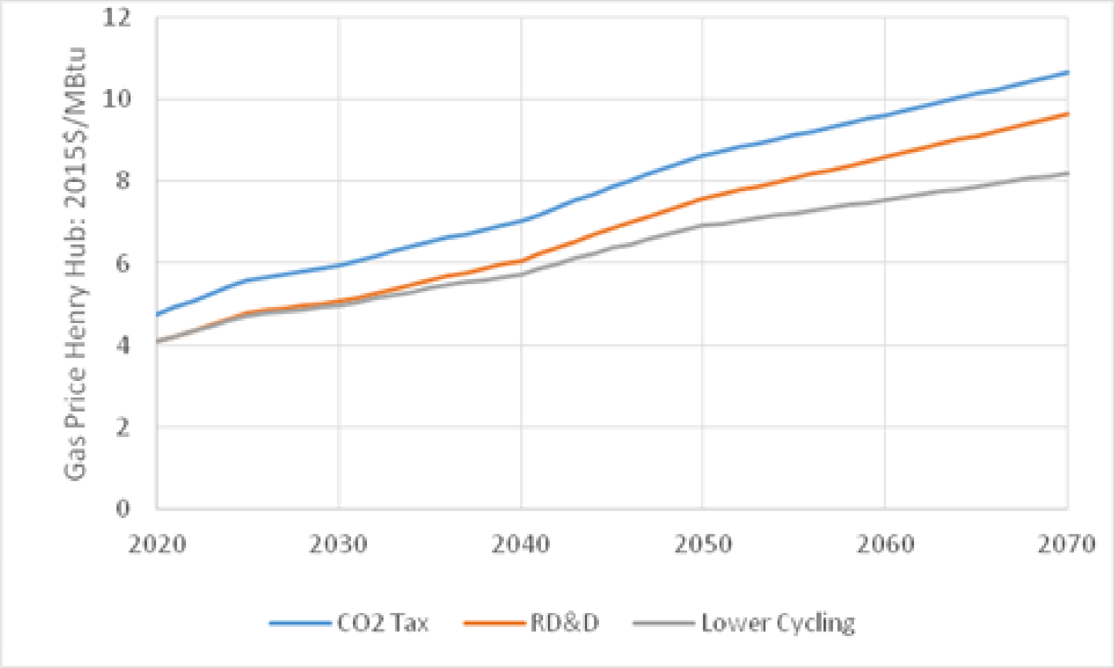


Coal by scenario

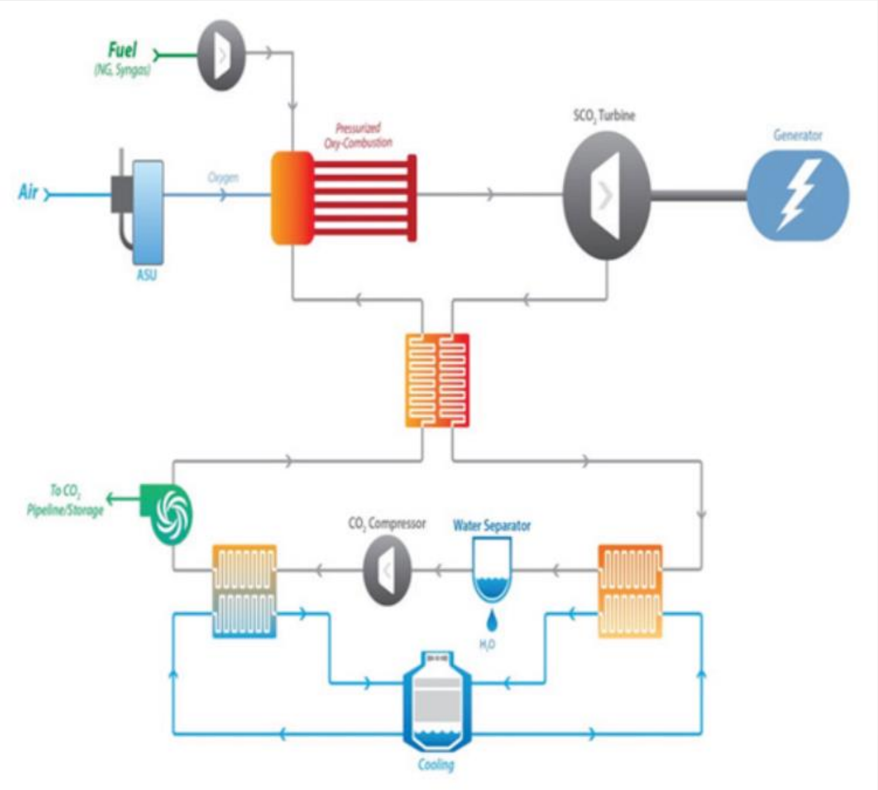


Gas by Scenario

THERE IS A SIGNIFICANT CHANGE IN GAS PRICES



DIRECT SUPERCRITICAL CO_2 CYCLE



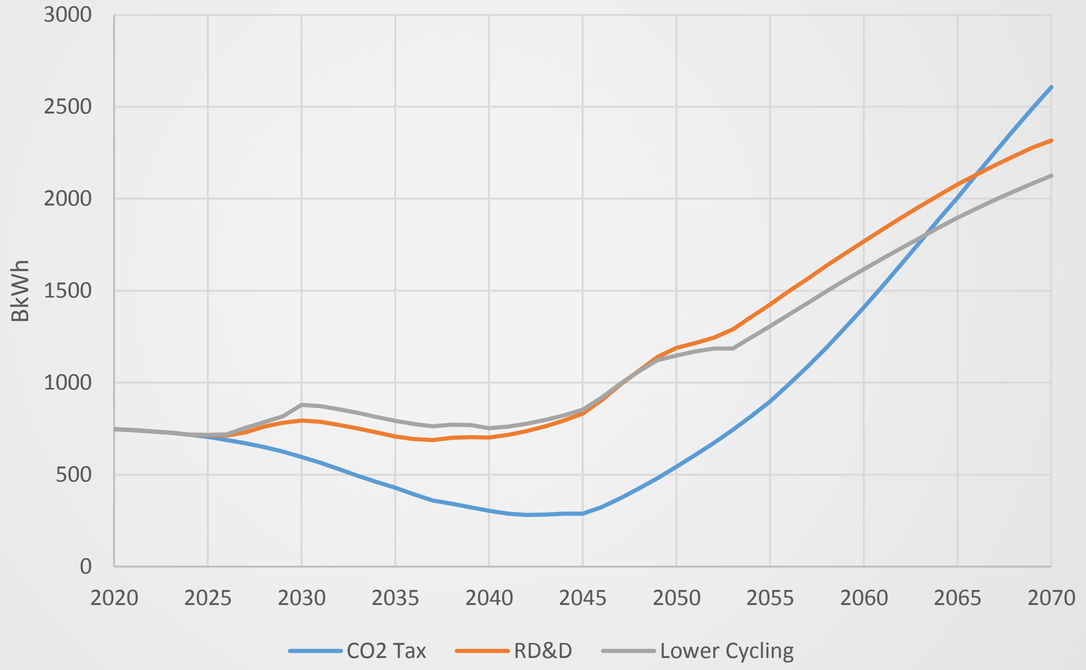
Fuel carbon to pipeline or sequestration

Issues -
- Smaller turbines
- Larger compressors
- Materials & seals
- Properties near critical point
- CO_2 purity

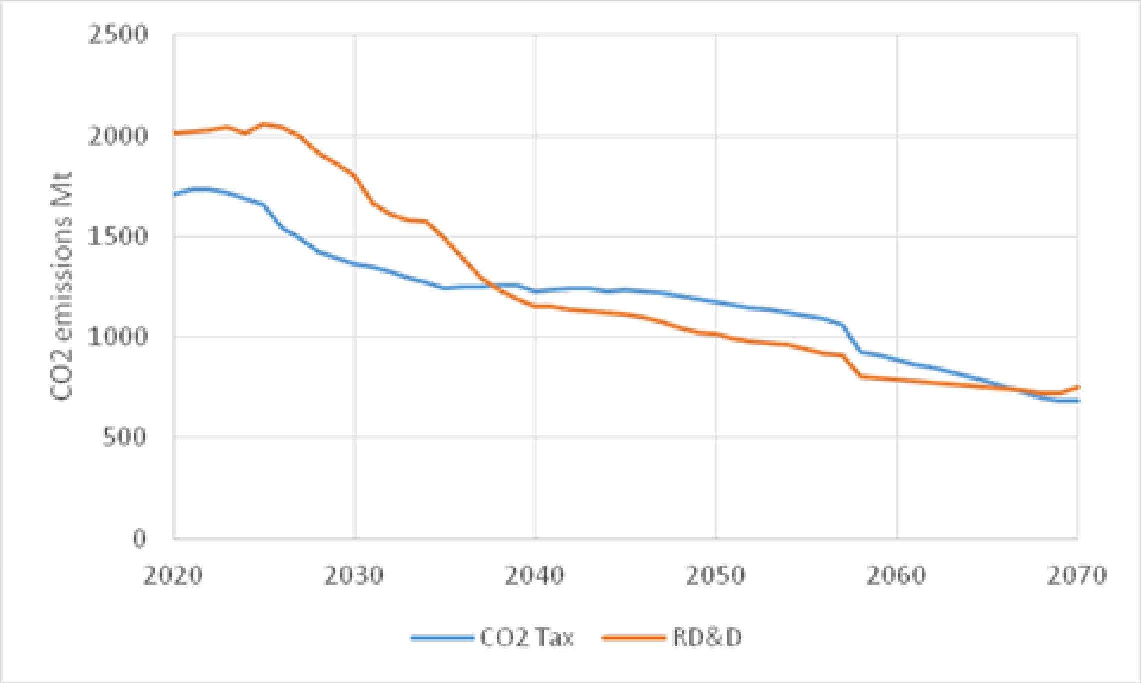
Developments –
- Pilot plants x 2

Source: NETL

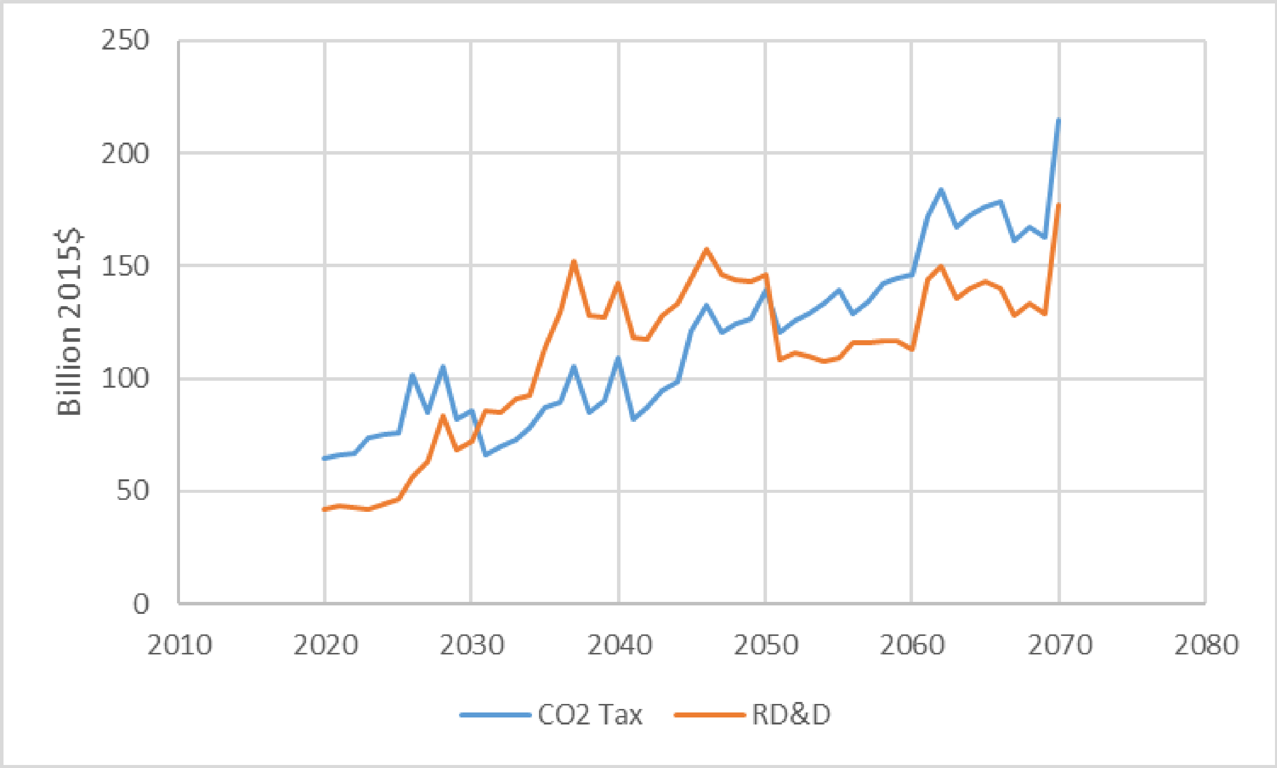
ROLE FOR ADVANCED BASELOAD TECHNOLOGIES



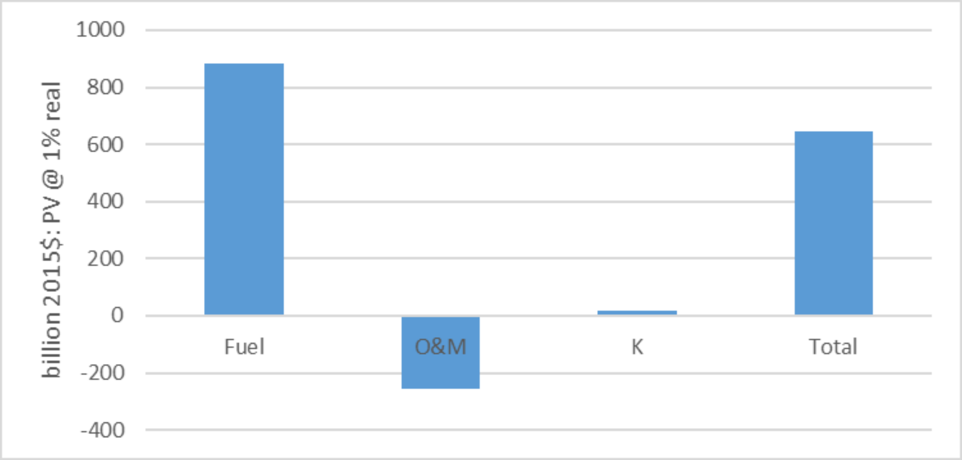
CUMULATIVE CO2 EMISSIONS END UP ABOUT THE SAME ACROSS SCENARIOS WITH THE RD&D SCENARIO HAVING GREATER PENETRATION OF ADVANCED TECHNOLOGIES



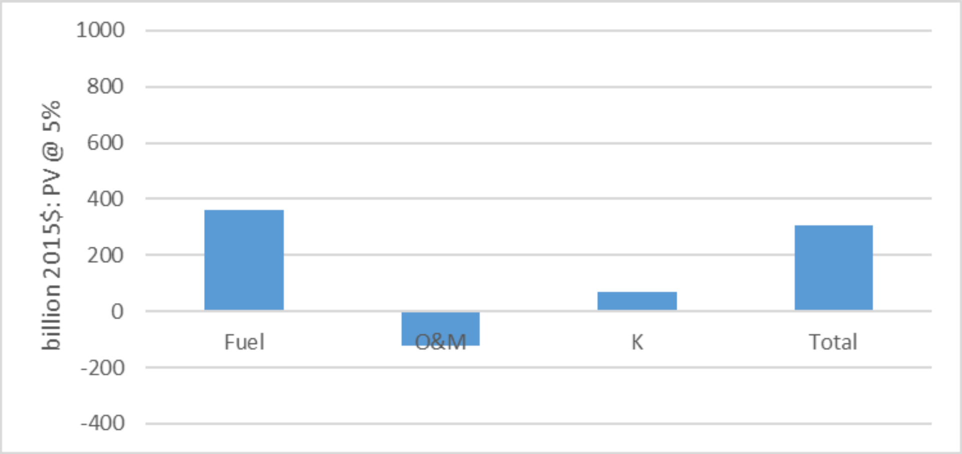
COMPARISON OF SCENARIO CAPITAL OUTLAYS



COST COMPARISON GOING OUT 50 YEARS TO 2070



Discounted Present Value
At 1% real rate



Discounted Present Value
At 5% real rate

Key Findings

- We should avoid taking near-term actions which preclude future options with lower present-value cost of CO_2 cumulative reductions
- Reducing cycling damage on the better coal-fired power plants would allow greater CO_2 reductions by adopting CCS technology sooner
- Business-As-Usual may lock-in expanding NGCC capacity for many years
- Promising advanced fossil energy and biomass technologies with CCS are being demonstrated at the 10MW level – see next slides
- A long term focus can lead to the United States being in a better position by year 2050 for continued deep CO_2 reductions