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# COST OF FLEXIBILITY FROM NUCLEAR POWER PLANTS

## ESIG 2020 Spring Technical Workshop

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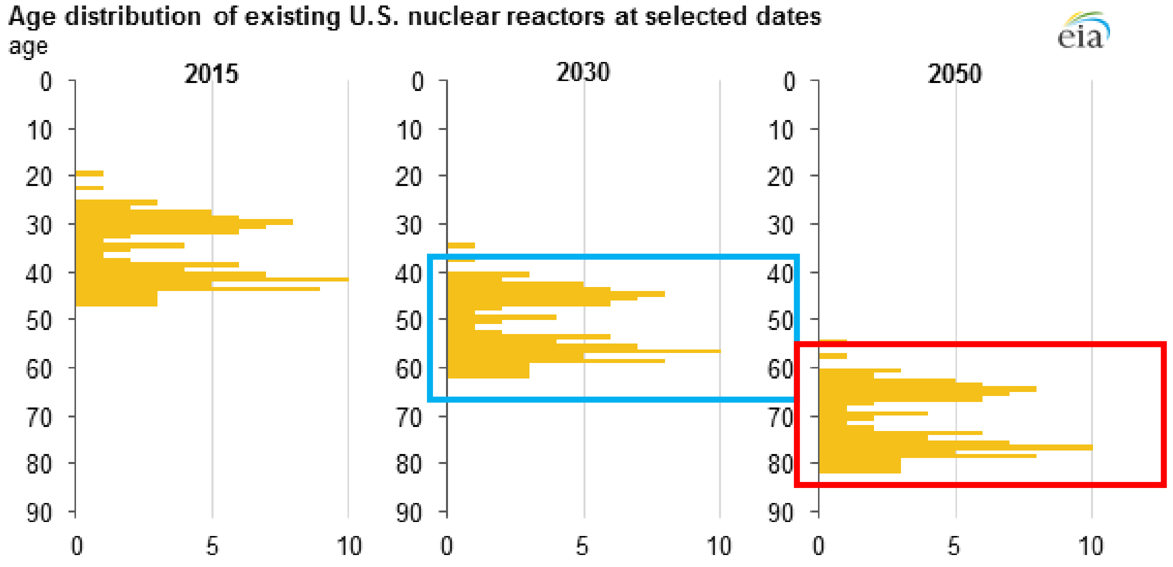
# INTRODUCTION

| Present | Near Future |
|---|---|
| Safety | Risk Mitigation (Financial & Physical) |
| Lifecycle Cost Management | Personnel (Experience) |
| Reliability, Availability, Maintainability | LTO |
| Risk Mitigation (Physical) | Policy/Regulation |
| Ageing Management | Decommissioning and waste disposal costs |
| | Flexible Operation |




- Average age of U.S. commercial reactors is about 37 years.
  - NRC licenses up to 40 years, with 20 year extensions.
  - Operators can apply for an additional 20 year extension (80 total)
- Majority (86 units) of currently operating nuclear plants are currently operating under or have applied for 20-year license renewals.

# OUR GOAL

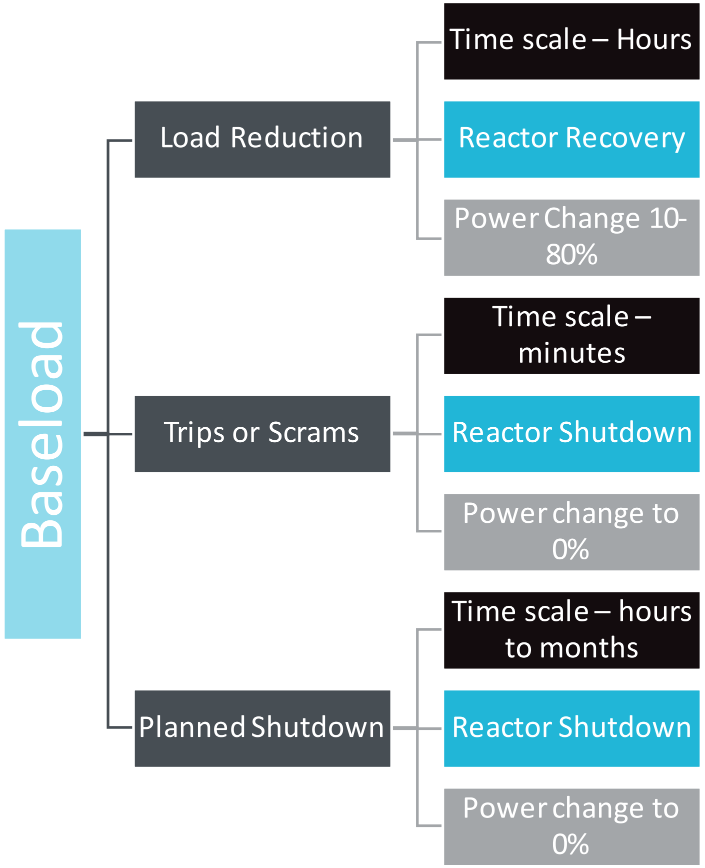
Grid Flexibility + Generator Flexibility **+ Safety** **+ Reliability** = Increased RE

**Incentive** **Cost Recovery** **Goal**

# NUCLEAR FLEXIBILITY

Most existing plants are designed to respond to and stabilize a limited magnitude of rapid ‘load reduction’ by reducing reactor power without a reactor trip.

Another mode of operation to counter quick and short duration load follow without changing the thermal power of the plant could be accomplished by ‘dumping’ steam - **if permitted**.




Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operation / International Atomic Energy Agency

# NUCLEAR – MODES OF OPERATION

## Baseload Operation

- Typical mode of operation
- Ease of operation
- More efficient
- Design and license constraints

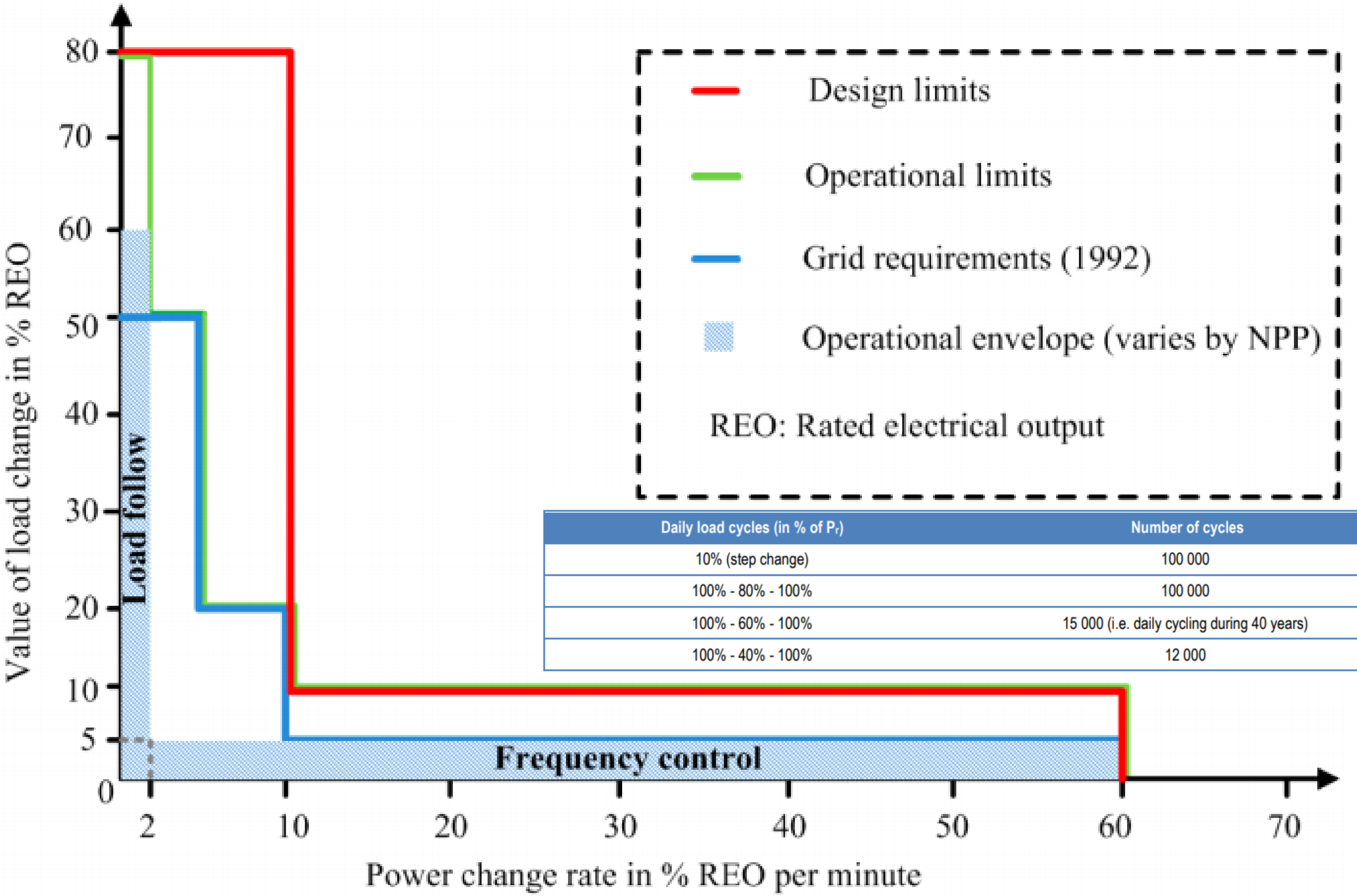
## Frequency Control

- Most NPPs already perform.
- No additional operational or upgrades required

## Load Following

- Larger MW output change
- Ramping constraints
- Minimum load requirements
- Equipment damage
- Fuel Cycle Limitations
- Economics
- Costs

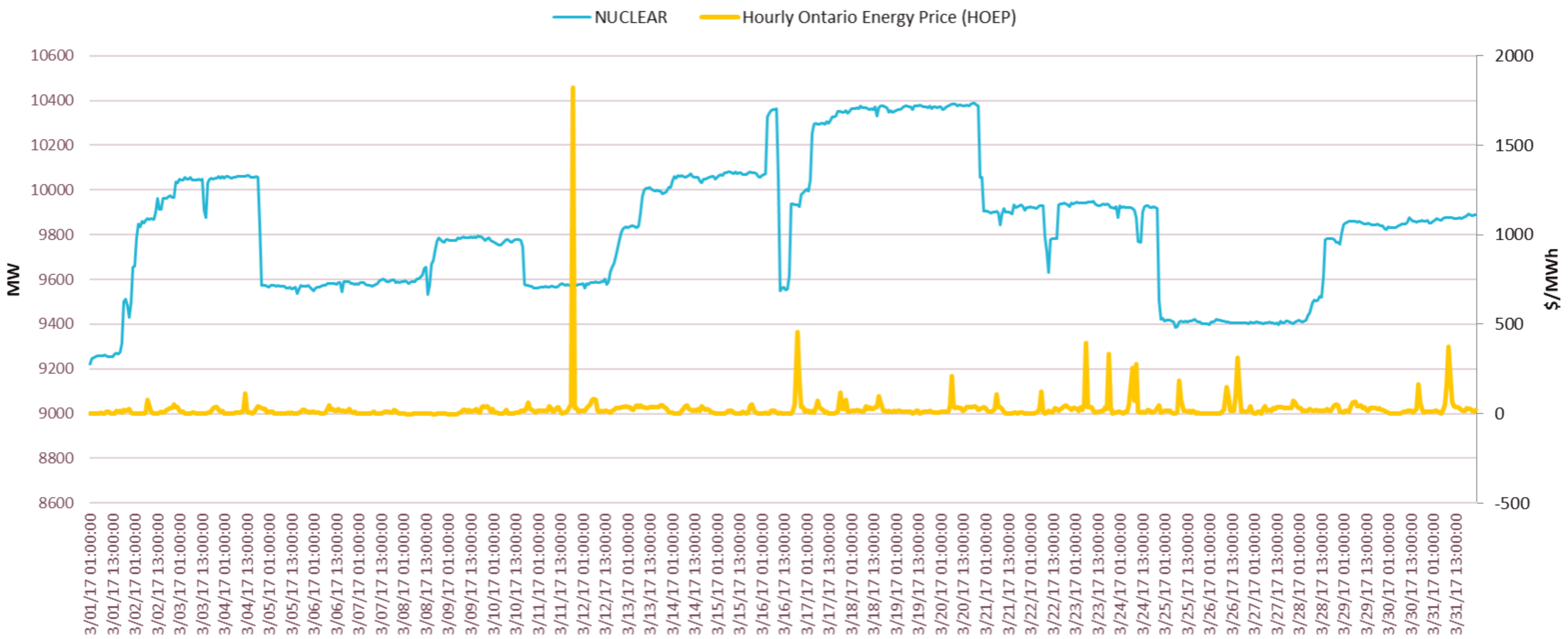
# GERMAN PRESSURIZED WATER REACTOR (PWR) - FLEXIBILITY SCHEME CONSIDERED IN THE DESIGN




| Daily load cycles (in % of $P_r$) | Number of cycles |
|---|---|
| 10% (step change) | 100 000 |
| 100% - 80% - 100% | 100 000 |
| 100% - 60% - 100% | 15 000 (i.e. daily cycling during 40 years) |
| 100% - 40% - 100% | 12 000 |

German pressurized water reactor flexibility requirements and designed capabilities (courtesy of H. Ludwig, AREVA GmbH)

# IESO – NUCLEAR (MARCH 2017) – FLEXIBILITY ACHIEVED WITH RETROFITS



# ECONOMICS (U.S. PERSPECTIVE)

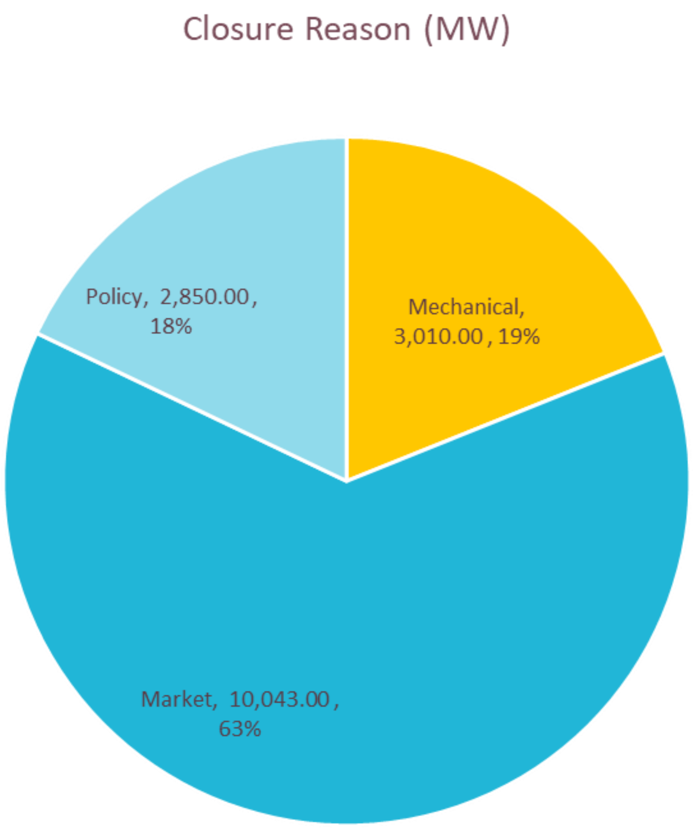
11 GW of capacity have announced plans to retire by 2025.

99 GW of capacity in U.S. (60 plants), with approximately half operating in deregulated markets.

At least five currently operating nuclear plants have requested state-level price support to continue operating.

Natural gas capacity is primary replacement technology, but wind and solar are fastest growing.

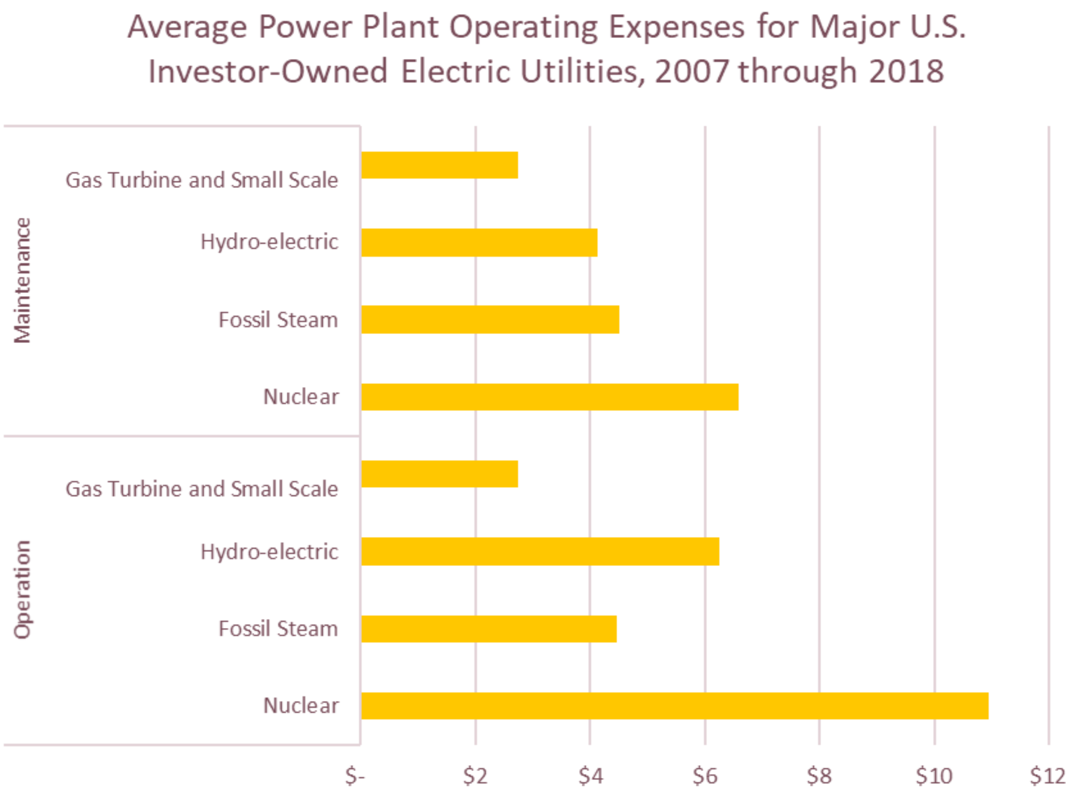
**Operating costs have played a major role in recent retirement decisions.**

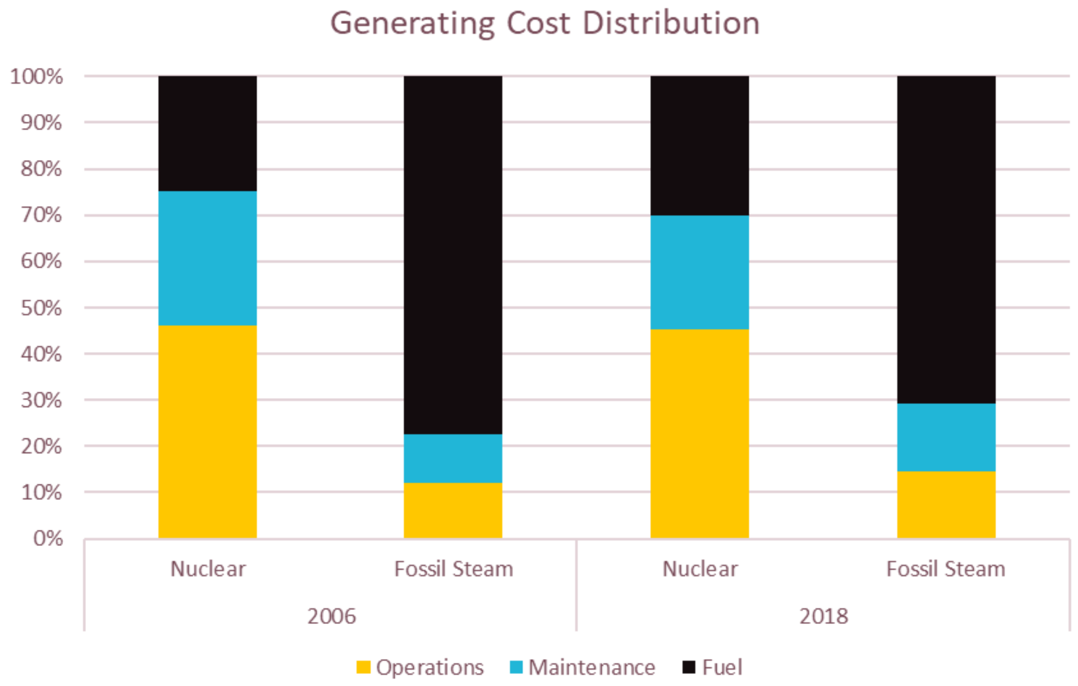


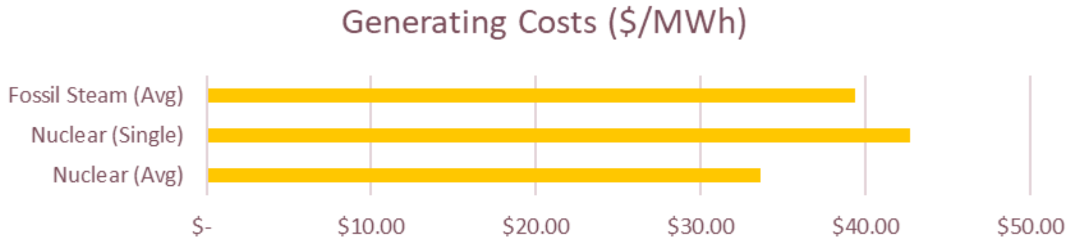

Source: *U.S. EIA*

Source: *Nuclear Energy Institute*

# U.S. GENERATING COSTS

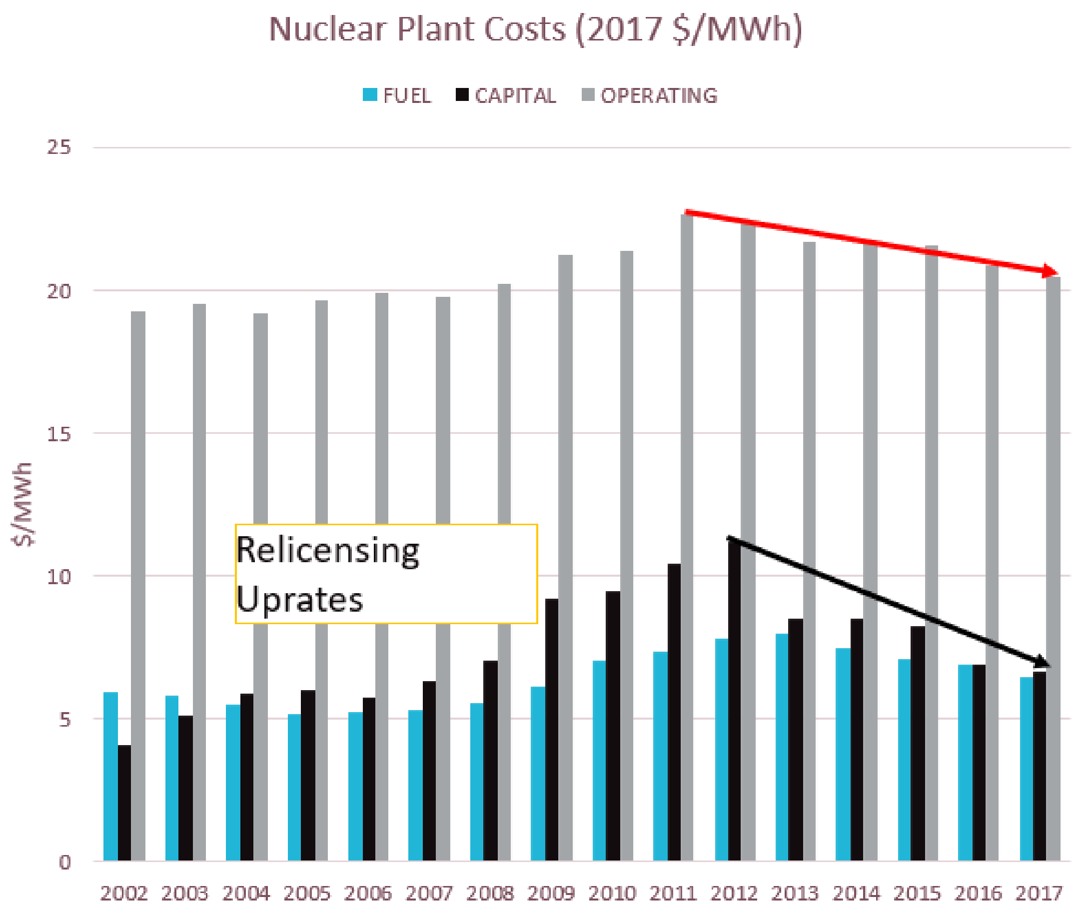



The generation-weighted average price for the four nuclear units in ERCOT (approximately 5 GW of capacity) was only $24.73 per MWh in 2017. Source: RTO Insider 2017-ERCOT State-of-the-Market-Report

# U.S. NUCLEAR GENERATION TREND




Source: *Electric Utility Cost Group*

Over half of the capital expenditure (51%) in 2012 related to power uprates and license renewals, while 26% was for equipment replacement.

The license renewal process typically costs $16-25 million, and takes 4-6 years for review by the NRC.

The minimum amounts that are required to provide a reasonable assurance of funds for decommissioning are $420 million for PWRs and $650 million for BWRs Source NUREG 1628, Staff Responses to Frequently Asked Questions Concerning Decommissioning of Nuclear Power Reactors). (2017$)



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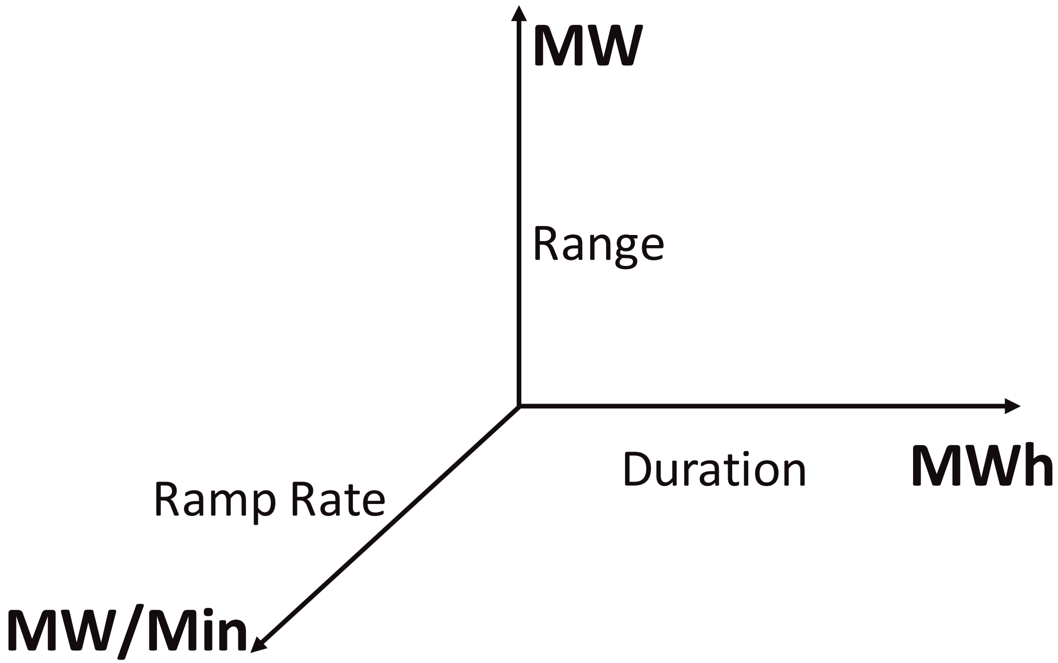
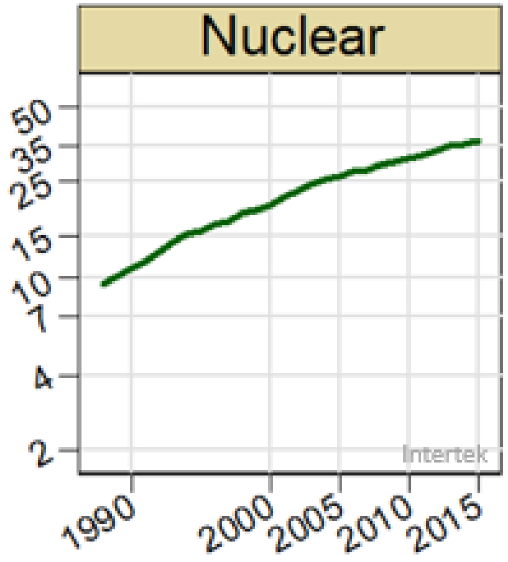
# NPP FLEXIBILITY

- Consider the following:
  - Cycle chemistry
  - Thermally induced cyclic stress
  - Extent of fatigue damage
  - Nature & frequency of the transients
  - Material properties
  - Damage is difficult to identify

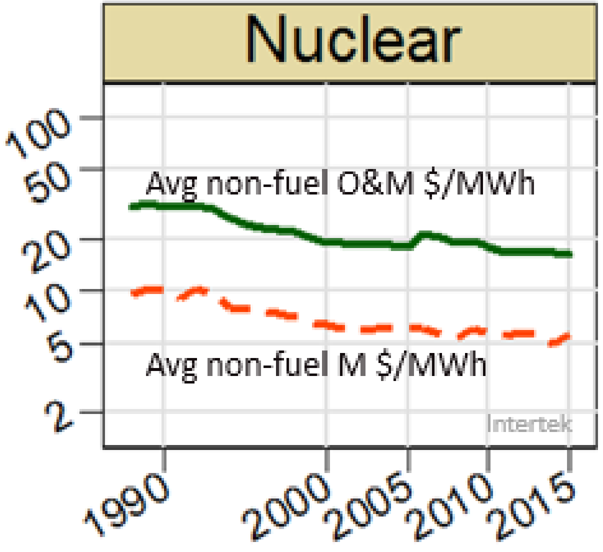


# U.S. NPP STATISTICS

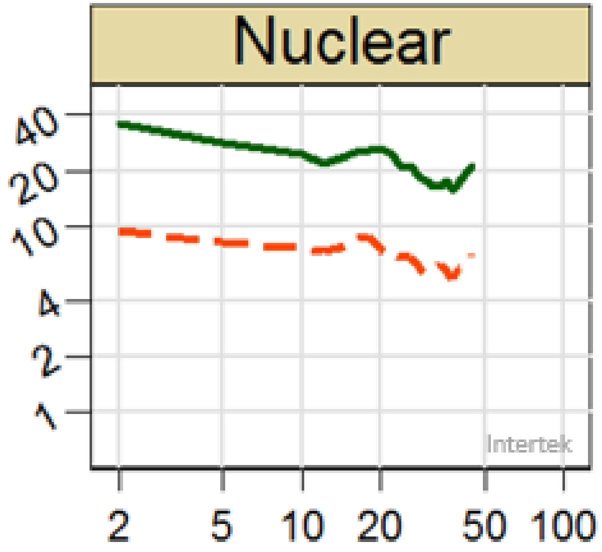
NPP Average Age




NPP Non-Fuel Spend




NPP Non-Fuel Spend by Age

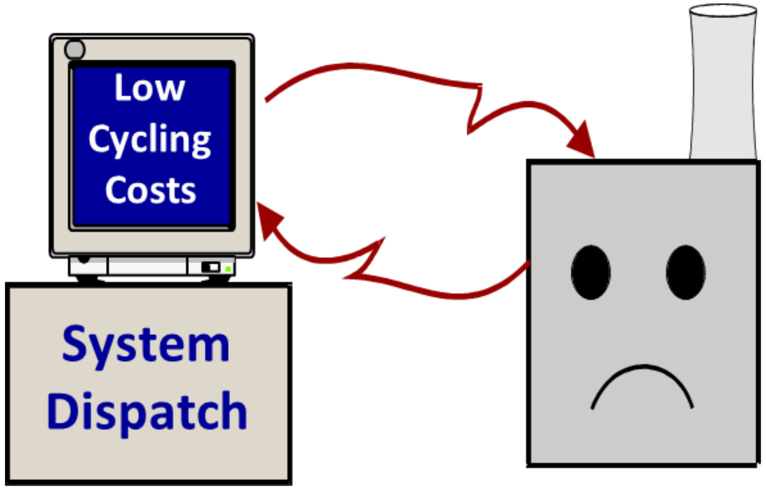



All Y-axis are log scale.

Source: *Power Plant Spending in U.S. – Trends and Impact, Intertek TP 305, Nikhil Kumar & Phil Besuner*

# PROBLEM STATEMENT

- Why do we need to incentivize power plant flexibility?
  - A major root cause of increase in Capital and Operations & Maintenance (O&M) cost for many fossil units is unit cycling.
  - Utilities have been forced to cycle aging fossil units that were originally designed for base load operation.
  - Market signals are resulting in lower revenue.
- What can and should we do once we understand the impacts and costs?




Generation Units Originally Designed for Baseload Operations Running in Cycling Modes

# FACTORS AFFECTING POWER PLANT FLEXIBILITY COSTS

| | | | |
|---|---|---|---|
| Maintenance-related activities | Vintage / Equipment design and manufacturer | Fuel Management | Turbine design and pressure and MW capacity |
| Time between planned outages | Timing of turbine/generator overhauls | Plant configuration, size, economies of scale and scope | Controls and instrumentation |
| Retrofit of equipment, especially, for greater flexibility in moving among duty cycles | Modes of operation over time | Ageing | Regulatory/ Licensing |



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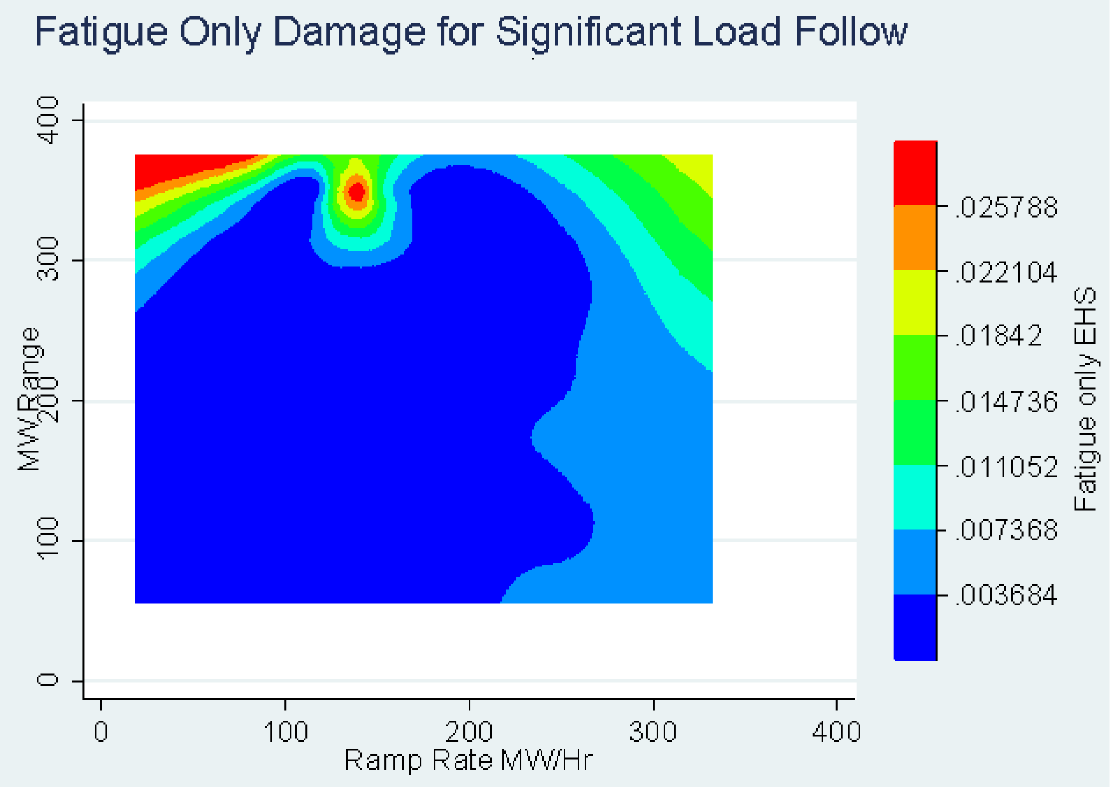
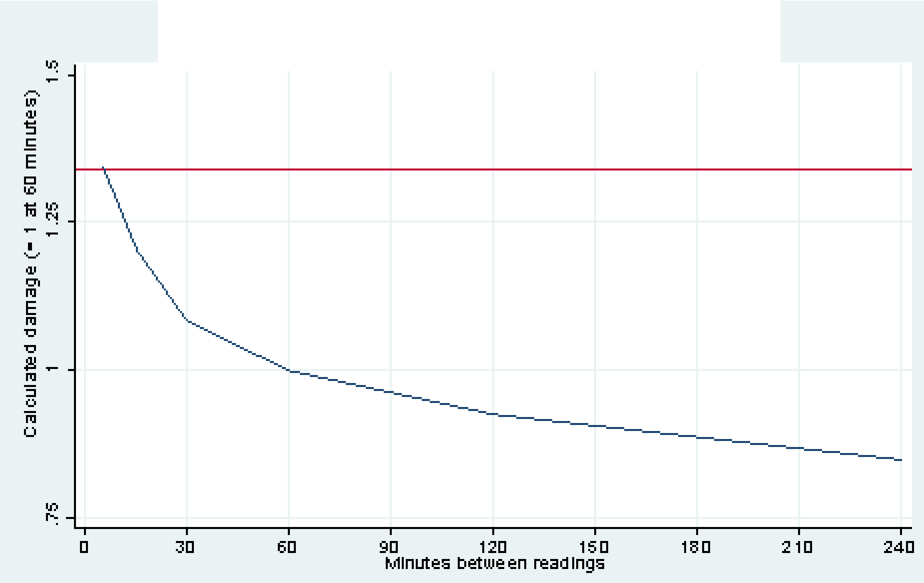
# MODELING EQUIPMENT DAMAGE



# LOAD FOLLOWING DAMAGE

**Electrical and Controls**

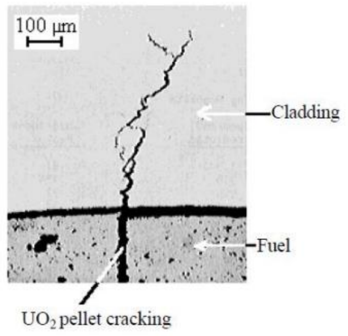
- Increased Controls Wear and Tear
- Increased Hysteresis Effects that Lead to Excessive Pressure, Temperature, and Flow
- Controls Not Repeatable
- Motor Control Fatigue
- Motor Insulation Fatigue
- Motor Insulation Failure Due to Moisture Accumulation

**Generators**

- Stators
  - End-winding Vibration/Loosening
  - Core looseness
  - Slot support system
- Fatigue cracking can occur in high stress concentration areas of copper conductor
- Increased risk of poor brush / collector performance due to low current densities

**Fuel**

- In PWRs, during load changes, fuel undergoes significant variations of the linear heat generation rate and of the temperature gradient.




(c)
Stress corrosion cracking (SCC) cladding failure

Source: *Brochard, J., et al., (2001), "Modelling of Pellet Cladding Interaction in PWR fuel", SMiRT 19, Washington DC, United States, August 2001*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# HOW DO WE MEASURE THE COSTS OF INCREASED CYCLING?

## Total Cost of Cycling

= Δ Maintenance and Capital Spending

+ Δ Replacement Power Cost Due to Forced Outages

+ Δ Long-Term Efficiency Impacts

+ Δ Operational Efficiency Impacts

+ Δ Auxiliary Power and Chemicals

+ Δ Manpower

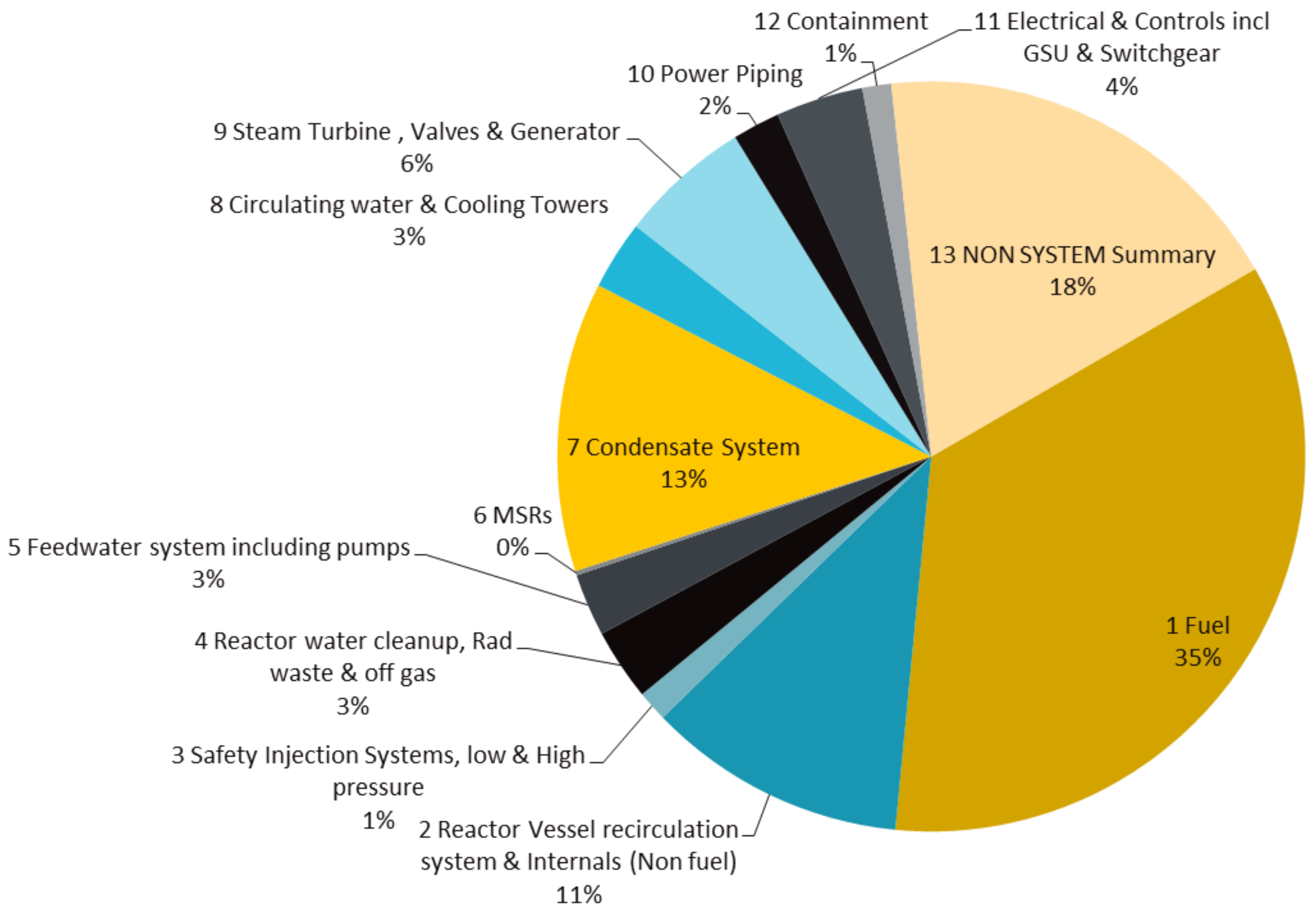
+ Δ Capital Cost Impacts Due to Unit Life Shortening

Here, Δ Refers Only to Those Costs Attributed to Cycling

**Top-Down Method**
Annual Cycling damage regression of EHS vs. Costs

**Bottom-Up Method**
Detailed analysis of 7-10 years of Work orders

# "CANDIDATE" VARIABLE COST (C+O&M) AT A NPP



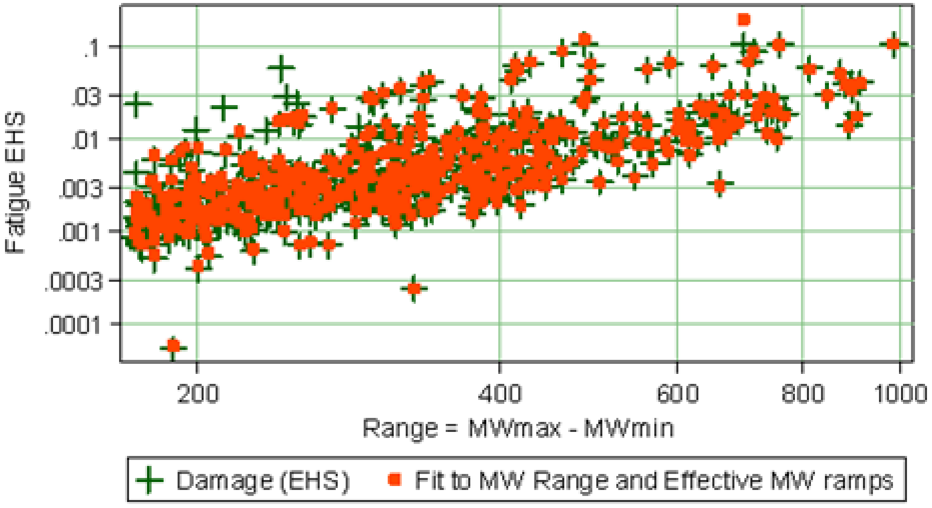

Candidate costs are those cost categories that will be "impacted" by increase in flexibility. Other costs, such as buildings, vehicles are not included in the analysis.

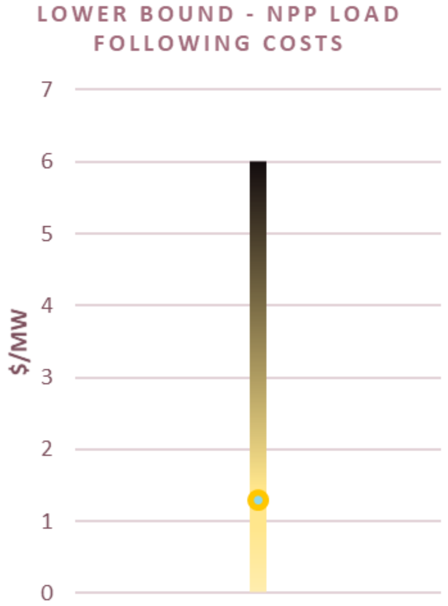
Source: *A New Paradigm – Cycling Operations At Nuclear Power Plants In The United States, ASME Power 2013 2013-98079*

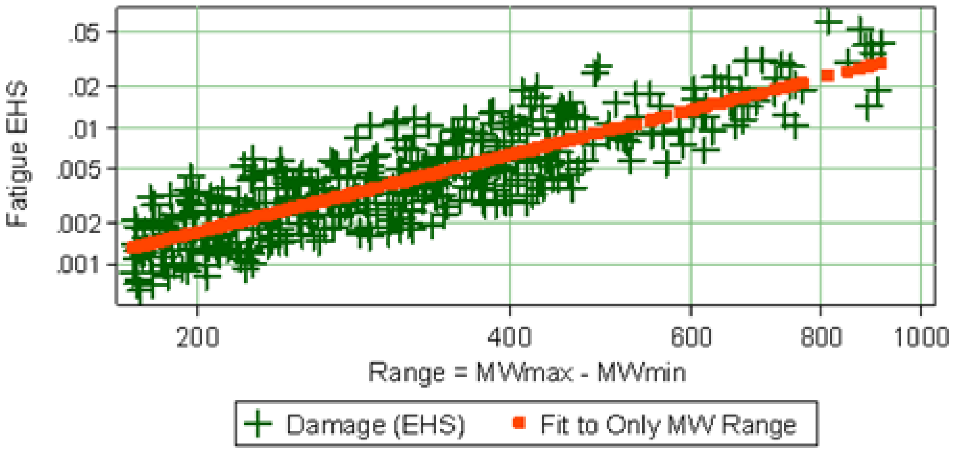
# NPP FATIGUE DAMAGE (OR COSTS) DURING LOW LOAD OPERATION

**FOR ILLUSTRATION PURPOSES ONLY – Each Site is unique, with design/regulatory constraints**

**These chart shows all cycles over a long time horizon.**




Fit for all down-powers (significant load follows and dither cycles) **BEFORE** removing atypical ramp rates

Fit for all down-powers (significant load follows and dither cycles) **AFTER** removing atypical ramp rates

# NON BASELOAD OPERATION IN NPP


Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operation / International Atomic Energy Agency
https://www.iaea.org/publications/11104/non-baseload-operation-in-nuclear-power-plants-load-following-and-frequency-control-modes-of-flexible-operation

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