

Stack Operating Strategies for Central Station SOFC

J. H. Thijssen, J. Thijssen, LLC

*W. A. Surdoval, US DOE National
Energy Technology Laboratory*

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J. Thijssen, LLC

4910 163rd Avenue NE, Redmond, WA 98052, USA
t: 206 229 6882; e: jant@jthijssen.com

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2 Operating Strategies

3 Cost Impacts

4 Conclusions

Performance degradation impacts all current power plant technologies.

- All existing power plant technologies experience performance degradation
- Management to:
 - Ensure $>90\%$ plant availability
 - Subsystems have different degradation characteristics
- Approaches:
 - Improved component design
 - Preventative maintenance / replacement
 - Overdesign / spare capacity

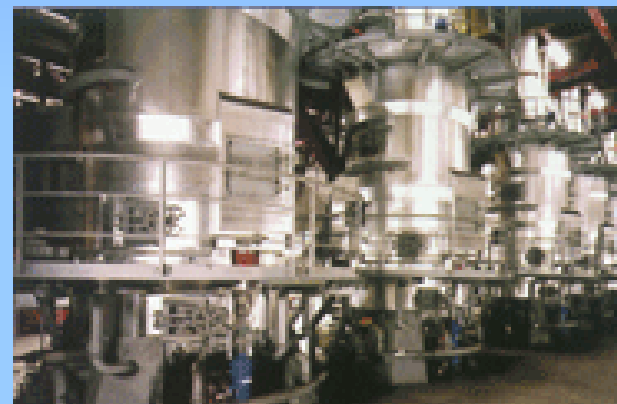
Turbines have been gradually improved to provide long life and limited degradation.

- Turbines are core of powerplant
- Designs optimized to minimize degradation:
 - Last >15 yrs (or life of plant)
 - $\sim 3-5$ yrs between overhauls
 - Degradation $<10\%$ between overhauls



Coal pulverizers degrade rapidly, requiring continuous maintenance and spare capacity.

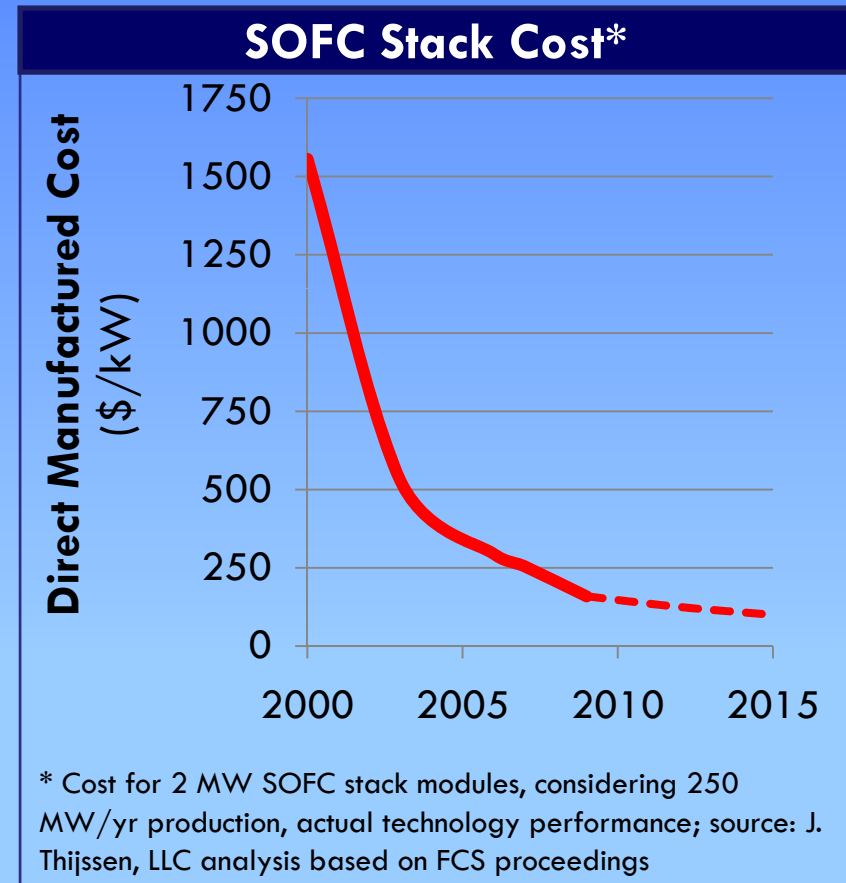
- Early on thought fatal flaw for pulverized coal power plants
- Pulverizers are relatively inexpensive <100 \$/kW
- But degradation is rapid:
 - Rebuild every 4 – 12 weeks
 - Spare capacity (30 -60%)



Since the start of SECA, SOFC stack cost has been driven down significantly.

Since 2000:

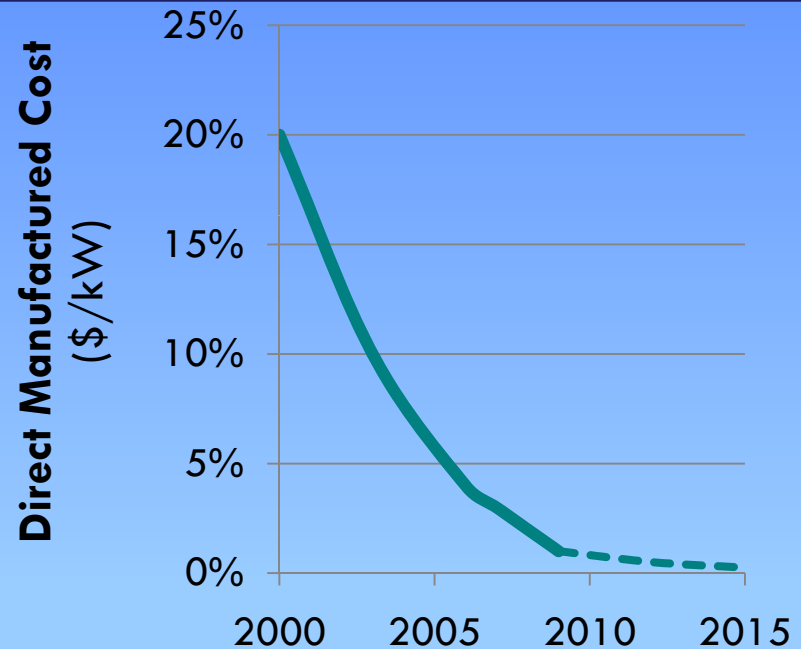
- Power density: up 3x
- Cell-size: up 10x
- Cells per stack: up ~5x
- Cost: reduced 90%



Simultaneously, SOFC degradation rates have been drastically reduced.

- >10x improvement due to better:
 - Materials
 - Architecture
 - Processes
- Better understanding of mechanisms will allow further reduction

Planar SOFC Degradation Rate*



* Degradation rates for planar SOFC stacks based on FCS proceedings from 2000 - 2008

Stack management options deserve a new look!

This study aimed to consider the best operating strategy for SOFC.

- How do we best manage degradation?
 - Operating mode (Voltage vs Current Control)
 - System implications
 - Maximum acceptable degradation
- What is the impact on the cost of electricity?
 - Cost of stack replacement on maintenance cost
 - Impact of efficiency on fuel cost
 - Impact of overdesign on capital cost
- What R&D is needed?

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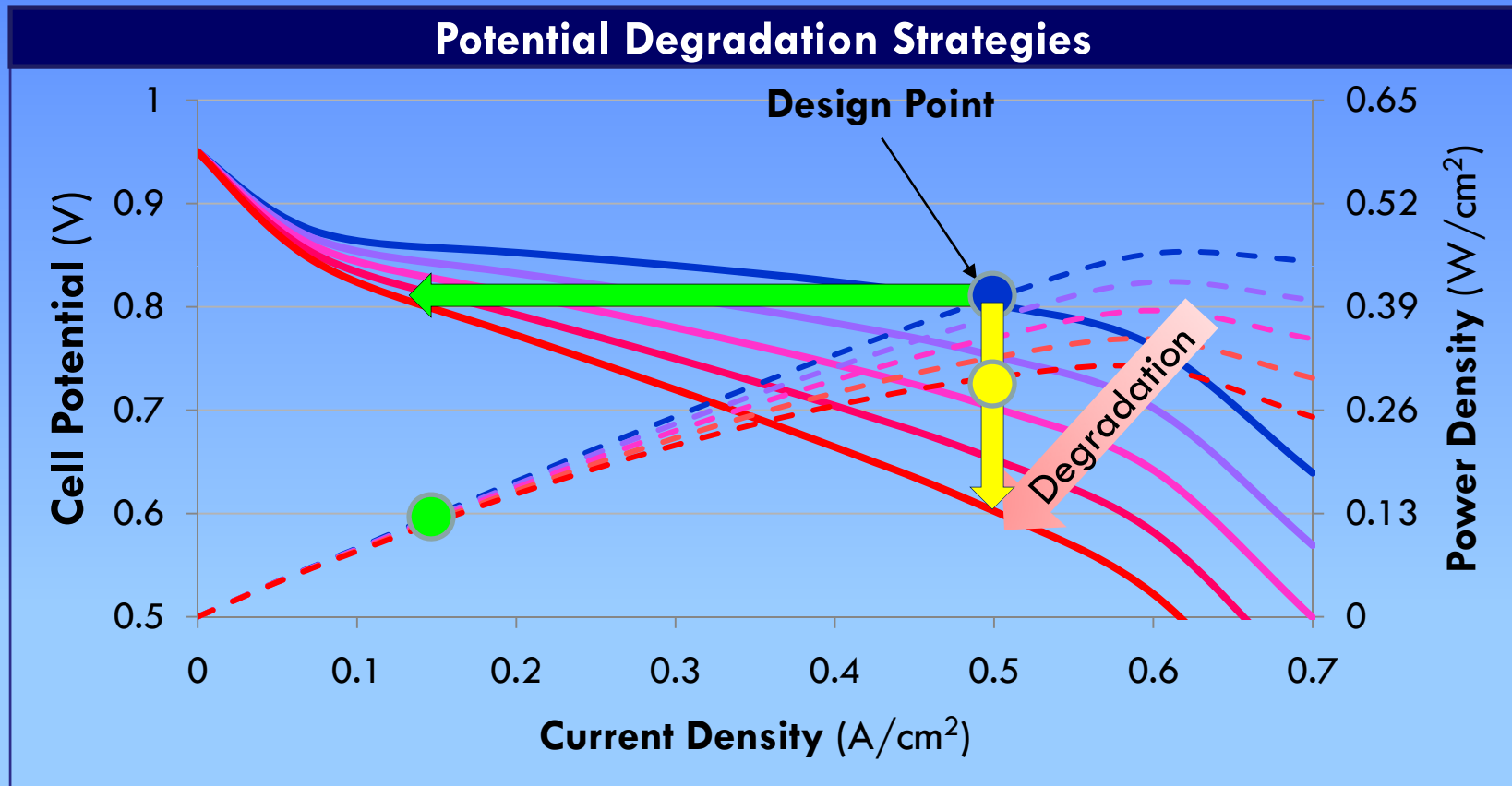
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Constant current and constant voltage operation represent two extreme operating strategies.



At first it seems constant-current operation is better.

But system performance under constant-current mode degrades very rapidly.

- 10% voltage drop:
 - Gross output: down 10%
 - Stack cooling: up 80% (parasitics up >250%)
 - Net output: down 40%*
 - Efficiency down proportionally
- Replacement strategy:
 - Replace all stacks when system output < threshold
 - Overdesign BoP to accommodate increased airflow
 - Stack replaced when at ~90% of initial capacity

* Combination of reduced voltage, increased parasitics, BoP limitations

Practically, constant-current operation requires frequent stack replacement + excess BoP capacity.

- Practically, constant current operation requires:
 - Replace stack @~5-6% degradation
 - Provide excess BoP capacity (esp. in air delivery & recuperation)
 - Excess stack capacity has no benefit
- This results in short stack life, or requires very low degradation rates:
 - With current degradation rates (1%), stack life would be less than 4,000 hrs
 - 40,000 hrs life would require ~0.1%/1,000 hrs

Constant voltage operation doesn't impact system performance.

- 10% degradation:
 - Current density down 60-70%
 - With spare stack capacity:
 - Output same
 - Efficiency ~unchanged
- Replacement strategy:
 - Overdesign stacks
 - Replace portion of stacks when system output < threshold
 - Stacks replaced when at 30 – 50% of initial capacity

Constant voltage operation requires excess stack capacity but can substantially extend stack life.

- Constant voltage operation requires excess stack capacity:
 - Without it stack life would be impractically short
 - With excess stack capacity, system performance remains ~constant
 - Stack life limited by capital cost, thermal considerations
- With excess stack capacity:
 - With current (1%) degradation: stack life >20,000 hrs
 - For >40,000 hr life, 0.5% degradation suffices

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The impact on LCOE was assessed for a well-studied IGFC system*.

- Coal-based system:
 - 250 MW
 - 100% CCS
 - Catalytic gasifier
- >80% power from SOFC

Selected Performance Assumptions

Nernst Potential	0.9 V
Initial ASR	200 mΩcm ² / 1,000 hrs
Initial current density	0.5 A/cm ²
Initial Cathode Stoichiometry	2.9
Stack Temperature	650 – 800 °C
Stack Pressure	Near Atmospheric
Initial Parasitic Power (% output)	Air movement: ~4.1% Miscellaneous: 1%
System Efficiency	52.4% (HHV, Coal)

*Based on DiPietro, Kearns *et al*

Cost assumptions were identical to those used in numerous previous studies.

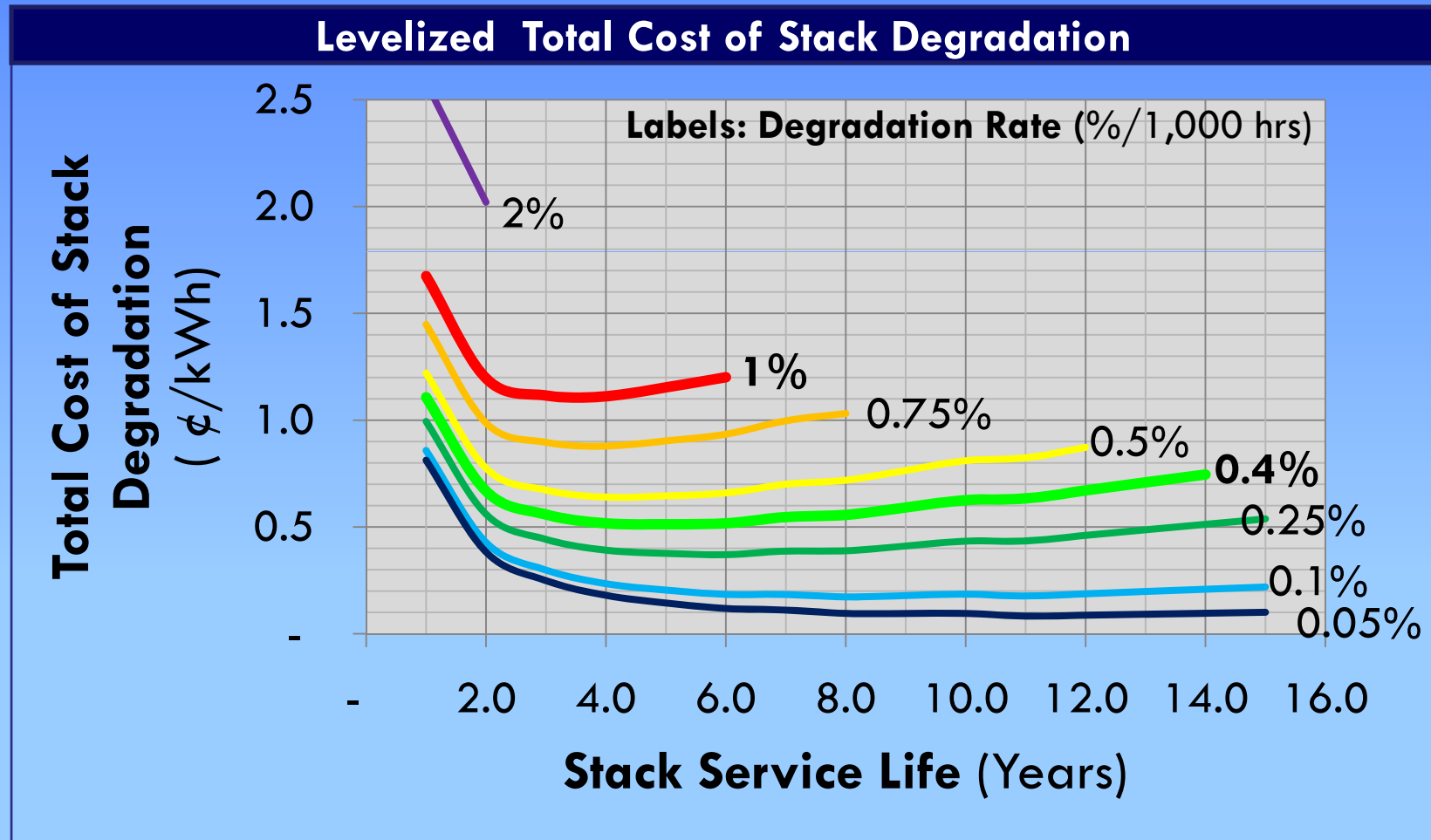
- SOFC production > 200 MW/yr
- Baseline cost assumptions (coal plant):
 - Stack cost (incl manifolding): \$225/kW
 - Stack replacement: \$150/kW
 - Total SOFC Subsystem: \$700/kW
 - Total plant: \$1800/kW
- Levelization factors consistent with DOE practice
- Baseline LCOE: 7.4 ¢/kWh

- All in 2007 \$

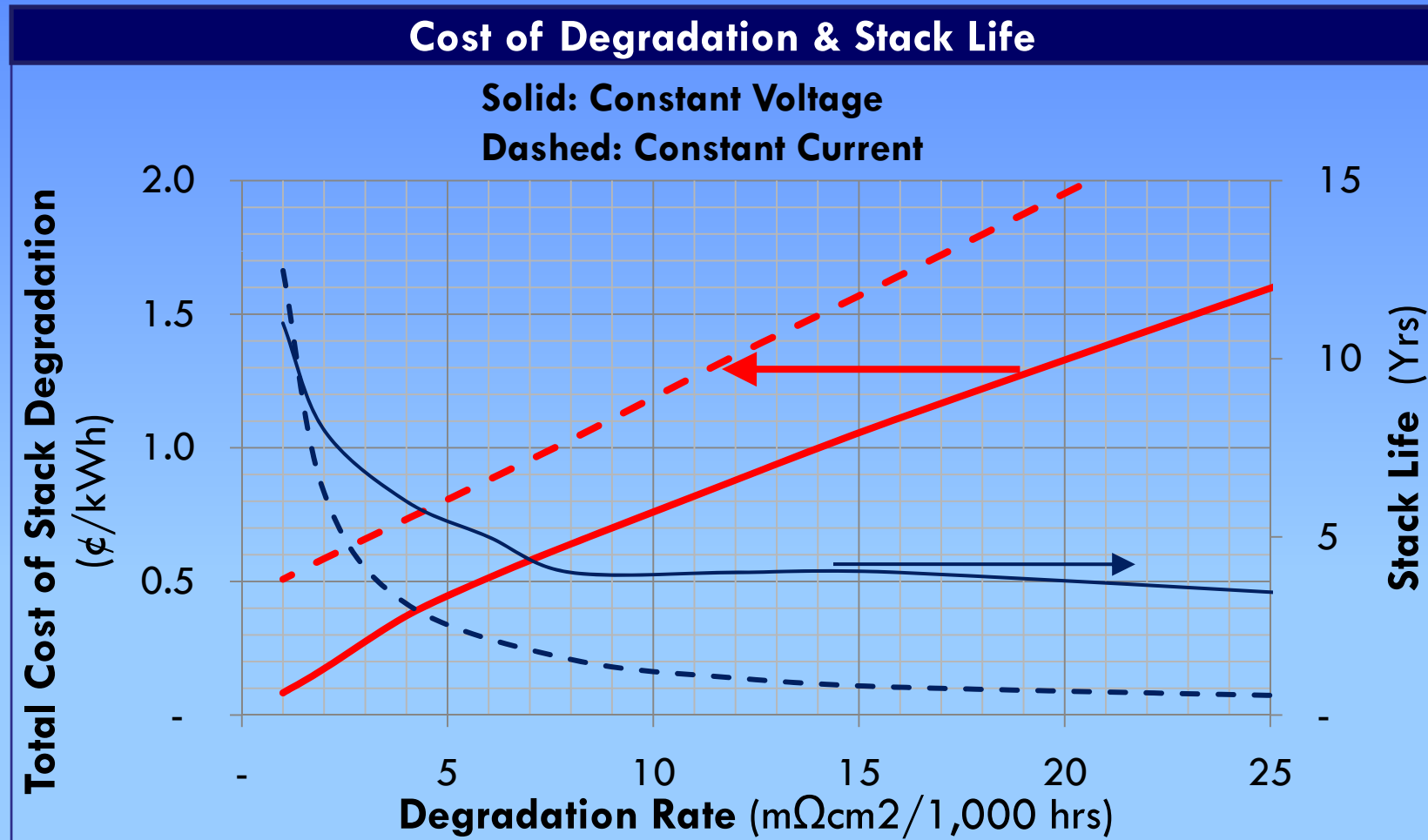
Aside from stack replacement OPEX, impacts on CAPEX, O&M, and fuel cost were considered.

- Stack replacement cost
- Additional CAPEX due to overdesign
- Additional O&M due to overdesign
- Changes in fuel cost
- All impacts were levelized

Constant voltage operation allows optimization of stack capacity & life vs LCOE.



Constant voltage operation leads to lower cost, allowing commercialization sooner.



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Constant voltage operation allows minimization of system and cost impacts of stack degradation.

- **Constant current operation:**
 - Requires BoP overdesign
 - Rapidly & severe impacts on system output & efficiency
 - Stack replacements at $\sim 95\%$ of initial capacity
 - 0.5 ¢/kWh impact requires $\sim 0.05\%/1,000 \text{ hrs}$
- **Constant voltage operation:**
 - Requires stack overdesign
 - Only marginal system impact
 - Stack replacement at $30\text{-}50\%$ of initial capacity
 - 0.5 ¢/kWh impact requires $\sim 0.4\%/1,000 \text{ hrs}$

Degradation rates are approaching the target levels, but better understanding of mechanisms is needed.

- $<0.5\%/1,000$ hrs has been shown in 1-cell stacks
- Most data to date with constant current
- Future tests should include constant voltage
- (Better) mechanistic and quantitative understanding:
 - Robust predictions of degradation & cost
 - Optimize operating map to minimize degradation
- Ultimately, long-term test of large stacks is critical

Many thanks

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Thank you for your attention!