SOFC Stack Operating Strategies

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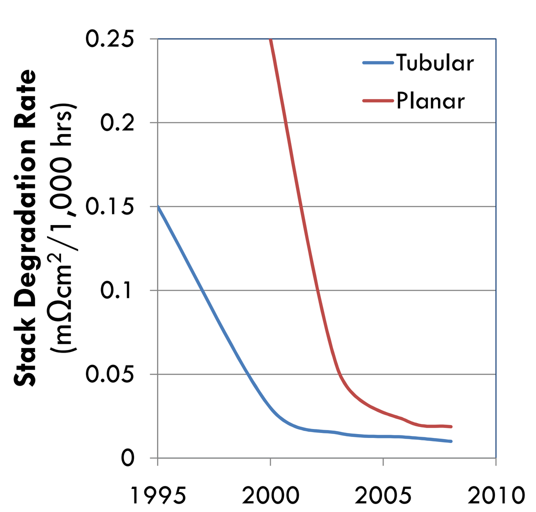
Degradation & Plant Availability

- Managing component degradation is critical to power plant availability
- Achieving this cost-effectively requires a combination of:
  - Improved component design to minimize degradation
  - Preventative maintenance to improve performance predictability
  - Spare capacity to provide back-up during routine maintenance or in case of failure
- Examples of different approaches:
  - Gas turbines run for 3 -5 yrs without minimal maintenance with <7% degradation
  - Coal pulverizers are rebuilt every 4 – 12 weeks, necessitating 1/6 spare capacity
  - Most IGCC plants carry spare gasifiers to meet availability requirements

SOFC Degradation

- Degradation has been seen as a major barrier to SOFC commercialization
- SECA has been key in reducing degradation:
  - Degradation (planar stacks) reduced by factor 10[1]
  - But most data on stack still limited to constant current
  - Impact of operating conditions not yet well-understood
- Degradation targets are based on rule of thumb:
  - Similar approach as used for gas turbine
  - 5 years w/ <10% degradation (or ~0.2%/1,000 hrs)
  - Constant current operation implied in most discussion
  - Maybe in-appropriate with low-cost stacks
  - System impacts of degradation are not considered



Objectives

We carried out an analysis asking:

- How can we best manage degradation?
  - With stack cost in the 100 – 200 $/kW range
  - Considering system implications
- What is an appropriate degradation target?
- What additional knowledge do we need about degradation?

Approach

- Evaluate impact of various operating strategies:
  - Constant current, constant voltage, constant heat output
  - Replacement rates
- Determine overcapacity needed for >90% availability
- Use baseline IGFC cost model
  - State-of-the-art planar stacks, 2000 cm^2 cells
  - Mature production (>200 MW/yr)

Performance Assumptions	
Average Nernst Potential	0.9 V
Initial ASR	200 $m\Omega cm^2$/1,000 hrs
Initial current density	0.5 A/cm^2
Initial Cathode Stoichiometery	2.9
Stack Operating Temperature	650 – 800 °C
Stack Operating Pressure	Near Atmospheric
Initial Parasitic Power Demand	Blowers: 4.1% (Gross DC Stack Output) Miscellaneous: 1% (Gross DC Stack Output)
Power Conversion Efficiency	96%
System Efficiency	52.4%

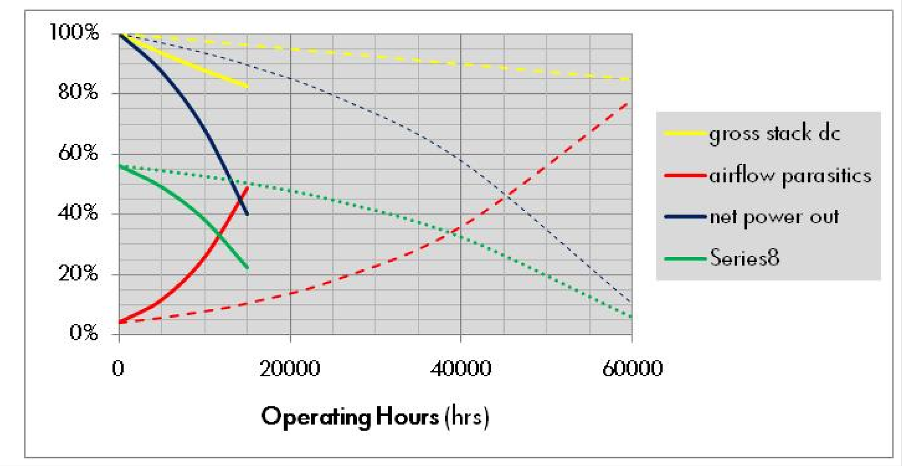
System cost structure

SOFC Stack	Basic Stack	100	$/kW
	Balance of	22	$/kW
	Stack Infra:	50	$/kW
	Total	172	$/kW
Stack replacement cost		100	$/kW
Balance of SOFC Subsystem	Blowers	60	$/kW
	Recuperat	100	$/kW
	Power Elec	150	$/kW
	Misc	75	$/kW
	Total	385	$/kW
Total SOFC Subsystem Cost		699	$/kW
Balance of Plant		1101	$/kW
Total Plant Cost		1800	$/kW

Other Assumptions

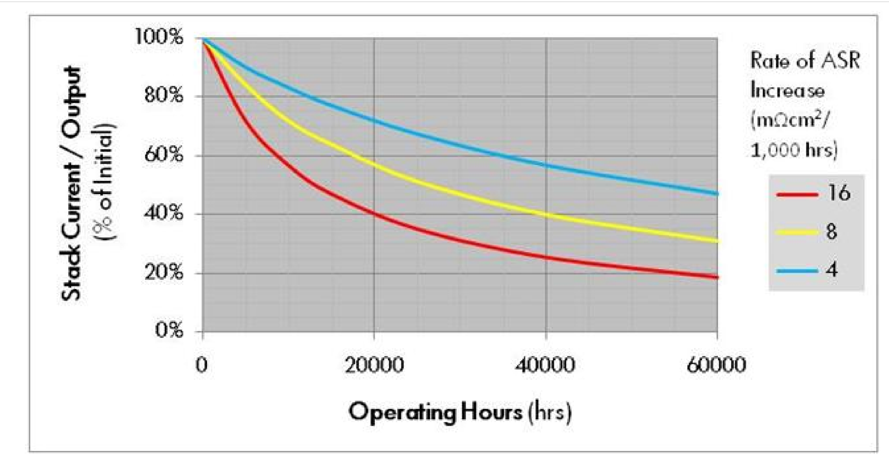
Variable O&M	0.75	¢/kWh
Fixed O&M (non-stack)	2%	of installed capital
Efficiency	52.40%	HHV Basis
Coal Price	1.8	$/MMBTU
CAPEX amortization	17.50%	%/yr
Capacity factor	80%	of nominal capacity
O&M levelization factor	1.1568	
Fuel levelization factor	1.2022	

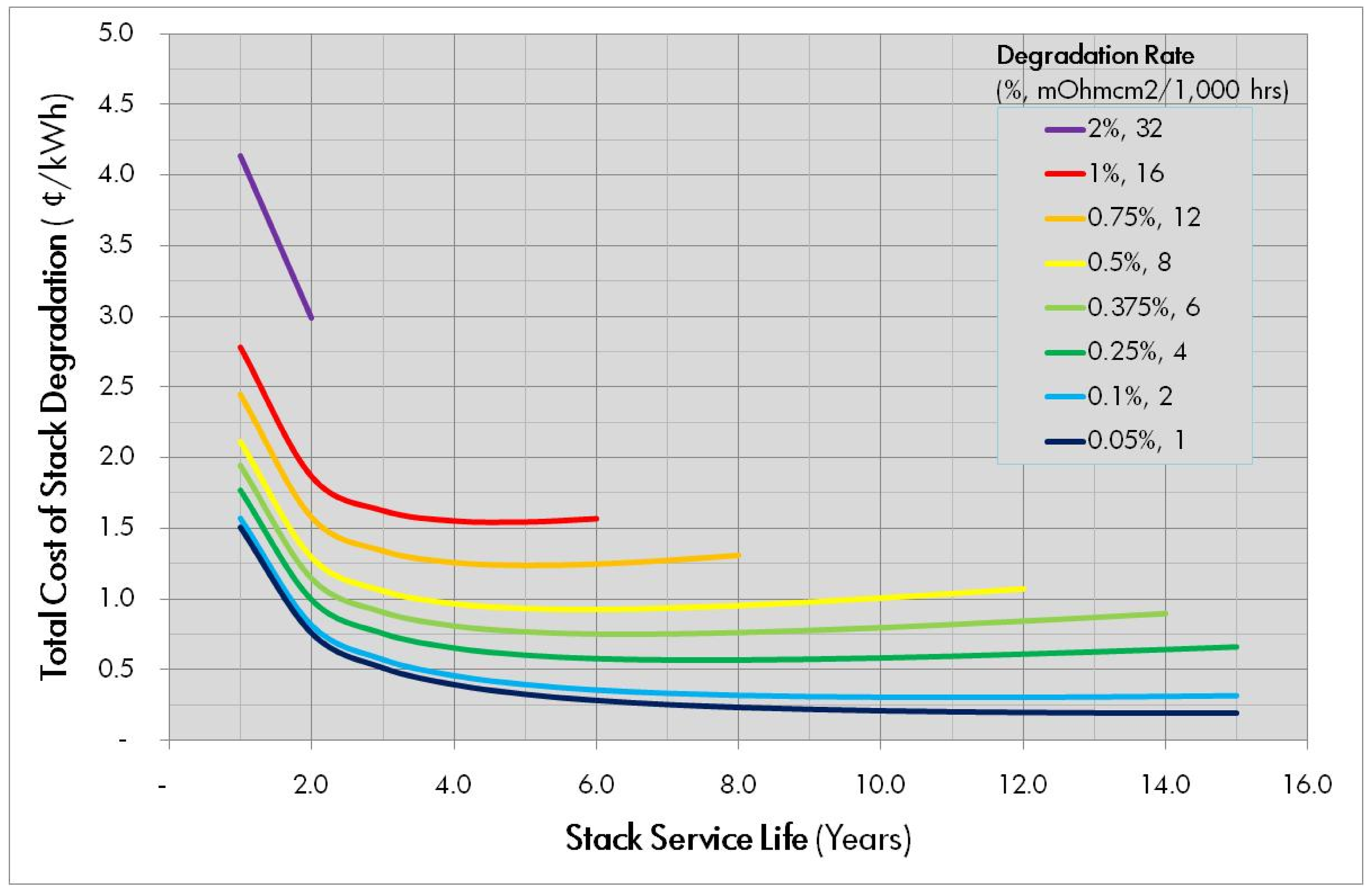
System Impact Constant Current[e]

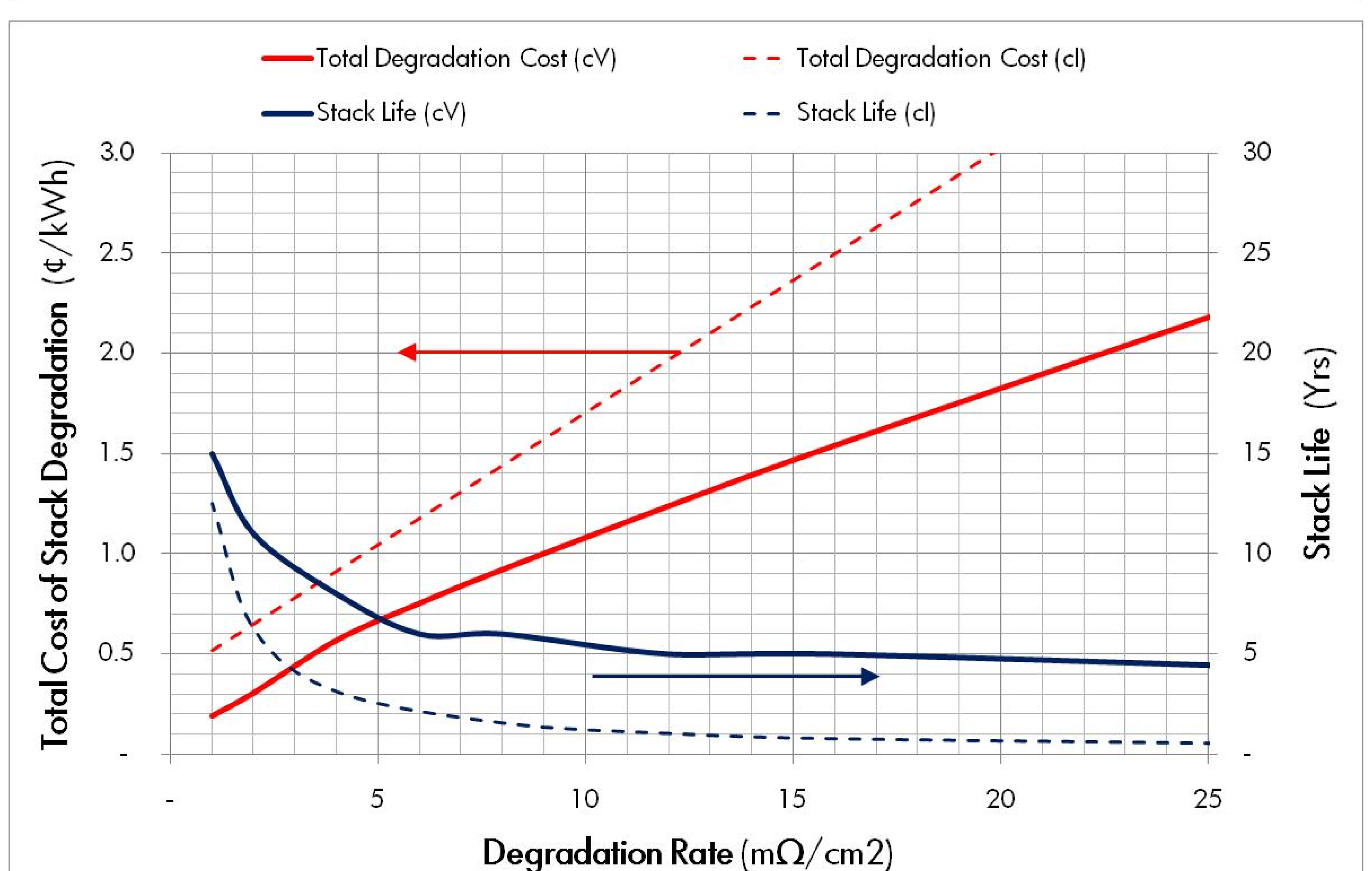


solid lines: 4 mΩcm²/1,000 hrs
Dashed lines: 16 mΩcm²/1,000 hrs

System Impact Constant Voltage







System Impact

- 10% degradation under typical[a] constant-current mode operation leads to:
  - Immediate 10% reduction in stack output (V x I)
  - 80% increased in stack cooling air flowrate AND >200% increase in pressure drop result in >5x parasitic power for air flow (typically several percent of stack output)[b]
  - Increase in polarization likely accelerates degradation further
  - To maintain >90% availability, these factors have to be off-set by significant overdesign of all system components, especially cathode air handling
  - System efficiency degrades rapidly
- Similar degradation[c] under constant voltage operation:
  - Requires significant reduction in stack current to compensate increased polarization[d]
  - System heat balance and opeartion is not affected (except for heat losses)
  - To maintain >90% availability requires only addition of stack capacity:
    - Pick stack maintenance interval (e.g. 1 year)
    - Determine excess capacity with degradation rate to achieve >90% availability
    - Optimize stack life to minimize cost
  - System efficiency is only marginally affected by degradation

Conclusion

- Constant-voltage operation appears to provide the most attractive operating strategy for SOFC
- With 0.5%/1,000 hrs degradation rates, stack management cost of below 1 ¢/kWh appear feasible, with 1.5%/1,000 hrs cost would be over 2¢/kWh:
  - 1.5%/1,000 hrs has been demonstrated in complete systems
  - In certain short stack tests 0.5%/1,000 hrs has been demonstrated
  - Available constant-current test data likely represent worst-case
- Given other compelling benefits of IGFC over conventional technology, 0.5%/1,000 hrs would likely be acceptable for initial commercial systems
- Long-term, degradation below 0.25%/1,000 hrs would be desirable, which would benefit early plants as their stacks are replaced
- To achieve costs below 0.5 ¢/kWh, degradation rates must be below 0.25%/1,000 hrs
- More degradation data under constant=current operation is needed:
  - Basic operating data for stacks under constant current
  - Short stack data on impact of operating conditions (temperature, polarization, gas composition)

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References & Notes

1 Data from SECA meetings since 2002
a Assuming operating at 0.8V cell voltage, 0.9 V Nernst potential
b Benefit of increased airflow on Nernst potential is negligible
c In terms of $m\Omega cm^2$/1,000 hrs
d As we don't have public data under constant voltage operation, we assume that for modest degradation the rate of ASR increase is the same as under constant current
e Assumes atmospheric stacks, initial pressure drop 100 Pa