Liquid Tin Anode SOFC for Direct Coal Conversion: A System Perspective

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Liquid Tin Anode SOFC (LTASOFC) could revolutionize power generation from coal ...

- Liquid anode regeneration allows conversion of almost all fuel in LTASOFC: promises **high electrical efficiency** and **straightforward carbon capture**
- Is tolerant of many coal impurities (oxidizes sulfur as fuel): promises **robust operation**
- Eliminates expensive and gasifier, ASU, and gas turbines compared with IGCC: holding potential for **low cost**

… but it is at a very early stage of development.

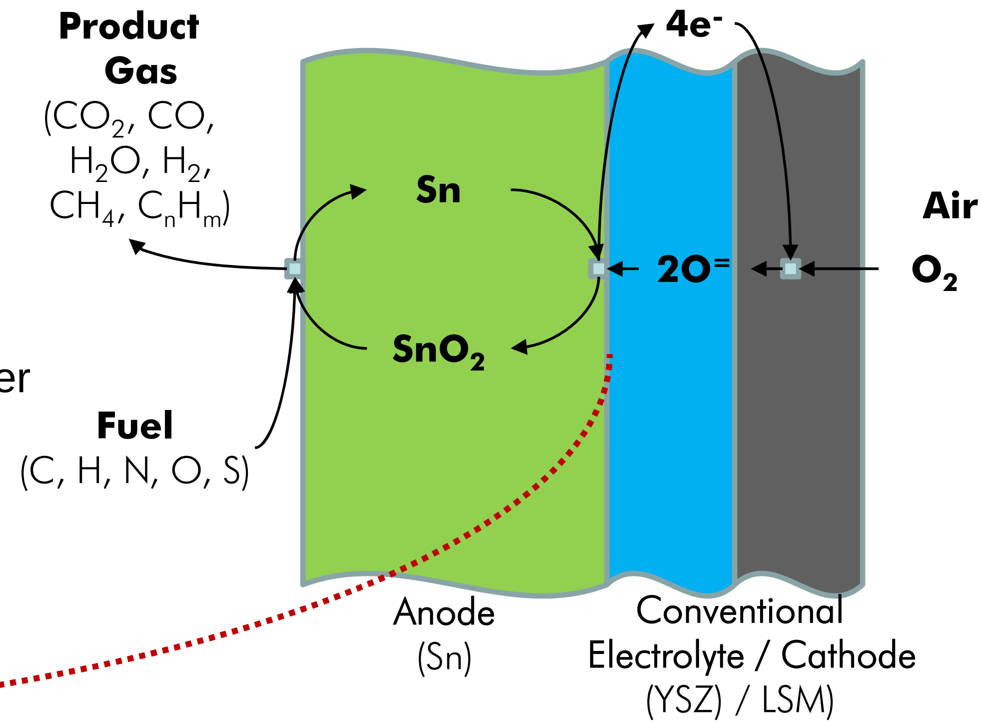
- Basic feasibility has been proven in single cells and 2-cell stacks since 1990s
- Key data for coal conversion lacking, leaving key questions:
  - Can LASOFC be made sufficiently robust for reliable power generation?
  - Can power densities be raised to achieve acceptable cost?
  - Can the technology be scaled-up?

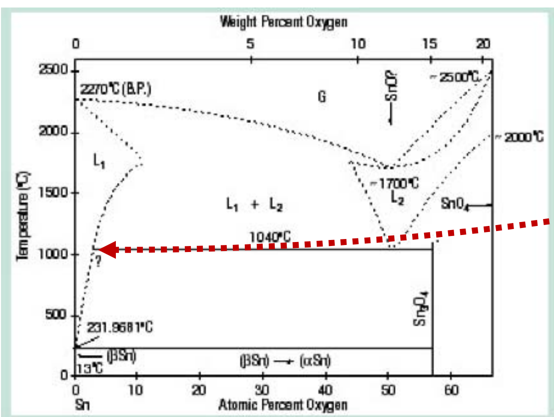
Thus DOE’s NETL wanted to understand the technical and economic potential for LTASOFC, as well as key challenges.

Strictly speaking the LASOFC is a metal-air fuel cell with continuous regeneration of the metal oxide produced.

LTASOFC Operating Principle

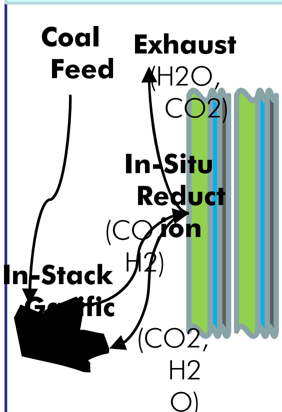
- Anode reactions are quite fast at 1000 °C operating temperature
- Potential for SnO_2 precipitation limits LTASOFC power density:
  - Drives high T (~1000°C)
  - Theoretically: 1-2% O?
  - Practical operation shows lower limit (0.1 – 0.2%)

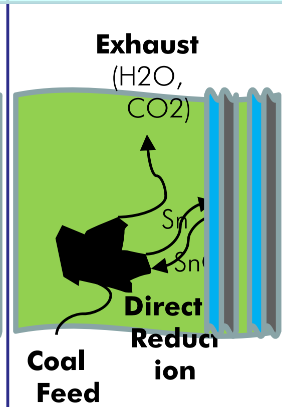


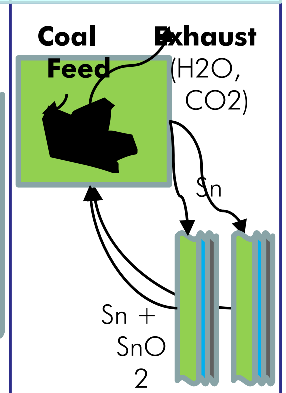


In equilibrium, the effects of the Sn reactions cancel out.

LTASOFC Sn Reduction: Options

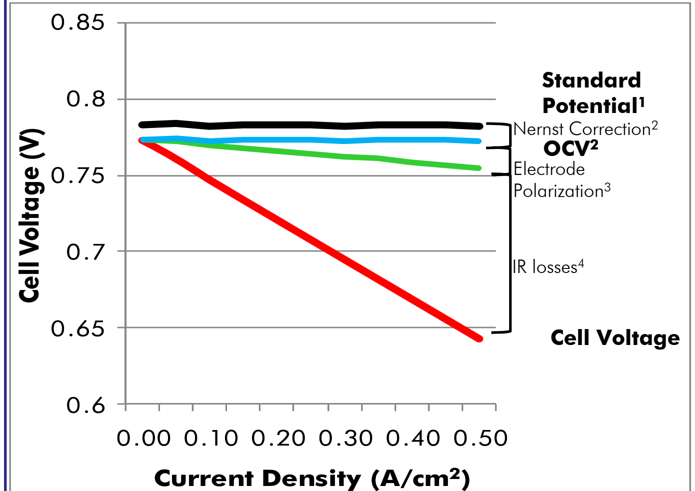






	In-Situ	In-Stack	Central
+	• Can build up voltage • No direct contact coal / cells / tin stays in place	• High conversion • Higher power density possible • Easiest thermal integration	• Central coal / ash handling • High conversion • Tin quality management possible • Highest power density possible
-	• Complex coal / ash handling • Large volume • Poor control fuel conversion • No on-stream tin quality mgmt • Power density diffusion - limited	• Cannot build up voltage inside stack • Complex coal / ash handling per stack • Direct contact coal with stack	• Requires recirculation of large Sn volumes • Voltage build-up requires current interruption

LTASOFC Cell Voltage



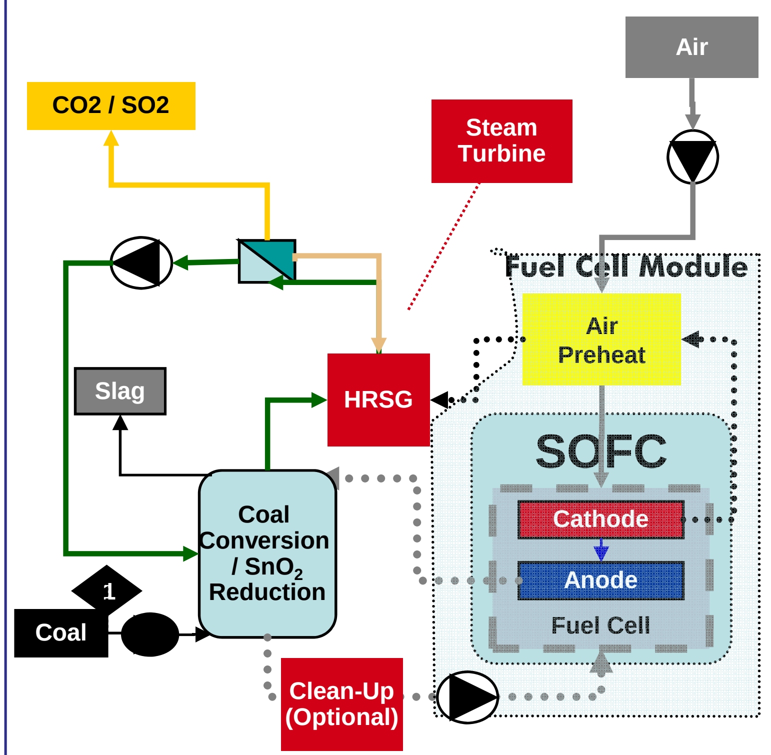
1 For Sn-O2 reaction at 1000 °C and with unit activities for reactants and products
2 Based on ambient pressure air with a stoichiometry of 2, max O in Sn of 0.1%
3 Assuming similar polarization overpotential as for conventional SOFC
4 IR losses based on estimates for Siemens-Westinghouse tubular technology

For perspective:

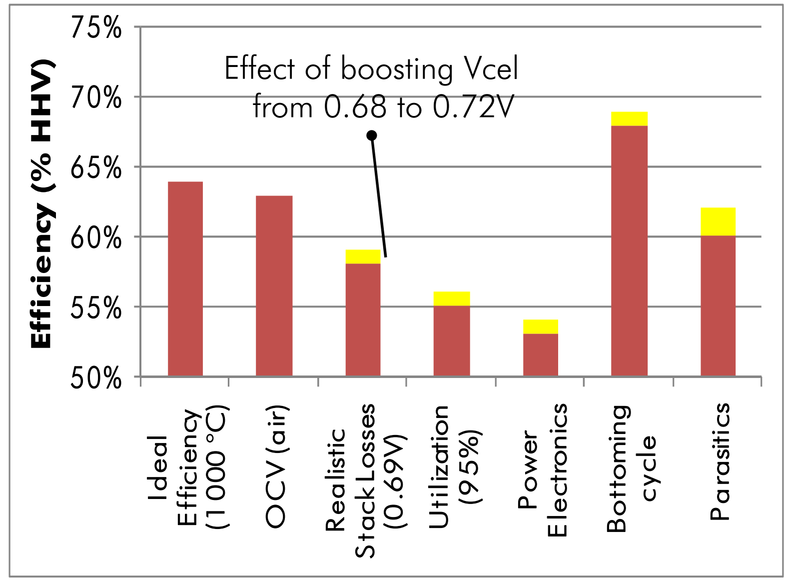
- Sn circulation: ~0.5 million tpd (cell voltage 0.65V/cell, max oxygen content in tin 0.2%)
- Impact of cell voltage build-up:
  - each micro-ohm of busbar resistance results in 15% I^2R loss
  - Keeping I^2R loss <1% would require >300 cm^2 cross-section for 20 cm long busbar

Preliminary analysis indicates that 60+% efficiency is feasible with LTASOFC with CCS, provided efficient thermal integration.

LTASOFC Process Flow Schematic



LTASOFC System Efficiency

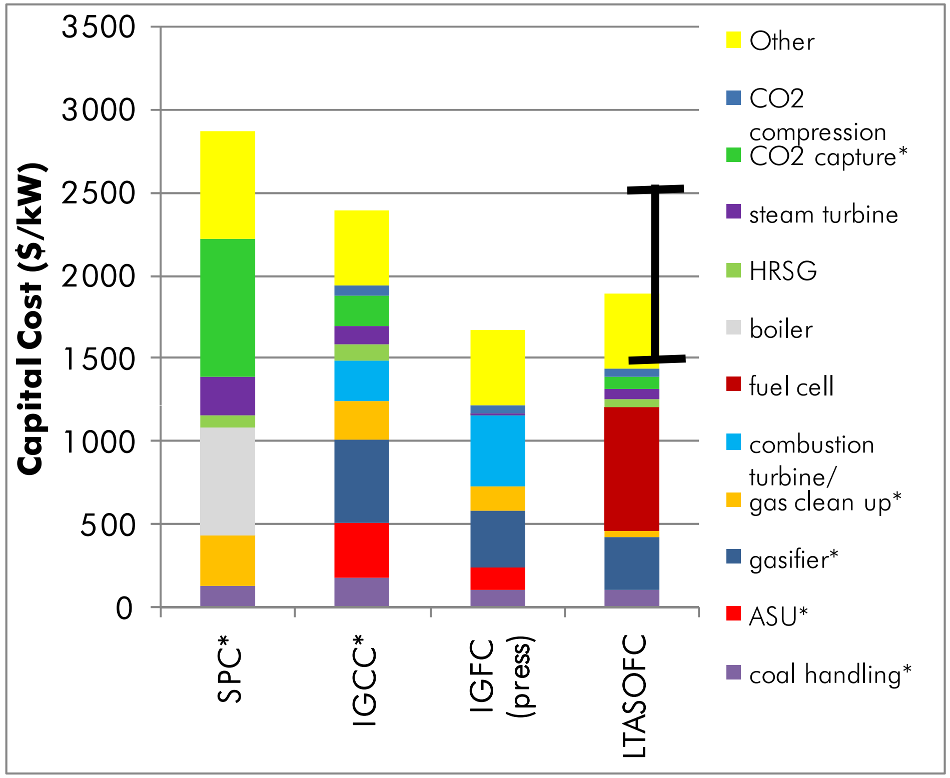


1 Ideal efficiency: unit activities
2 OCV figures in Nernst correction (anode and cathode side)
3 Stack losses comprise I2R losses, electrode polarization, mass transfer)
4 Utilization of 97% is likely only achievable with anode gas recycle
5 HRSG/ST bottoming cycle heated by syngas purge, cathode air exhaust, and syngas cooling
6 Parasitics include power for fans, tin pump, amine units, and miscellaneous factors

The capital cost for an LTASOFC system would likely be $1400 - $2400 per kW, and a LCOE of around 70 $/MWh with CCS.

- Capital cost assumptions:
  - For stack modified from earlier analysis for Siemens tubular stacks
  - For tin reduction reactor, based on estimates for molten metal gasifiers (e.g.Hymelt, Hydromax)
  - Other system components scaled from DOE baseline IGCC
- LCOE analysis based on DOE baseline study
- Narrowing down the uncertainty on the stack and SnO2 reduction reactor is critical:
  - O/Sn
  - Thermal integration / losses
  - Power density
  - Tin flow control system

LTASOFC System Capital Cost



- From 2007 baseline with CO2 capture
- Coal conversion / SnO2 reduction reactor is listed as gasifier

LTASOFC could have the potential for high-efficiency, low-cost, clean coal power generation , but there are key uncertainties.

- Systems based on LTASOFC may be relatively simple and may achieve;
  - 60% electrical efficiency based on coal based on a high-efficiency fuel cell stack
  - >90% carbon capture by recycling unconverted anode tailgas
  - <10% increase in LCOE if stack cost can be kept to less than $750/kW
- There appear to be no fundamental showstoppers for LTASOFC at this point, but there are significant uncertainties about it viability as a coal-based power technology:
  - No thermodynamic limitation known that would prevent a LTASOFC from being realized, but the solubility of oxygen in molten tin must be better-understood
  - Basic technology challenges include:
    - Stack operation in presence of coal contaminants other than sulfur
    - Power density limitations, including the limitations imposed by the limited solubility of SnO_2 in Sn(l)
    - Ability to break the conductive path through the flowing tin to allow voltage build-up in the stacks
  - In addition, a host of engineering challenges will have to be addressed:
    - Stability of materials under hostile conditions (temperature, molten metal, mechanical stresses, erosion)
    - Sealing of cells and components
    - Insulation to mitigate against unacceptable heat losses
    - Reactor engineering of the SnO_2 reduction / coal conversion reactor

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