McMaster Institute for Energy Studies
ADAMS LABORATORY

McMaster Advanced Control Consortium

GREEN POWER PLANTS OF THE FUTURE

Using rolling-horizon optimization to achieve load-following grid power with near-zero emissions from next generation power plants.

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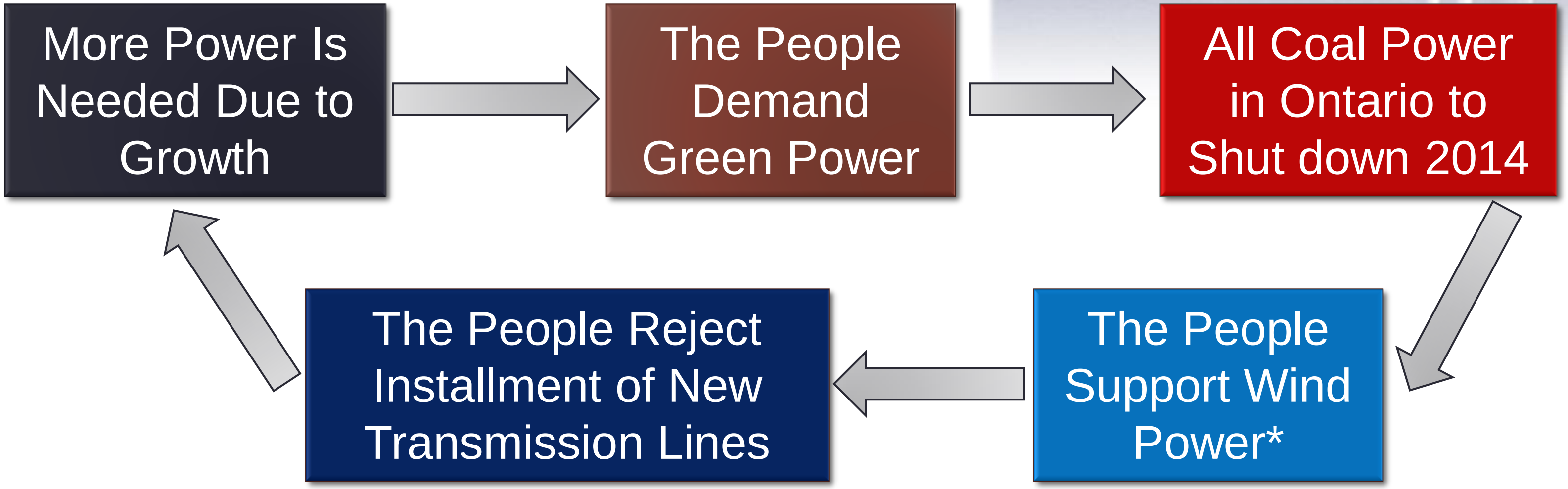
Motivation: The Toronto Problem

Clean Energy – A set of conflicting goals?

- People want clean energy, whatever that means to them.
- But they don't want to pay for it, in money or inconvenience.

Example: The Toronto Problem



* Some people oppose wind power due to bird deaths. Example, March 31, 2013, Wind farm in Nevada faces $200,000 fine after the death of a gold eagle.

Triple Bottom Line of Sustainability

ECONOMICS

- Capital
- Operating
- Supply chain, materials
- Job creation and losses
- Profitability
- Uncertainty and Risk

This talk:
Profitability analysis

ENVIRONMENT

- Particulates
- CO_2, NOx, SOx
- Deforestation & Land Use
- Mining & Resource Extraction
- Water consumption
- Resource Depletion
- Toxicity
- Wildlife impact
- Noise

This talk:
Life Cycle Analysis

SOCIETY

- Public acceptance
- NIMBYs / BANANAs
- Health Impacts
- Safety of workers and community
- Accidents
- Public policy
- Elections and Politics

This talk: How CO_2 Tax Policy affects design choices

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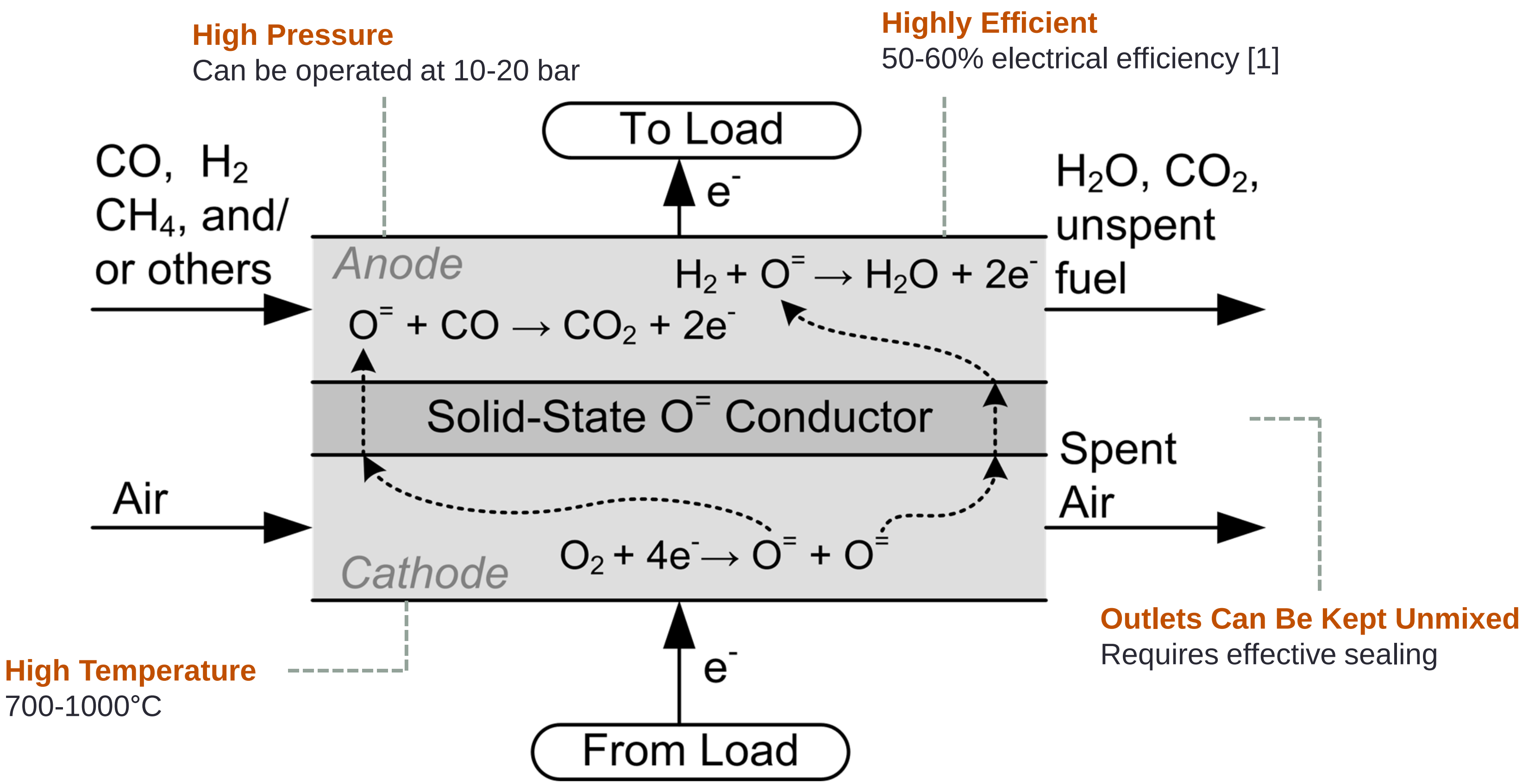
Sources Jimenez-Gonzales and Constable, Green Chemistry and Engineering. 2012. And others.

1. BULK SCALE POWER

Integrates SOFCs and CAES, controlled by a real time optimizer.

Solid Oxide Fuel Cells

Electrochemical reactions between O_2 and a fuel gas occur across an impermeable oxide barrier, producing current



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Sources: Adams, Nease, Tucker, & Barton. *Ind Eng Chem Res*. (2013) DOI:10.1021/ie300996r

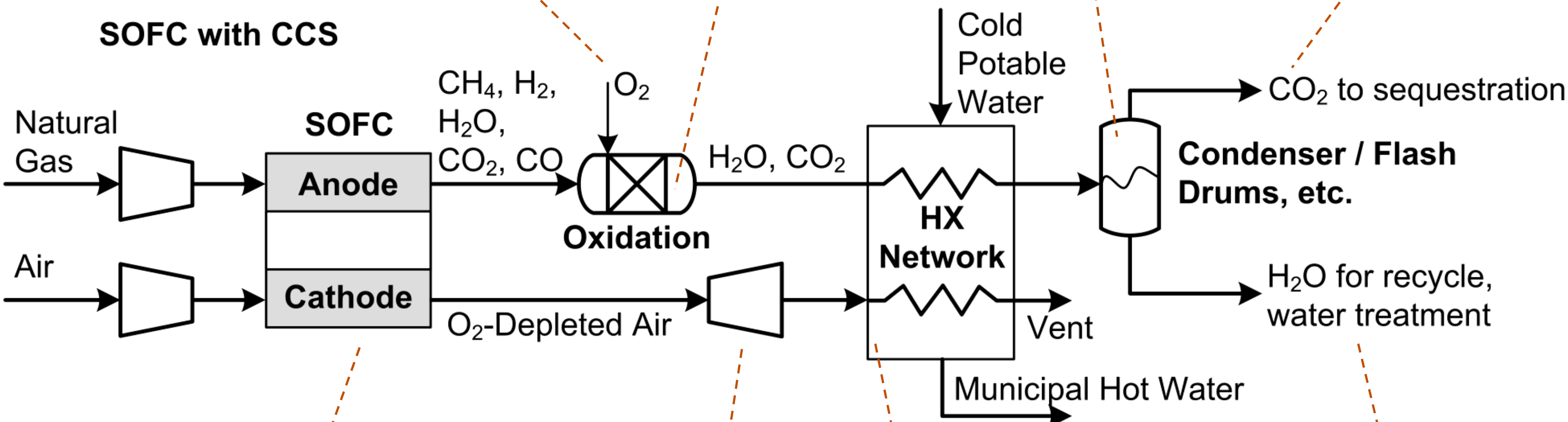
Vision: Long Term Bulk Power (NGFC)

Need high purity O_2 from air separation unit

Catalytically oxidize.
No flame!
No burning!

Very little energy penalty here

Pipeline purity CO_2
~100% capture
Still at 10-20 bar!



Operate at pressure (10-20 bar)
>80% Fuel Utilization

Higher difficulty: High pressure plus effective seals.

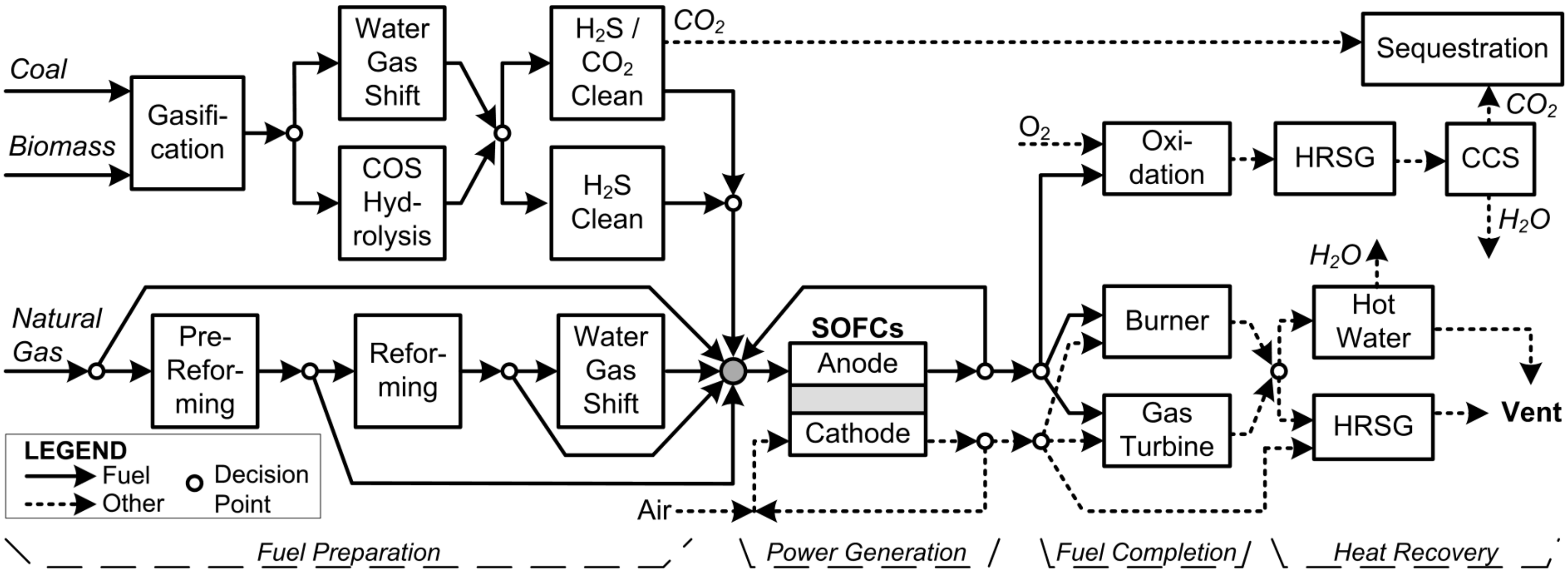
Extra power here from Brayton Cycle turbine

Can use the waste heat for hot water, or **steam for power**

Water is actually drinkable!

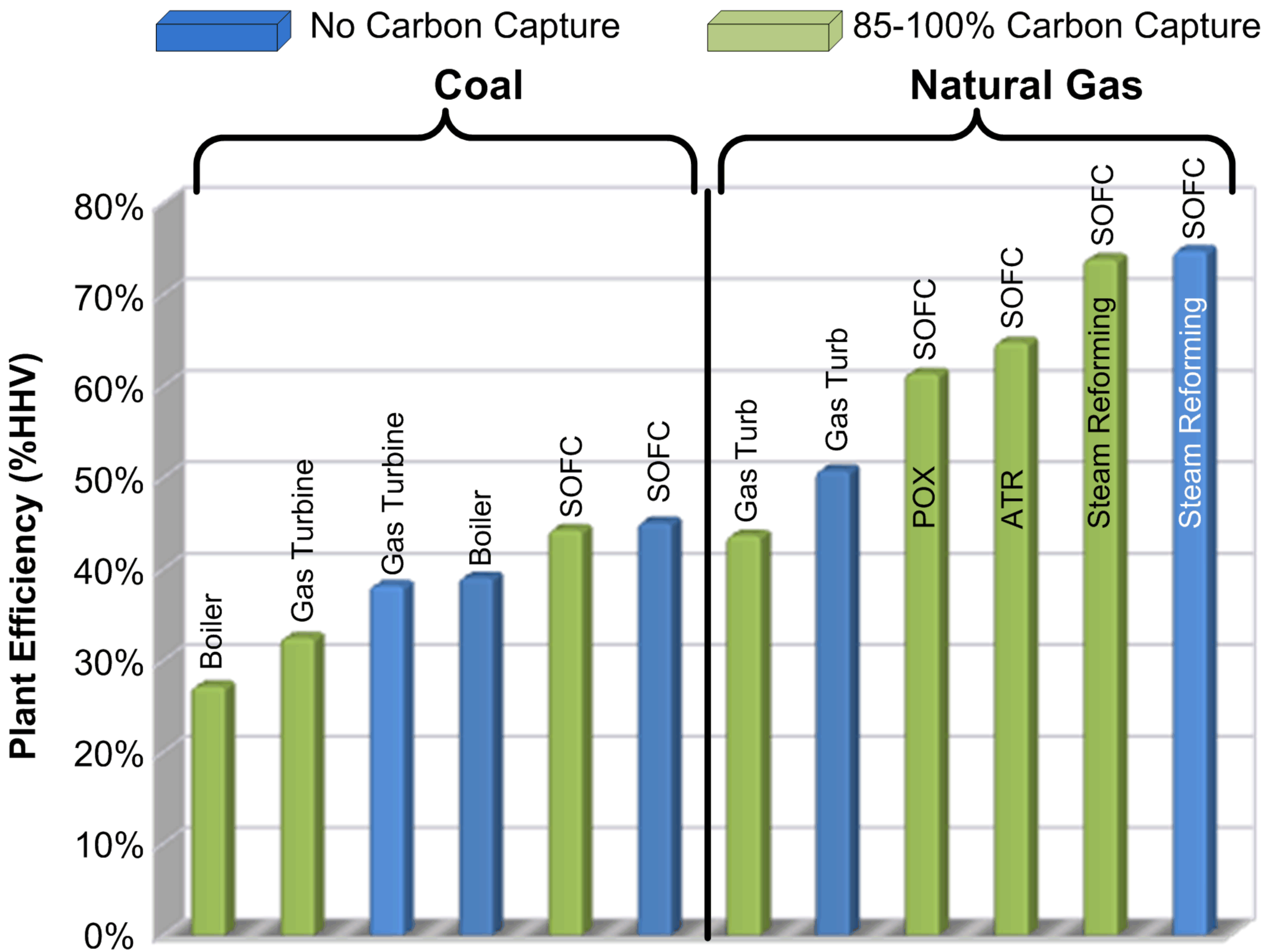
Sources: Adams, Nease, Tucker, & Barton. *Ind Eng Chem Res*. (2013) DOI:10.1021/ie300996r

1st and 2nd Generation Superstructure



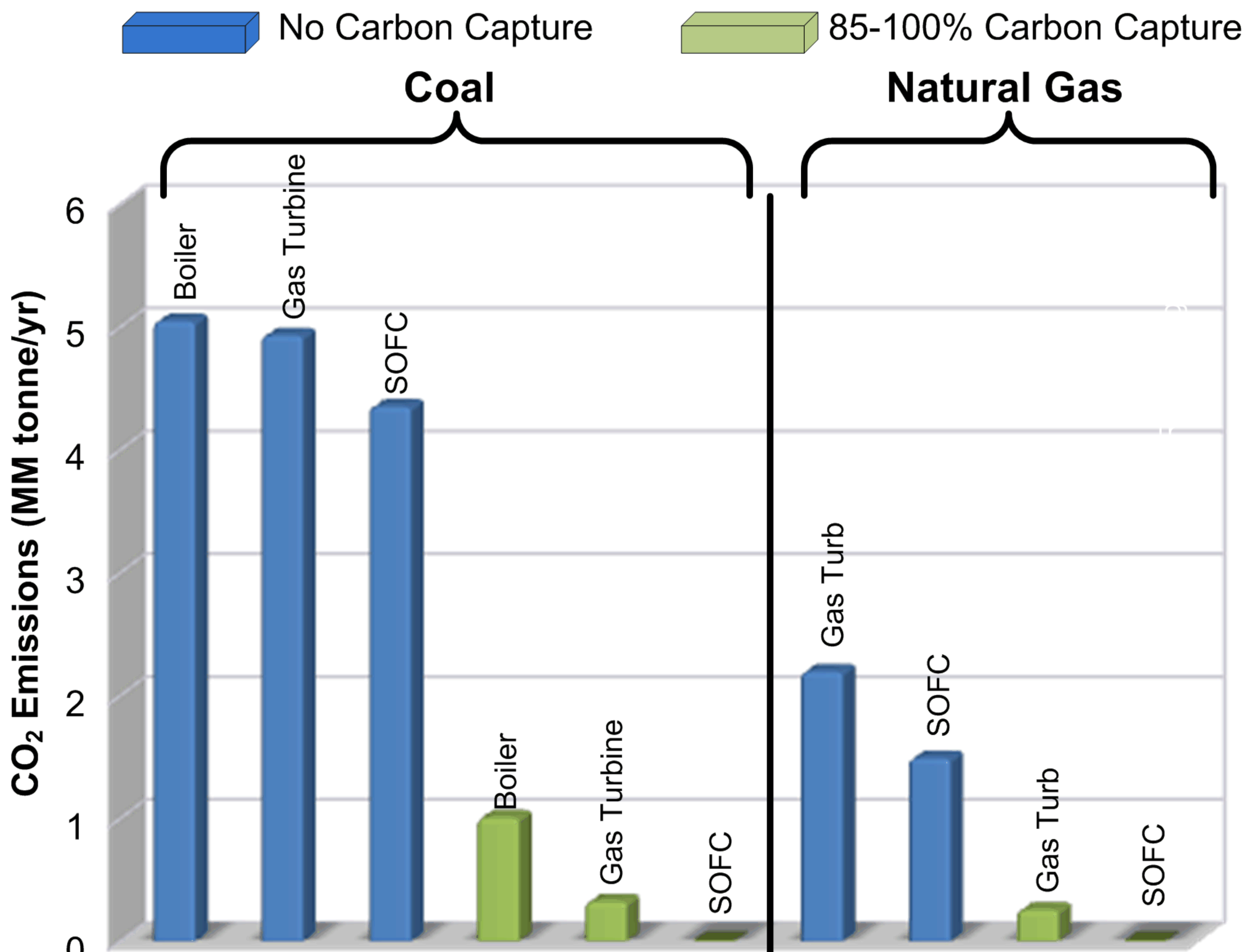
Sources: Adams, Nease, Tucker, & Barton. *Ind Eng Chem Res*. (2013) DOI:10.1021/ie300996r

Efficiencies



Sources: Adams & Barton. J Power Sources (2010).
Adams & Barton, AIChE J (2010)

CO_2 Emissions

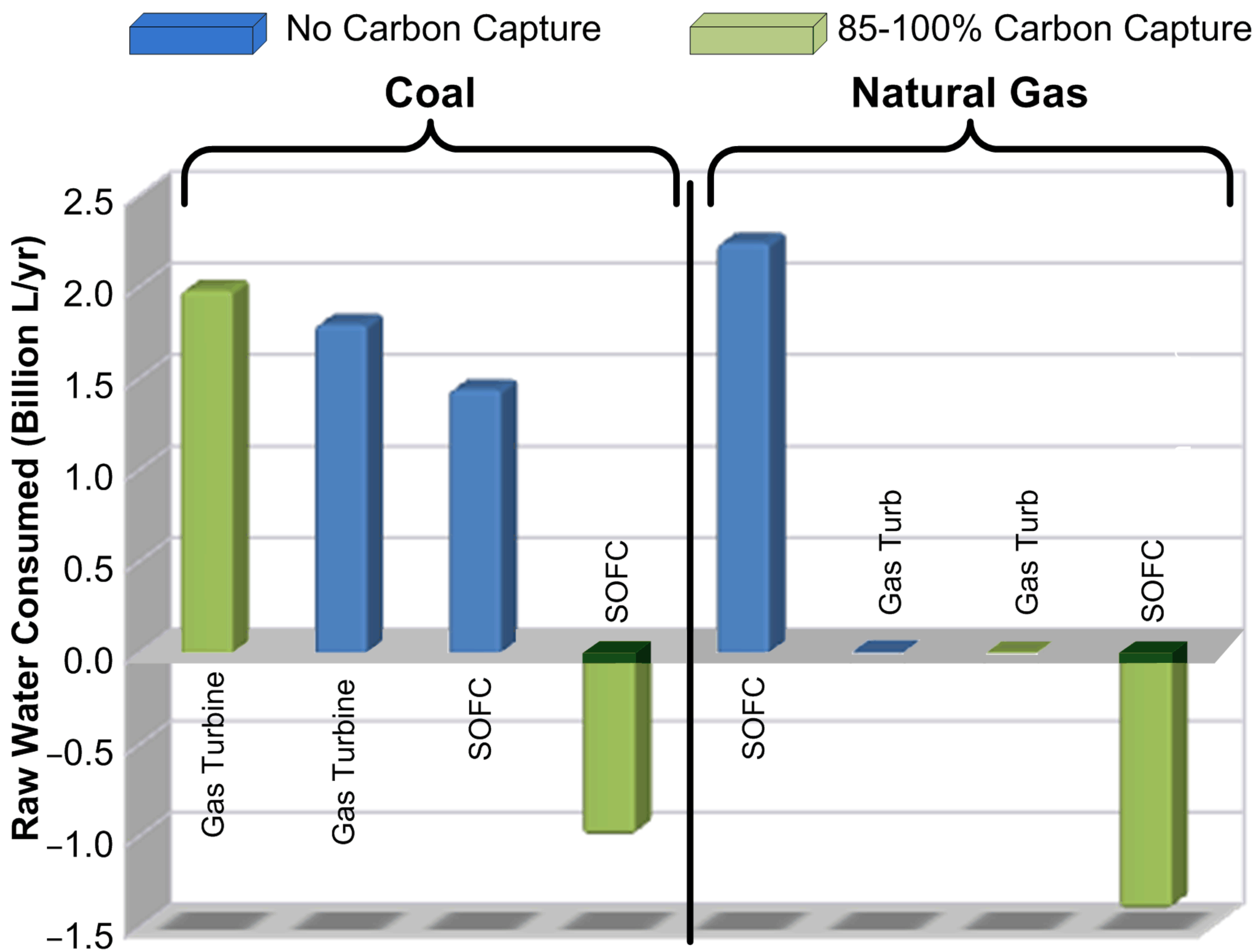


700MW Net Output

All NG-SOFC plants use steam reforming

Sources: Adams & Barton. J Power Sources (2010).
Adams & Barton, AIChE J (2010)

Water Consumption



700MW Net Output

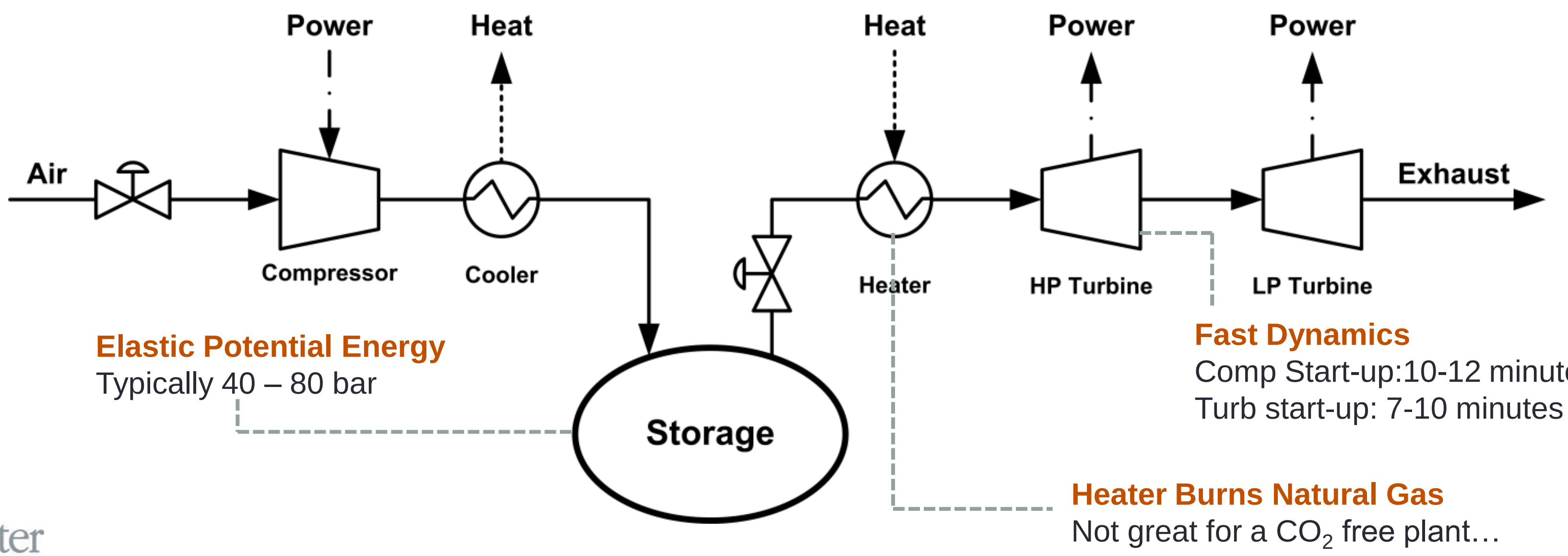
All NG-SOFC plants use steam reforming

Dry cooling used (no water losses from cooling)

Sources: Adams & Barton. J Power Sources (2010).
Adams & Barton, AIChE J (2010)

Compressed Air Energy Storage

- CAES: an intermittent source or sink
  - Consumes power to compress and store air as elastic potential energy, which may be released as needed
- Two CAES plants already operational
  - Alabama Electric Co (110 MW)
  - E.N. Kraftwerke [8] (290 MW)
  - Apex Energy (317 MW in 2014)
  - Chamisa Energy (270 MW, planned)



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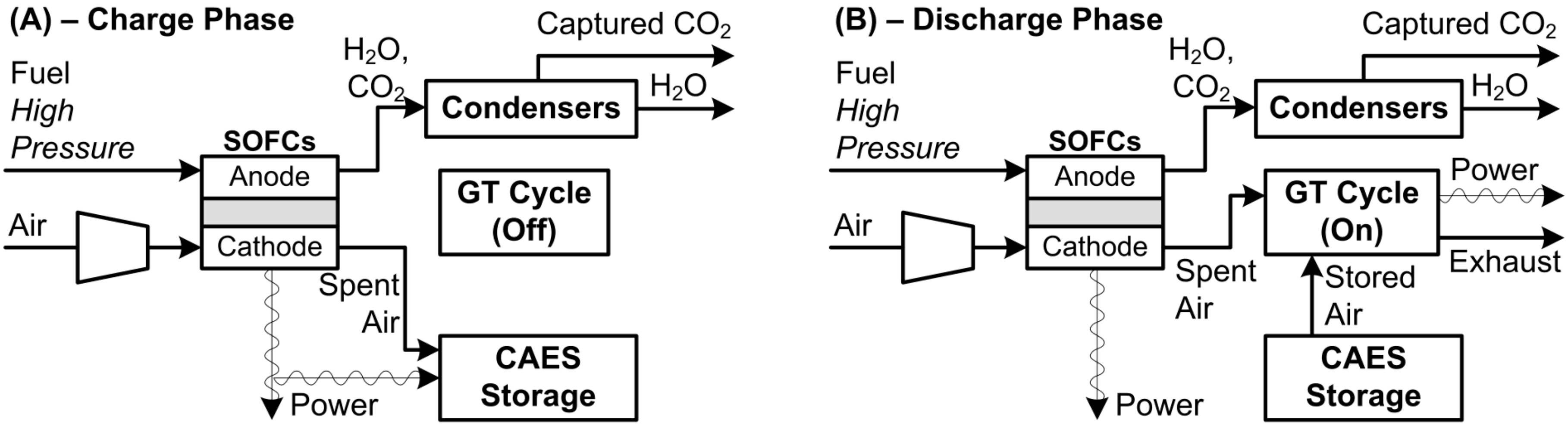
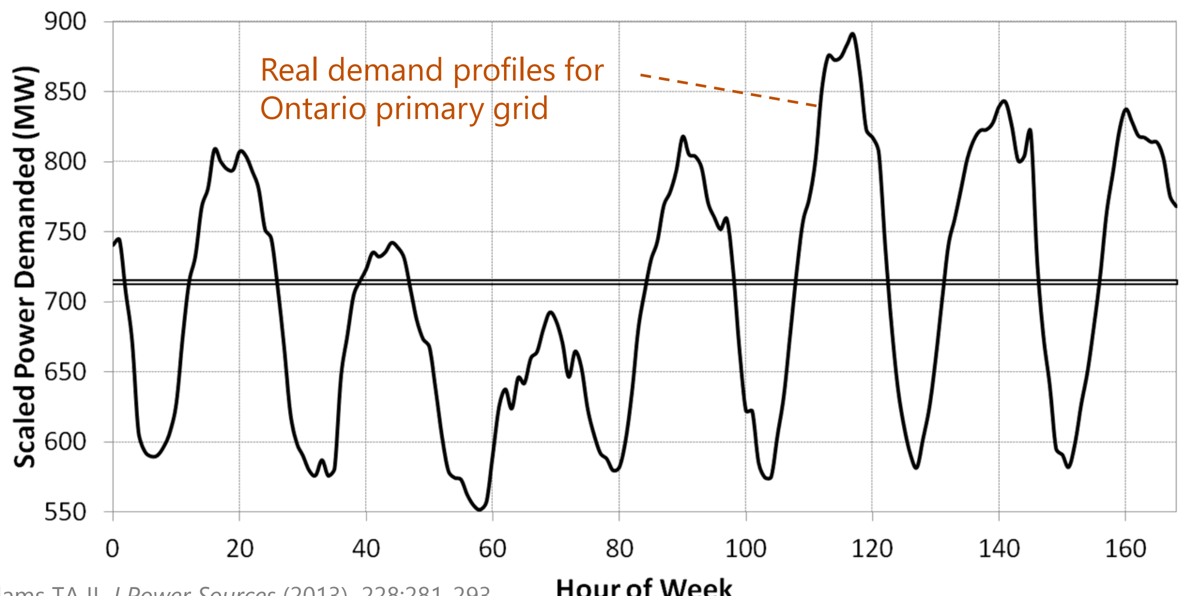
Sources: Nease J, Adams TA. J Power Sources, 228:281-293 (2013)

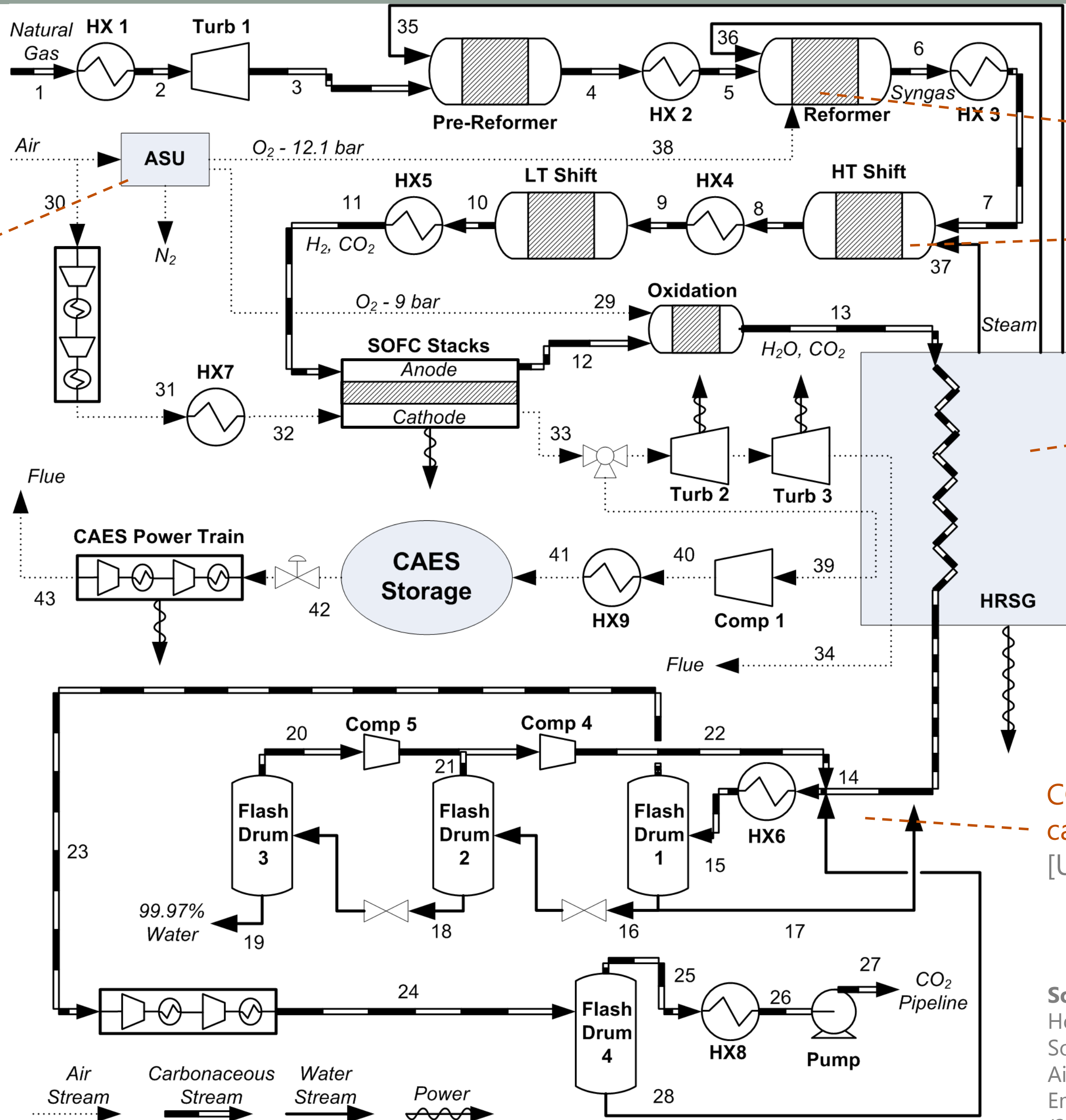
SOFC / CAES Integrated Systems





Sources: Nease J, Adams TA II. *J Power Sources* (2013). 228:281-293
Adams TA II, Nease J, Tucker D, & Barton PI. *Ind Eng Chem Res*. (2013) 52:3089-3111

System Details



Gas reforming steps are heat-integrated with SOFCs (planar design)

Small "coldbox" needed for fuel completion

WGS is an optional step (we found it better to use)

Complete plant heat integrations considered

CO_2 capture system uses flash cascade for efficient capture [US Patent 8,500,868 (2013)]

Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

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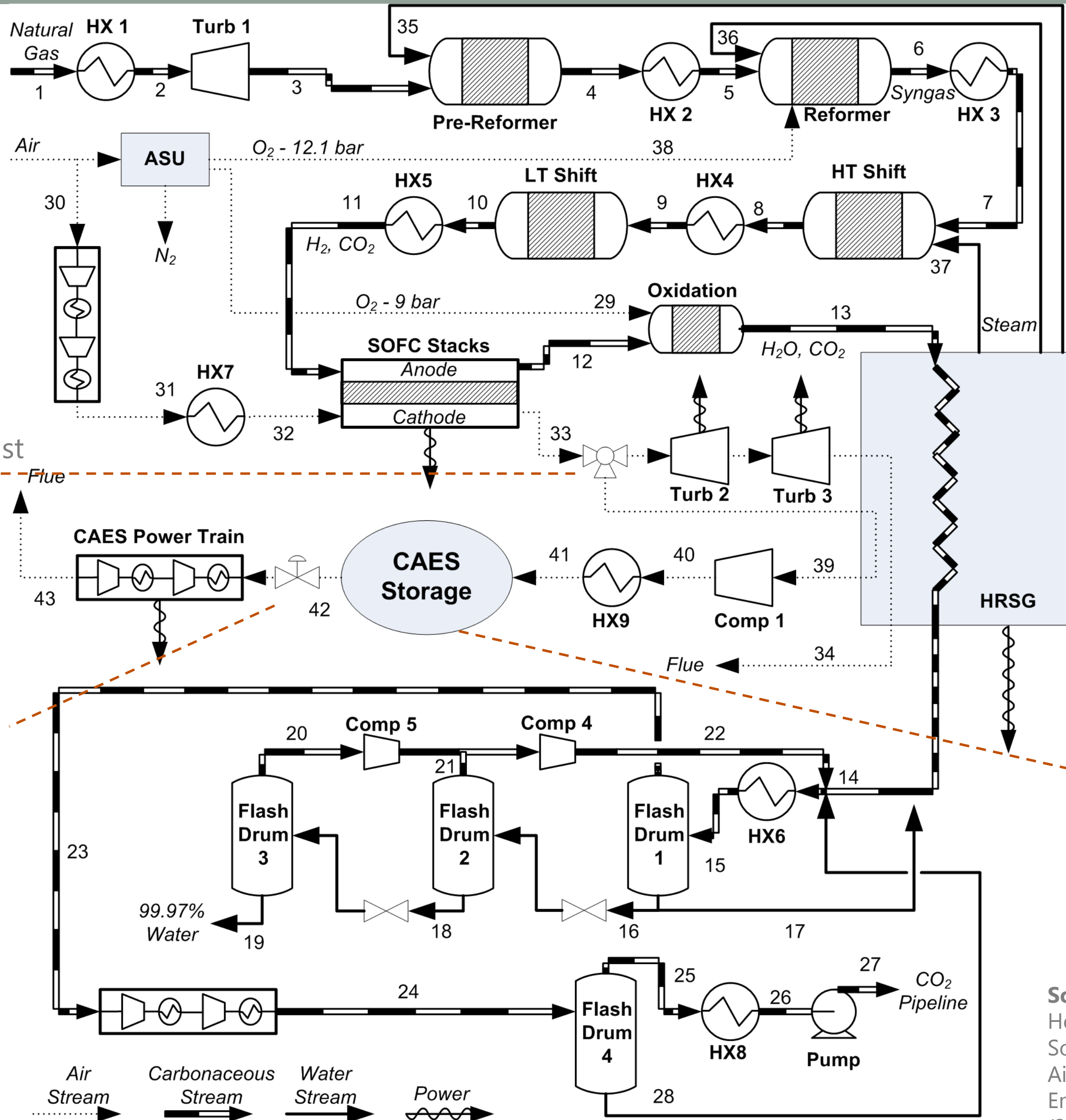
Optimal Performance Strategy



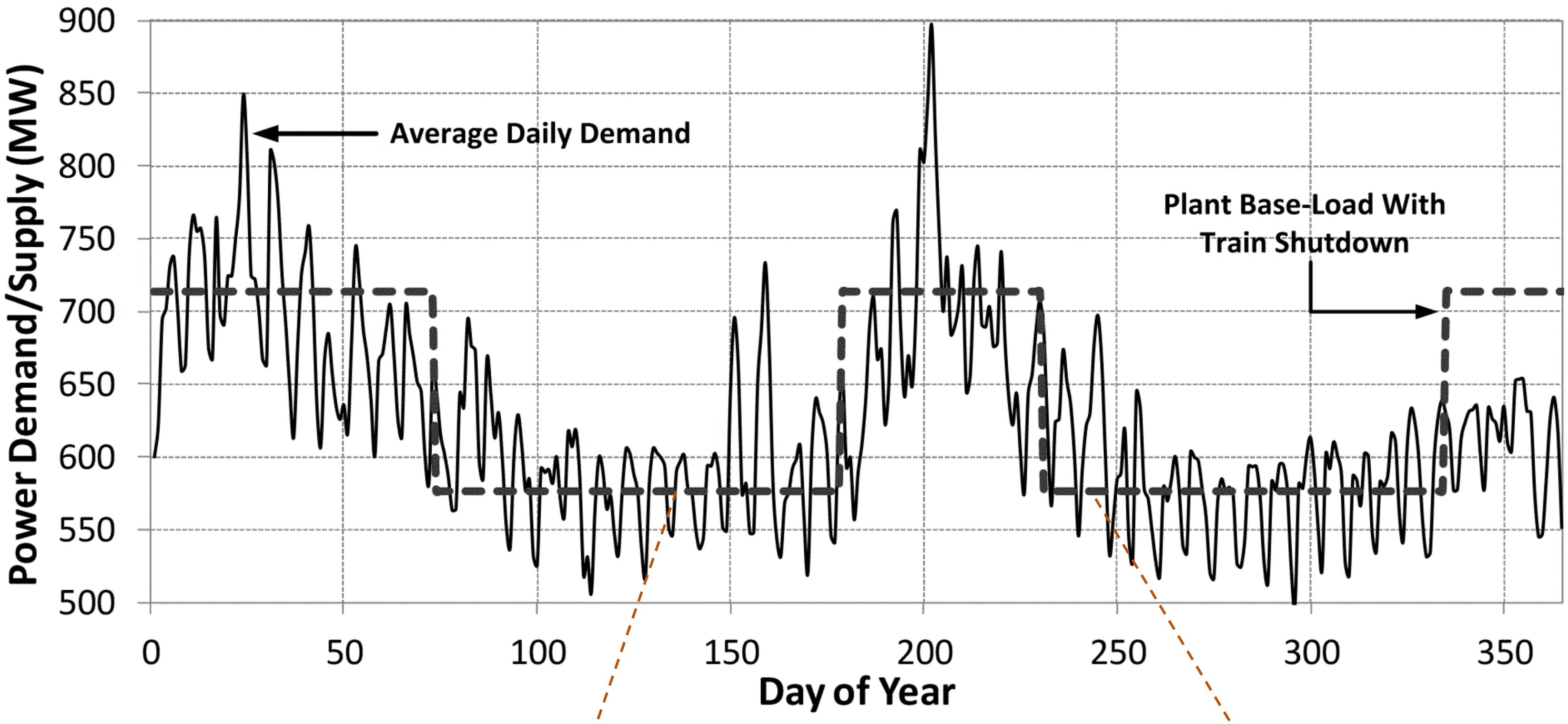
Manipulated: % of Cathode Exhaust diverted to CAES

Manipulated: Air Release Valve % opening

Storage Pressure: Major impact on downstream power generated

Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Note: Seasonal Variability



1 of 6 SOFC Modules turned off Each Spring/Fall
Each gets 3 month break for repairs every 3 years
Fits the real demand curve quite well.

For our study, we pre-selected the maintenance schedule ahead of time.

Sources: Nease J, Adams TA II. Coal-based systems for peaking power with 100% CO2 capture with solid oxide fuel cells and compressed air energy storage. J Power Sources 251:92-107 (2014)

Rolling Horizon Optimization

- How do we best use the storage capability in real time in order to match real market demand?
  - We have access to excellent predictive models for demand
  - We have access to less excellent predictive models for price
  - We have access to our own models of plant performance

Problem Definition

How can rolling horizon optimization be used to achieve better system performance? Two approaches:

OBJECTIVE 1: Load Matching

$$\min_{\delta_{i,t},\, F_{i,t}} SSE_i = \sum_{t=1}^{N} \left(E_{i,t} - D_{i,t}\right)^2$$

Decision variables: The hourly schedule of how much we store or withdraw from the cavern for the next N hours

Power Produced
Hourly schedule for next N hours

Predicted Power Demand
Hourly schedule for next N hours

OBJECTIVE 2: Maximize Profit

$$\max_{\delta_{i,t},\, F_{i,t}} \mathcal{R}_i = \sum_{t=1}^{N} \left(E_{i,t}\omega_{i,t}\right),$$

Predicted Market Price
Hourly schedule for next N hours

CONSTRAINTS

- Model equations for the system
- Pressure limits for the cavern ($40\ \boldsymbol{bar} \leq P_{i,t} \leq 72\ \boldsymbol{bar}$)

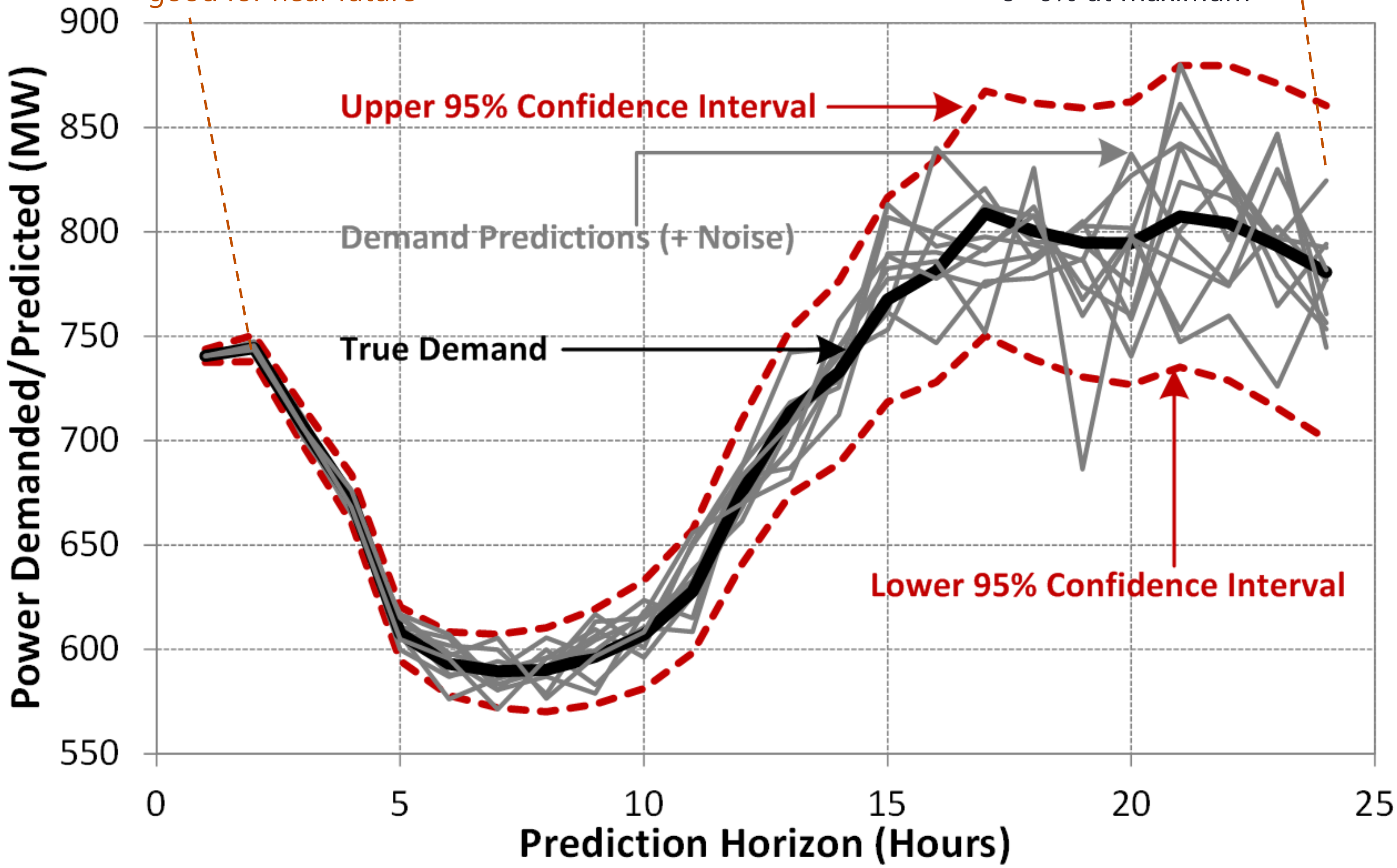
Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Our Approach for Predictions

Problem: Only actual demands and prices are kept
Have to create our own predictive curves to test the RTO

Predictions are very good for near future

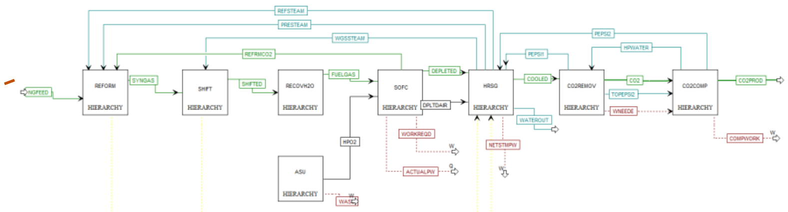
Statistical data available show error σ=6% at maximum

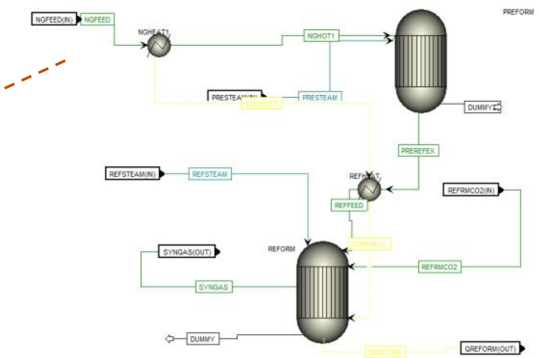


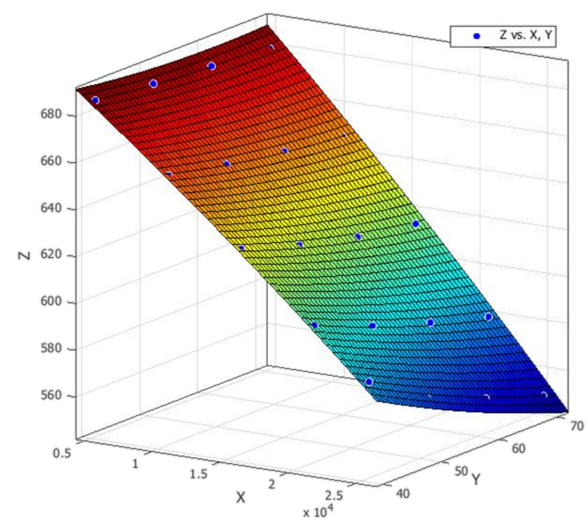
Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Step 1: Create Reduced Models

- Detailed models in Aspen Plus
  - Steady-state parts need only 1 model
  - Dynamic parts modeled with pseudo-steady-state approach:
    - 1000s of Aspen Plus models for different potential combinations of cavern inlet/outlet flows and cavern pressure.
    - Reduced model for the dynamic system created by linear-in-the-parameters regression (polynomial basis functions)
  - Cavern behaviour modelled separately using PSRK equation of state







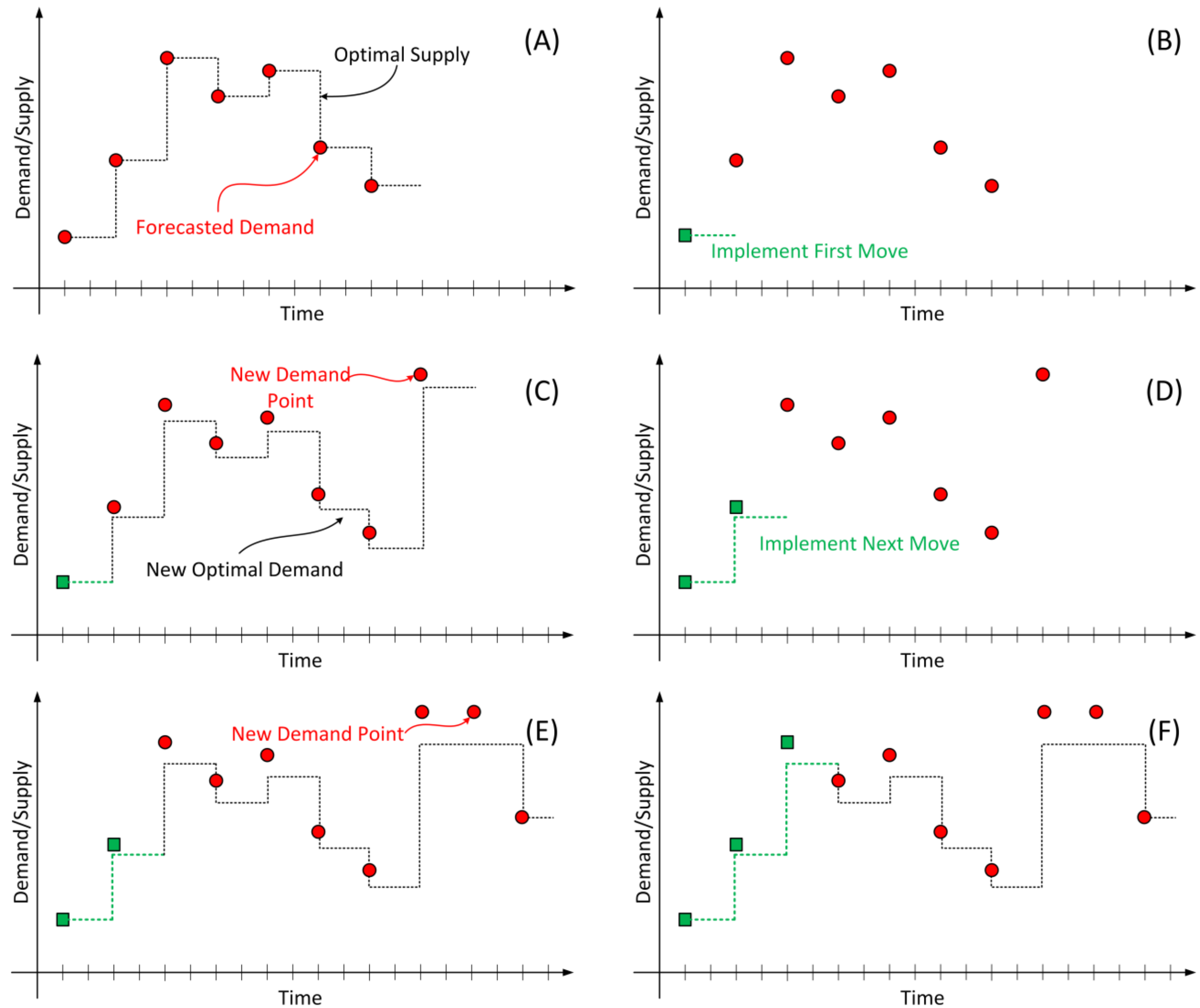
Step 2: Optimize in GAMS

The optimization and reduced models are implemented in GAMS

Solved as a series of 8760 problems

Once each hour, for the entire year

(Only the first timestep result is actually implemented from reach result)



Challenges and Methods

- Need good initial guesses
  - avoid the locally optimal trivial solution: "don't use the CAES"
  - The results from the previous problem used as initial guesses for the next problem.
- Per each of 8760 problems:
  - 217 variables (including 143 in nonlinear terms, 24 discrete)
  - 169 constraints
  - 1.9 million total variables solved per "yearlong run"
- DICOPT → Finds global optimum about 98% of problems
  - → If DICOPT fails, use BONMIN
  - → If BONMIN fails, use KNITRO
  - → BARON was terrible, slower than real time
  - Global optimal found in 99.7% of cases eventually.
  - Fast enough to use in real time.

Objective 1: Try to Match Profiles

Matching is quite excellent in general, even with uncertain predictions accounted for

Occasionally we underproduce a bit, but:

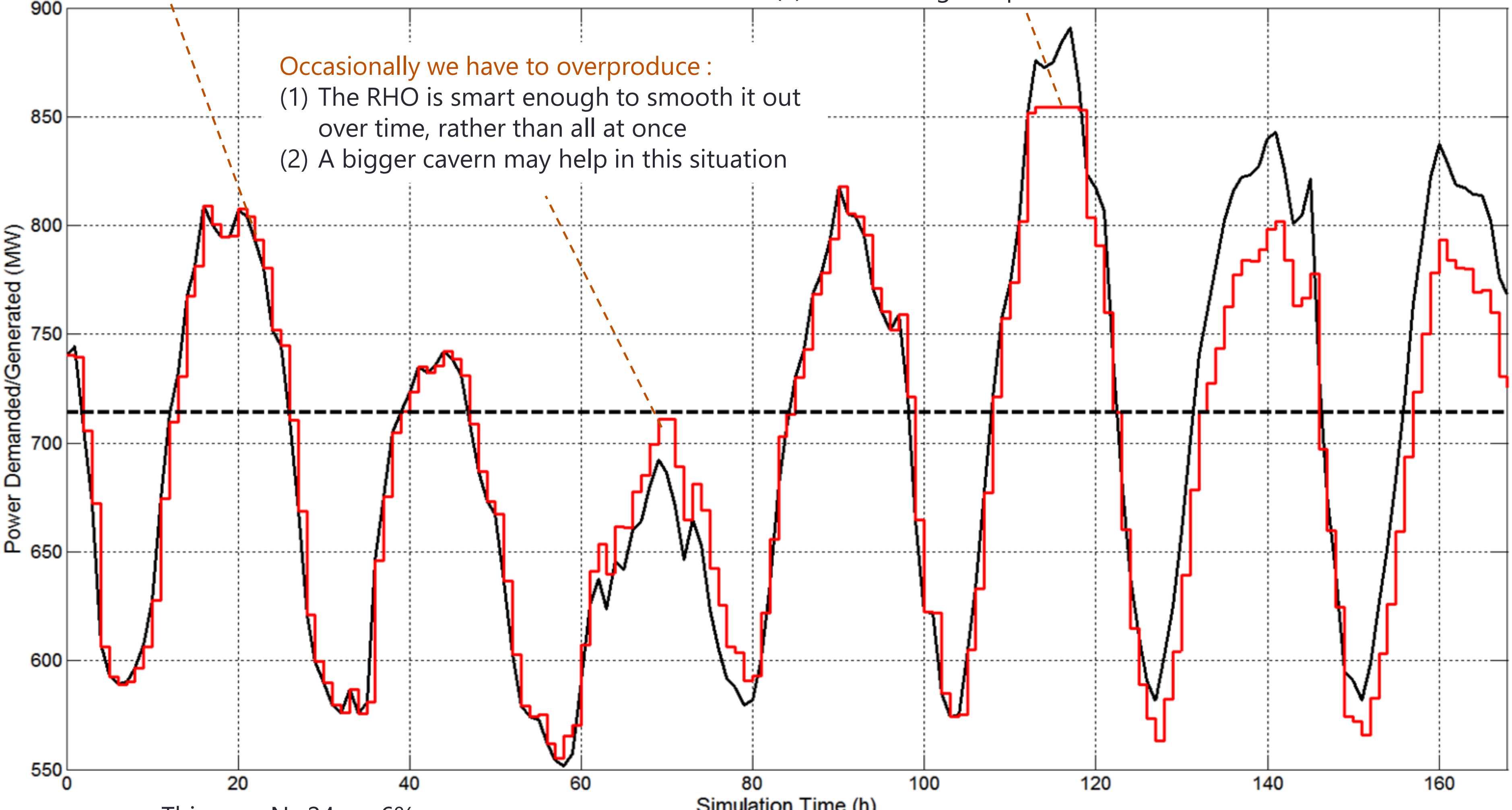
(1) That's either less NG firing that's needed, or:

(2) More storage helps too. So does more fuel cells.

Occasionally we have to overproduce :

(1) The RHO is smart enough to smooth it out over time, rather than all at once

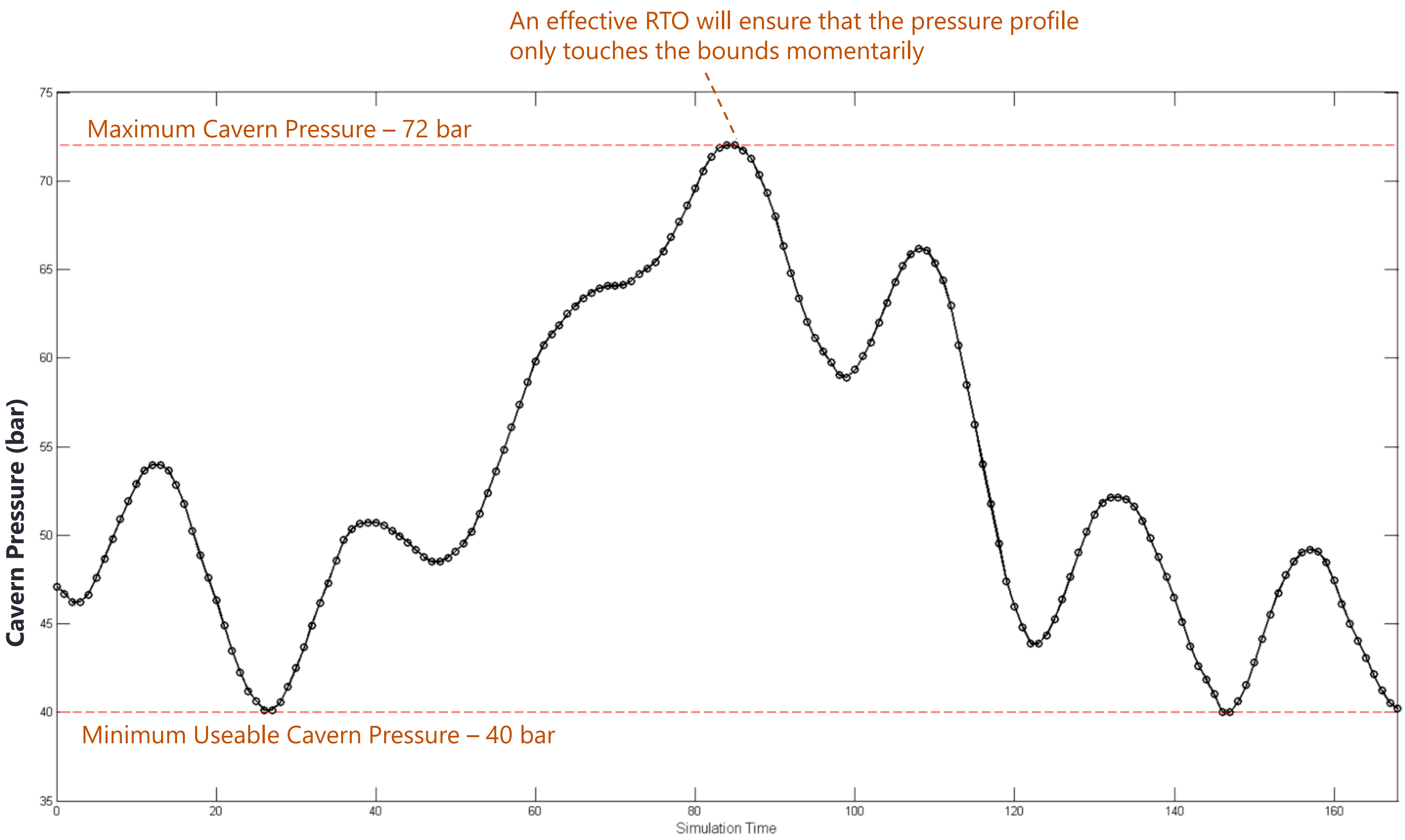
(2) A bigger cavern may help in this situation



This uses N=24, σ=6% error

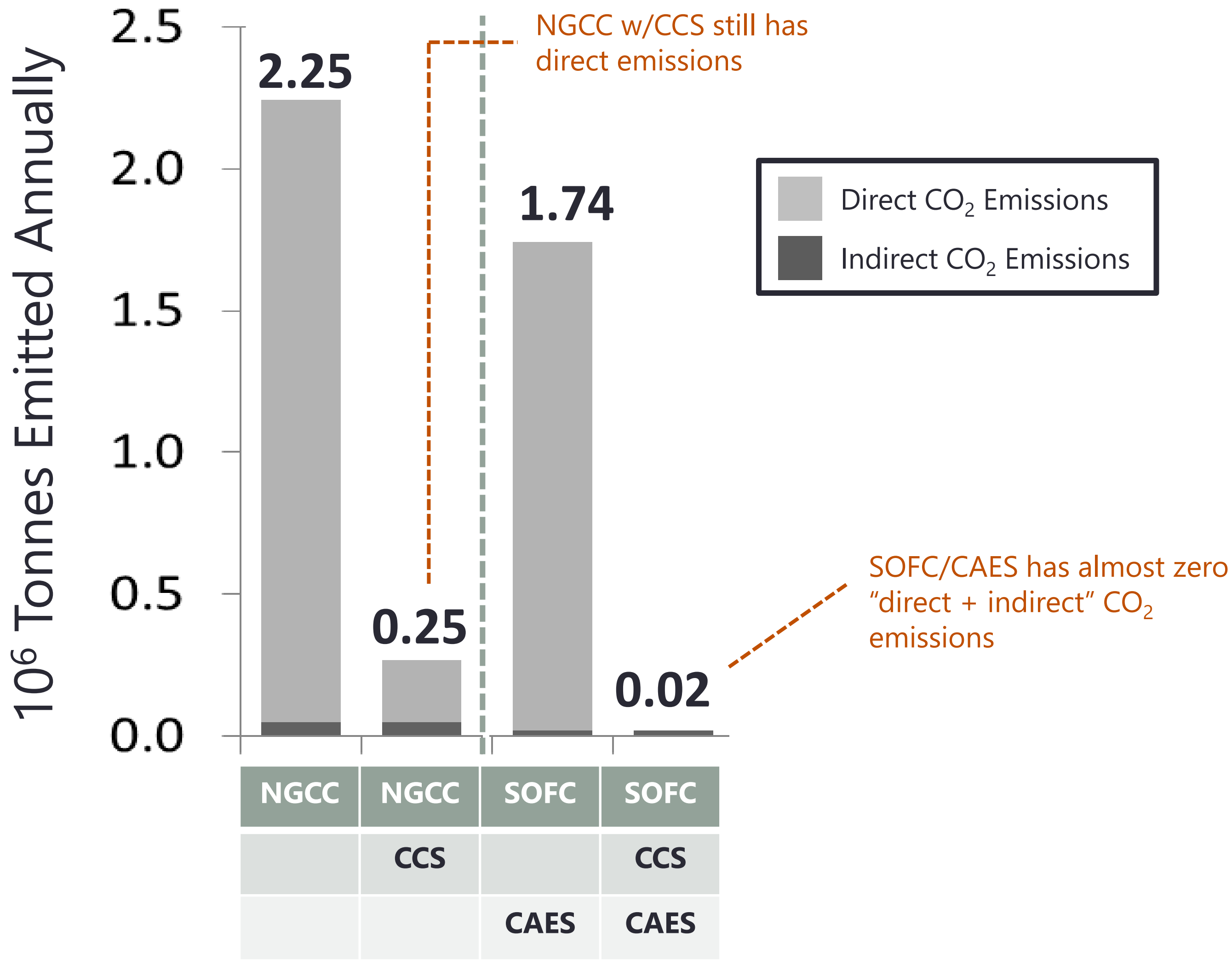
Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Cavern Pressures



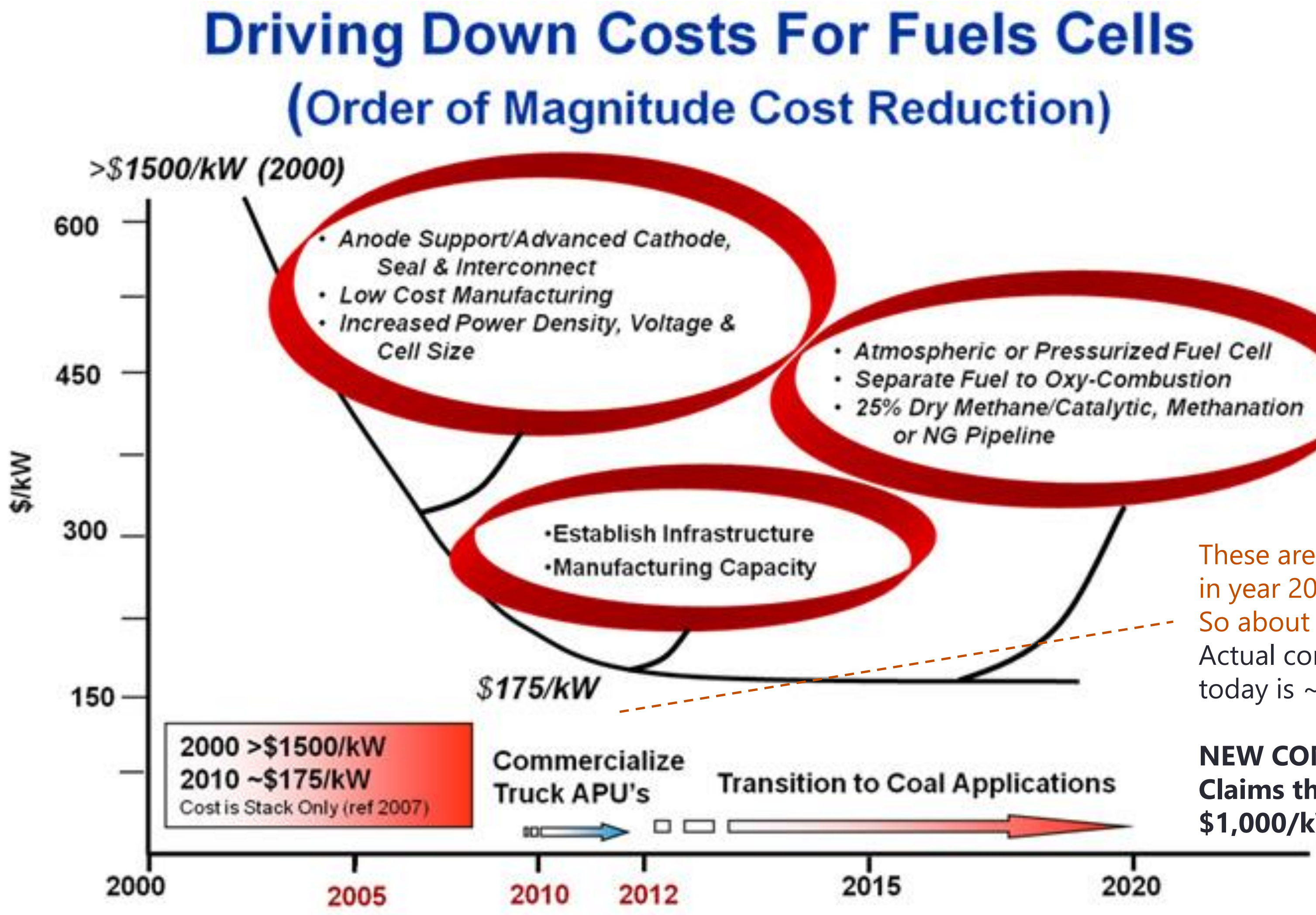
Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

CO_2 Emissions



Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Costs

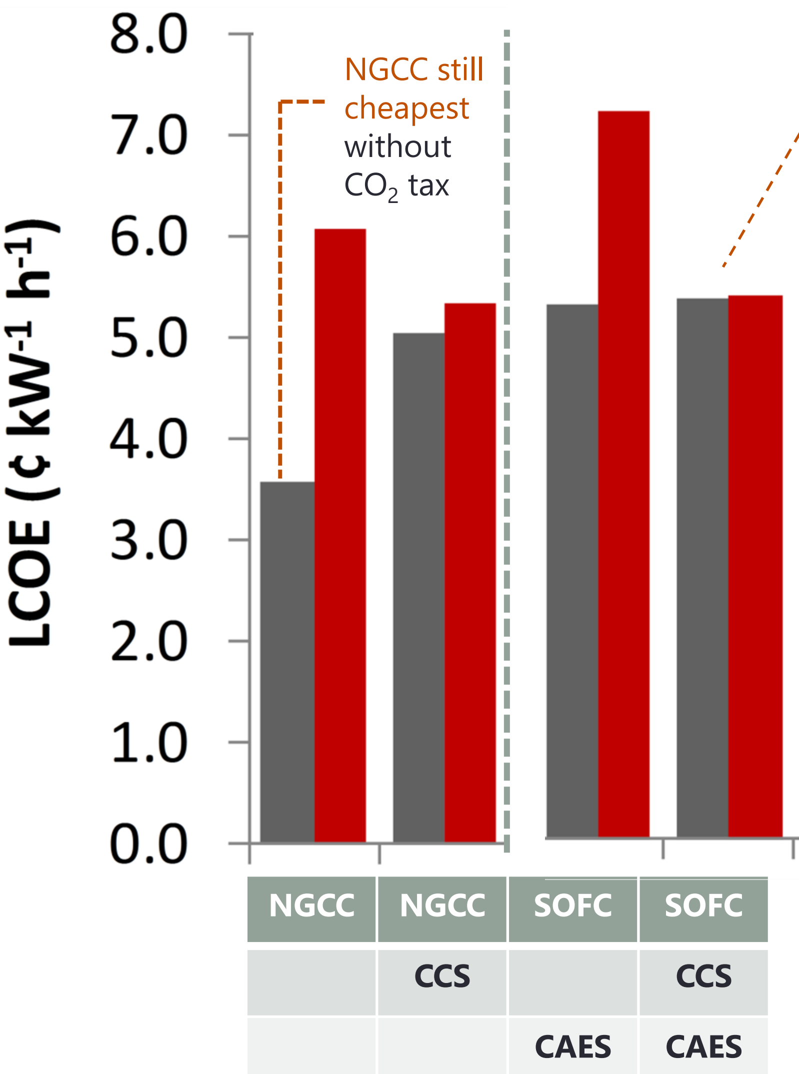


These are for mature plants in year 2000 dollars.
So about $250/kW today.
Actual commercial price today is ~$8,000/kW.

NEW COMPANY (ReDox) Claims they will make $1,000/kW <u>this year.</u>

Sources: NETL / SECA Homepage. http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/

Levelized Costs of Electricity



The cost of adding CCS is very small

The SOFC/CAES system has the same LCOE as NGCC even with today's low natural gas prices when CO_2 taxes are implemented, but this has load following capabilities and zero emissions!

It also consumes less fuel and has less CO_2 to sequester in this first place.

Costs here are for base case and assume $1000/kW installed SOFCs
(**Conservative**: 4x the expected mature cost tech)

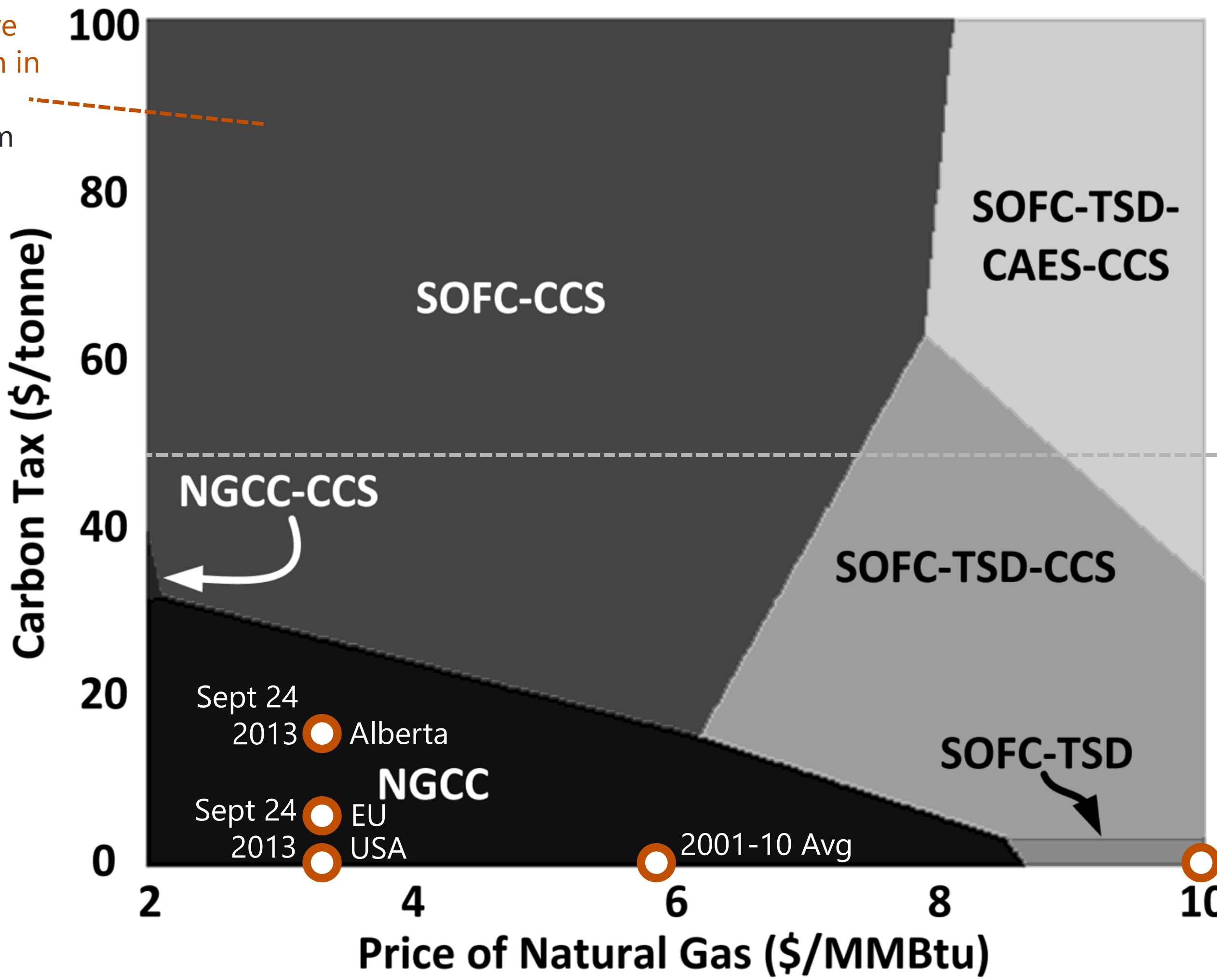
CO_2 is considered a liability… no EOR revenues considered.

Sources: Nease J, Adams TA. J Power Sources, 228:281-293 (2013)

Market Impacts

Lowest LCOE depending on fuel price and CO_2 tax

CAES more expensive by 0.08 – 0.3 ¢/kW-h in this area
(Small price premium for flexibility)



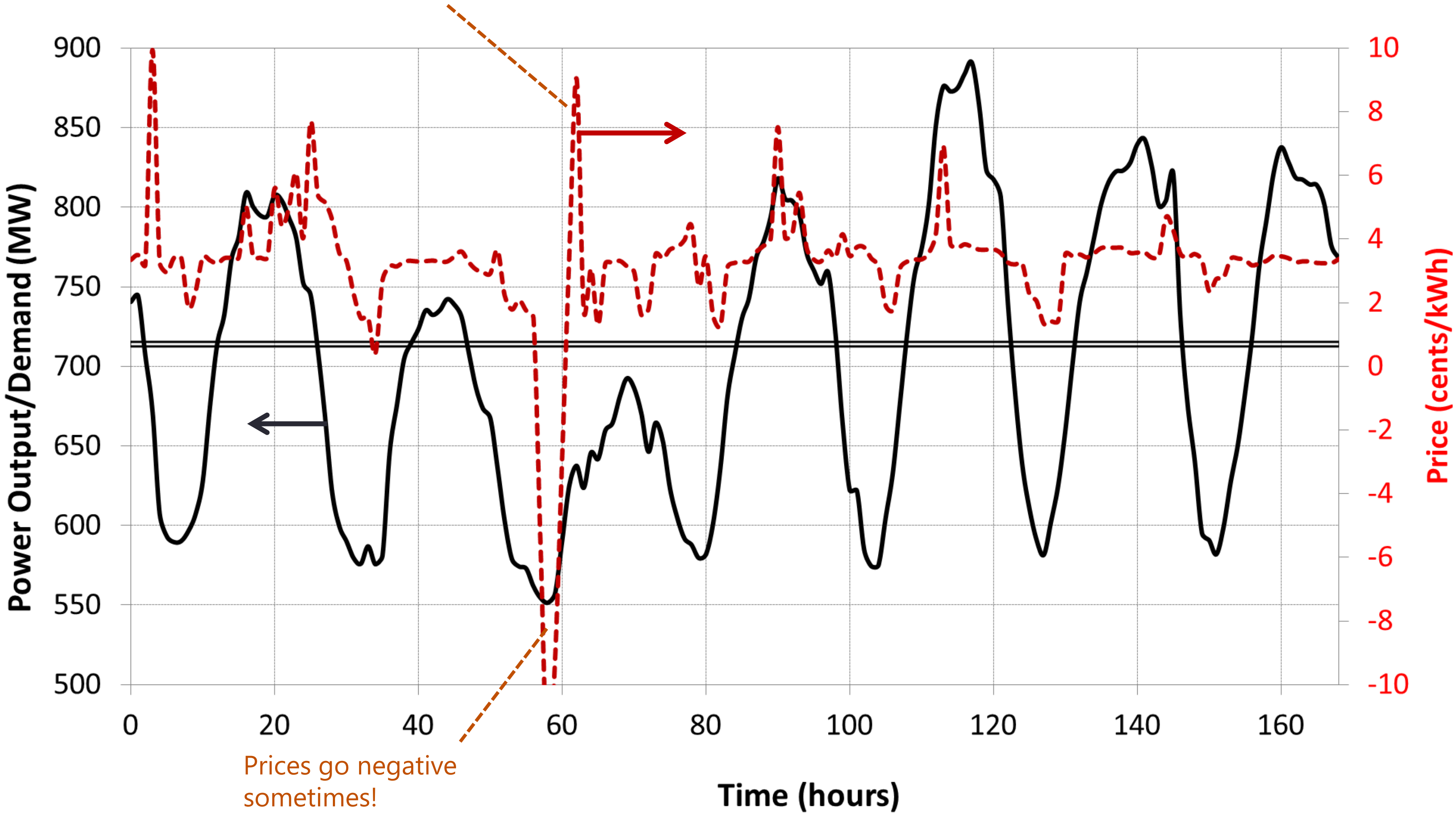
"Expected" free market CO_2 price for any regulation with teeth: $40-60

Mid 2008
(Peak $13-15)

Sources: Nease J, Adams TA. J Power Sources, 228:281-293 (2013)
Prices from Offsetters.ca & Bloomberg.com

Objective 2: Maximize Profits

Price is only weakly correlated with demand
Much higher prediction error



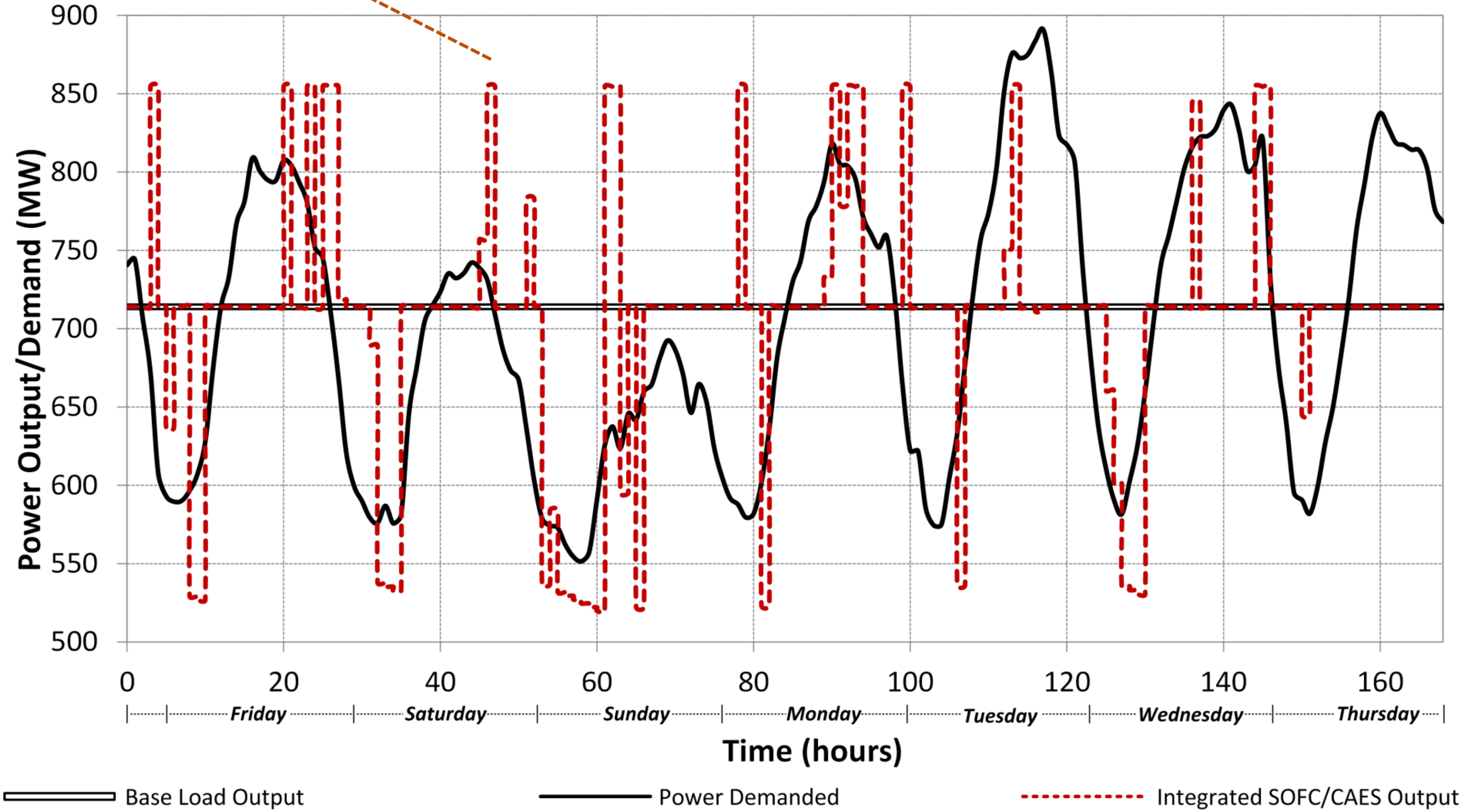
Prices go negative sometimes!

Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Objective 2: Maximize Profits

Very weakly correlated with demand
Almost all sudden swings between store and release

Only about 4% revenue increase
Does not justify the cost of building CAES for purely economic purposes.



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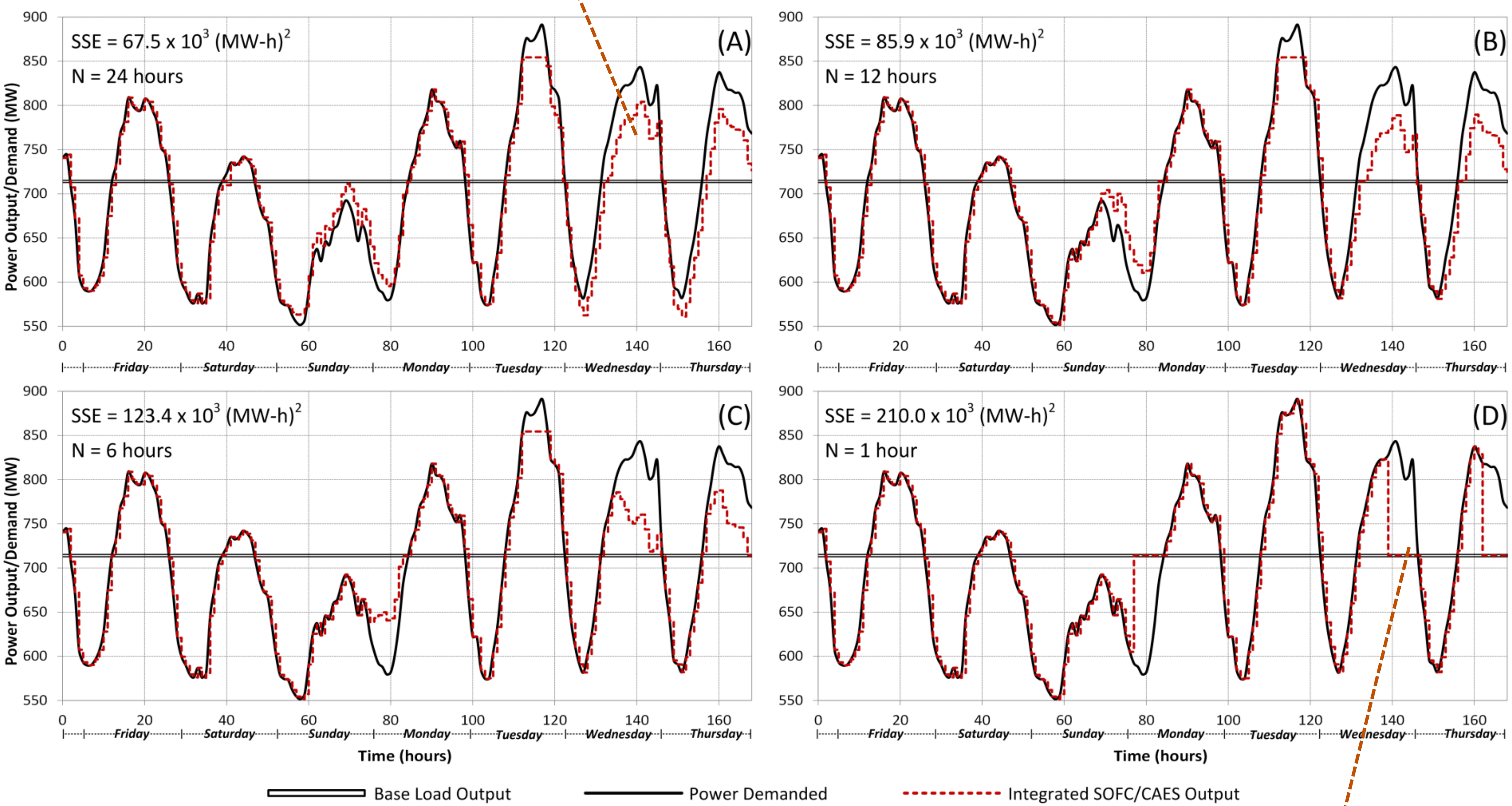
Source: Nease J, Adams TA II. Rolling-Horizon Optimization of Integrated Solid-Oxide Fuel Cell and Compressed Air Energy Storage Plant for Zero-Emissions Peaking Power. Submitted (2014)

Examples: Effect of Prediction Horizon

The bigger your prediction horizon
The smoother the curves

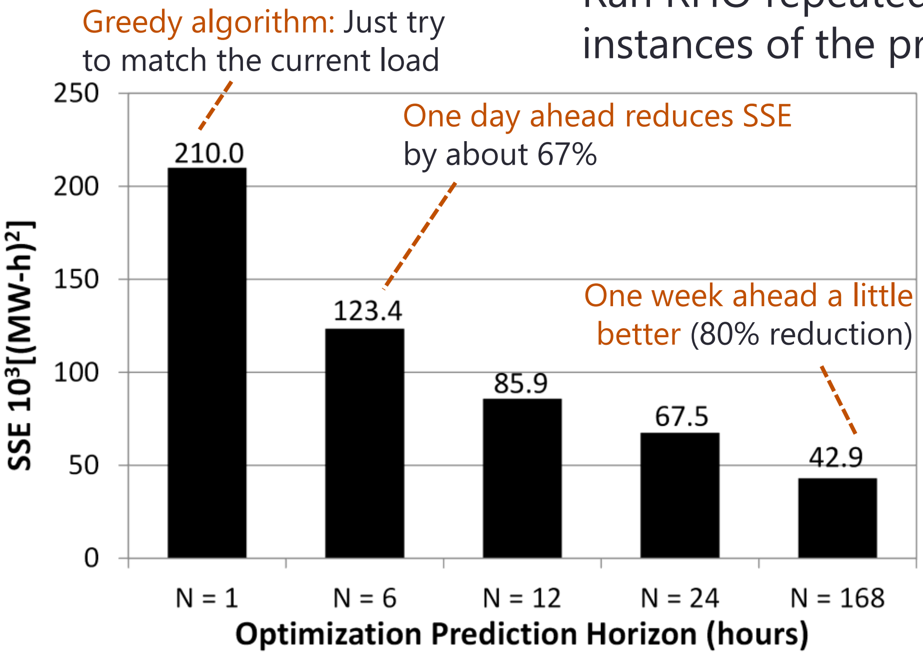


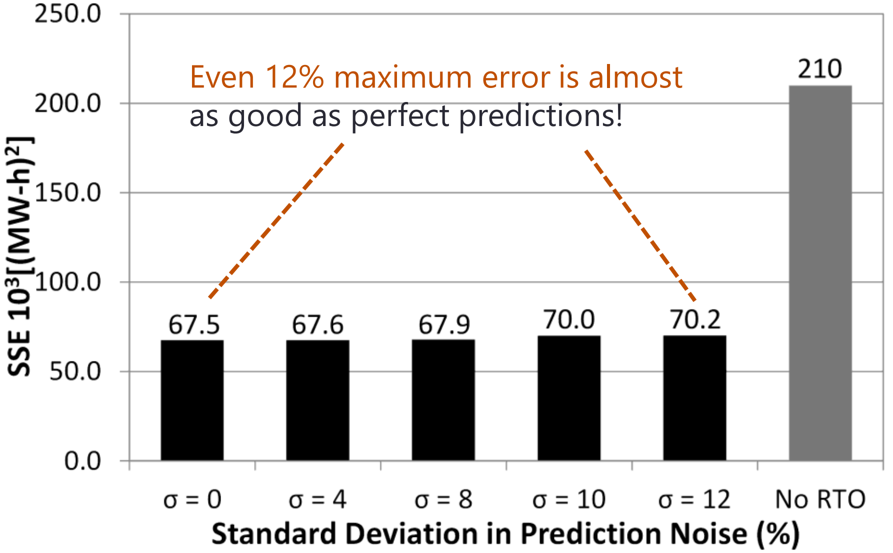
With no horizon, we experience sudden shutoffs due to lack of cavern pressure.

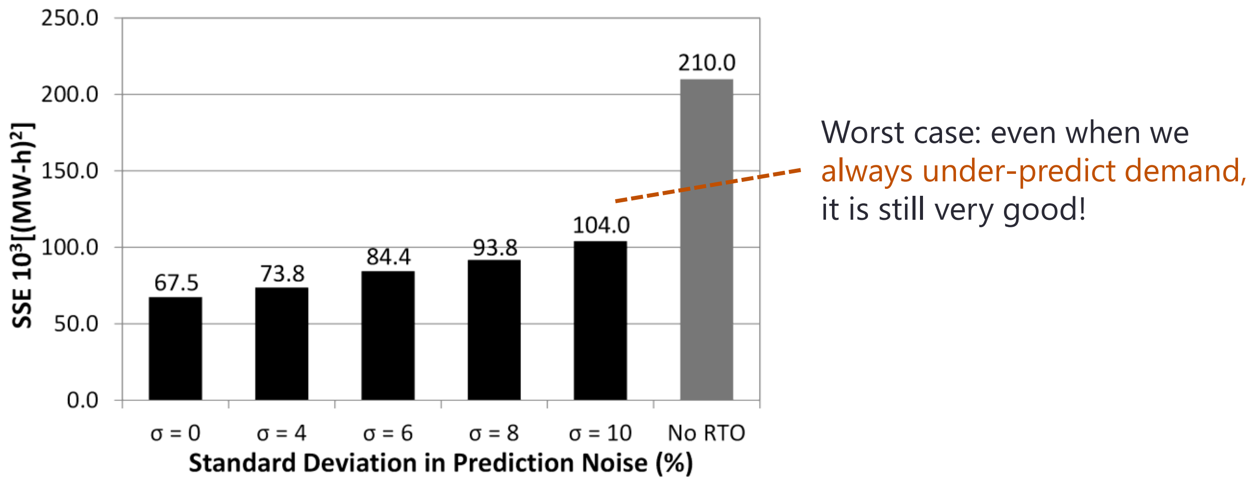
Source: Same as previous

Sensitivity Analysis

Monte Carlo Methods:
Ran RHO repeatedly for 1000s of different random instances of the prediction errors over an entire year







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Source: Same as previous

Is this actually better for the Earth?

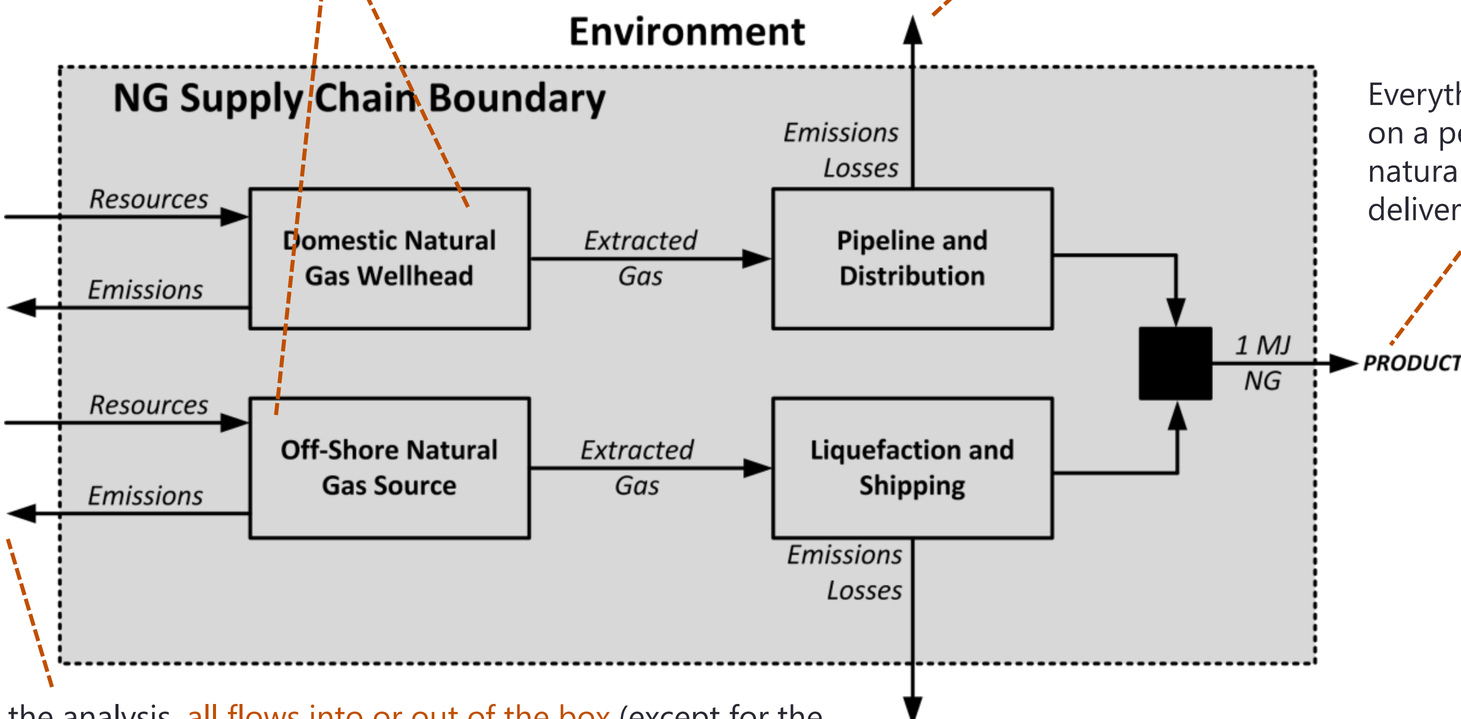
- So far, this looks great!
  - We can hugely reduce water consumption
  - Remove almost all CO_2 emissions from all power production,
  - We can load follow very effectively
  - We can do it all with only a small price premium!!!
- *But*:
  - Do we cause other kinds of problems instead?
  - What about the rest of the supply chain?
  - Is making SOFCs so bad that it counteracts all of the global warming benefits?
- So how do we know if is actually better for the Earth?
- Solution:
  - The ReCiPe Life Cycle Analysis methodology.

Step 1: Cradle-to-Grave Inventories

Determine how much comes in and out of your box for the entire supply chain. Simplified example for natural gas production:

Considered the US average mix of conventional, gas unconventional gas, shale gas, and LNG imports.

Methane leaks during transport a major source of global warming emissions.



Everything is done on a per MJ of natural gas delivered basis

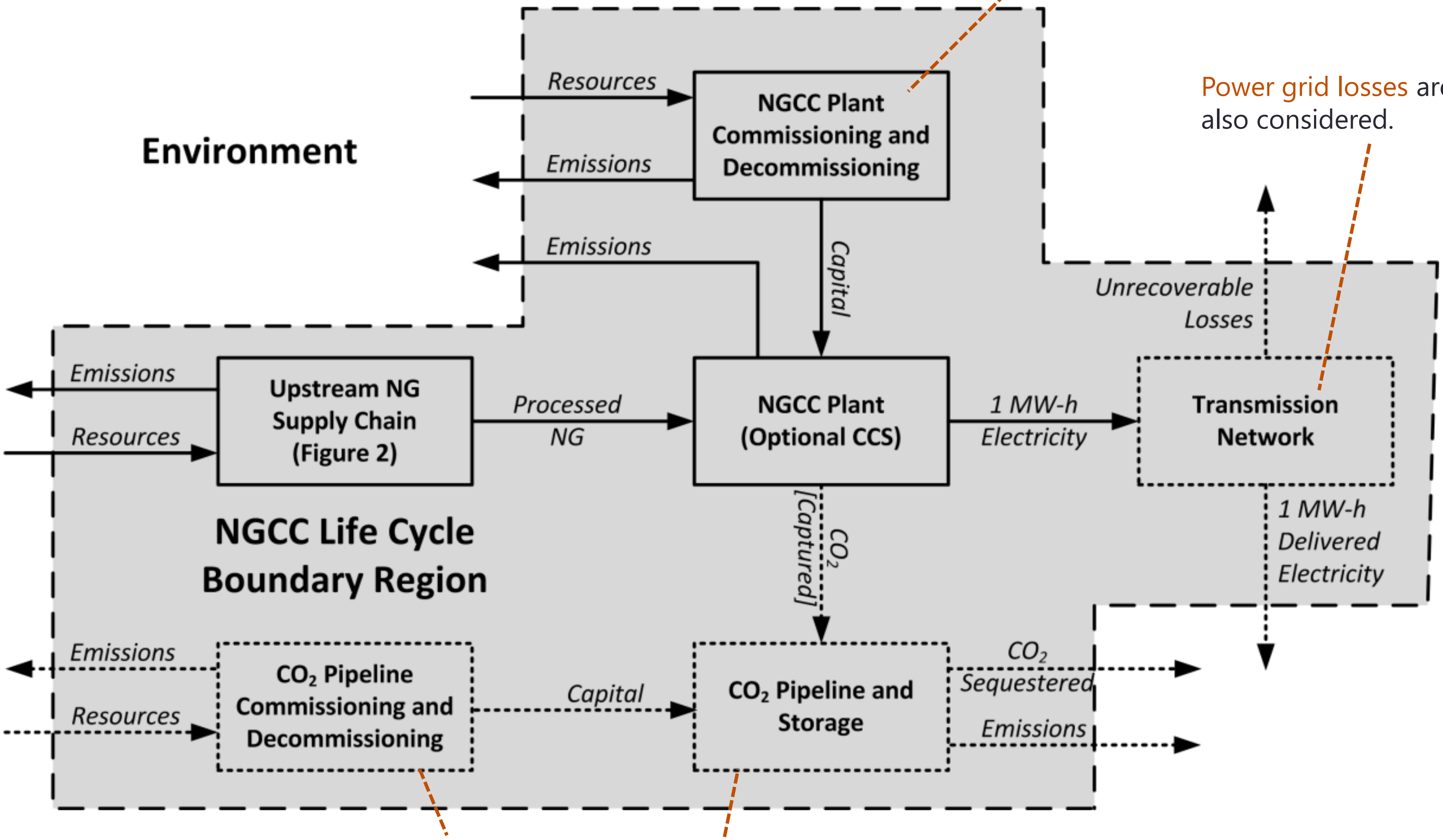
In the analysis, all flows into or out of the box (except for the final delivered electricity) are either direct emissions to the air, water, soil, or resource pool, or direct removals from the air, water, soil or resource pool.

Source: Nease J, Adams TA II. Life cycle analyses of bulk-scale solid oxide fuel cell power plants. (in preparation 2014)

Boundaries for NGCC

Construction and deconstruction of the facility is considered.

Power grid losses are also considered.

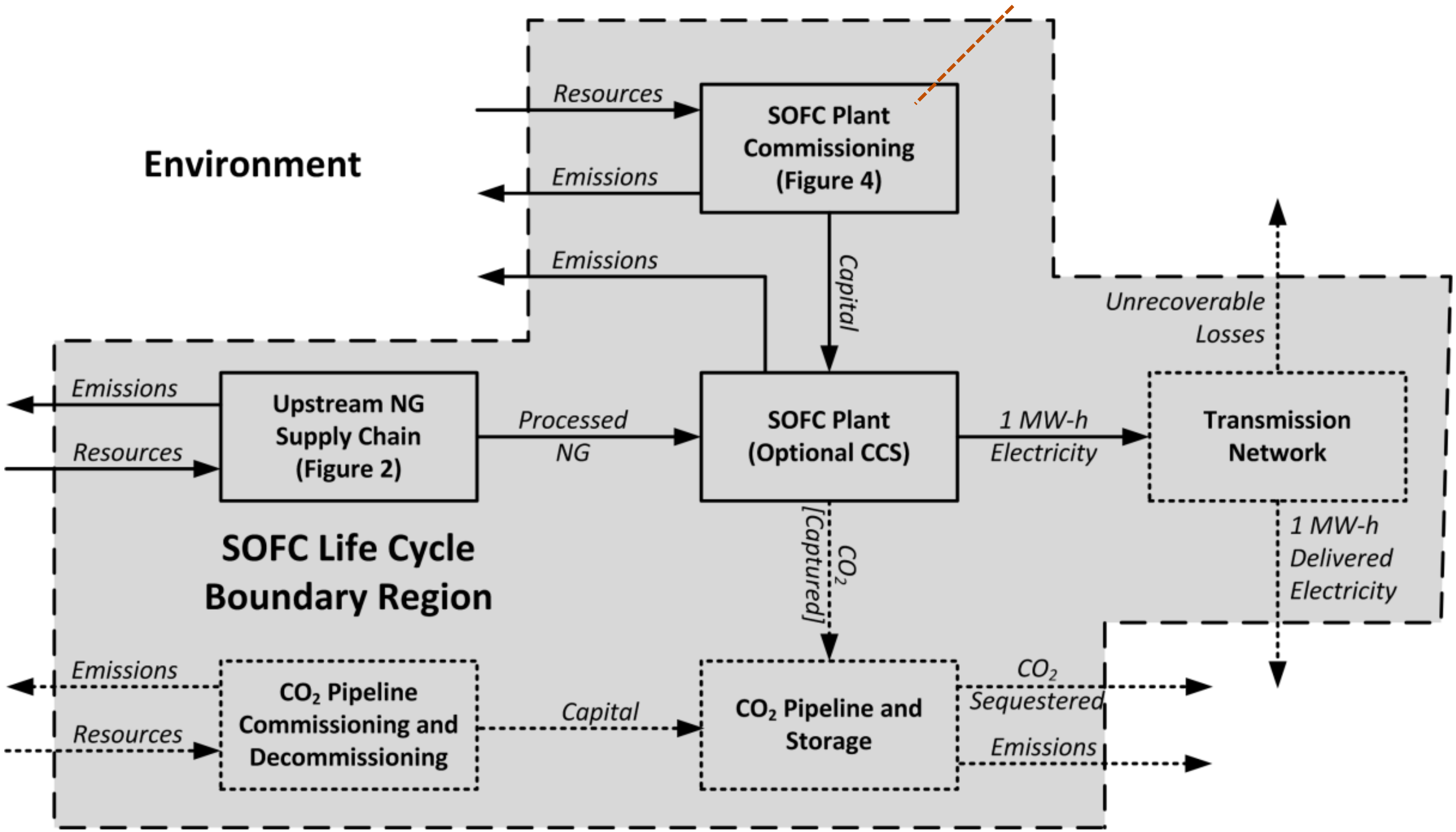


Optional CO_2 sequestration is considered.

Source: Nease J, Adams TA II. Life cycle analyses of bulk-scale solid oxide fuel cell power plants. (in preparation 2014)

Boundaries for SOFC

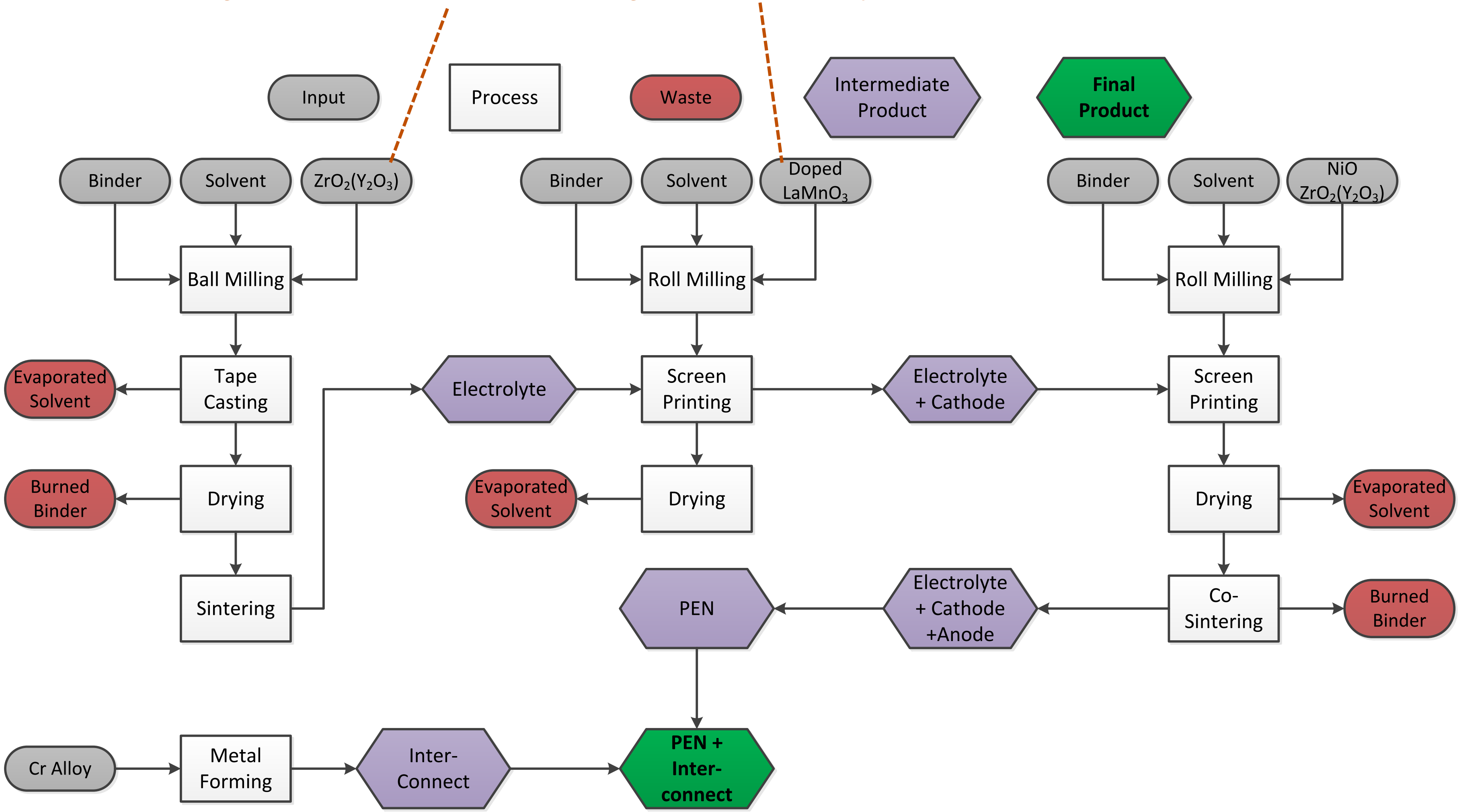
Basically the same boundaries, except the SOFC plant construction is a lot more impactful (short lifetime for cells… need to by them more often)



Source: Nease J, Adams TA II. Life cycle analyses of bulk-scale solid oxide fuel cell power plants. (in preparation 2014)

SOFC Stack Construction

Lots of details are factored into these boxes.
Here the difficult to get materials could contribute to large environmental impacts.



Cradle-To-Grave Life Cycle Inventory

Once we have constructed the boundaries, we get a nice table showing everything that comes from the environment, and everything that goes out to it, and where.

Inventory	NGCC	NGCC w/CCS	SOFC	SOFC w/CCS
Input Flows (kg)				
Natural Gas (44.1 MJ/kg)	219.23	235.73	144.80	155.61
Water (unspecified natural origin)	129.64	139.40	84.68	91.00
Output Flows (kg)				
Emissions to air (kg; unspecified population density and height)				
Ammonia (NH_3)	0.02	0.02	1.42×10^{-3}	1.53×10^{-3}
Carbon Dioxide (CO_2)	**74.39**	**79.99**	**21.03**	**22.59**
Carbon Monoxide (CO)	0.11	0.12	0.07	0.07
Dinitrogen Monoxide (N_2O)	7.50×10^{-4}	8.06×10^{-4}	4.81×10^{-4}	5.17×10^{-4}
Lead (Pb)	4.32×10^{-6}	4.64×10^{-6}	2.95×10^{-4}	3.15×10^{-4}
Mercury (Hg)	1.02×10^{-7}	1.09×10^{-7}	9.53×10^{-7}	1.02×10^{-6}
Methane (CH_4)	3.10	3.33	4.58×10^{-8}	4.92×10^{-8}
Nitrogen Oxides (NO_x)	**0.43**	**0.47**	**2.05**	**2.20**
NMVOC (non-methane volatile organics)	0.02	0.03	0.27	0.28
Particulates > 2.5 µm and < 10 µm	0.01	0.01	0.02	0.02
Sulfur dioxide (SO_2)	0.02	0.02	3.39×10^{-3}	3.64×10^{-3}
Product Flows (MW-h)				
Electricity Delivered, AC, Grid Quality	1.00	1.00	1.00	1.00

(I'm listing only a few things here for space)

SOFC produces less CO_2 but more Nox and particulates. So what is better?

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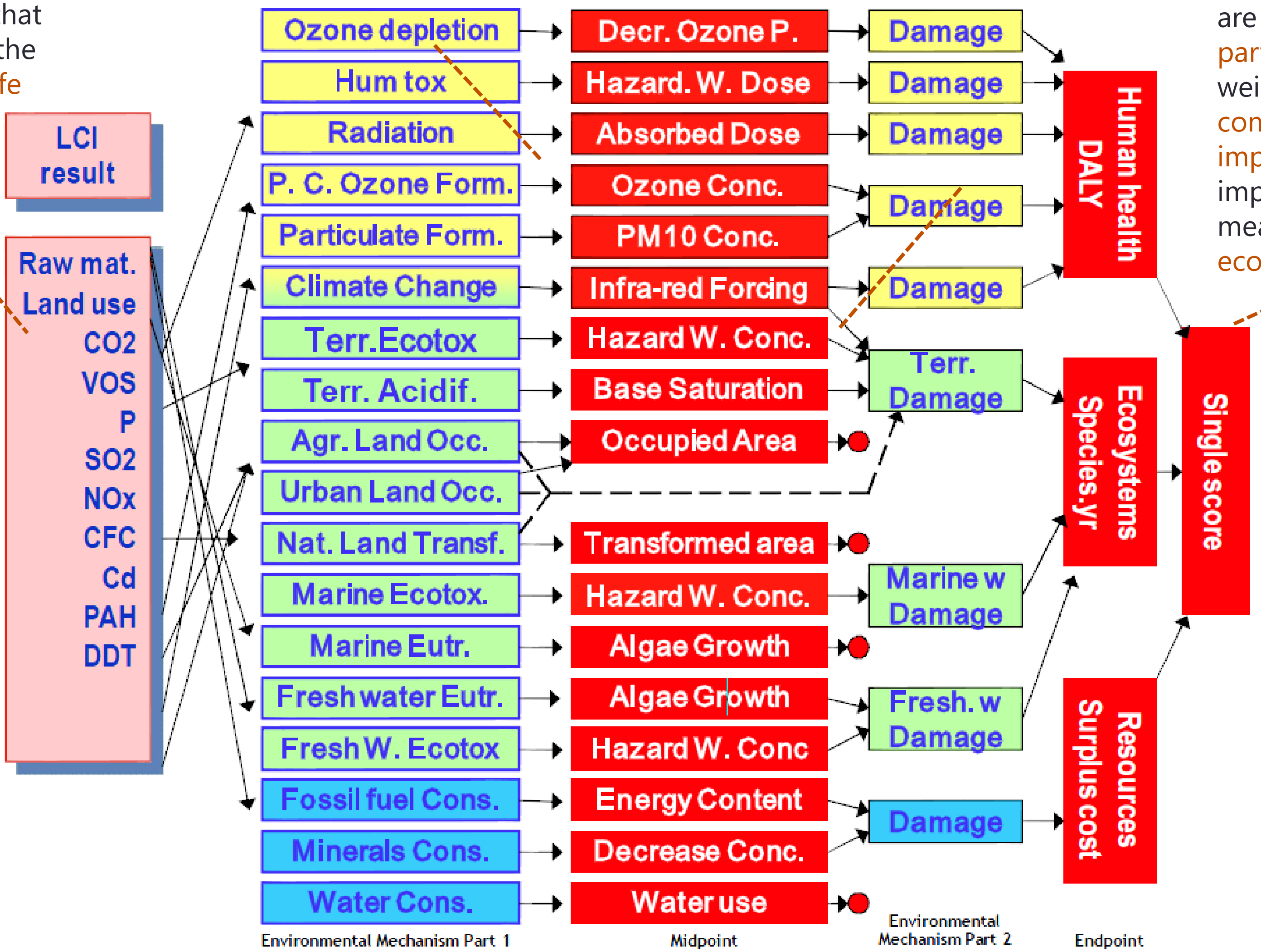
Step 2: Life Cycle Impact Assessment

The results of that table become the inputs to the life cycle impact assessment

These are converted into midpoints. Midpoints are scientific and objective ways of quantifying how different chemical affect the same impact (like global warming) with one number.

Midpoints are converted into endpoints. These are scientific but partially subjective weightings of how comparatively important each impact is. These are measured in ecoPoints.



Source: Goedkoop M, et al. ReCiPE 2008: Report I Characterization. (July 2012)

Results:

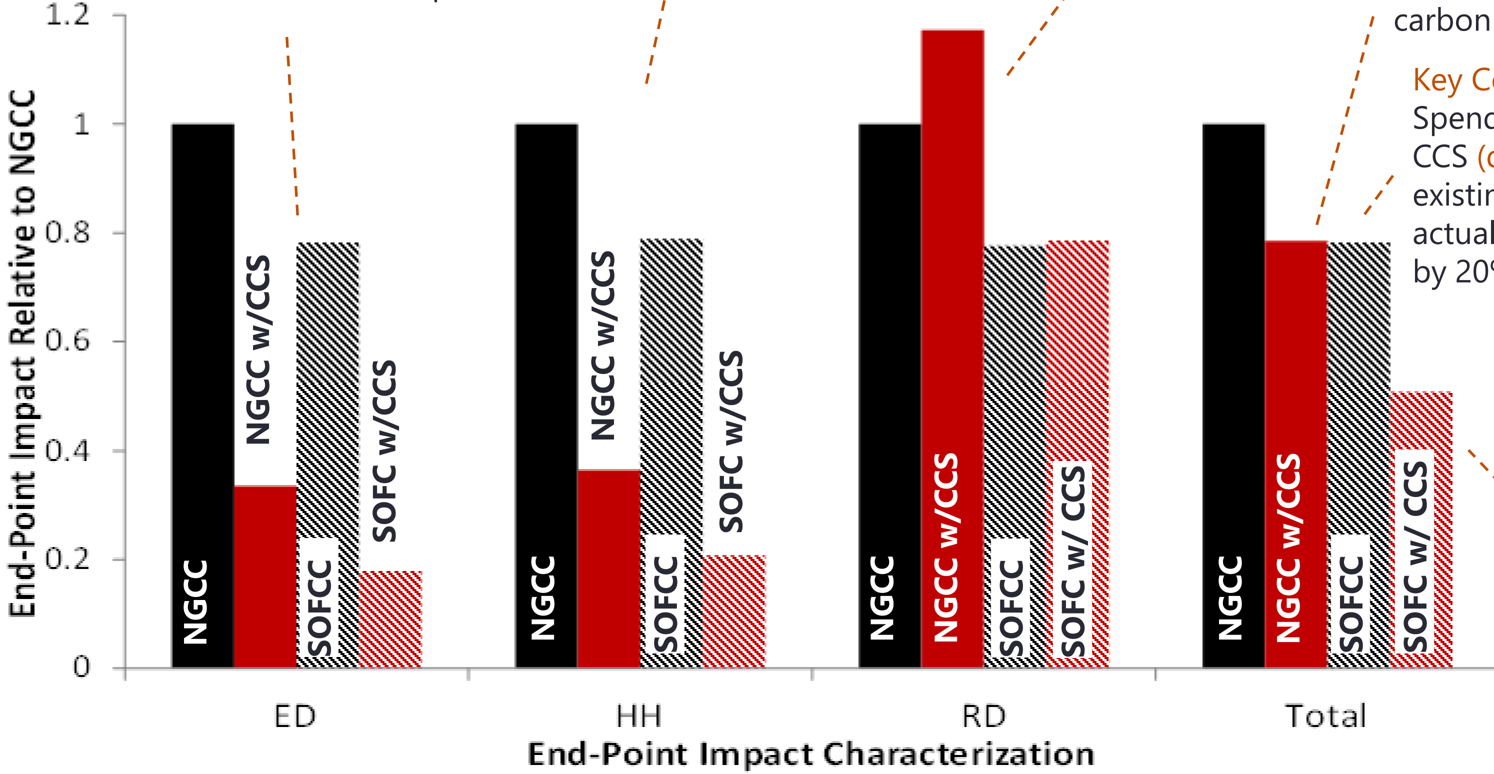
Includes global warming, water eutrophication, etc. SOFCs are naturally 20% lower even without capture.

Global warming, smog formation, etc. SOFCs 20% lower.

Natural gas consumes much more fossils, CO_2 capture even worse.

Key Conclusion 1:
SOFC systems without CCS have the same total life cycle impact as natural gas combined cycle WITH carbon capture!

Key Conclusion 2:
Spending considerably extra on CCS (double electricity price!) for existing power plants reduces the actual environmental impact only by 20%



Key Conclusion 3:
SOFCs with CCS are considerably better (more than double the impact) compared to status quo.
(Even though 100% capture, still has some environmental impact)

Environmental Destruction
(Species destroyed, etc.)

Human Health
(Damage to humans)

Resource Depletion
(Robbing future generations of limited resources)

McMaster University ENGINEERING

Sources: Nease J, Adams TA II. Life cycle analyses of bulk-scale solid oxide fuel cell power plants. *In preparation (2014)*

2. BUILDING SCALE

A new “green building” venture.

Student Researcher: Kyle Lefebvre

McMaster University ENGINEERING

Building scale SOFC/CAES

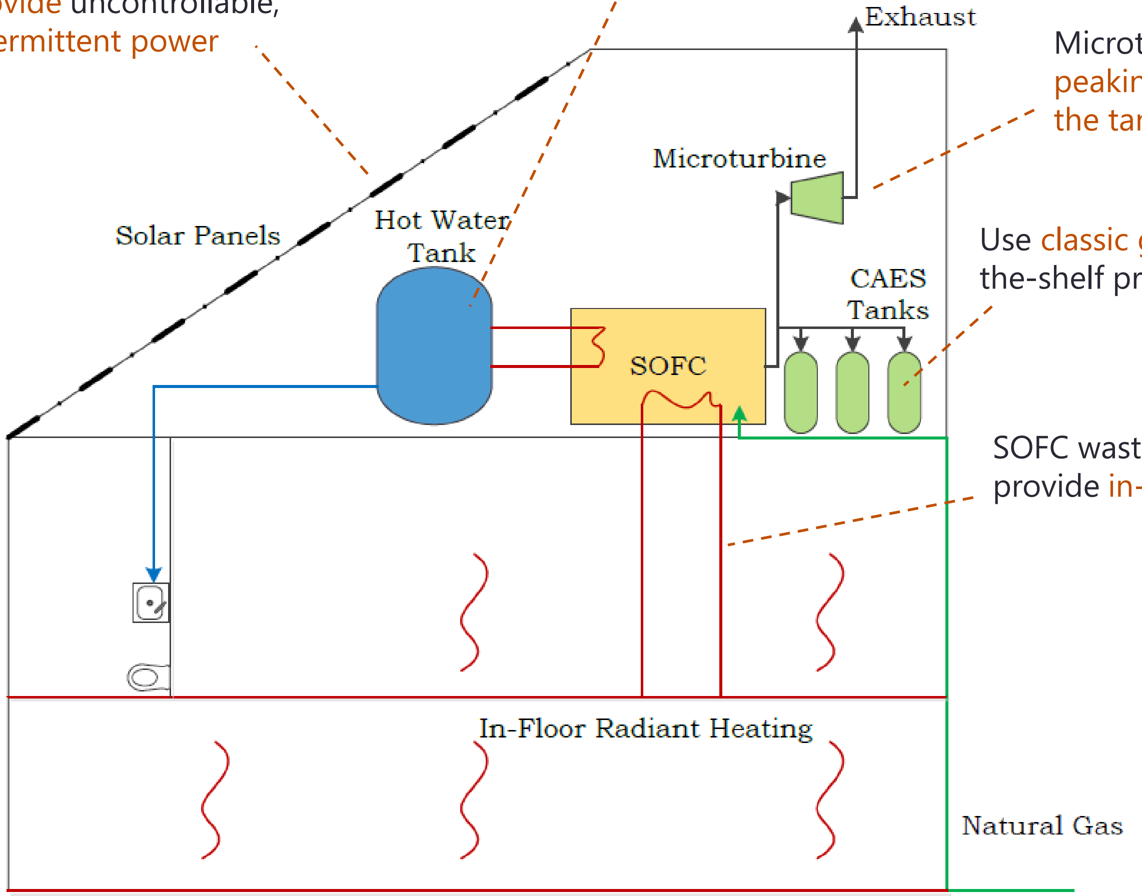
Solar panels or other renewables provide uncontrollable, intermittent power

SOFC waste heat used to provide potable hot water needs

Microturbine provides on-demand peaking power from the SOFC system or the tanks as needed

Use classic gas cylinders or off-the-shelf pressure vessels

SOFC waste heat used to provide in-floor radiant heating



Work in Progress

What is the optimal system design?

How big should each component be, and which do we use?

How should we use the system for different priorities?

❖ Economic objective?

❖ Environmental objective?

❖ Mix of two?

Case study for ExCeL building…

McMaster's "ExCEL" Building

Solar Panels on Roof
Direct DC circuits in walls ***

Grid connection for sale-back of excess power
(Or draw for additional power)

Integrated Power, Heat, Water Systems
*****Experimental energy storage systems**
*****Experimental building-scale power generation**

Pilot plant would:

- ❖ Demonstrate first SOFC/CAES system
- ❖ Provide model validation opportunities
- ❖ RHO uses real time occupancy/weather data
- ❖ Be adjustable for different "buildings" for different climates
- ❖ Integrate with subsets of other energy systems (geothermal, solar, hot water, in-floor heating, steam-heating systems) in order to experiment with different types of green buildings

Sources: Engineering Centre for Experiential Learning Initiative, Jan 24 (2013) Promotional presentation.

3. MID-LEVEL SCALES

Medium term impacts.

Student Researcher: Nor Farida Harun

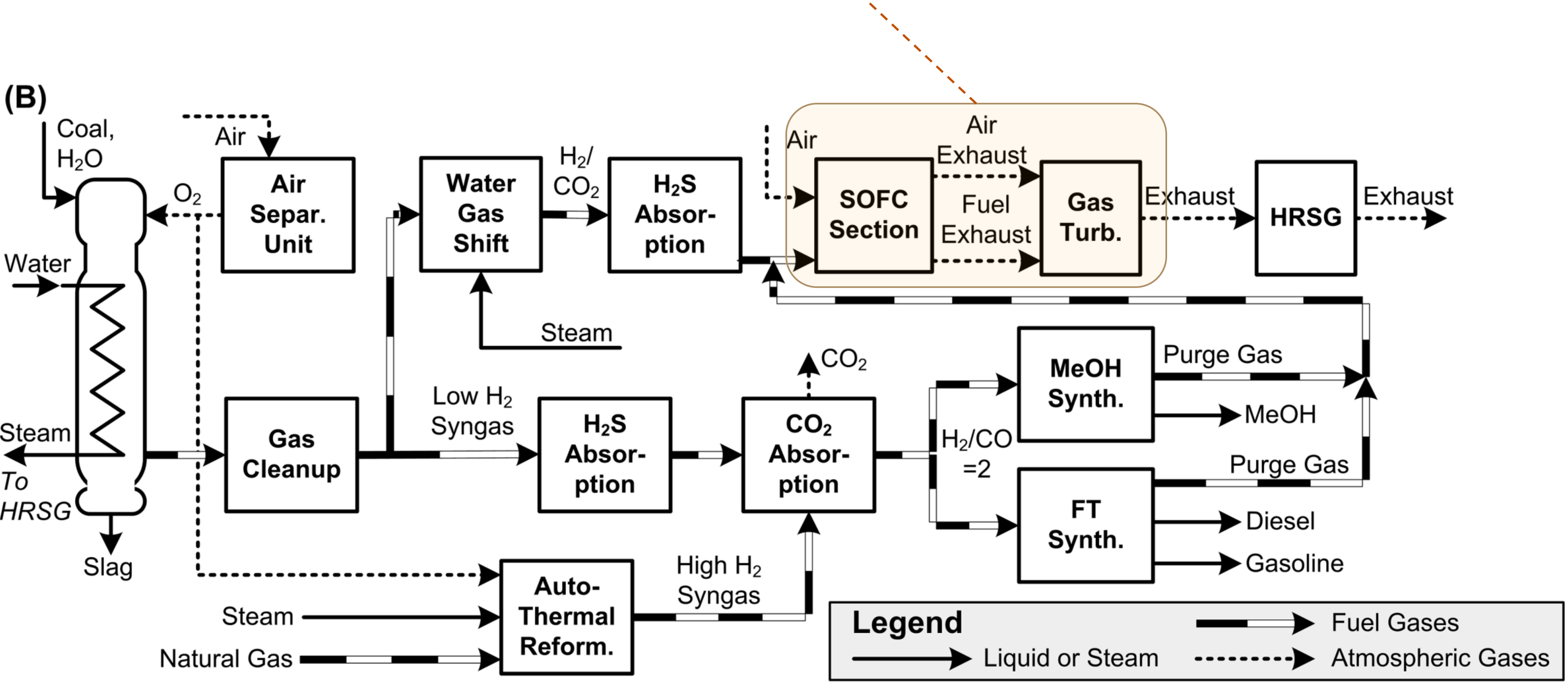
SOFC/Gas Turbines (Medium Term)

This section exists as combined hardware software simulator

(1) Real turbine, combustor, compressors, control, and heat exchange

(2) Real-time simulated SOFC (1D spatial-temporal model)

(3) Real SOFC exhaust gases generated based on model results in real-time



Sources: Adams TA II, Nease J, Tucker D, & Barton PI. *Ind Eng Chem Res*. (2013) DOI:10.1021/ie300996r

Current Team

Polygeneration Team

Yaser Khojestah
PhD
Gas, Coal, and Nuclear to Liquids

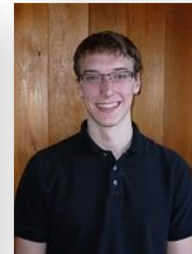
Jaffer Ghouse
PhD
Integrated Coal & Gas Design

Dominik Seepersad
Master's
Integrated Coal & Gas Control

SOFC Systems Team

Jake Nease
PhD
SOFCs with Energy Storage

Farida Harun
PhD
Flexible Fuel SOFCs



Kyle Lefebvre
Master's
Building-scale SOFC Systems

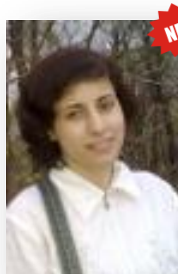
Giancarlo Dalle Ave
Master's (Sept)
PBBBBB

Sustainable Energy Systems

Chinedu Okoli
PhD
Thermochemical BioButanol

NEW

Haoxiang Lai
Undergrad
Energy Storage for Concentrated Solar



NEW

Leila Hoseinzadeh
Research Associate
Waste Flare Gas to Butanol

NEW

Kalia Akkad
Undergrad
Tailing Pond Reduction

Semicontinuous

Vida Medianshahi
PhD
Novel SC Design & Control

Kushlani Wijesekera
Master's
Ultra-intensified SC

Sarah Ballinger
Master's (Sept)
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Optimization Team

Government of Canada / Gouvernement du Canada — Ontario — NSERC CRSNG — UTM Universiti Teknologi Malaysia — Esso — Imperial Oil — PIONEER ENERGY — U.S. DEPARTMENT OF ENERGY