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

More Power Is Needed Due to Growth ➔ The People Demand Green Power ➔ All Coal Power in Ontario to Shut down 2014

The People Reject Installment of New Transmission Lines ➔ The People Support Wind Power*

* 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

**ENVIRONMENT**
- Particulates
- CO₂, NOx, SOx
- Deforestation & Land Use
- Mining & Resource Extraction
- Water consumption
- Resource Depletion
- Toxicity
- Wildlife impact
- Noise

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

**This talk:** Profitability analysis

**This talk:** Life Cycle Analysis

**This talk:** How CO₂ Tax Policy affects design choices

*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.

- **High Pressure**: Can be operated at 10-20 bar
- **Highly Efficient**: 50-60% electrical efficiency [1]
- **High Temperature**: 700-1000°C
- **Outlets Can Be Kept Unmixed**: Requires effective sealing

**Anode**
- $H_2 + O^\equiv \rightarrow H_2O + 2e^-$
- $O^\equiv + CO \rightarrow CO_2 + 2e^-$

**Cathode**
- $O_2 + 4e^- \rightarrow O^\equiv + O^\equiv$

**Vision: Long Term Bulk Power (NGFC)**

**SOFC with CCS**

- **Natural Gas**
- **Air**

**SOFC**

- Anode: CH$_4$, H$_2$, H$_2$O, CO$_2$, CO
- Cathode: O$_2$-Depleted Air

**Oxidation**

- Catalystically oxidize.
- No flame! No burning!

**HX Network**

- Very little energy penalty here
- Pipeline purity CO$_2$ ~100% capture
- Still at 10-20 bar!

**Condenser / Flash Drums, etc.**

- CO$_2$ to sequestration
- H$_2$O for recycle, water treatment

**Vent**

- Municipal Hot Water
- Water is actually drinkable!

**Extra power here from Brayton Cycle turbine**

**Operate at pressure (10-20 bar)**

**>80% Fuel Utilization**

**Higher difficulty:** High pressure plus effective seals.

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

**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

Adams & Barton, AIChE J (2010)
$\text{CO}_2$ Emissions

- **Coal**
  - Boiler
  - Gas Turbine
  - SOFC

- **Natural Gas**
  - Boiler
  - Gas Turbine
  - SOFC

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

- **700MW Net Output**
- All NG-SOFC plants use steam reforming
Water Consumption

700MW Net Output

All NG-SOFC plants use steam reforming

Dry cooling used (no water losses from cooling)

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)

**Diagram Description**
- **Air** enters the system and is compressed by the **Compressor**.
- The compressed air is then cooled by the **Cooler**.
- The cooled air is stored at high pressure in the **Storage**.
- The **Heater** burns natural gas to raise the temperature of the air before it enters the **HP Turbine**.
- The **LP Turbine** further reduces the pressure of the air, generating power.

**Additional Notes**
- Elastic Potential Energy: Typically 40 – 80 bar
- Fast Dynamics: Comp Start-up: 10-12 minutes, Turb start-up: 7-10 minutes
- Heater Burns Natural Gas: Not great for a CO₂ free plant...

**Sources**: Nease J, Adams TA. J Power Sources, 228:281-293 (2013)
SOFC / CAES Integrated Systems

(A) – Charge Phase

Fuel
High Pressure

Air

SOFCs
Anode

Captured CO₂

H₂O, CO₂

Condensers

H₂O

Spent Air

GT Cycle (Off)

Power

CAES Storage

(B) – Discharge Phase

Fuel
High Pressure

Air

SOFCs
Anode

Captured CO₂

H₂O, CO₂

Condensers

H₂O

Spent Air

GT Cycle (On)

Power

CAES Storage

Real demand profiles for Ontario primary grid

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

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

Complete plant heat integrations considered.

CO₂ capture system uses flash cascade for efficient capture [US Patent 8,500,868 (2013)].

**Optimal Performance Strategy**

Manipulated:
- % of Cathode Exhaust diverted to CAES
- Air Release Valve % opening

Note: Seasonal Variability

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)

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.
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

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

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

**OBJECTIVE 2:** Maximize Profit

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

**Power Produced**

Hourly schedule for next \( N \) hours

**Predicted Power Demand**

Hourly schedule for next \( N \) hours

**Predicted Market Price**

Hourly schedule for next \( N \) hours

**CONSTRAINTS**

- Model equations for the system
- Pressure limits for the cavern (40 bar \( \leq P_{i,t} \leq 72 \) bar)
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 $\sigma=6\%$ at maximum

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 $N=24$, $\sigma=6\%$ error

Cavern Pressures

An effective RTO will ensure that the pressure profile only touches the bounds momentarily.

Maximum Cavern Pressure – 72 bar

Minimum Useable Cavern Pressure – 40 bar

**CO₂ Emissions**

NGCC w/CCS still has direct emissions

SOFC/CAES has almost zero “direct + indirect” CO₂ emissions

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 this year.

The SOFC/CAES system has the same LCOE as NGCC even with today’s low natural gas prices when CO₂ taxes are implemented, but this has load following capabilities and zero emissions!

It also consumes less fuel and has less CO₂ to sequester in this first place.

The cost of adding CCS is very small.

NGCC still cheapest without CO₂ tax.

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

CO₂ 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 CO₂ tax

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

“Expected” free market CO₂ price for any regulation with teeth: $40-60

Prices from Offsetters.ca & Bloomberg.com

Thomas A. Adams II
Objective 2: Maximize Profits

Price is only weakly correlated with demand
Much higher prediction error

Prices go negative sometimes!

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.

Examples: Effect of Prediction Horizon

The bigger your prediction horizon
The smoother the curves

(A) $\text{SSE} = 67.5 \times 10^3 (\text{MW-h})^2$
$N = 24$ hours

(B) $\text{SSE} = 85.9 \times 10^3 (\text{MW-h})^2$
$N = 12$ hours

(C) $\text{SSE} = 123.4 \times 10^3 (\text{MW-h})^2$
$N = 6$ hours

(D) $\text{SSE} = 210.0 \times 10^3 (\text{MW-h})^2$
$N = 1$ hour

With no horizon, we experience sudden shutoffs due to lack of cavern pressure.
Monte Carlo Methods:
Ran RHO repeatedly for 1000s of different random instances of the prediction errors over an entire year

Greedy algorithm: Just try to match the current load

One day ahead reduces SSE by about 67%

One week ahead a little better (80% reduction)

Even 12% maximum error is almost as good as perfect predictions!

Worst case: even when we always under-predict demand, it is still very good!

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

<table>
<thead>
<tr>
<th>Inventory</th>
<th>NGCC</th>
<th>NGCC w/CCS</th>
<th>SOFC</th>
<th>SOFC w/CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Flows (kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas (44.1 MJ/kg)</td>
<td>219.23</td>
<td>235.73</td>
<td>144.80</td>
<td>155.61</td>
</tr>
<tr>
<td>Water (unspecified natural origin)</td>
<td>129.64</td>
<td>139.40</td>
<td>84.68</td>
<td>91.00</td>
</tr>
<tr>
<td><strong>Output Flows (kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissions to air (kg; unspecified population density and height)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>0.02</td>
<td>0.02</td>
<td>1.42 × 10⁻³</td>
<td>1.53 × 10⁻³</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>74.39</td>
<td>79.99</td>
<td>21.03</td>
<td>22.59</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>0.11</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Dinitrogen Monoxide (N₂O)</td>
<td>7.50 × 10⁻⁴</td>
<td>8.06 × 10⁻⁴</td>
<td>4.81 × 10⁻⁴</td>
<td>5.17 × 10⁻⁴</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>4.32 × 10⁻⁶</td>
<td>4.64 × 10⁻⁶</td>
<td>2.95 × 10⁻⁴</td>
<td>3.15 × 10⁻⁴</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>1.02 × 10⁻⁷</td>
<td>1.09 × 10⁻⁷</td>
<td>9.53 × 10⁻⁷</td>
<td>1.02 × 10⁻⁶</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>3.10</td>
<td>3.33</td>
<td>4.58 × 10⁻⁸</td>
<td>4.92 × 10⁻⁸</td>
</tr>
<tr>
<td>Nitrogen Oxides (NOₓ)</td>
<td>0.43</td>
<td>0.47</td>
<td>2.05</td>
<td>2.20</td>
</tr>
<tr>
<td>NMVOC (non-methane volatile organics)</td>
<td>0.02</td>
<td>0.03</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Particulates &gt; 2.5 μm and &lt; 10 μm</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>0.02</td>
<td>0.02</td>
<td>3.39 × 10⁻³</td>
<td>3.64 × 10⁻³</td>
</tr>
<tr>
<td><strong>Product Flows (MW-h)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Delivered, AC, Grid Quality</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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

**SOFC produces less CO₂ but more Nox and particulates. So what is better?**
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.
**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, CO₂ 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)

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**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
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...
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

3. MID-LEVEL SCALES

Medium term impacts.
Student Researcher: Nor Farida Harun
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

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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
- 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)

SOFIC Systems Team
- Chinedu Okoli PhD
  Thermochemical BioButanol
- Haoxiang Lai Undergrad
  Energy Storage for Concentrated Solar
- Leila Hoseinzadeh Research Associate
  Waste Flare Gas to Butanol
- Kalia Akkad Undergrad
  Tailing Pond Reduction
- Vida Medianshahi PhD
  Novel SC Design & Control
- Kushlani Wijesekera Master’s
  Ultra-intensified SC
- Sarah Ballinger Master’s (Sept)

Optimization Team
- Leila Hoseinzadeh Research Associate
  Waste Flare Gas to Butanol
- Vida Medianshahi PhD
  Novel SC Design & Control
- Kushlani Wijesekera Master’s
  Ultra-intensified SC
- Sarah Ballinger Master’s (Sept)