

Maximizing Our Impact

A call for the standardization of techno-economic analyses for sustainable energy systems design research.

jfr photography



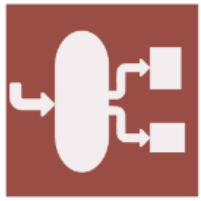
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processes

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Keywords

Biomedical systems
Chemical processes
Computational systems biology
Dynamic modeling
Materials manufacturing
Microbial systems
Process systems engineering



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- Links to articles cited in the study
- Links to data sets and simulations used in cited studies

A screenshot of the LAPSE website interface. The header includes the LAPSE logo and navigation links. The main content area displays the title of the conference presentation, the author's name, and the date. A summary paragraph follows. To the right, there is a 'Download' section with a file download link and a 'Meta' section with record statistics and version history. The footer of the screenshot shows the author's affiliation and a URL to download slides.

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LAPSE:2019.0620

Maximizing Our Impact: A call for the standardization of techno-economic analyses for sustainable energy systems design research

Conference Presentation

Thomas A Adams II

July 11, 2019

This presentation makes the case for the development of a new ISO standard for conducting eco-technoeconomic analyses (eTEAs) within the field of energy systems engineering and chemical process systems engineering. The talk provides a motivating example of a recent study that showed how standardization of eTEAs made it possible to make fair comparisons between different types of power plants using carbon capture and sequestration by using eTEAs reported in the literature that have been converted to certain standards. That led to informed decisions which were not possible without standardization methods, because the major variables are controlled such that analyses can focus on the value of the process concept itself rather than external factors like size, financing, and case-specific assumptions. Then, the talk outlines how the proposed ISO standards would work, their goals and scope, examples of standard practices, methods, and assumptions that could be used and what they might look like. The talk ends with a call for interested stakeholders to participate in the standardization process.

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Keywords: eco-Technoeconomic Analysis, Life Cycle Analysis, Standardization, Technoeconomic Analysis

Subject: Process Design

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Original Submitter
Thomas A. Adams II

Triple Bottom Line of Sustainability

Economical

- Capital
- Operating
- Supply Chain & Materials
- Job Creation / Losses
- Profitability
- Loans/Financing
- Stockholders
- Uncertainty and Risk

Environmental

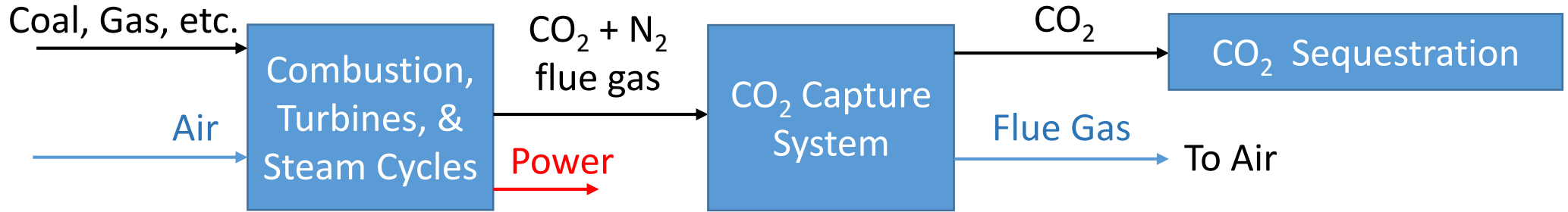
- Greenhouse Gases
- Particulates
- Deforestation
- Land Use / Transformation
- Resource Depletion
- Water Consumption
- Toxicity
- Wildlife Impact
- Noise

Societal

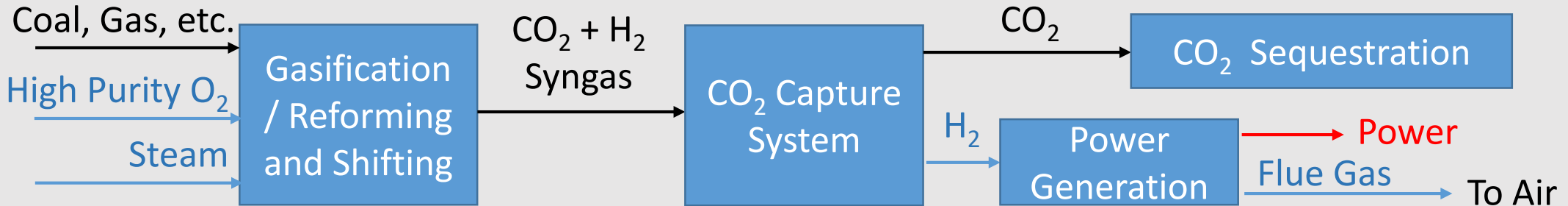
- Public Acceptance
- NIMBYs
- BANANAs
- Health Impacts
- Public/Employee Safety
- Accidents
- Public Policy
- Electoral Politics

Motivation: Power Plant w/ CCS Comparisons

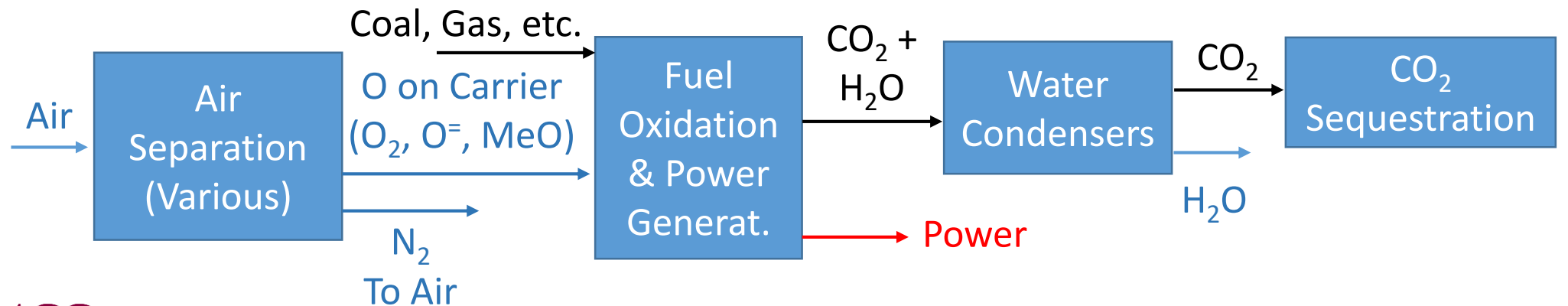
Post-combustion Strategies



Pre-combustion Strategies



Advanced Strategies



Motivation: Power Plant w/ CCS Comparisons

Type	Separation Problem	ASU Requirements	CO ₂ Capture Pressure	Example Applications
Solvent-based Post-Combustion	CO ₂ /N ₂	—	1 bar	Pulverized Coal, NGCC
Membrane-Based Post-Combustion	CO ₂ /N ₂	—	Vacuum	Pulverized Coal, NGCC
Solid-Based Post-Combustion	CO ₂ /N ₂	Low	1 bar	Pulverized Coal, NGCC
Solvent-Based Pre-Combustion	CO ₂ /H ₂	Medium	10-50 bar	IGCC, pre-reforming NGCC
Membrane-Based Pre-Combustion	CO ₂ /H ₂	Medium	Vacuum	IGCC, pre-reforming NGCC
Oxyfuels	CO ₂ /H ₂ O	High	1 bar	Gasified Coal/Nat Gas
Chemical Looping	CO ₂ /H ₂ O	—	10-50 bar	Gasified Coal/Nat Gas
Solid Oxide Fuel Cells	CO ₂ /H ₂ O	Low	1-20 bar	Gasified Coal/Nat Gas

Key Problems

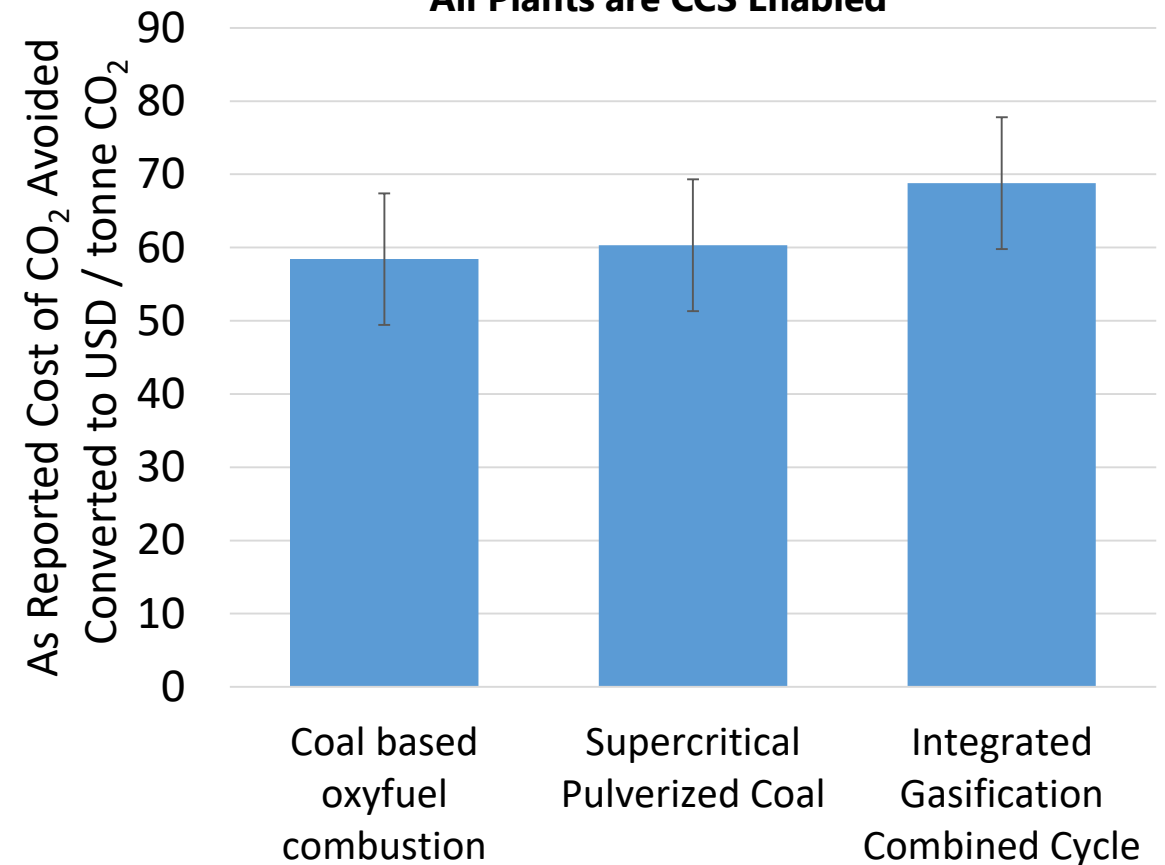
- **No systematic comparison** between processes
 - Lack of consistency between studies, especially between different author groups
- Everyone **claims their own process is the best** when compared against some other
 - **Example:** Don't compare against some common status quo, find another innovative idea that is worse and compare against that
- **Wide variation** in assumptions, strategies and ideas.
 - Different locations
 - Different definitions of key performance indicators
 - Different project years
 - Different analysis boundaries
- **Cannot examine the literature** to make fair comparisons between them.

Example of Literature Noise

$$CCA = \frac{LCOE_{scaled,standard} - LCOE_{basecase}}{GWP_{basecase} - GWP_{scaled,standard}}$$

- **Disparity** in GWP and LCOE computations
- **Huge disparity** in definition of the base case
- Yet this is a **primary key performance indicator** for identifying the best technologies to fight climate change

Survey of 44 ecoTEAs in Open Literature
All Plants are CCS Enabled



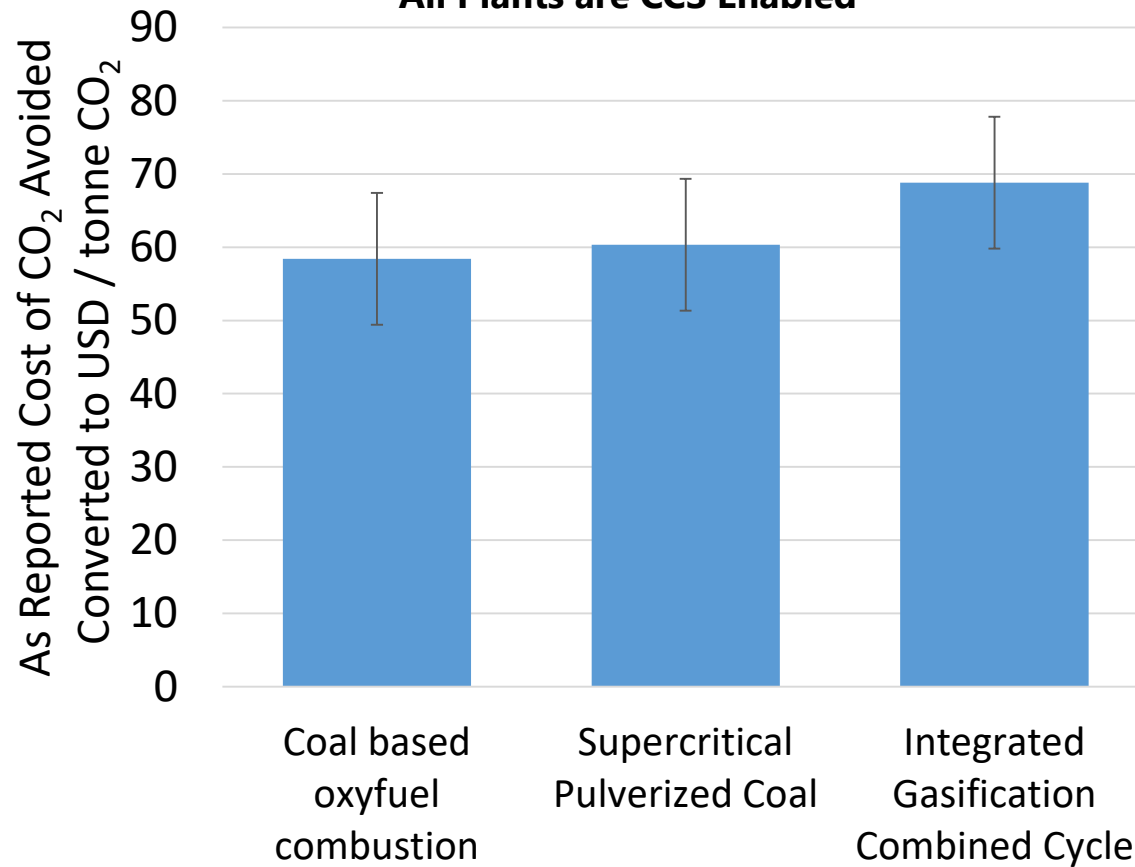
Notes: Error bars are for 90% Confidence Interval
Error bars assumes all power plants are equal within a category, which is not quite true, and so are for guidelines only.

Solution: Standardization

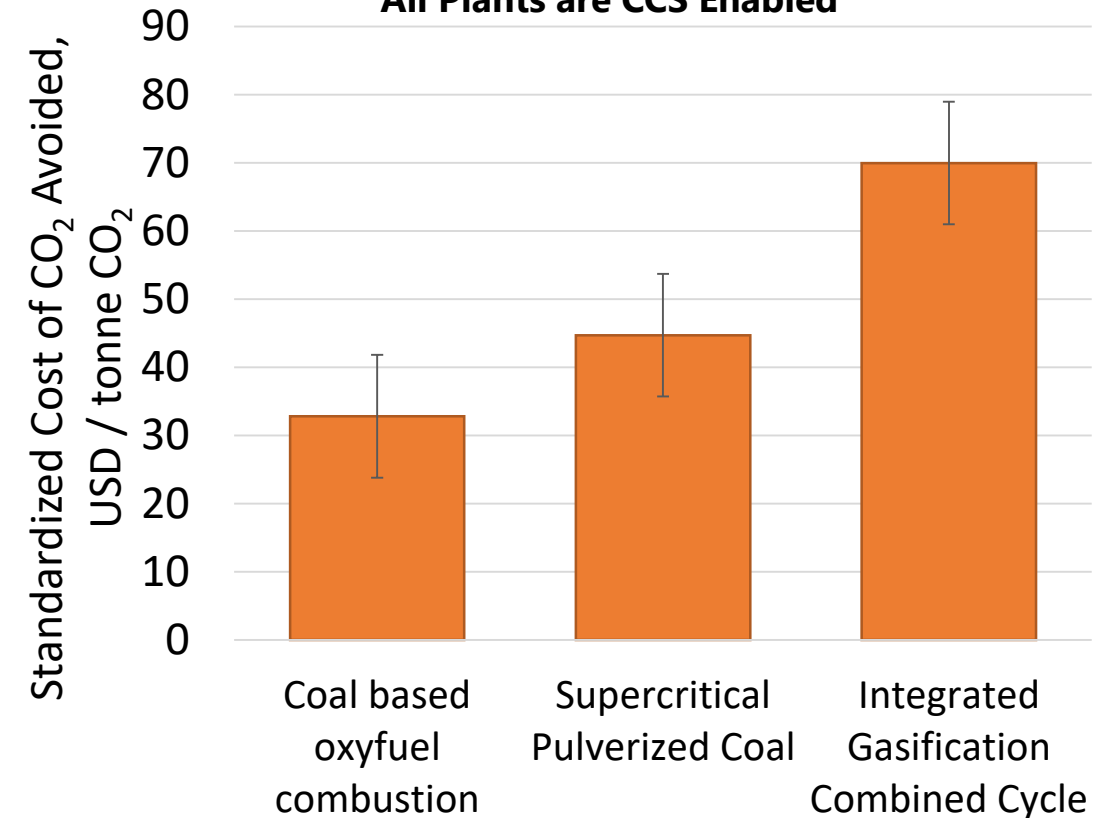
- **Size:** 550 MW net, plant gate
 - Nonfuel costs scaled with power law method $p=0.9$
- **Time & Place:** 1Q2016 USA
 - **Time:** North American Plant Cost Index
 - **Place:** Purchasing Power Parity Index
- **Fuel**
 - US Bituminous Coal #6 2016 Avg Price
 - US Conventional Average Gas Mix 2016 Avg Price
- **Captured CO₂ at plant gate**
 - **Pressure:** >115 bar
 - **Purity:** >95 mol%
 - **Capture Rate:** 90-100%
- **LCA:** Cradle to Gate GHG
 - Consistent NO_x production where neglected in original
 - Standardize cradle-to-plant-entrance life cycle impacts
- **CCA:** Cost of CO₂ Avoided
 - Same standard plant without CCS
 - SCPC and NGCC US baseline std's

Example: After Standardization

Survey of 44 ecoTEAs in Open Literature
All Plants are CCS Enabled



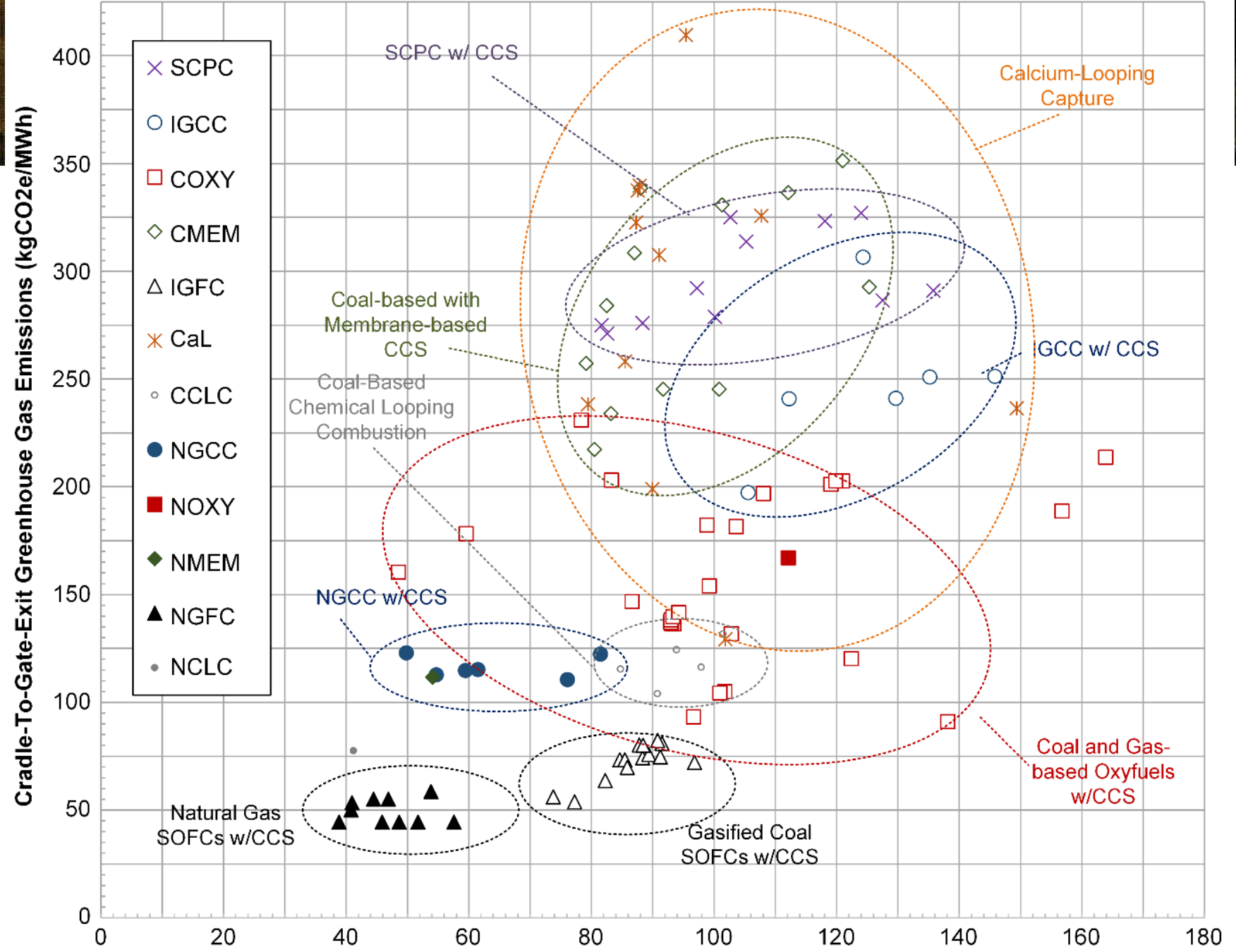
After Standardization
All Plants are CCS Enabled



Notes: Error bars are for 90% Confidence Interval
Error bars assumes all power plants are equal within a category, which is not quite true, and so are for guidelines only.

Overall

- Clear trends emerge once standardized
- Able to group technologies into clear areas
- Macro-level comparisons are now possible.
- Value of the design concept now more evident



Expanding and Standardizing

Big Picture Lessons from Study

- **Rather hard** to do cross-comparative research of eco-techno-economic analyses (**eTEAs**)
- But the **rewards** of doing meta-studies like this **are significant**
- A **standardization of eTEA methodology** for the field **would greatly amplify the impact** of each of our own studies

~O(1,000-10,000) researcher-hours

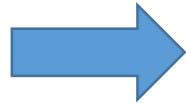
Very useful society, business, and policy conclusions

Individual studies would have greater influence

Proposal: Develop recognized standards for performing TEAs and eTEAs

Standard Types	Details...
Base Case Status Quo For Comparison	“Standard” power plants, “standard” refineries, “standard” chemical processes, etc.
Life Cycle Analysis Methodologies	Existing ISO standards, boundary definitions, impact analyses assumptions, methods, etc.
Plant Sizing / Delivered Products	Standard representative capacities and qualities
Metric Definitions	CCA, NPV, efficiencies, HHV vs LHV, other assumptions
Cost Estimations	Standard cost curves, approaches, and assumptions
Transparency and Verifiability	Spreadsheets and models released open-access
Data Formats	Open document formats, etc.

Example Use of Standards: Readers



$$NPV_{PSE-3} = \$1.2 \text{ bln}$$
$$CCA_{PSE-3} = \$40.3/\text{tonne}$$
$$GHG_{PSE-3} = 4.5 \text{ tCO}_2\text{e}$$



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```
10000 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10001 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10002 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10003 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10004 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
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10010 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10011 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10012 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
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10015 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10016 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10017 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10018 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10019 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
10020 $reactor_label_name = $reactor_specs -> REACTOR_TABLE;
```



Reader studies paper using PSE standard

Reader sees standard metrics, immediately understood

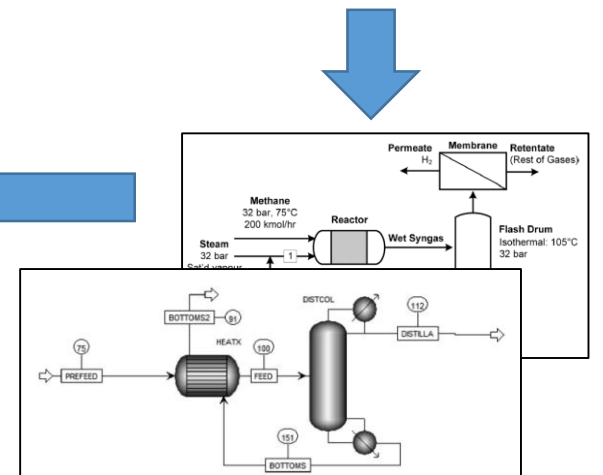
Reader downloads files and data to verify results

Reader considers other papers using the same standards



Reader rapidly performs comparisons and research

Reader easily incorporates standardized models into own work



All standardized research has high impact and citations!

Key Standards Characteristics (Goals)

Goals: Want standards that...

- result in **unambiguous calculations that are directly comparable** across research studies
- are **useful**
- are **easy to use**
- are **transparent**
 - transparency in reporting
 - transparency in calculations
 - ease of adoption
 - reproducible
- are **international** or **regional**
 - balance between breadth and detail
- are **convertible**
 - **Example:** metrics reported for a north American application easily converted to a European one.
- are **accessible**
 - digital reporting
 - standard meta data / tagging
 - databasing
 - open / cheap access of results

Standards Scope

Scope: eco-Technoeconomic analyses of chemical and energy systems.

- **Applications:**

- Electricity
- Transportation
- Energy Conversion
- Energy Product Production
- Energy Storage
- Chemicals

- **Scales**

- Large
- Neighbourhood
- Personal

- **Focus On:**

- Major system components
- Important supply chain elements
- Big-picture concepts
- “Major on the majors”

- **Avoid**

- Prescribing minutae
- Too tight definitions and requirements

Key Definitions

Key Performance Indicators (KPIs)

- Common **metrics of quality**
- Potential Examples:

$$NPV_{PSE-3} = \$1.2 \text{ bln}$$

$$CCA_{PSE-3} = \$40.3/\text{tonne}$$

$$GHG_{PSE-3} = 4.5 \text{ MtCO}_2\text{e/yr}$$

$$\eta_{\text{therm},PSE-3} = 45.3\% \text{ HHV}$$

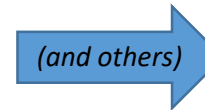
$$PBP_{PSE-3} = 6.7 \text{ years}$$

Intermediate Calculation Elements (ICEs)

- Used to compute KPIs
- **Convertible** from one standard basis to another. Example:

$$TCI_{PSE-3} = \$1.11 \text{ billion USD}$$

$$TOC_{PSE-3} = \$123 \text{ million/yr USD}$$



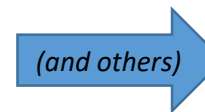
$$NPV_{PSE-3} = \$1.2 \text{ bln}$$



Convert to PSE-3E Standard (Fuels, Large Scale, Europe)

$$TCI_{PSE-3E} = € 0.84 \text{ billion}$$

$$TOC_{PSE-3E} = € 95 \text{ million/yr}$$



$$NPV_{PSE-3E} = € 0.94 \text{ bln}$$

Example Standards: Size

- **Size** incredibly important! **Example:**

- Same plants, 50% difference in size:



Pulverized Coal
w/CCS
550 MW

10.6 ¢/kWh

(standardized literature
averages)



Pulverized Coal
w/CCS
225 MW

11.3 ¢/kWh

(standardized literature
averages)

6.6% LCOE Difference

- Different plants, same size, standardized conditions



Pulverized Coal
w/CCS
550 MW

10.6 ¢/kWh

(standardized literature
averages)



Coal Oxyfuel Combustion
w/CCS
550 MW

9.9 ¢/kWh

(standardized literature
averages)

7.1% LCOE Difference

- The effect of size is equal to the effect of the process technology itself!
 - **Need to control this variable** in order to make technology value judgments.

And Yet We Do It All The Time

Common example

- Plant 1: 750 MW power plant **without** CCS



- Plant 2: 500 MW power plant **with** CCS



- Same Fuel Input

- **CCS parasitic effect**

- But what about the remaining 250MW of power out! I want it!

LCA Concept of Functional Unit:

- **Need to be outputs based**
 - Comparisons should be based on **like products and scales**
 - BUT! Per-unit costs (like LCOE) are sensitive to size
 - Capital costs are non-linear (**economies-of-scale**)
 - i.e. power law scaling
 - **We'll need to choose** good size standards for comparison.
 - Environmental impacts are linear, so per-unit impacts are fine

Example Standards: Size

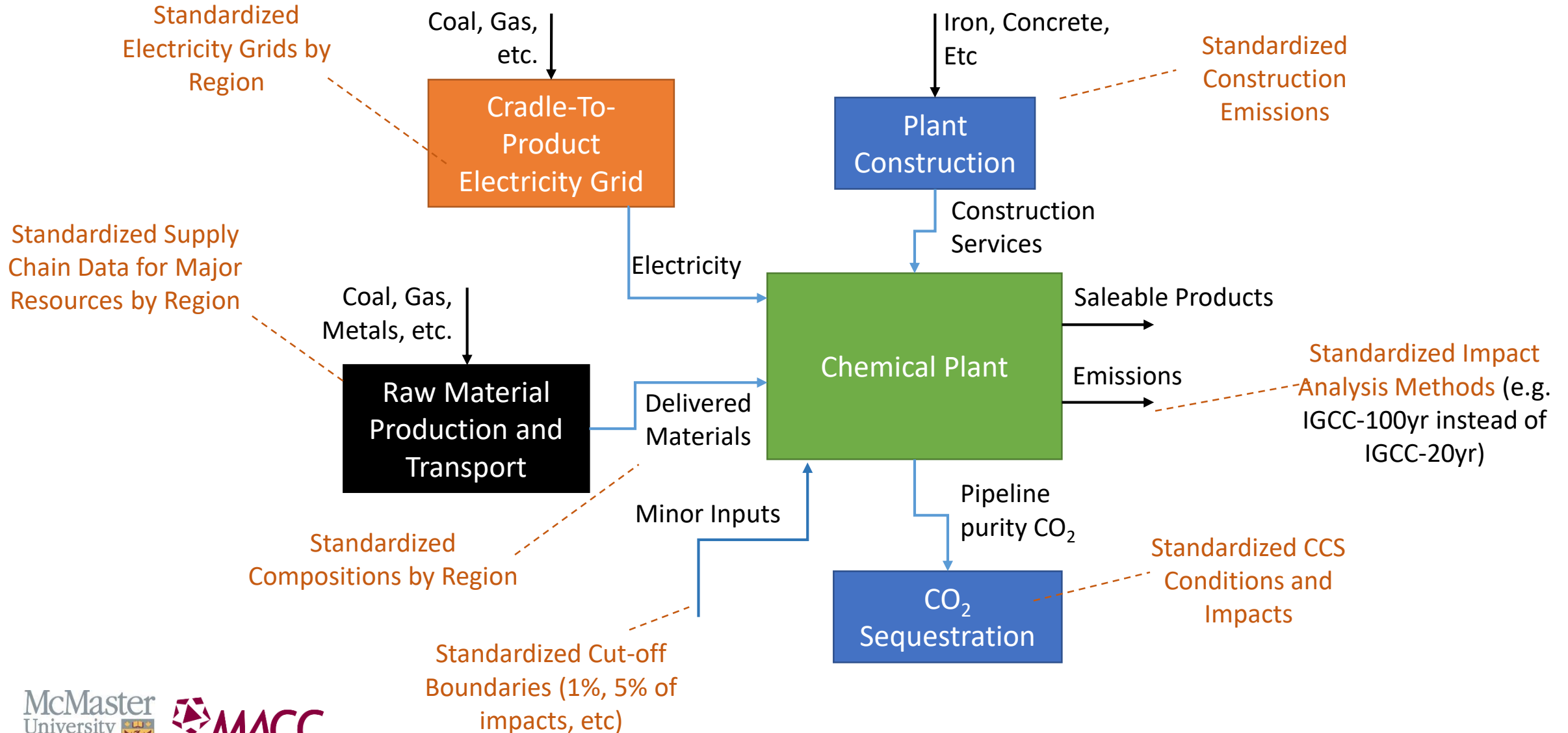
- User would choose which size standard to pick
 - Others could compare directly
 - Others could use Intermediate Calculation Elements to convert to their size of interest.

Size Standards by Category

PSE-1:	Electricity, Municipal	550 MW net output
PSE-2:	Electricity, Community	500 kW net output
PSE-3:	Electricity, Building	10 kW net output
PSE-4:	Fuels, Large plant	1 GW _{HHV} output
PSE-5:	Fuels, Small plant	10 MW _{HHV} output
PSE-6:	Transport, Personal	200,000 km
PSE-7:	Transport, Mass Transit	100,000 tonne-km

Etc. (hypothetical numbers for sake of discussion)

Example Standards: LCA Boundaries & Data



Example Standards: Regional Breakdown

LCA Standards by Region for PSE-1 (Electricity, Municipal). Electricity Grid Cradle-to-Product Emissions

<i>Basis: 1 MWh Electricity, AC, grid quality, delivered</i>		CO ₂ (kg/MWh)	NO _x (kg/MWh)	CH ₄ (kg/MWh)	GWP (kgCO ₂ e/MWh)
PSE-1N:	North America	655	1.63	2.62	728
PSE-1E:	Central Europe	500	1.11	1.31	537
PSE-1S:	South America	157	0.37	0.93	183
<i>Etc.</i>

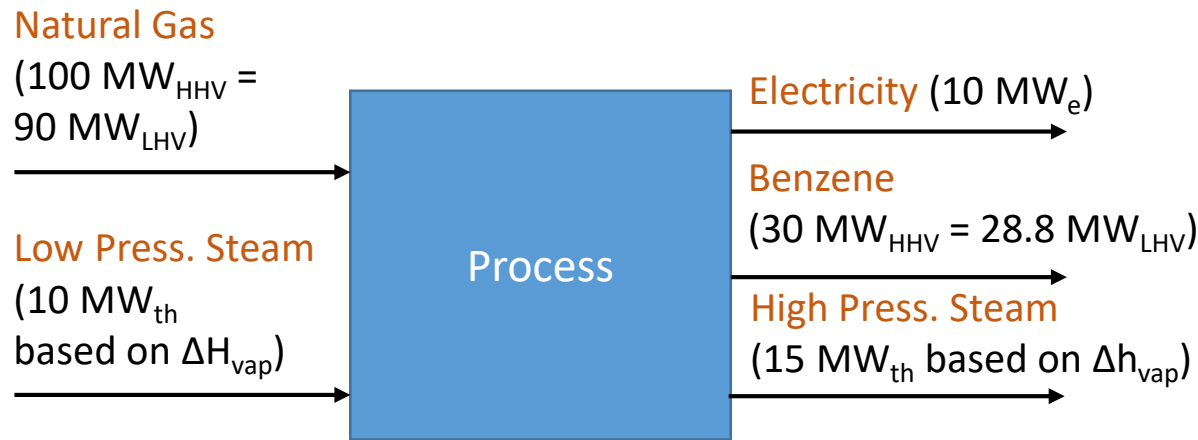
Similar tables would exist for many aspects of the supply chain

Numbers hypothetical for sake of discussion / do not use.

Approximated based on citations below.

Example Standards: Metrics

- Example: **Efficiency**. What is the efficiency of this system? Which do you report?



Is the steam energy just Δh_{vap} ?
Does it include specific heat effects?
Does it include pressure effects?

Do you use LHV or HHV?

$$\eta = \frac{\text{benzene (primary product)}}{\text{gas (raw material)}}$$

$$\eta = 30\%_{\text{HHV}} \quad \eta = 32\%_{\text{LHV}}$$

How do you add electric, thermal, and chemical energies?

$$\eta = \frac{\text{all saleable products}}{\text{gas (raw material)}}$$

Without specific heat/pressure counted

$$\eta = 55\%_{\text{HHV}} \quad \eta = 60\%_{\text{LHV}}$$

With specific heat/pressure counted

$$\eta = 56\%_{\text{HHV}} \quad \eta = 61\%_{\text{LHV}}$$

$$\eta = \frac{\text{all saleable products}}{\text{all inputs}}$$

$$\eta = 50\%_{\text{HHV}} \quad \eta = 54\%_{\text{LHV}}$$

$$\eta = 51\%_{\text{HHV}} \quad \eta = 55\%_{\text{LHV}}$$

Example Standards: Transparency

DIAGNOSTIC AND STATISTICAL
MANUAL OF
MENTAL DISORDERS
FIFTH EDITION

DSM-5™

AMERICAN PSYCHIATRIC ASSOCIATION

- New DSM-5 medical anxiety conditions*:

Aspen·alium·errata·phobia

Fear of others finding mistakes in your Aspen Plus models

Aspen·alium·quæstrum·iniquumo·phobia

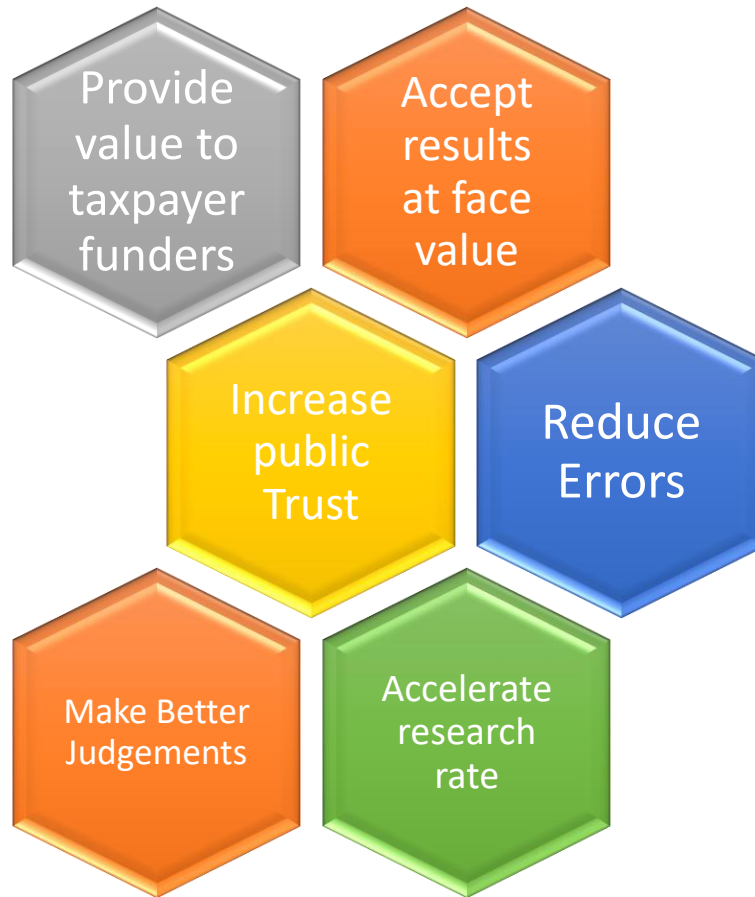
Fear of others taking your Aspen Plus models and publishing papers with them really fast even though it took you, like, a year to make!

- Recent review of over 300 papers which use energy systems modelling found **just 3 released their models to the public.**

* Not really of course

Example Standards: Transparency

Goals



Techniques

Spreadsheets

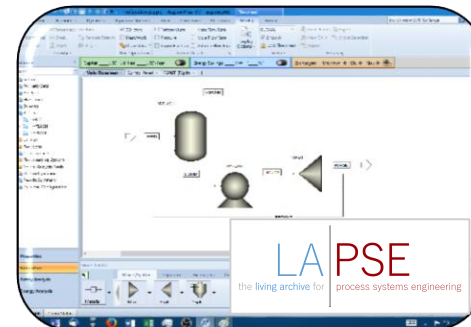
- With formulas!
- As journal supplementary material

```

public function get_sanitized_external_link_from_string($link) {
    global $wp;
    $options = get_option('user');
    $archivetag = $options['archivetag'];
    $archivetaglength = strlen($archivetag);
    // check for our repository first
    $data = null;
    if (strlen($archivetag) == strlen($url)) {
        $url = substr($url, 0, -strlen($archivetag));
        // check if the partial tag exists in the
        $prefix = absint(strpos($url, "/"));
        $posfix = absint(strpos($url, "?"));
        if (0 < $prefix or 0 < $posfix) {
            $records_table_name = $wp->prefix . $url;
            $records = $wp->get_row($wp->prepare("SELECT RecordID FROM $records_table_name WHERE $url"));
            if (!empty($records)) {
                $RecordID = absint($records->RecordID);
                if (0 < $RecordID) { // finally a
                    $data[0] = self::get_wp_record($RecordID);
                    $data[1] = CLASS_URL;
                    $data[2] = $RecordID;
                }
            }
        }
    }
    if ($data) {
        return strtolower(substr($link, 0, 4));
    }
}
    
```

Source Code (.py, .cpp, .m)

- Compliant for non-experts
- Binaries too
- GitHub, CodeBase, LAPSE



Simulations and Flowsheets

- Converged
- CAPE-OPEN compliant
- LAPSE

```

alpha      intercept term
beta(m)    input coefficients
objvib     objective value;

POSITIVE VARIABLES
    beta(m);

PARAMETERS
    phi(m)      predicted output
    xx(m)       input level of interest;
    1
    2
    * Assign data to variables
    phi(m) = alpha(m) + sum(m, beta(m)*xx(m));
    xx(1)*OBJEX = 1000;
    6
    obj('CAPEX') = 1000;
    7

EQUATIONS
    objv     objective value calculation
    objv     regression;
    1
    2
    * Assign Equations
    objv.. objvib == alpha
    3
    4
    5
    6
    7
MODEL
    Lowerbound    model / obj;
    27
    
```

Optimization

- GAMS code
- LAPSE
- Journal supplementary material

Similar Standards Movements

- **NETL/US DOE: Quality Guidelines for Energy Systems Studies**
 - Internal / recommended
 - **Modeling params** (e.g. Aspen models)
 - **Economic** (e.g. debt/equity ratios)
 - **Fuel standards** (e.g. gas quality, price)
 - Used in making the "**baseline**" studies
 - Can help to **address some standardization** elements
 - **Some likely to be adopted** in proposed standard
 - **USA** Focused. A great start!
- **ISO 14040 series**
 - Life Cycle Analyses
 - Boundaries and Guidelines
 - Not specific enough for standardization
 - Incorporate as best practices
- **ISO 50006/50015/17741**
 - Energy management systems
 - Defines metrics like efficiency
 - Useful terminology
 - Analysis boundary definitions
 - Some portions incorporated
 - But eTEAs out of scope

Similar Standards Movements (continued)

- **White paper:** Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO₂ Utilization (2018)
 - Technische Universität Berlin
 - RWTH Aachen University
 - Univ Sheffield
 - Institute for Advanced Sustainability Studies eV Potsdam
 - University of Michigan
- Proposes TEA standards in a **parallel way to ISO 14040+** life cycle analysis standards
 - A similar best-practices theme
 - Means not specific enough for the cross-research results application
 - Scope too specific/narrow
 - Well thought out and described
- An **excellent start**
 - Much that could be included in or greatly inform new ISO standard

Standardization Committees and Process

- Stage 1 (Now)

- **Letters of support** from universities, companies and agencies
 - no commitments
 - no money
- You can help by **sending me a letter of support on your letterhead**
 - Template available at link below
- Interested? Join the mailing list at
 - <http://PSEcommunity.org/standards>

- Stage 2

- **Standards Council of Canada** and affiliates will lead international development of a **technical specification document**



Standards Council of Canada
Conseil canadien des normes



- Works as a **“trial run”** to get out there and get used within 1 year.
- After stakeholder feedback, this becomes the working document that is the **starting point for developing the full ISO standard.**

Wrap Up

- We can learn a lot from **eco-techno-economic meta studies**
 - Critical for **taking meaningful and near-term action** on climate change
 - Critical for **policy** and **business**
 - **See through the hype.**
- Current **culture of the field:**
 - Hide models and code
 - C.Y.A.
 - Nonstandard methods
 - Not working toward common goal
- **Goal:** Make it **as easy as possible** for others to use and understand your research for societal benefit
 - **Join me!**
 - <http://PSEcommunity.org/standards>