Oxygen Carrier Production Cost

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NETL-PUB-22255

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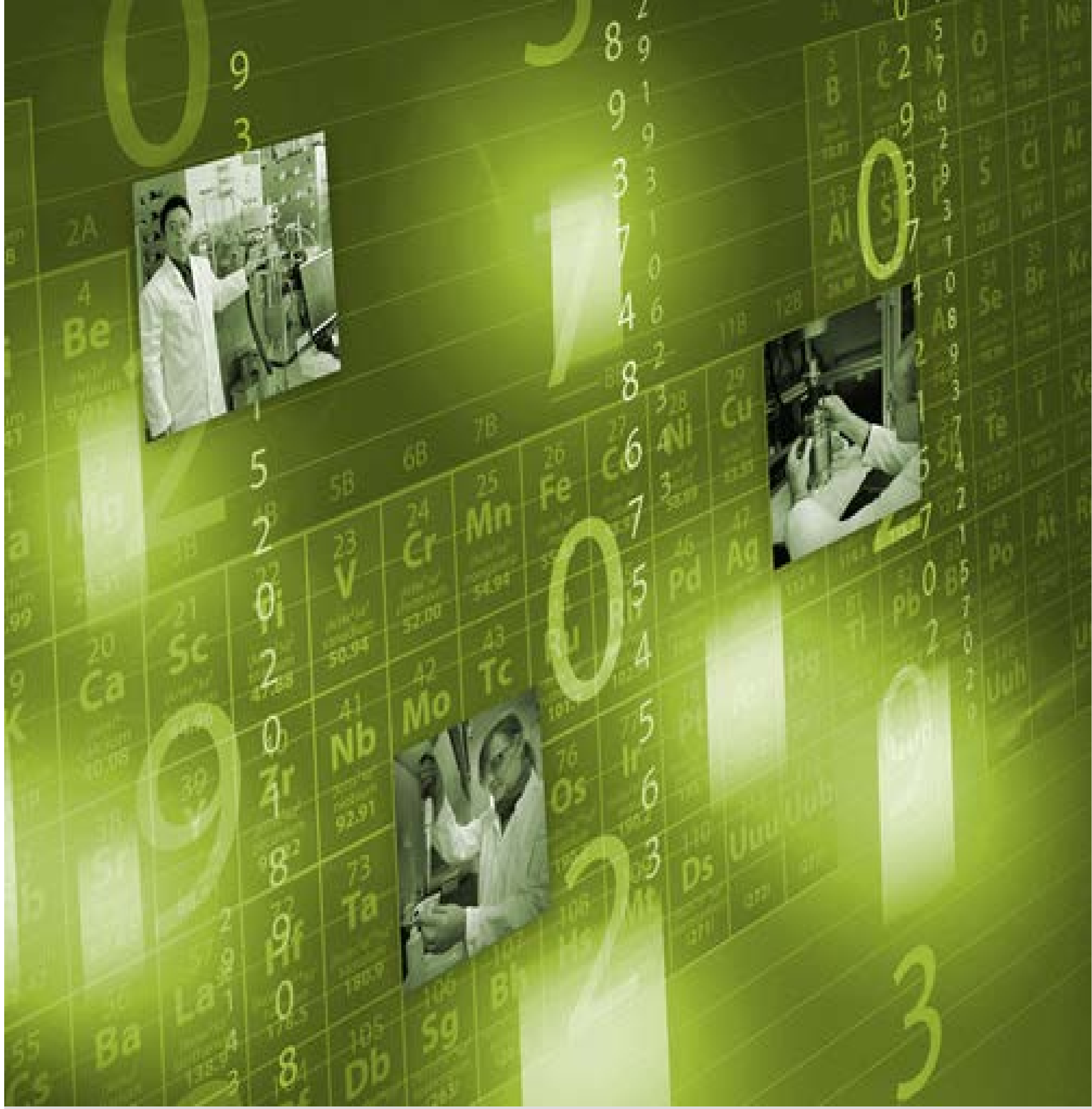
Clearwater Clean Energy Conference



U.S. DEPARTMENT OF ENERGY

Objectives

- **Estimate the cost of oxygen carrier (OC) production at a future commercial level for large-scale chemical looping combustion (CLC) power generation**
  - Consider different types of carriers (e.g., naturally occurring, engineered)
  - Estimate the cost as a function of production volume

Utilization of results:

- Assess if commercial-scale production indicates potential for cost reduction for the carrier
- Provide research and development (R&D) guidance
- Provide input for techno-economic analysis (TEA)

Major Task Steps

1. Oxygen Carrier Specifications
2. Preparation Procedures
3. Production Facility Scenarios
4. Oxygen Carrier Production Rate Range
5. Raw Material Sources and Prices
6. Production Facility Descriptions
7. Material & Energy Balances
8. Production Facility Capital Cost
9. OC Makeup Cost/Price

Step 1: Oxygen Carrier Specifications

- **Each OC product considered should be commercially appropriate**
  - OC component materials availabilities >1 million mt/yr (CLC power generation industry supply capacity)
- **Property, composition, and preparation method specifications should coincide with an analogous OC material that has been fabricated and tested at small scale**
  - This is not practical since small-scale testing rarely applies commercially appropriate raw materials
- **Hypothetical, but commercially-representative OCs are considered in this evaluation**

Step 1: Oxygen Carrier Specifications (cont'd)

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Oxygen carriers (OCs) selected:

1. *Natural CLC OC material*: Ilmenite sand ($FeTiO_3$)
2. *Engineered CLC OC*: Fe_2O_3 supported on Al_2O_3
3. *Engineered CLC OC*: NiO supported on Al_2O_3
4. *Engineered (CLOU) OC*: CuO supported on TiO_2
5. *Engineered composite OC*: CuO-Fe_2O_3-Al_2O_3 (NETL Research and Innovation Center [RIC] Gen-2 OC)

Step 2: Preparation Procedures

Two general preparation procedures are considered:

1. Mechanical mixing process (continuous process)
2. Co-precipitation process (continuous process)

Comments on laboratory OC preparation information:

- Tend to use ultra-high purity raw materials
- Apply batch processing methods
- Lab processing steps do not scale to commercial conditions and equipment

Step 3: Production Facility Scenarios

Estimates are made for two scenarios:

1. Build and operate an OC production facility located at the CLC power plant site (plant location Chicago area)
2. Build and operate a central production facility to produce and distribute OC to the U.S. CLC power generation industry (facility location in the Chicago area)
   - Domestic transport cost = $0.006/lb of OC
   - Operates with a profit margin of 10%

Step 4: OC Production Rate Range

- CLC power plant generating capacity: 550 MW (base load)
- Coal: Illinois No. 6
- CLC technology: CFB
- CLC power plant capacity factor: 85%
- OC production plant capacity factor: 76.5% (based on solids handling process expectations)
- CLC power plant OC annual makeup rate range: Up to 50,000 mt (2,960 to 14,800 lb/hr design-rate based on 0.6% to 3% of coal feed rate)
- Central production site annual product rate: Up to about 1,000,000 mt

Step 5: Raw Material Sources and Prices

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Metal oxide forms for mechanical mixing (availability > 1 million mt/yr):

- **Ilmenite**: $FeTiO_3$ [China, Australia, Vietnam, Canada]
- **Taconite**: Pelletized Fe_2O_3 (with binder) beneficiated from low-grade magnetite ore [United States]
- **Fe_2O_3 pigment**: Precipitated Fe_2O_3 (0.1 to 10 µm) [China, India, Germany]
- **CuO pigment**: Precipitated CuO (0.1 to 10 µm) [China]
- **NiO powder**: Produced by Ni powder oxidation or Ni compound pyrolysis (<200 µm) [China]
- **Al_2O_3**: Smelter-grade (for aluminum), or calcined alumina forms [China, Australia, Brazil]
- **TiO_2 pigment**: Crystalized TiO_2 [China, Australia, Canada]

Step 5: Raw Material Sources and Prices

Representative Raw Material Purchase Prices

OC Component	Component Price ($/lb)
Mechanical Mixing Components	
Ilmenite sand	0.14 – 0.23
Taconite pellets	0.027 – 0.091
Fe_2O_3 pigment	0.23 – 0.55
CuO pigment	0.4 – 0.75
NiO powder	3.0 – 10.0
Alumina	0.12 – 0.21
TiO_2 pigment	0.75 – 1.35
Co-Precipitation Components	
Iron(III) nitrate [$Fe(NO_3)_3 \cdot 9\ H_2O$]	0.23 – 0.41
Aluminum nitrate [$Al(NO_3)_3 \cdot 9\ H_2O$]	0.18 – 0.36
Copper(II) nitrate [$Cu(NO_3)_2 \cdot 3\ H_2O$]	0.68 – 1.59
$TiCl_4$ (liquid)	0.55 – 0.73

Raw materials are commodities and their purchase prices fluctuate with market conditions – Historically seen to fluctuate ±50%*

*From infomine.com; markets.businessinsider.com; focus-economics.com

Step 5: Raw Material Sources and Prices

Mechanical Mixing Raw Materials Transportation Costs

Raw Material	Taconite pellets	Iron oxide pigment	NiO powder	Calcined alumina	CuO pigment	TiO_2 pigment
Bulk density (lb/ft³)	116	69	126	50	50	41
Source location	Northern Minnesota	Singapore	Singapore	Vitoria, Brazil	Singapore	Singapore
U.S. Port	NA	Los Angeles	Los Angeles	New York	Los Angeles	Los Angeles
Transport method	NA	Ship (bags in containers)	Ship (bags in containers)	Ship (bulk in containers)	Ship (bags in containers)	Ship (bags in containers)
Cost of sea transport ($/lb)	NA	0.05	0.05	0.05	0.05	0.07
Plant location	Chicago, IL	Chicago, IL	Chicago, IL	Chicago, IL	Chicago, IL	Chicago, IL
Land transport method	Rail (bulk)	Rail (containers)	Rail (containers)	Rail (containers)	Rail (containers)	Rail (containers)
Cost of land transport ($/lb)	0.006	0.02	0.02	0.01	0.02	0.02
Total transport cost ($/lb)	0.006	0.07	0.08	0.06	0.08	0.09

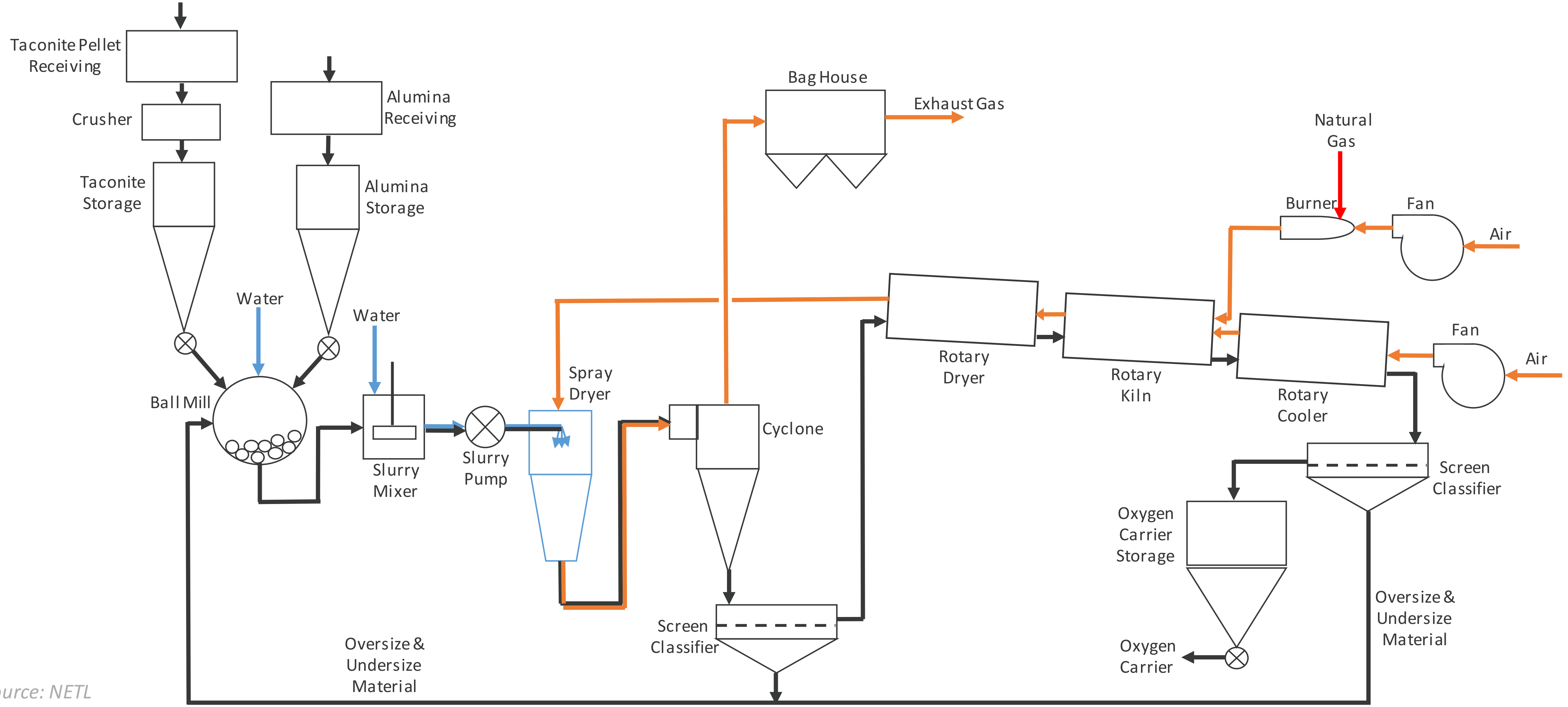
- **Standard 20-ft containers used (TEU) = 1,172 ft³**
- **Transport cost varies with bulk density (volume transported) and value of shipment (insurance)**
- **Taxes and duties not included**

Step 6: Production Facility Descriptions

- Raw material receiving and storage equipment
- Production plant solids handling and processing equipment train
- Product storage equipment
- Emissions control equipment (particulate, and maybe NO_X)
- Auxiliary equipment (fans, pumps, burners, and control and instrumentation)

Step 6: Production Facility Descriptions

Mechanical Mixing Process: Taconite-based Fe_2O_3-Al_2O_3 OC



Source: NETL

Step 7: Material & Energy Balances

- **Set design basis (OC production rate, raw material compositions, processing steps, operating conditions, and exposure times)**
- **Set production facility equipment performance assumptions**
- **Compute material and energy balances**
  - Stream flows and stream compositions
  - Auxiliary power
  - Heating duties
  - Cooling duties
  - Chemical feed rates
  - Waste stream flow rates
  - OC material loss rate estimates

Step 7: Material & Energy Balances

Material & Energy Balances for Base Plant

Base Plant: Mechanical Mixing with Design OC Production of 2,960 lb/hr (0.6% of coal feed rate)

OC Type	Fe_2O_3-Al_2O_3	Fe_2O_3-Al_2O_3	NiO-Al_2O_3	CuO-TiO_2	Fe_2O_3-CuO-Al_2O_3	Fe_2O_3-CuO-Al_2O_3
OC Composition (wt%)	Taconite 45 Alumina 55	Fe_2O_3 45 Alumina 55	NiO 45 Alumina 55	CuO 50 TiO_2 50	CuO 30 Taconite 30 Al_2O_3 40	CuO 30 Fe_2O_3 30 Al_2O_3 40
Raw materials (lb/hr)	Taconite 1,332 Alumina 1,628	Fe_2O_3 pigment 1,332 Alumina 1,628	NiO powder 1,332 Alumina 1,628	CuO pigment 1,480 TiO_2 pigment 1,480	CuO pigment 888 Taconite 888 Alumina 1,184	CuO pigment 888 Fe_2O_3 pigment 888 Alumina 1,184
Burner air feed rate (lb/hr)	6,400	6,400	6,400	6,400	6,400	6,400
Cooling air feed rate (lb/hr)	8,000	8,000	8,000	8,000	8,000	8,000
Exhaust gas rate (lb/hr)	20,886	20,886	20,886	20,523	20,523	20,523
Exhaust gas temperature (˚F)	179	179	179	179	179	179
Auxiliary power (kW)	87	86	86	71	89	88
Process water (lb/hr)	6,167	6,167	6,167	6,167	6,167	6,167
Natural gas (lb/hr)	320	320	320	320	320	320

Step 8: Production Facility Capital Cost

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Base Plant Capital Cost Breakdown

Base plant: Mechanical Mixing with Design OC Production of 2,960 lb/hr (0.6% of coal feed rate) (June 2011$)

OC Type	Taconite-Alumina & Fe_2O_3-Alumina	NiO-Alumina	CuO-TiO_2	CuO-Taconite-Alumina & CuO-Fe_2O_3-Alumina
Material receiving	798	798	799	923
Taconite crusher & ball mill	198	194	194	197
Slurry tank, spray dryer & cyclone	1,360	1,360	1,328	1,360
Spray dryer classifier	100	100	100	100
Solids dryer stage	486	417	396	507
Induration stage	707	606	582	738
Solids cooler stage	422	362	337	441
Solids product classifier	102	102	102	102
Air fans & exhaust bag house	92	92	91	92
Product storage	135	135	129	140
Instrumentation & Controls	132	125	122	138
Total installed cost, BEC ($1,000)	**4,533**	**4,291**	**4,179**	**4,737**
Total plant cost, TPC ($1,000)	**6,769**	**6,408**	**6,241**	**7,074**

Step 9: OC Makeup Cost/Price

- **The OC production plant applies some operating cost premises identical to the CLC power plant premises and some tailored to the facility**
  - Number operators per shift: 2
  - Labor rate: 39.7 $/hr
  - Capital recovery factor: 0.124
  - Natural gas price: 6.13 $/MMBtu
  - Electricity price: 0.15 $/kWh
  - Zero waste disposal cost
  - Capacity factor: 76.5%
  - Product material loss rate: 3 wt%

Step 9: OC Makeup Cost/Price

Minimum and Maximum Oxygen Carrier Costs for Base Plant

Base plant: Mechanical Mixing with Design OC Production of 2,960 lb/hr (0.6% of coal feed rate) (June 2011$)

Oxygen Carrier	Ilmenite	Taconite-Alumina	Fe_2O_3-Alumina	NiO-Alumina	CuO-TiO_2	Taconite-CuO-Alumina	Fe_2O_3-CuO-Alumina
TOC* ($1,000)	3,732–5,276	9,624–10,966	11,562–14,700	30,639–81,750	18,611–26,851	12,016–14,790	13,309–17,279
Total raw material cost ($/lb)	0.16–0.25	0.11–0.19	0.23–0.43	1.45–4.65	0.66–1.14	0.22–0.38	0.30–0.54
Capital recovery ($/lb)	0.019–0.027	0.06–0.07	0.07–0.09	0.20–0.53	0.12–0.17	0.08–0.10	0.09–0.11
Variable cost ($/lb)	0.005–0.008	0.03–0.03	0.03–0.03	0.07–0.17	0.04–0.06	0.03–0.04	0.03–0.04
Fixed cost ($/lb)	0.001–0.001	0.07–0.07	0.07–0.07	0.07–0.07	0.07–0.07	0.07–0.07	0.07–0.07
OC price ($/lb)	**0.19–0.29**	**0.27–0.36**	**0.41–0.63**	**1.79–5.41**	**0.89–1.43**	**0.40–0.58**	**0.49–0.76**

*Total overnight cost (TOC) includes cost of initial fill of OC plus three months of OC consumption cost

Step 9: OC Makeup Cost/Price

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Minimum and Maximum Oxygen Carrier Costs for Base Plant
Base plant: Co-precipitation with Design OC Production of 2,960 lb/hr (0.6% of coal feed rate) (June 2011$)

Oxygen Carrier	Fe_2O_3-Al_2O_3	CuO-TiO_2
TOC* ($1,000)	64,781–83,676	48,575–74,738
Total raw material cost ($/lb)	1.82–2.96	1.90–3.51
Capital recovery ($/lb)	0.42–0.54	0.31–0.48
Variable cost ($/lb)	0.30–0.34	0.14–0.19
Fixed cost ($/lb)	0.10–0.10	0.08–0.08
OC price ($/lb)	**2.64–3.94**	**2.43–4.26**

*Total overnight cost (TOC) includes cost of initial fill of OC plus three months of OC consumption cost

Step 9: OC Makeup Cost/Price (cont'd)

Mechanical Mixing

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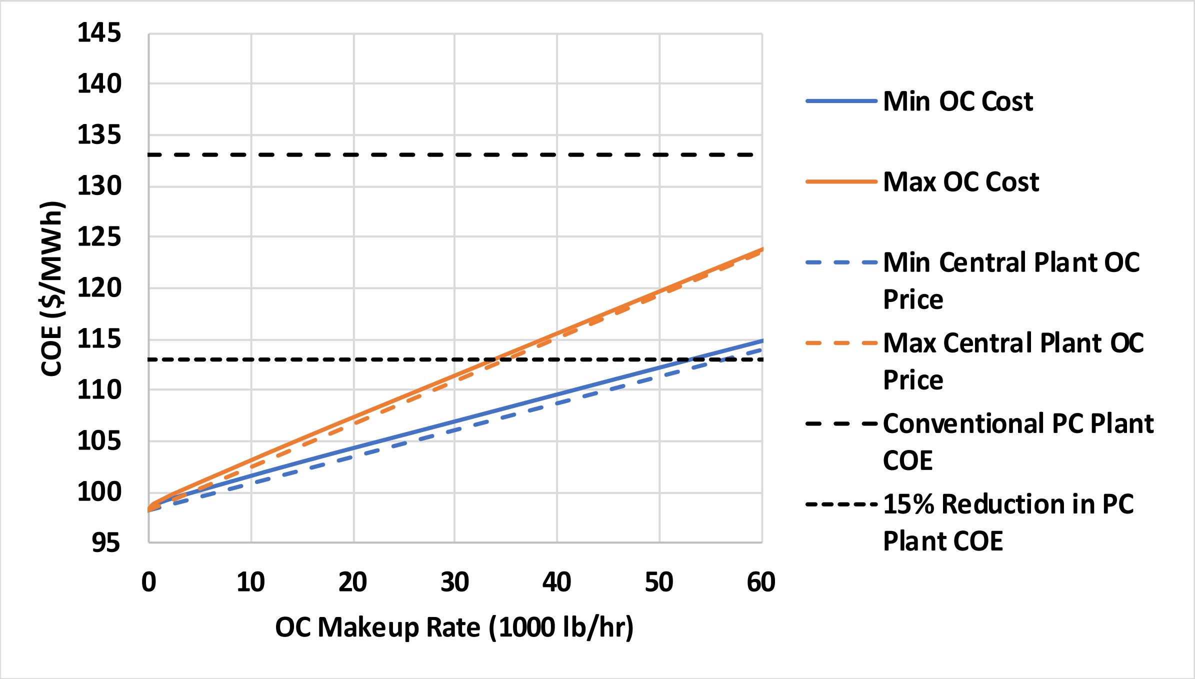
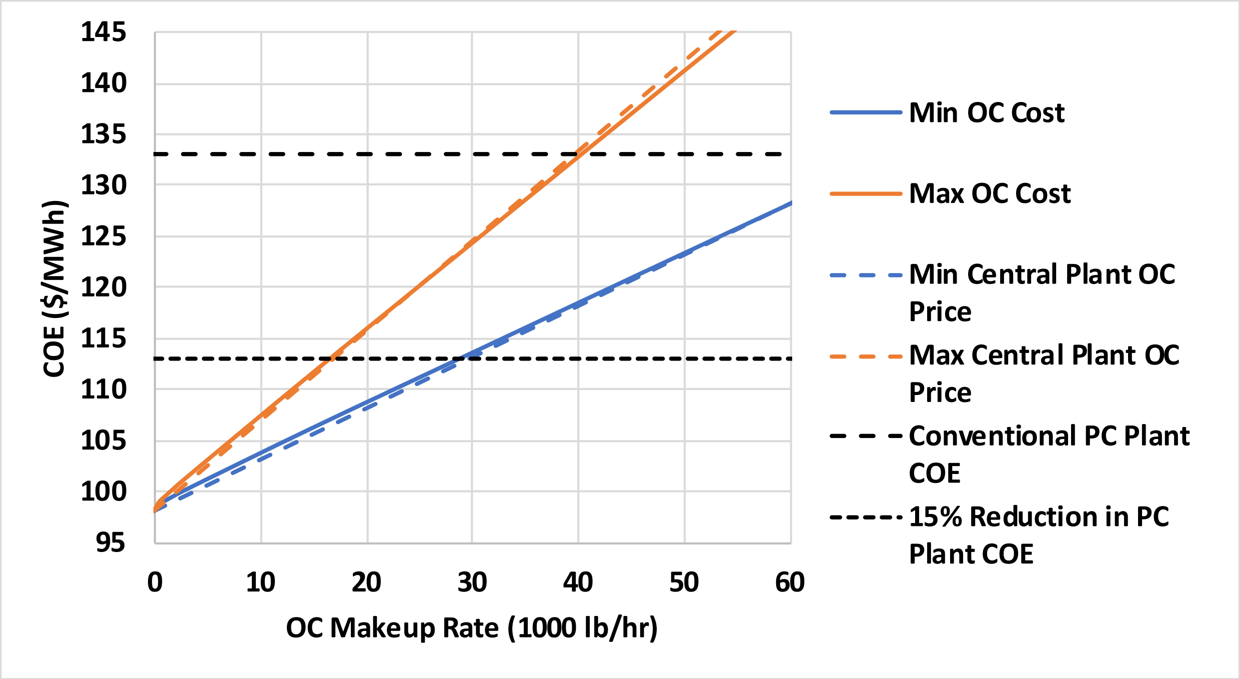
Taconite-Alumina OC



Fe_2O_3-Alumina OC



There is slight to no COE advantage for a central production plant over localized plants

Source: NETL

Conclusions

- OC raw materials to support a CLC power plant industry must be available on an order of ≥ 1 million mt/yr
- Raw materials for commercial OC production will need to be imported (except for taconite); transport costs (with fees and taxes) need to be included
- Raw material costs represent a major portion of the OC production cost and may fluctuate with time and market conditions
- There is little to no advantage for central OC production over individual, localized production facilities
- The costs of OCs produced by mechanical mixing are much lower than those produced by co-precipitation and related wet methods that utilize water-soluble raw materials

Stay tuned…

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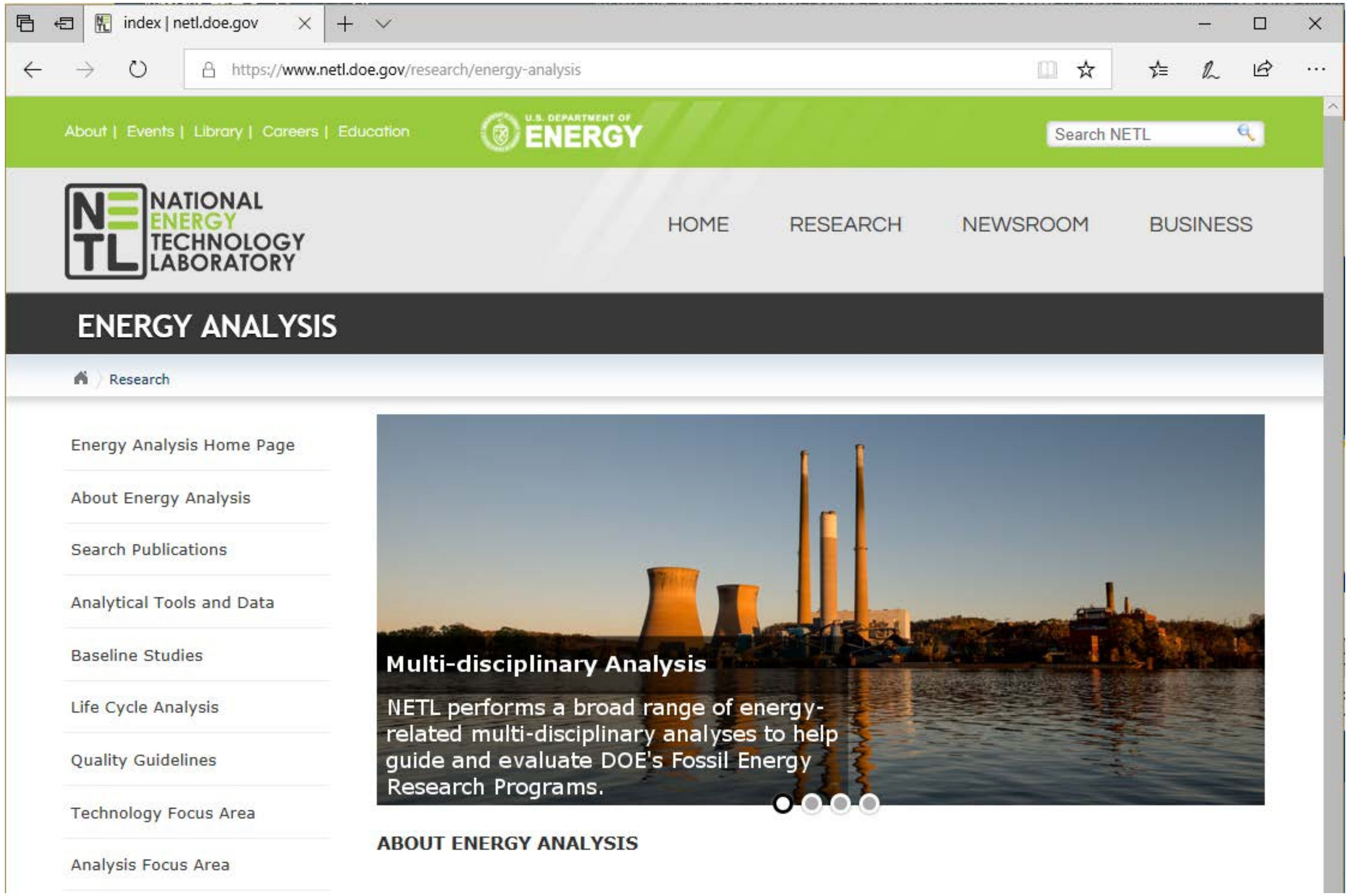
http://www.netl.doe.gov/research/energy-analysis



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