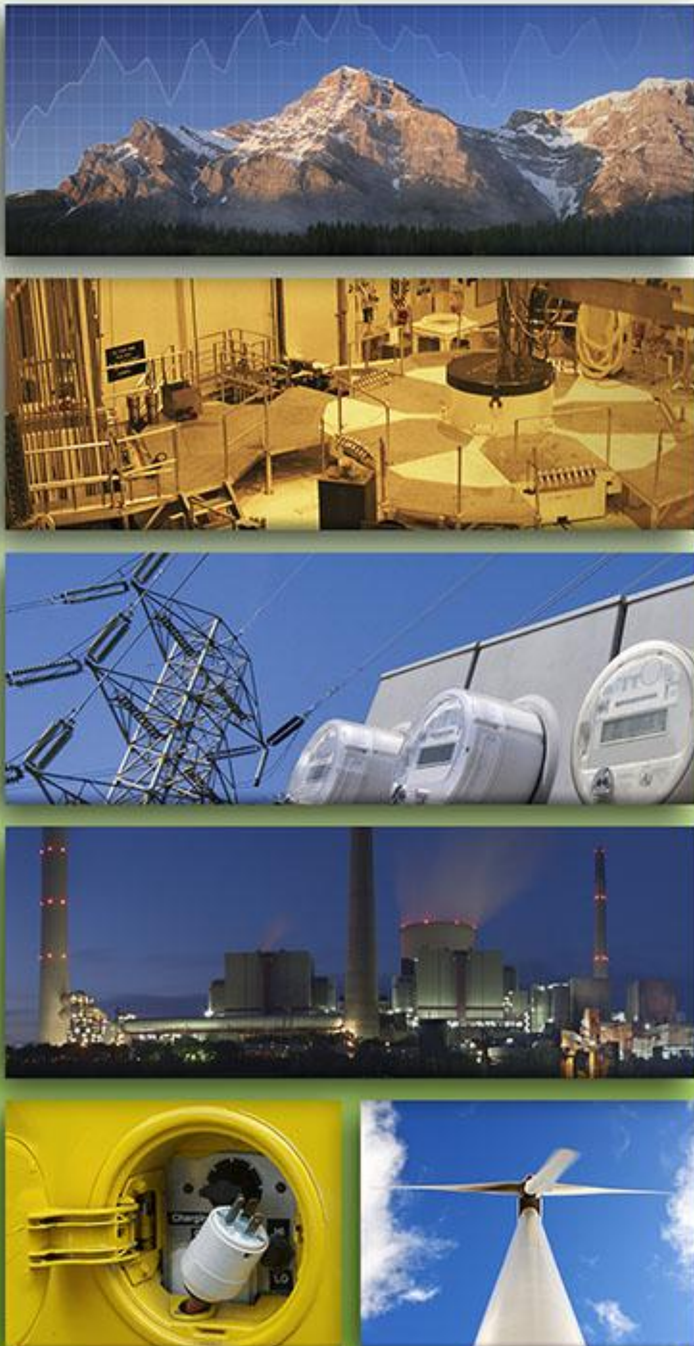

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Oxy-Coal for Electric Power Generation: Status and Prospects

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McIlvaine Oxy-fuel Combustion Update
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Why would an Electric Utility Consider Oxy-Coal?

Oxy-coal is only relevant to electric utilities if there is a specific cost associated with emitting CO_2 or value for capturing CO_2 .

- CO_2 capture from an oxy-coal plant does not seriously impact design or operation of the steam-electric power cycle.
- Unfamiliar power plant systems (Air Separation Unit, CO_2 Purification Unit) employ physical processes. Components of these systems are familiar to power plant operators: rotating machinery and heat exchangers.
- No need to inventory chemicals for the absorption processes associated with pre- and post-combustion capture. No air emissions of these.

Cost-Cost-Cost will be determinative!

Preliminary Look at Comparative Costs for CO_2 Capture

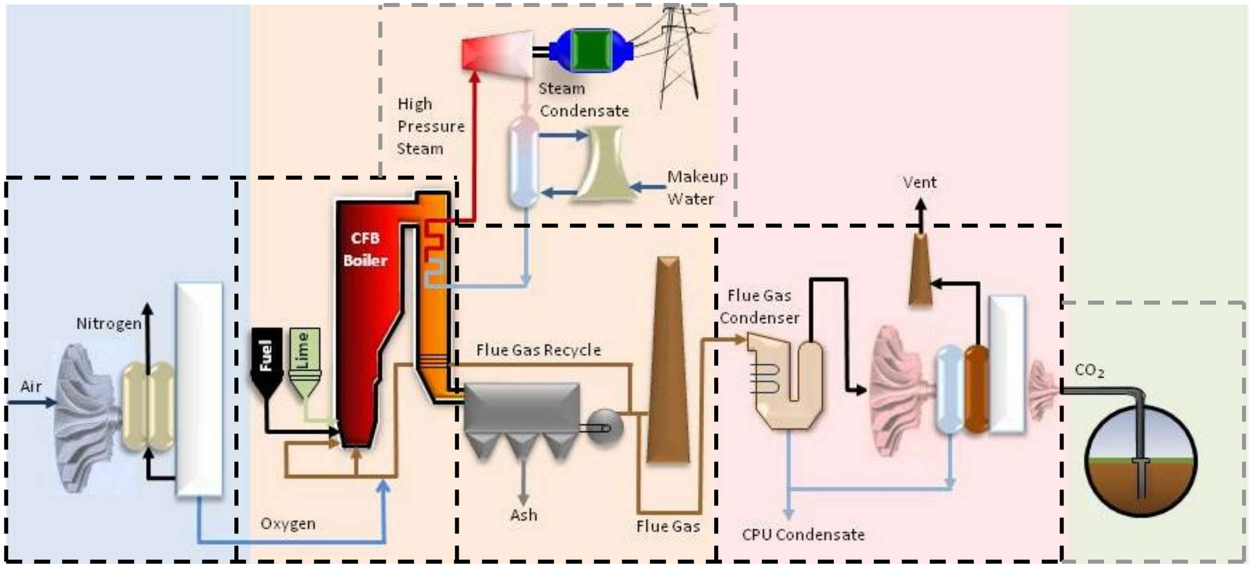
- The most definitive comparative cost study to date was done by Worley Parsons for USDoE (2008 update) with a follow-up for GCCSI (2009).
- Three broad CO_2 capture options:
  - Pre-combustion CO_2 capture (IGCC)
  - Post-combustion CO_2 capture (USC steam cycle)
  - Oxy-coal with CO_2 purification (USC steam cycle)

- Conclusion: Oxy-coal COE and cost of avoided CO_2 emissions are incrementally lower than costs for either pre- or post-combustion capture.

Caveats:

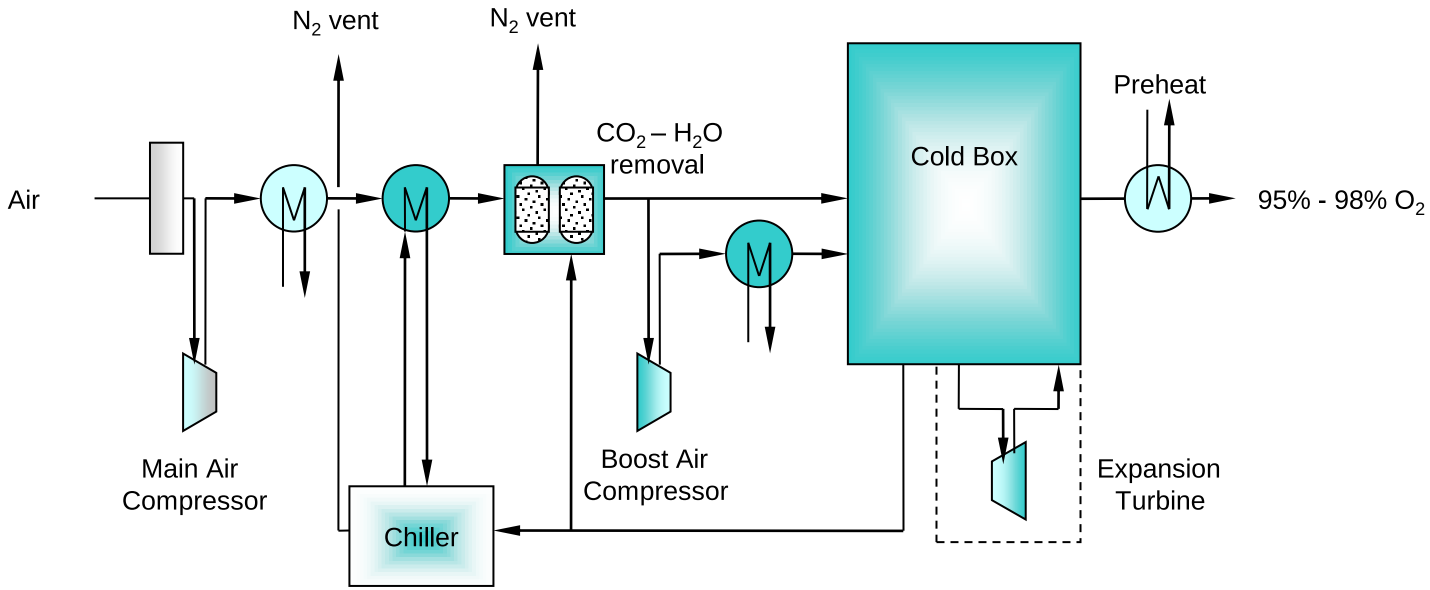
- *Oxy-coal COE and cost of avoided CO_2 emissions are sensitive to design basis CO_2 purity.*
- *Considerable oxy-coal flow sheet development has occurred since the original studies.*

Oxy-Coal Technology Modules



- Air Separation Unit (ASU)
- Steam generator
- Steam turbine cycle / electrical generator
- Air Quality Control System (AQCS, including flue gas recycle)
- CO_2 Purification Unit (CPU)
- CO_2 Storage

Air Separation Unit



- Full Scale Module Capacity: 5,000 t/day
- Product O_2 Purity: 95–98%
- Delivery Pressure: 10 psig (1.7 bar)
  130 psig (10 bar)

Delivery of large O_2 volumes with indicated purity at low pressure is a new wrinkle on air separation technology.

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Steam Generator

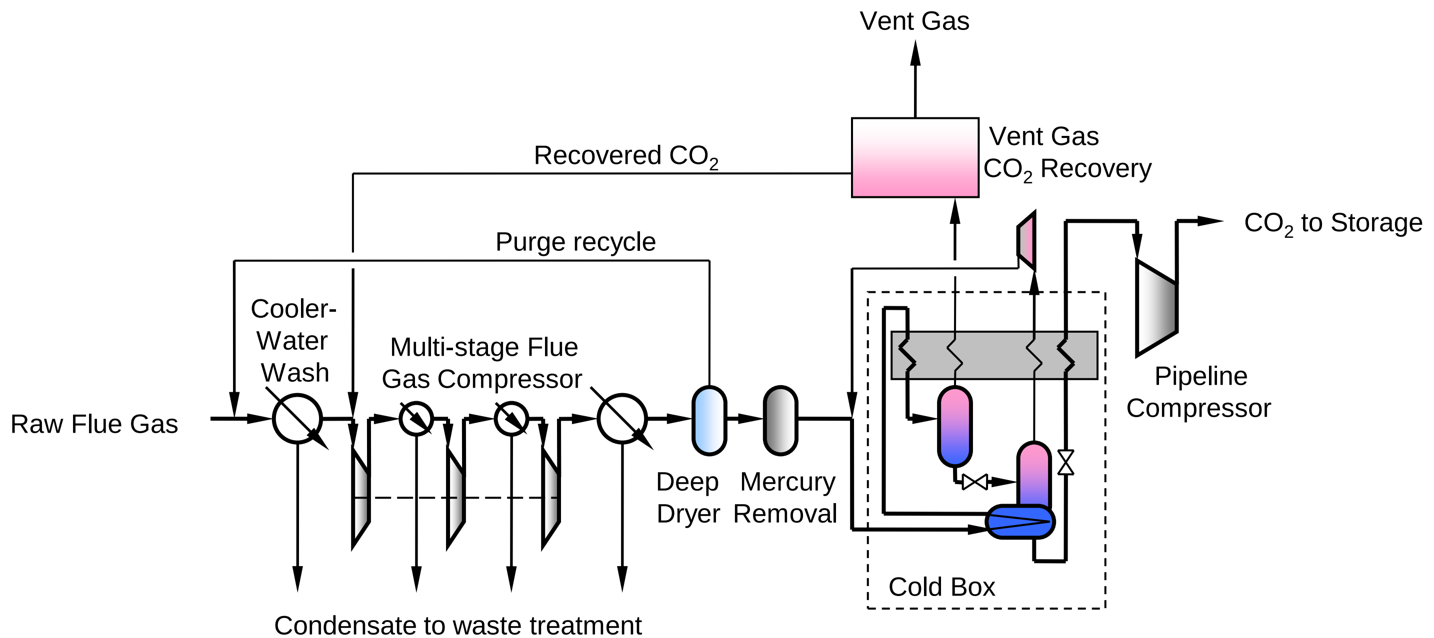
- Oxy-PC Combustion
- Oxy-CFB Combustion
- Pressurized Oxy-Combustion (10 bar)

- Includes:
  - Coal preparation/feed
  - Limestone preparation/feed (for CFB)
  - Burner technology
  - O_2/flue gas recycle mixing
  - Steam/water heat exchange surface
  - Air/recycle heater

Air Quality Control System

- NO_X
  - Inherently lower than air-fired coal units; minor thermal NOx production along with reburning NO_X in recycle flue gas
  - Staged combustion / low-NO_X burners likely to be adequate for oxy-coal operations.
  - Polishing removal in the warm end of CPU
  - SCR (for PC) and SNCR (for CFB) may be required if air-fired operation is part of the plan.
- SO_2
  - Furnace limestone addition / Spray-dryer absorption (for CFB)
  - Wet FGD (for PC) May need to be put inside the recycle loop if high S coal is fired.
  - Polishing Removal in the warm end of CPU
- Particulate Matter
  - ESP
  - Fabric filter (baghouse)

CO_2 Purification Unit



- Warm End
  - Flue gas cooling/water wash
  - SO_X/NO_X removal during compression
- Cold Box (if required)
  - Full scale will use liquid CO_2 as the refrigerant
  - Cold box design vs. required CO_2 purity
- Vent Gas CO_2 Recovery
  - Membrane
  - Adsorbent
- Pipeline compression

CPU design will be a strong function of design basis CO_2 purity specification.

Scope of Full-Scale Oxy-Coal Power Plant

- Electrical Capacity: 800 MWe (gross)
  ~ 600 MWe (net)
- Thermal Input: ~ 1,800 MWth (USC steam cycle)
- ASU Capacity: ~ 11,800 t/day (3 x 4000 t/day)
- CPU Capacity: ~ 17,200 t/day (4 x 4500 t/day)

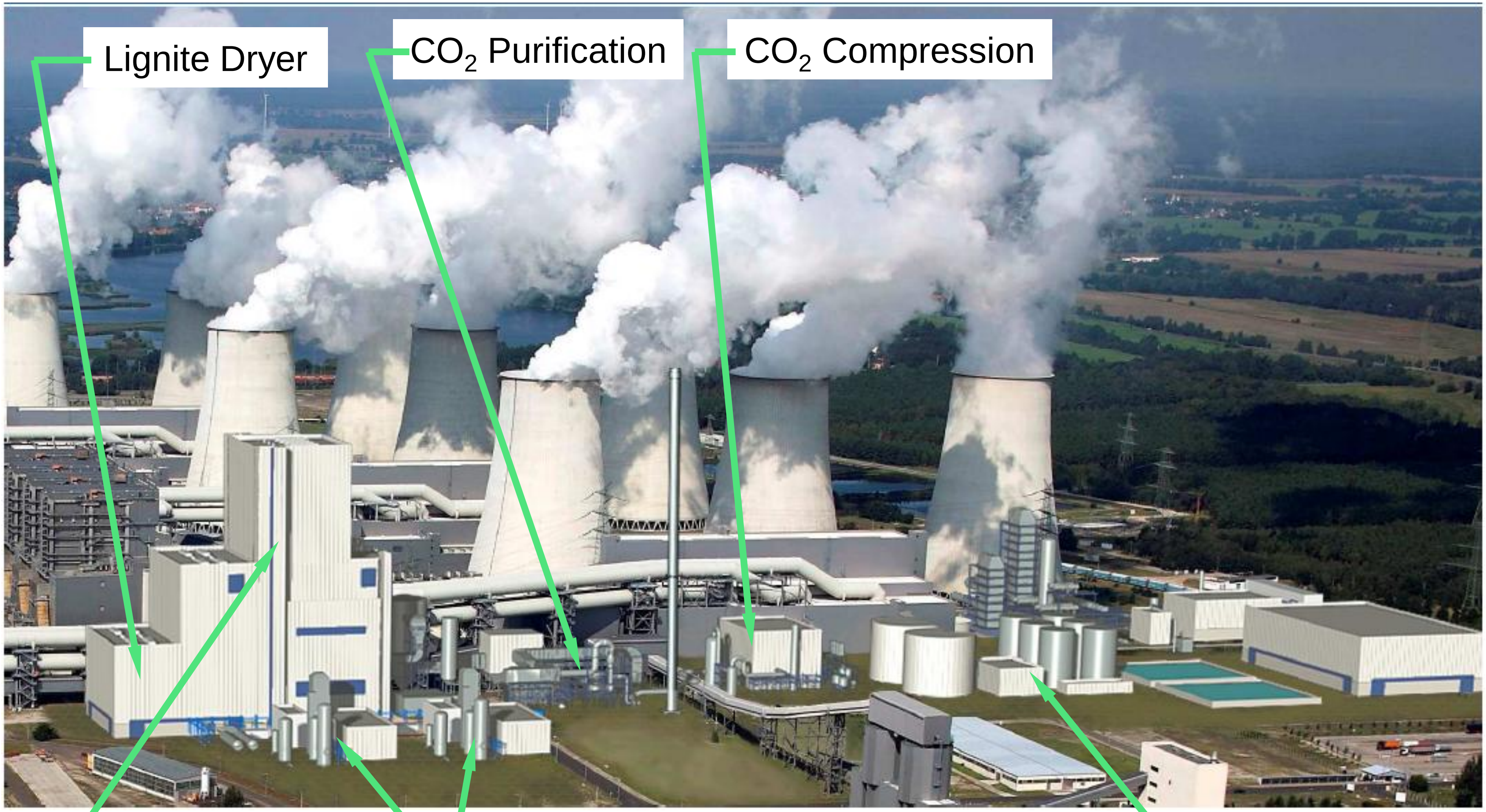
This scale is typical of the coal-fired power plants that electric utilities have purchased in the last few years.

Commercial Pilot Plants* in Planning

Project, Utility	Location	Electrical Output (Oxy, net)	In Service
Jänschwalde, Vattenfall	Peitz, Germany	250 MWe (40% full scale)	2015
Compostilla, Endesa	El Bierzo, Spain	300 MWe (50% full scale)	2015
Yong Dong, KOSEP	South Korea	100 MWe (17% full scale)	2018
Meredosia #4, Ameren	Meredosia, Illinois	200 MWe (33% full scale)	2015

**Commercial Pilot Plant: >25% full scale, revenue generation*

Proposed Commercial Pilot Plant: 250 MWe Oxy-PC Boiler at Vattenfall Jänschwalde



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Cost pushing €1,000 million

Oxy-Coal Pilot Plants* in Service or in Construction

Project, Utility	Location	Thermal Output	ASU	In Service
ITEA	Gioia del Colle, Italy	5 MWth (10%@4 bar)	LO_2	**2006**
Jupiter Oxygen	Hammond, IN	15 MWth (30% – PC)	(3%)	**2006**
B&W	Alliance, OH	30 MWth (60% – PC)	LO_2	**2008**
Schwarze Pumpe, Vattenfall **	Schwarze Pumpe, Germany	30 MWth (60% – PC)	(6%)	**2009**
Oxy-Coal UK, Doosan Power	Renfrew, Scotland	40 MWth (80% – PC)	LO_2	**2009**
Alstom	Windsor, CT	15 MWth (1% – T-fired)	LO_2	**2009**
Callide A, CS Energy **	Biloela, Australia	80 MWth, 25 MWe	(2x8%)	**2010**
CIUDEN **	El Bierzo, Spain	20 MWth – PC (40%) 30 MWth – CFB (2%)	**LO_2**	**2010** **2011**
Enel	Brindisi, Italy	48 MWth (100%@10 bar)	O_2 (g)	**2012**

** Pilot Plant: >5% full scale, little or no revenue generation*

*** Pilot Plants integrating a CO_2 Purification Unit*

Numerous university process development unit - scale and flow sheet design studies are in progress

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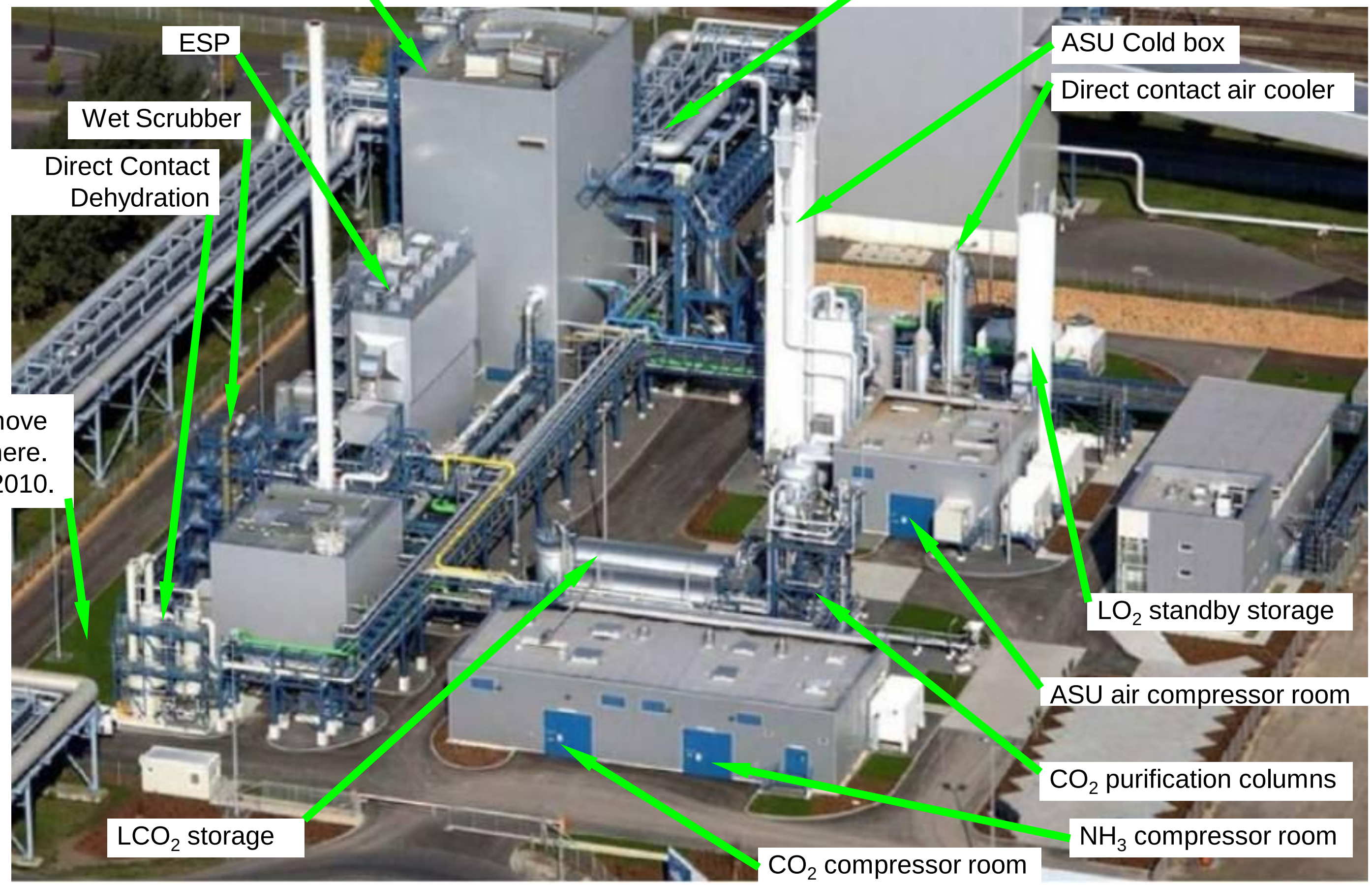
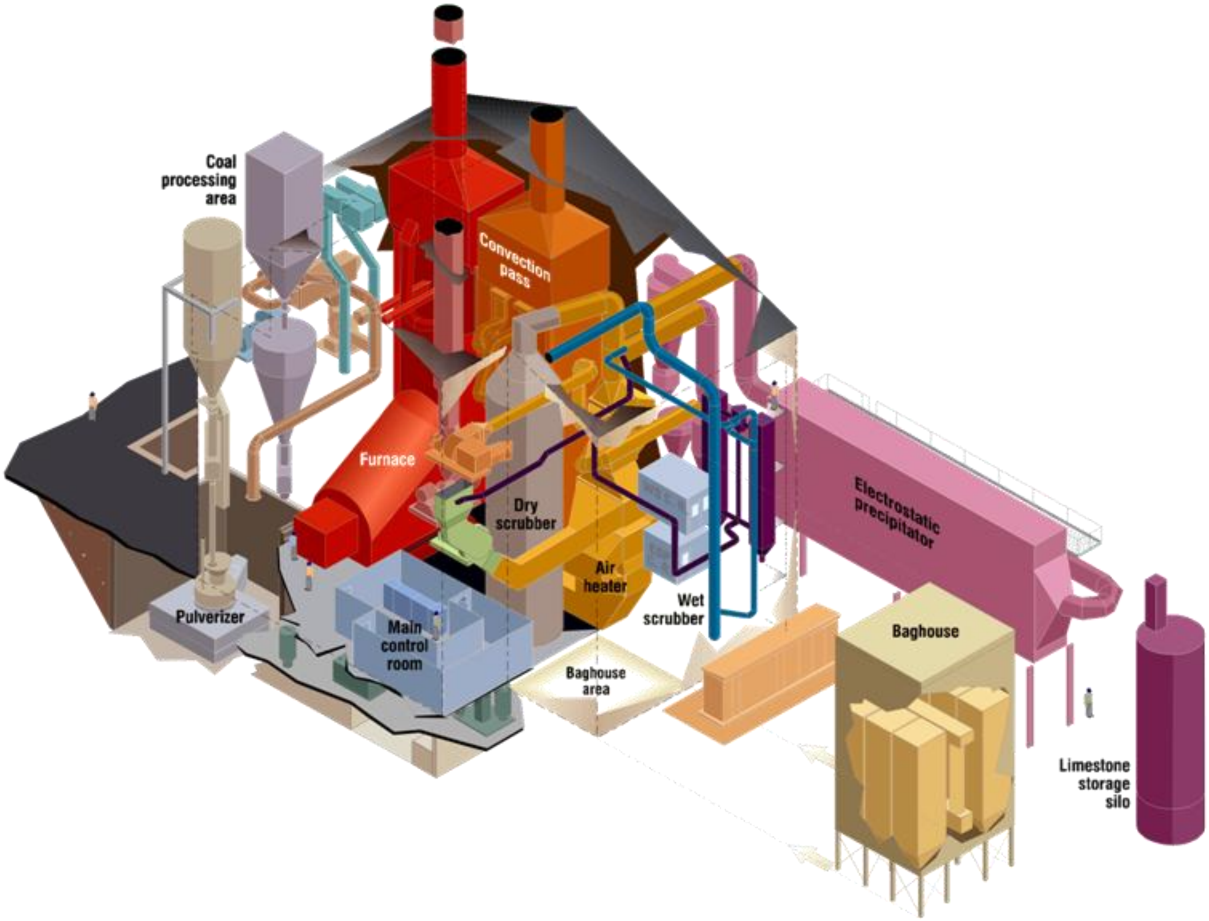
Vatenfall's Schwarze Pumpe Oxy-PC Pilot Plant in support of Jänschwalde



Cost > €80 million

B&W's 30 MWth Burner Test Facility



Operations focused on combustion, heat transfer and Air Quality Control Systems

Challenges for Oxy-Coal Development and Deployment

- **Oxy-coal is only relevant to electric utilities if there is a specific cost associated with emitting CO_2 or value associated with capturing CO_2.**
- No realistic way to do incremental development of oxy-coal with CCS. (Pre- and post-combustion CO_2 capture can be developed incrementally by treating flue gas slipstreams.)
- Commercial Pilot Plant projects are required to advance oxy-coal technology. Capex for these push ~$1 billion. Similar projects for pre- and post-combustion CO_2 capture cost half this, still significant money.
- In order for a commercial project to proceed in 2020, at least two commercial pilot plant projects need to be underway through one maintenance cycle. During these operations, significant Opex associated with CO_2 capture (ASU and CPU power use) is incurred.
- Refer to bullet #1 above. Absent a clear public policy that rewards CO_2 capture and storage, utilities are highly unlikely to incur the Capex and Opex associated with oxy-coal/CCS plants.

Improving Oxy-Coal (for Full Scale Deployment Beyond 2020)

- Achieve criteria pollutant emissions sufficient low to permit the plant as a “minor source”.
- Reduce steam generator size (cost) by reducing flue gas recycle. CFBs may be particularly suitable for this.
- Conduct oxy-coal combustion and heat transfer under ~10 atmospheres gas pressure to increase boiler efficiency (reduced latent heat losses).
- Replace the cryogenic ASU with:
  – Effusion membrane separation
  – Ion Transfer Membrane separation
  – Chemical Looping Combustion

Conclusions

- Pilot Plant activity to date has been primarily oriented to oxy-combustion component testing
  - B&W has completed a successful burner test program as have other equipment vendors.
  - Schwarze Pumpe pilot plant is underway and has achieved thousands of hours of operation
  - CIUDEN pilot plant is scheduled to start oxy-PC operation in 2010, and oxy-CFB operations in 2011
  - Callide-A plant (25 MWe) has restarted operation with air-firing of coal. Oxy-coal operations will commence late 2010 or early 2011.
- Commercial Pilot Plant operations will not commence before 2015. Four (4) projects are “on the table”, PC and CFB. All are awaiting finalization of their funding plans before receiving the “green light” to go.
- Successful operation of multiple Commercial Pilot Plants through one maintenance cycle are likely needed to pave the way for the 1st Full-Scale Commercial Plant in 2020.
- There are opportunities for improving oxy-coal technology (lower cost / higher efficiency) beyond that envisioned for commercial deployment in 2020.

Questions?

Together…Shaping the Future of Electricity

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