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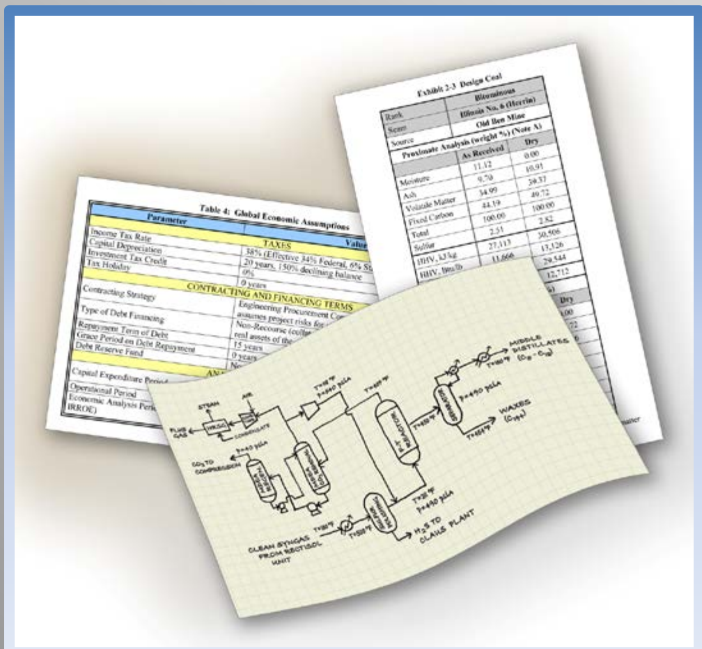

Emerging Technologies and the Changing Nature of Electrical Power Generation

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Regulations Related to Fossil Fueled Power Plants

- **Lowering emissions limits for SO_2, NO_X, particulates, Hg, etc.** requires new and upgraded emissions controls to existing coal plants … or plant retirement.
- **Recent New Source Standards for CO_2 emissions**
  - Coal plant – 1,100 lb_{CO2}/MWh_{gross} (requires CO_2 capture of ~30%)
  - NGCC – 1,000 lb_{CO2}/MWh_{gross} (no controls required because of lower carbon density of natural gas)

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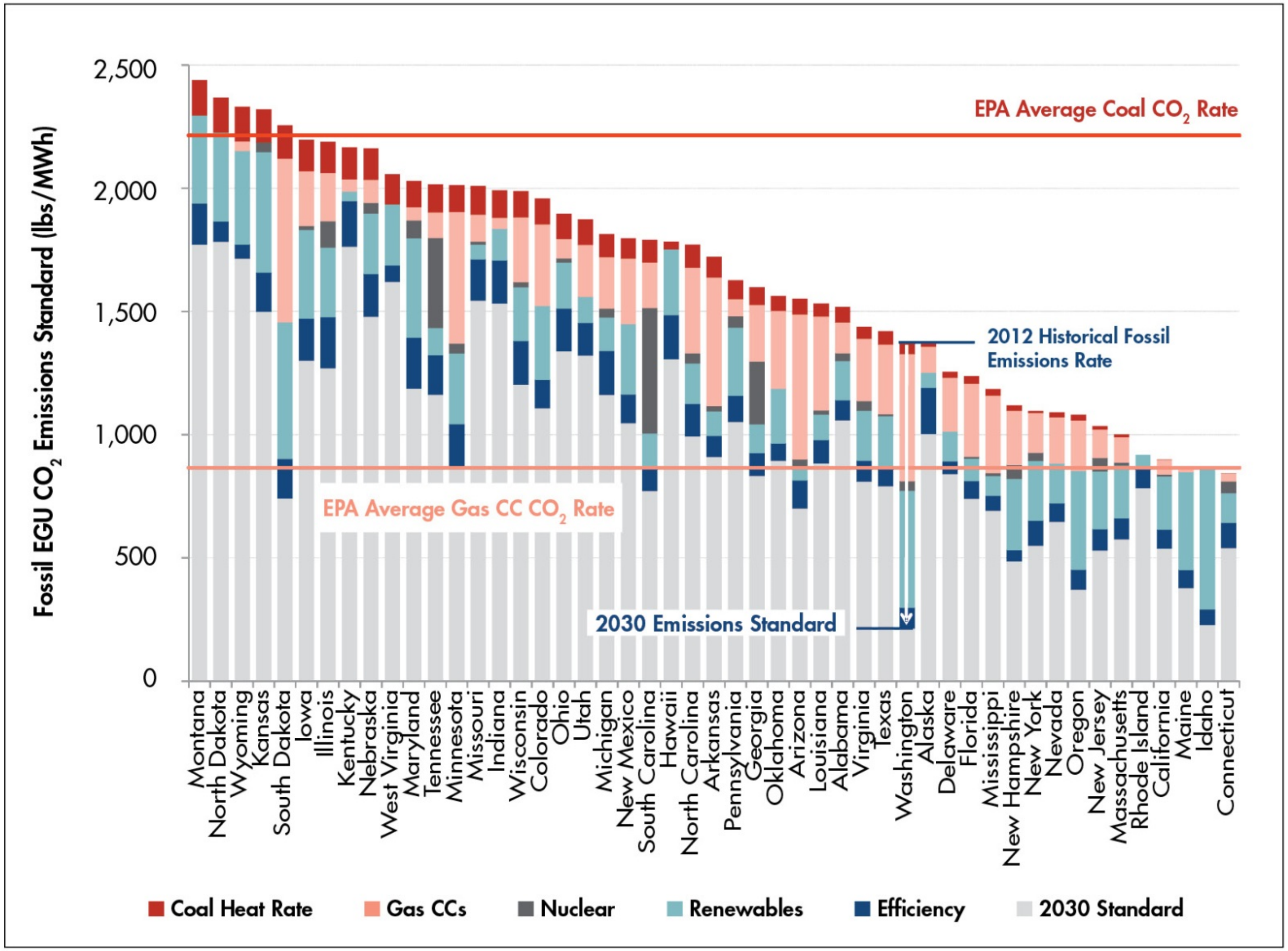
Proposed Existing Source CO_2 Standard

Four step approach to determine the CO_2 emissions limits on a state by state basis

1. **6% heat rate improvement for existing coal units**
2. **Displace existing coal generation with existing gas, up to 70% NGCC annual capacity factor**
3. **Increased renewable capacity/avoiding at-risk nuclear retirements**
4. **Increasing state demand-side efficiency programs**

Source: Grol and Kern, "Discussion of Proposed Existing Source Performance Standard for CO2 Emissions," to be presented at 2014 Pittsburgh Coal Conference

Figure 2: Fossil EGU CO_2 emissions standards by state



Source: The Brattle Group

http://science.house.gov/sites/republicans.science.house.gov/files/documents/ESPS%20Hearing%20Charter.pdf

Changing Landscape of Power Generation

- **Issues for evaluation**
  - ‘Base loaded’ plants are forced to load follow - load following has historically had negative impacts on maintenance cost and emissions as the plants are cycled increasing thermal stress and emissions control system performance suffers under transient conditions
  - With a change in the power generation profile required by the proposed CO_2 emissions regulations, is power available where needed for the existing demand and grid system?
  - Reduction in spinning reserve with addition of renewables can lead to grid stability issues.*

* Power Engineering youtube video - “Grid Stability and the Changing Landscape of Power Generation” - http://www.youtube.com/watch?v=ODFoHHbhiOM grid instability issue

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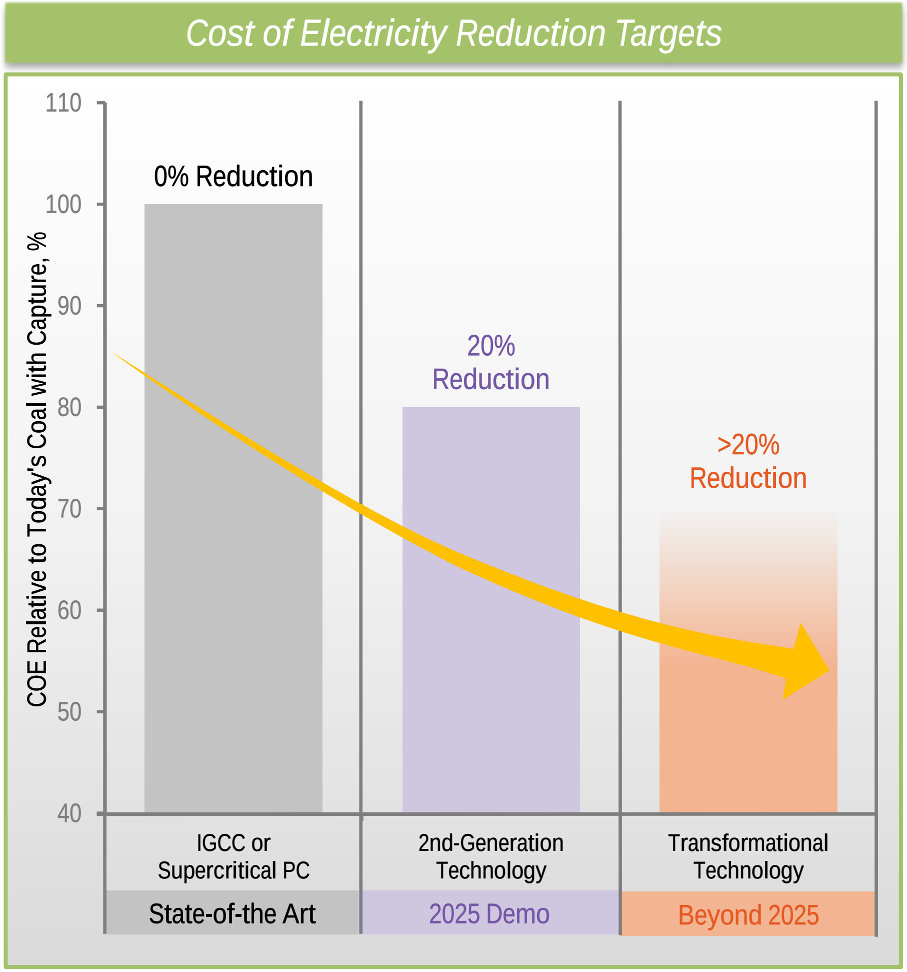
Clean Coal Research Program Goals

Driving Down the Cost of Coal Power with CCS



Goals shown are for greenfield plants. Costs are nth-of-a-kind and include compression to 2215 psia but exclude CO_2 transport and storage costs.

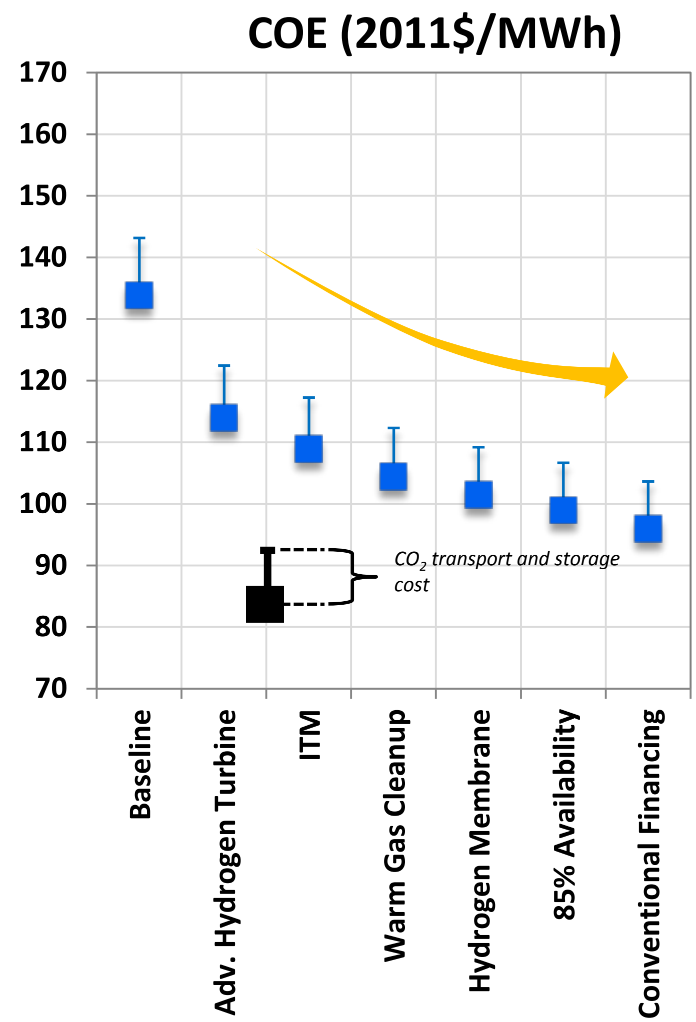
Emerging Power Generation Technologies

Advances to Existing Technologies

- **Advanced ultra-supercritical steam rankine cycles (NETL program goal 1,400 °F and 5,000 psi)**
- **Advanced gas turbine combined cycle (goal is 3100 °F turbine inlet temperature – targeting 63-65% CC efficiency w/o capture)**
- **Advances in IGCC with capture**
  - Oxygen production
  - Warm gas cleanup for particulate, sulfur, mercury removal
  - CO2 separation technologies, e.g. hydrogen membranes
  - Advanced hydrogen turbines

IGCC Pathway

- **2nd Generation**
  - Advanced H_2 turbine (2650F turbine inlet temp)
  - Advanced oxygen membrane
  - Warm gas cleanup (desulfurization)
- **Transformational**
  - H2 Turbine
  - Advanced gasification
    - Chemical looping gasification
    - Compact gasifier
  - Advanced H2 / CO2 separation
  - Direct SCO_2 power cycle



Emerging Power Generation Technologies

New Power Technologies

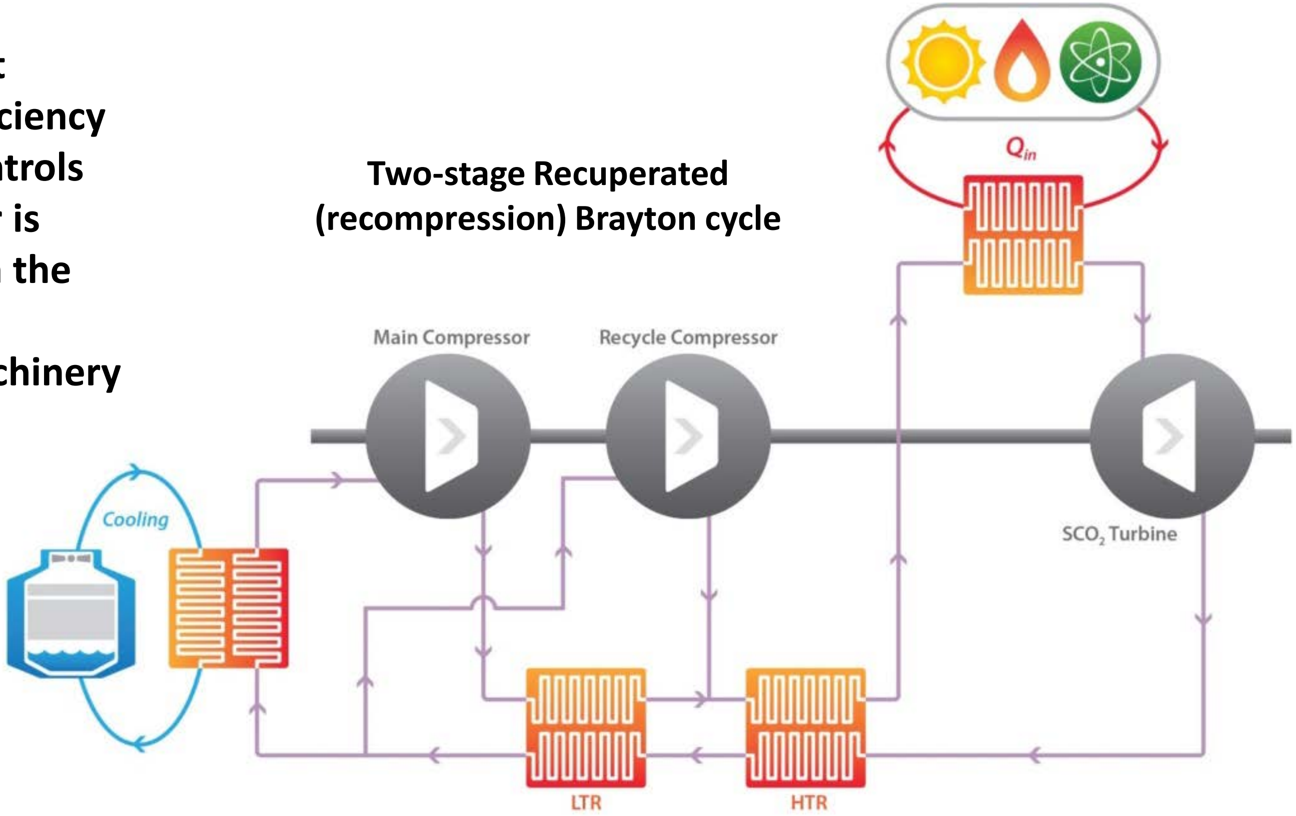
- **Supercritical CO_2**
  - Indirect
  - Direct
- **Chemical Looping (Combustion and Gasification)**
- **Pressurized Oxycombustion**
- **Fuel Cell System**
- **Pressure Gain Combustion (applicable to gas turbines)**
- **Magnetohydrodynamics (MHD) or Direct Power Extraction (DPE)**

SCO_2 Power Cycle
Indirect Heating

Advantages:
- **Suitable for wide spectrum of heat sources**
- **Compact turbomachinery**
- **Single-phase working fluid**

Challenges:
- **Operate near critical point required for optimum efficiency complicates operating controls**
- **Recuperated heat transfer is several times greater than the power output.**
- **Development of turbomachinery**

Two-stage Recuperated (recompression) Brayton cycle



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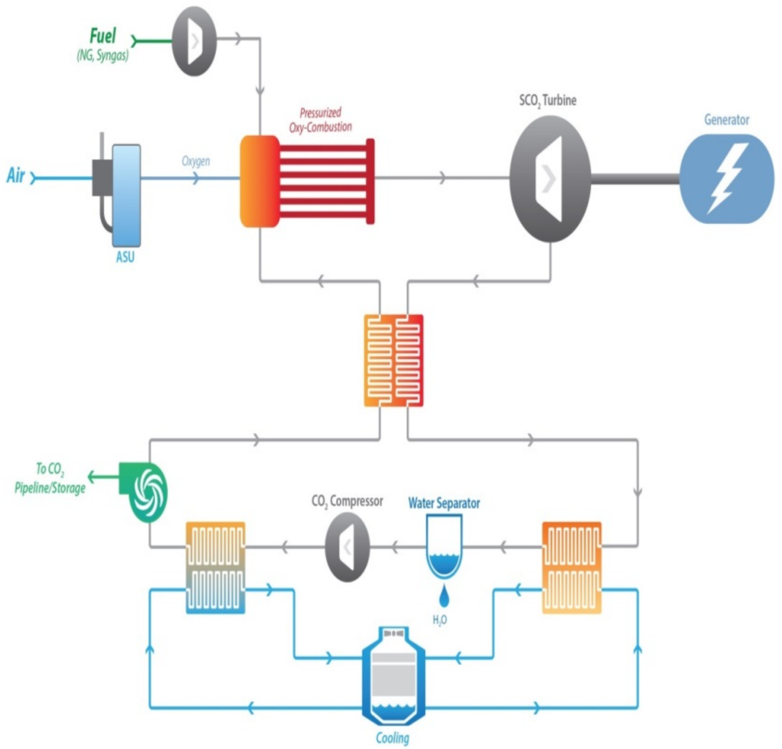
SCO_2 Power Cycle
Direct Heating

Advantages:

- **Flue gas from the pressurized oxycombustor is sent directly to the turbine eliminating the temperature limit imposed by heat exchange through an exchanger**
- **Flue gas stream exiting the turbine is at elevated pressure reducing or eliminating the need for CO2 compressing**
- **Compact turbomachinery**
- **Heat sources are fossil fuel based**

Challenges:

- **Oxycombustion at up to 4,500 psi requires development**
- **Recuperated heat transfer is significant and critical to the cycle efficiency**
- **Development of turbomachinery**



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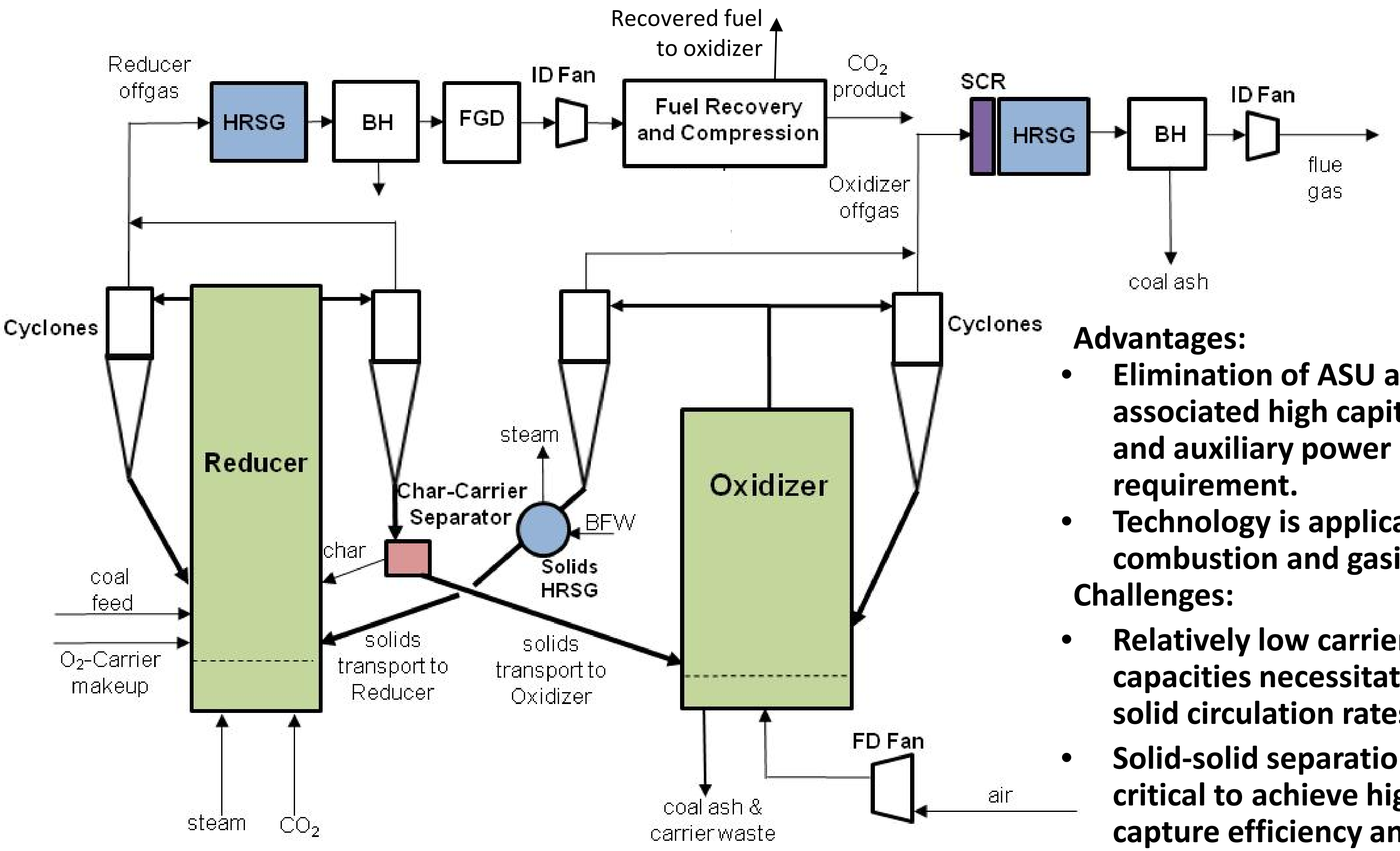
Chemical Looping Combustion



Advantages:

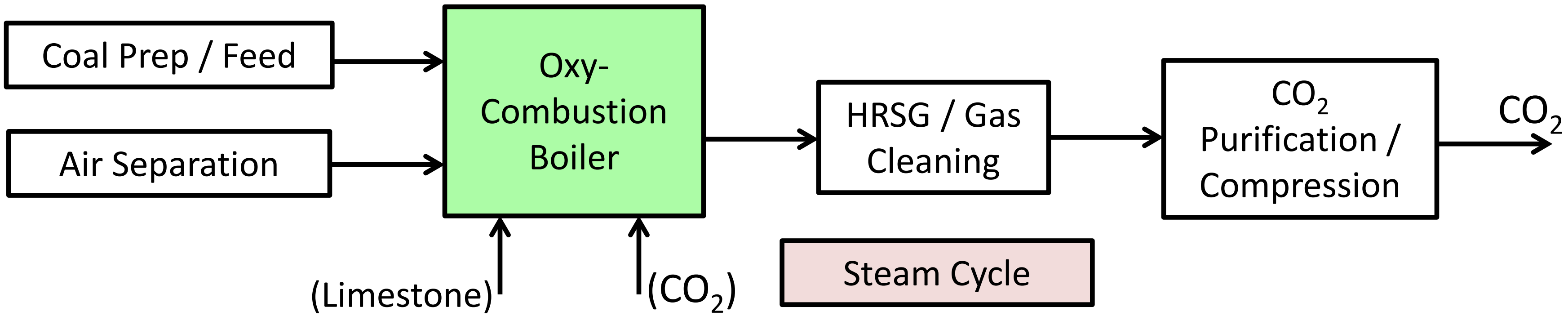
- **Elimination of ASU and associated high capital cost and auxiliary power requirement.**
- **Technology is applicable to combustion and gasification.**

Challenges:

- **Relatively low carrier capacities necessitates large solid circulation rates.**
- **Solid-solid separation is critical to achieve high carbon capture efficiency and efficient carrier utilization.**

Source: NETL

Pressurized Oxy-combustion



Advantages:

- **Operation at elevated pressure minimizes CO2 compression requirements**
- **Operation at elevated pressure enables recovery of latent heat in flue gas**
- **Elevated pressure boiler allows for physically smaller boiler design**

Challenges:

- **CO2 purification**
- **Achieving acceptably high efficiency and low capital cost**
- **Dry coal feed**

IGFC Systems

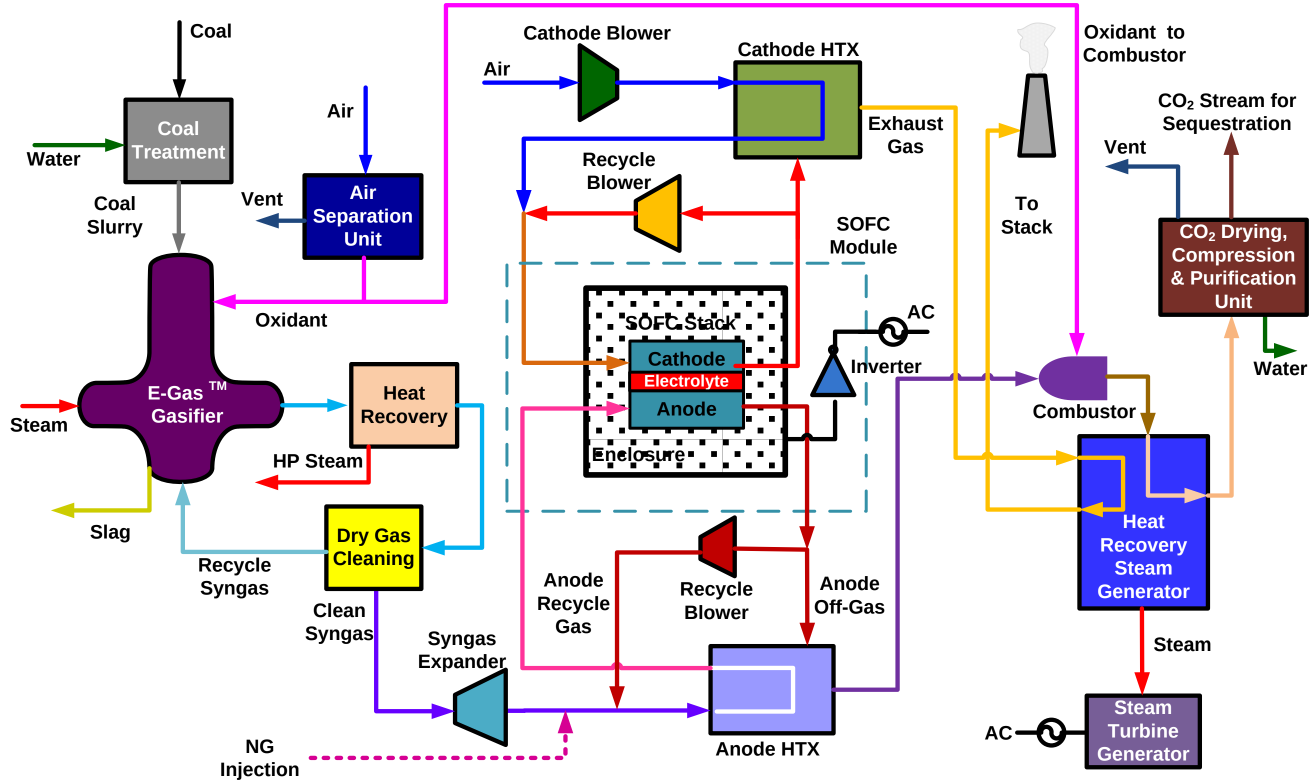
Process Diagram - Atmospheric

Advantages:

- High efficiency potential

Challenges:

- Fuel cell degradation
- Cost
- Inverter efficiency



Source: NETL

Pressure Gain Combustion

Advantages:

- **Utilizes explosive combustion to produce pressure gain simultaneously with heat generation**
- **Use in the combustor of a gas turbine would enable elimination of last compressor stages and associated power consumption.**

Challenges:

- **Demonstrating the concept in continuous operation**
- **Combustor wall cooling**
- **Intake valves with no moving parts and minimal pressure drop**

Acknowledgements

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Questions

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