Life Cycle Metrics for Comparing Alternative Electricity Generating Technologies

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The Electricity Debate

EU Greenhouse Emissions Up Second Year in a Row
– *THE ELECTRICITY DAILY* (May 14, 2003)

STUDY TOUTS NUCLEAR POWER AS WAY TO SLOW GLOBAL WARMING
– *THE BOSTON GLOBE* (July 30, 2003)

Free as the wind but not too cheap
– *Financial Times(London)* (July 19, 2003)

China's city-swamping Three Gorges dam project
– *The Times(London)* (May 31, 2003)

Power plant debate pits clean air, cheap electricity
– *The Atlanta Journal and Constitution*(September 11, 2001)

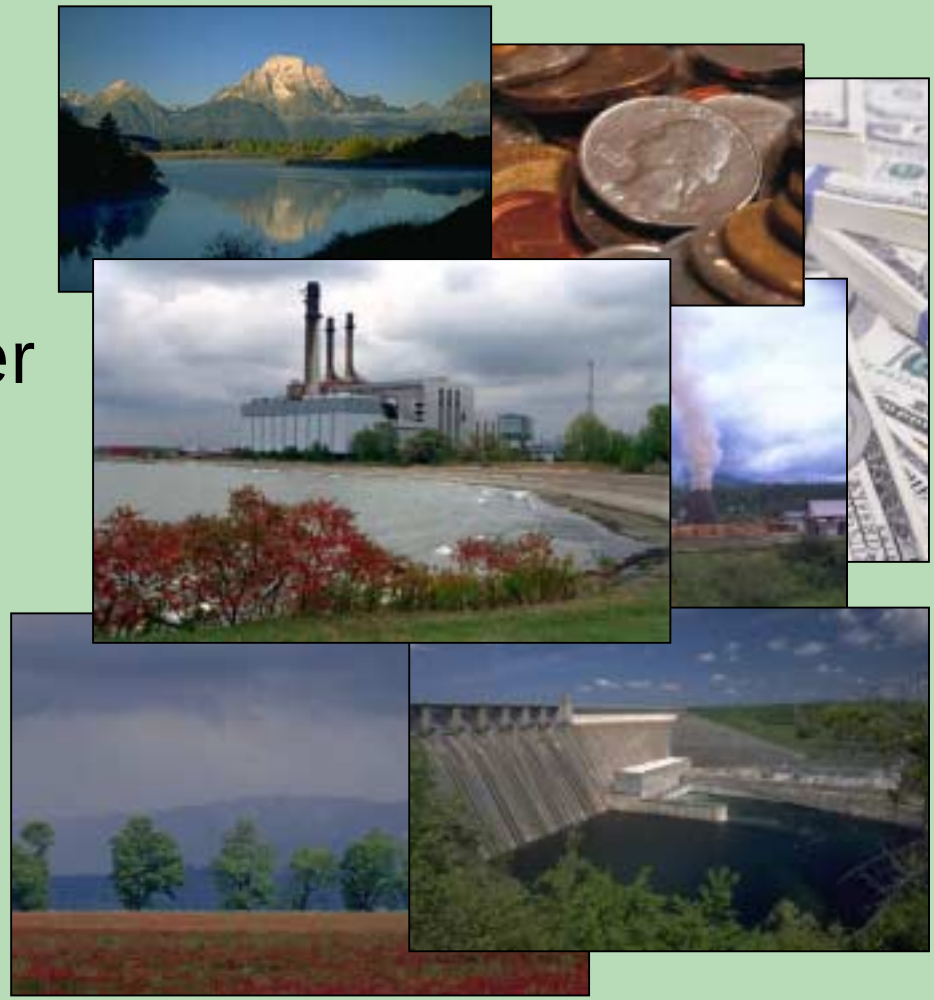
Farmers burned as green energy plant faces export: £30 million power station goes bankrupt after eight days, leaving growers high and dry
– *The Guardian(London)* (May 31, 2003)

It's clean and efficient but blighted by link to death and destruction
– *The Times(London) (September 2,2002)*

EU WAR ON ACID RAIN 'THREATENS COAL JOBS'
– *The Guardian(London)*(September 8, 1997)

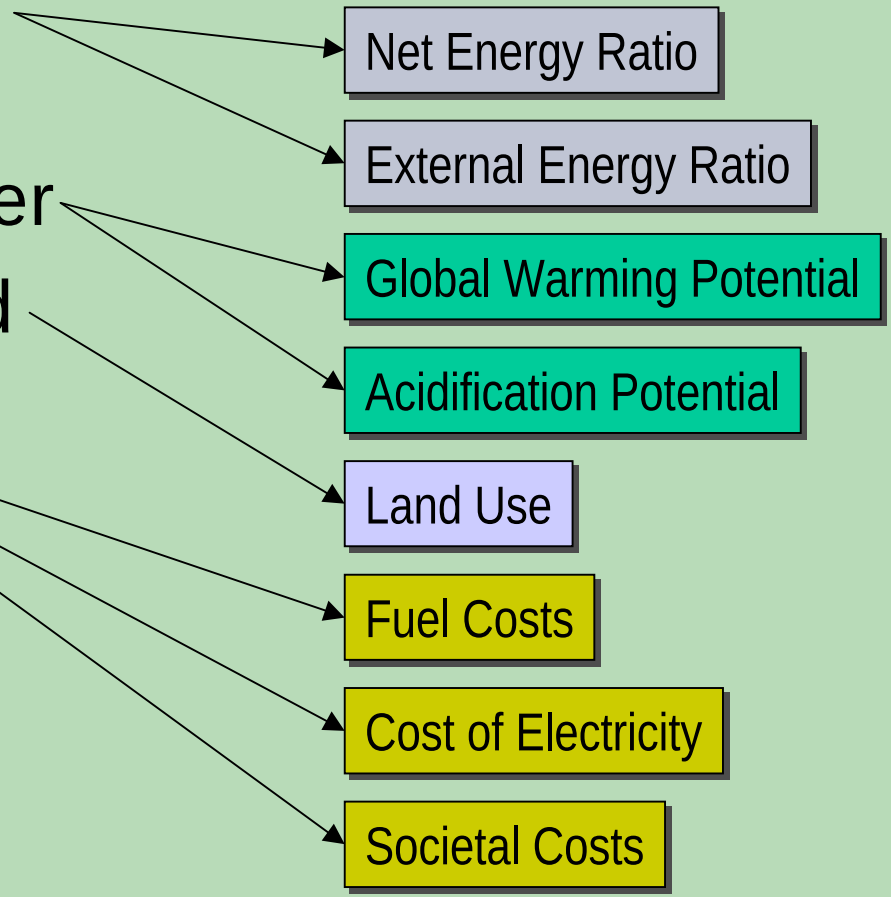
Key Issues and Metrics

- Issues
  - Effective Resource Use
  - Clean Air and Water
  - Availability of Land
  - Economics



Key Issues and Metrics

- Issues
  - Effective Resource Use
  - Clean Air and Water
  - Availability of Land
  - Economics
- Life Cycle Metrics



Technologies Examined

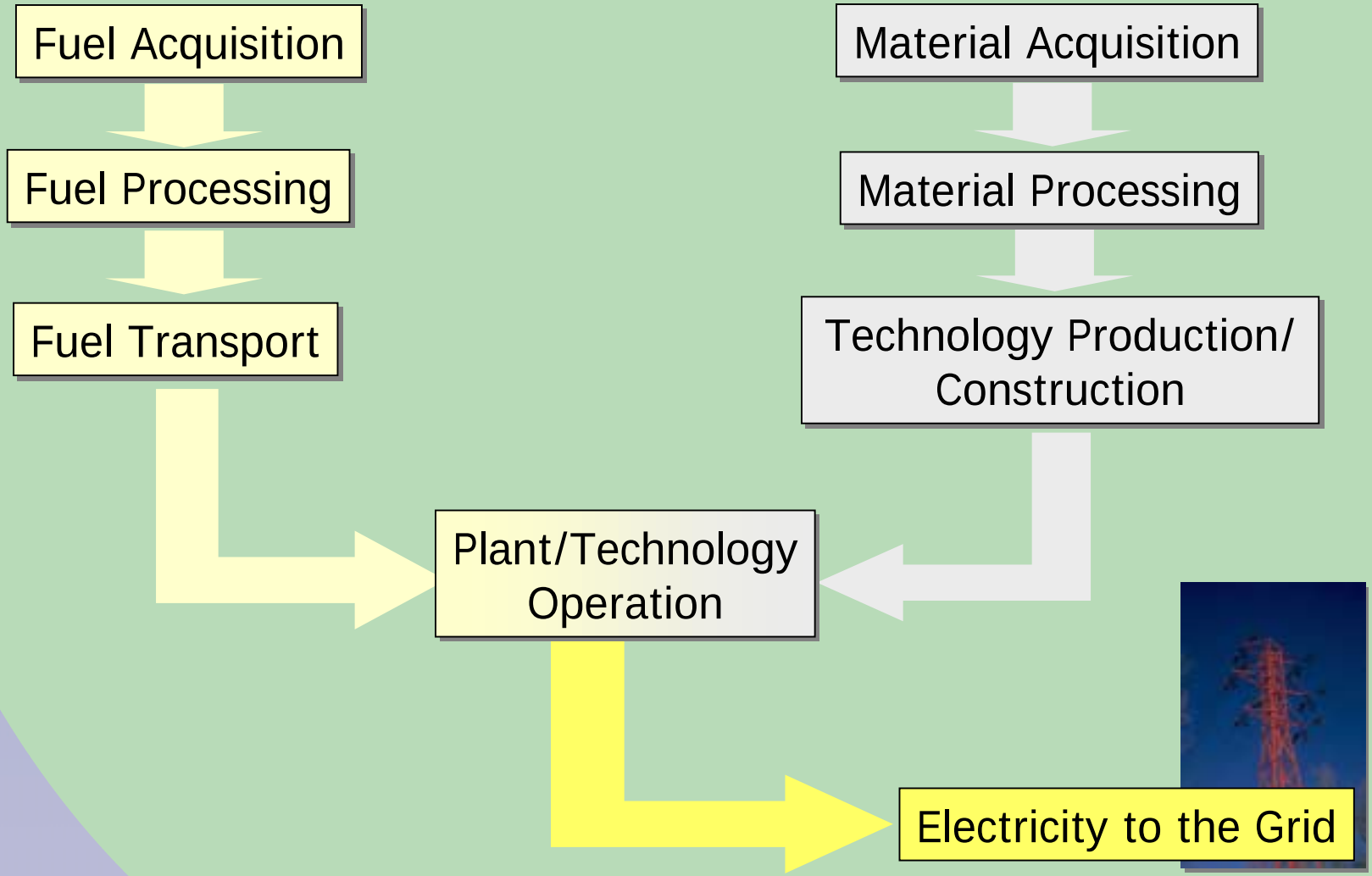
Fossil Fuel Systems

Based on Literature

CSS Research Focus

Renewable Systems

Electricity Generating Technology Life Cycle: Boundary Conditions



Willow Biomass System

- Willow Short Rotation Forestry (SRF) production system with:
  - Direct-fire boiler(1)
  - High pressure gasification(1)
  - Low pressure gasification(2)
- Example Data
  - Willow SRF Land Area: 13.6 odt/ha/yr
  - Willow Price: $35.86/dry ton(3)
  - Willow SRF Energy Use: 98.3 GJ/ha(4)

(1)Data source: EPRI/DOE, 1997
(2)Data source: Mann and Spath, 1997
(3)Farm gate price, ORNL Energy Crop County Level Database
(4)Seven harvest rotations

Photovoltaic System

- Building Integrated Photovoltaic (BIPV) modules (including balance of system)
  - Materials Acquisition
  - Module Production
  - Generation in 15 U.S. Cities:
    - Results for the Pacific Northwestern U.S. (Portland, OR) are discussed here.
- Example Data
  - BIPV Array: 34 m^2
  - BIPV total capital requirement: $16,000 (1999)
  - Stabilized conversion efficiency: 6%

Biomass/Coal Co-Fire

- Systems Considered
  - Operation of Dunkirk Power Plant Unit #1 (NY) with two feed alternatives:
    - Coal/Willow Biomass Blend
      - 90% Coal (wt. basis)/ 10% Willow Biomass
    - Coal/Wood Biomass Blend
      - 90% Coal/ 9.5% Wood Residue/ 0.5% Willow
- Example Data
  - Annual Operating Cost: $10.77/kW-yr(1)
  - Heating Value (HHV):
    - Coal: 30.6 MJ/kg
    - Wood Residue: 18.3 MJ/odkg
    - Willow: 19.8 MJ/odkg

(1)Relative to coal only operation; EPRI/DOE, 1997

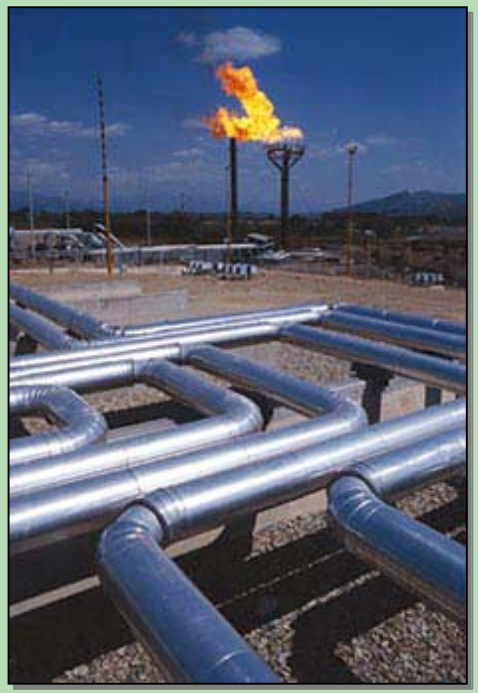
Coal

- Systems Considered[1]
  - Average Coal Plant
  - New Source Performance Standards (NSPS) Plant
  - Low Emission Boiler System (LEBS) Plant
- Example Data
  - Land Requirements
    - Coal mining: 4,015 tons/acre[2]
    - Utility Plant: 320 acre[3]
  - Coal Cost: $1.24/MMBtu[3]

(1) Plant operating data and life cycle inventory results provided by Spath, Mann and Kerr, 1999
(2) Typical Appalachian region production: *Energia*, University of Kentucky, 2002
(3) DOE, 1999

Natural Gas

- Systems Considered
  - Natural Gas Combined Cycle(1)
- Example Data
  - Economics
    - Natural Gas Cost: $2.70/MMBtu(2)
    - Operating Cost (non-fuel): $0.0032/kWh(2)
    - Total Capital Requirement: $562/kW(2)
  - Land Requirements
    - Pipeline area requirements: 290 acre(3)
    - Utility Plant: 100 acre(2)

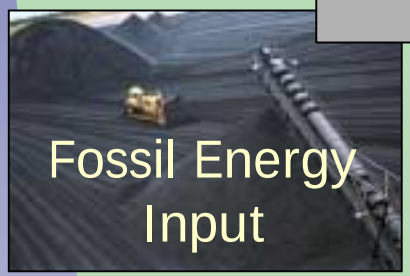


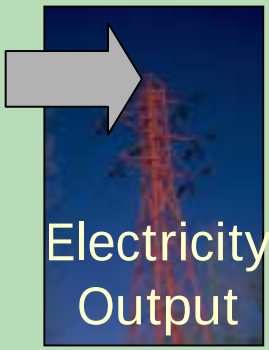
(1) Plant operating data and life cycle inventory results provided by Spath and Mann, 2000
(2) DOE, 1999
(3) Calculated from Spath and Mann, 2000 (2,486 pipe miles)

Which Technologies Provide the Most Effective Use of Energy Resources?

Net Energy Ratio =

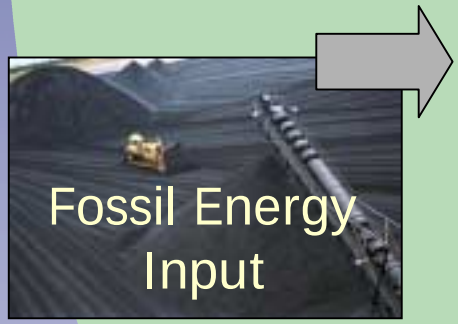
$$\frac{\text{Net System Electricity Generation}}{\text{Total Life Cycle Fossil Energy Use}}$$

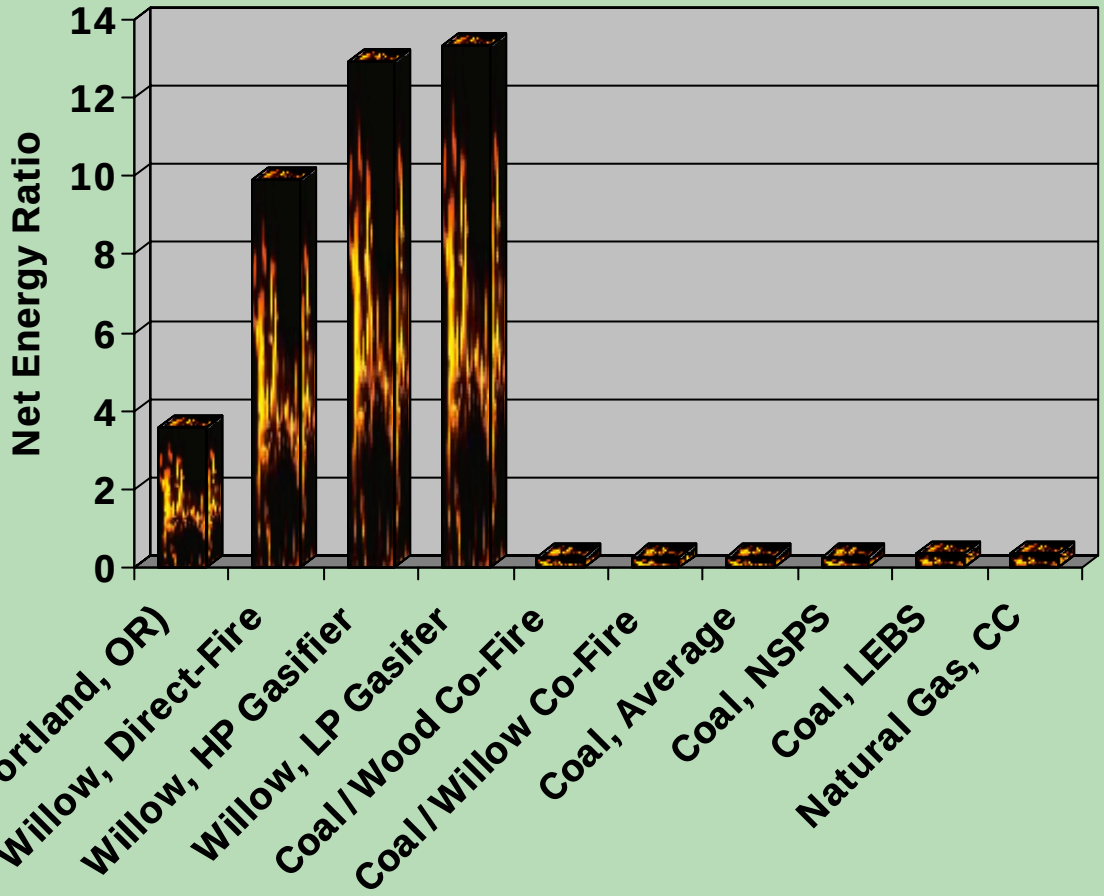


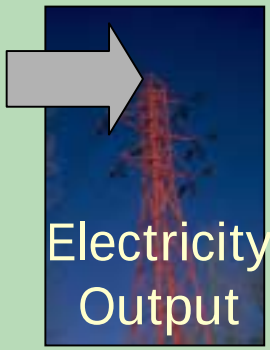


Values >1 Do Not Violate 1st Law of Thermodynamics

Which Technologies Provide the Most Effective Use of Energy Resources?

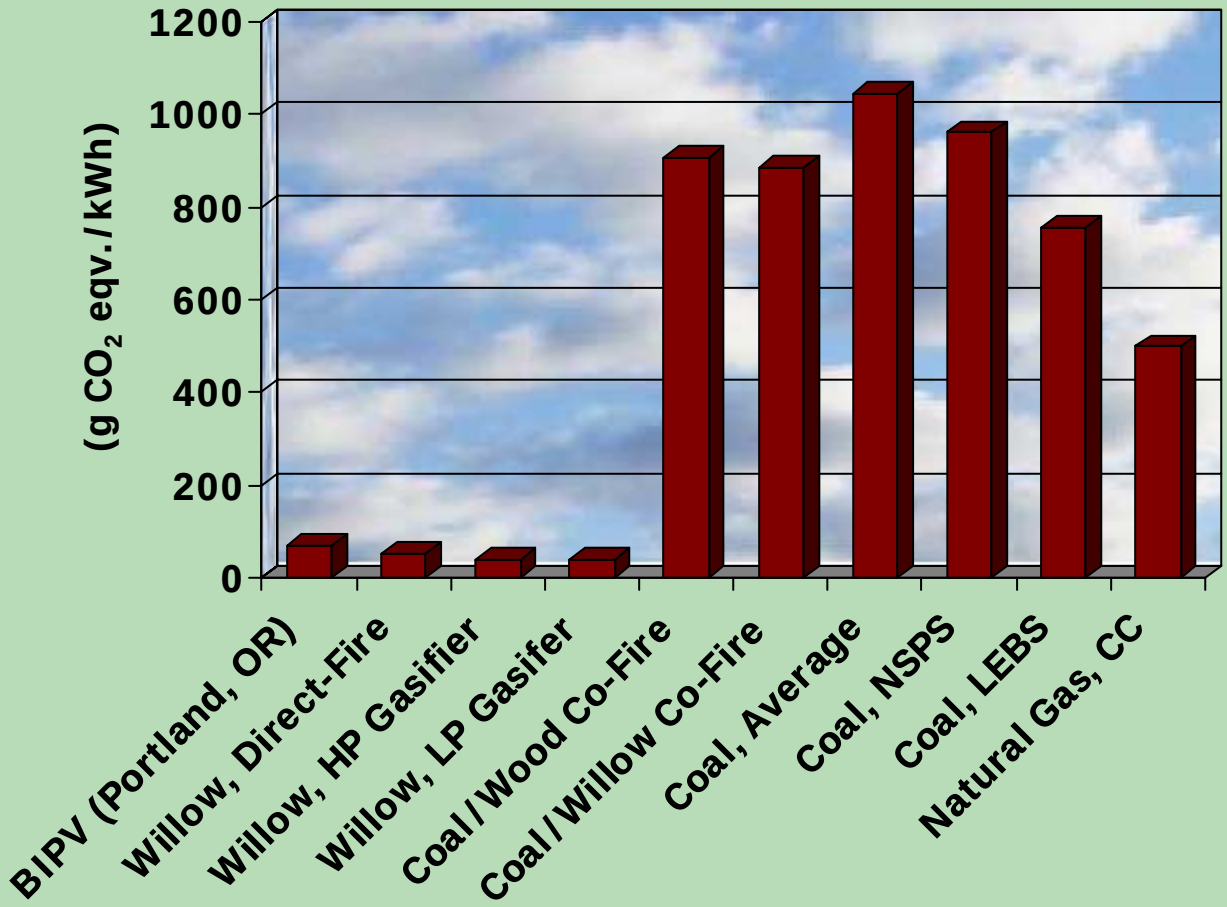






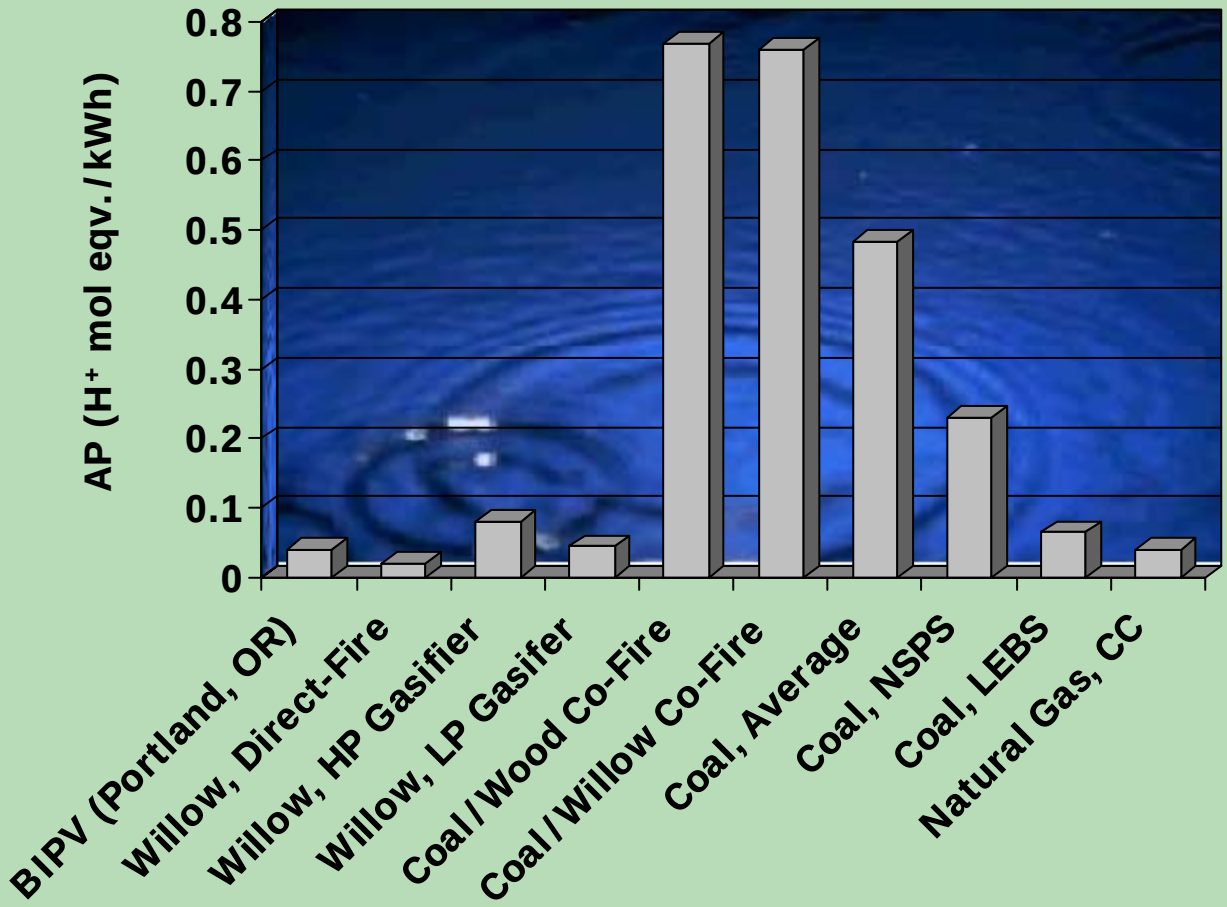
Values >1 Do Not Violate 1st Law of Thermodynamics

Which Technologies Generate the Least Greenhouse Gas Emissions?



Based on 100 year potential values reported in IPCC, *Third Assessment Report*, 2001

Which Technologies Most Effectively Limit Acidification?

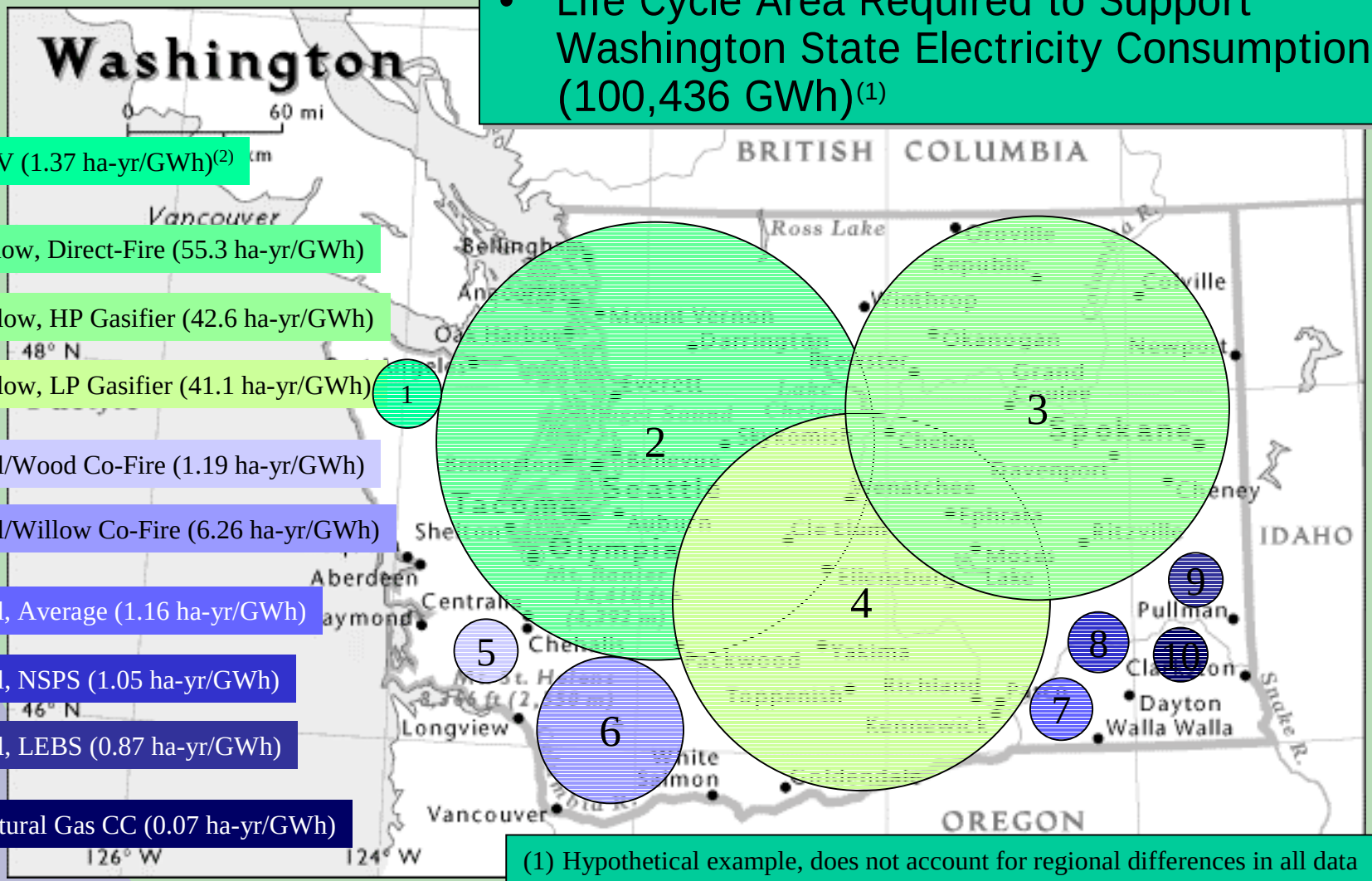


AP = Acidification Potential; Based on national average TRACI Characterization Factors, EPA, 2002

Which Technologies Provide the Most Effective Use of Land Resources?

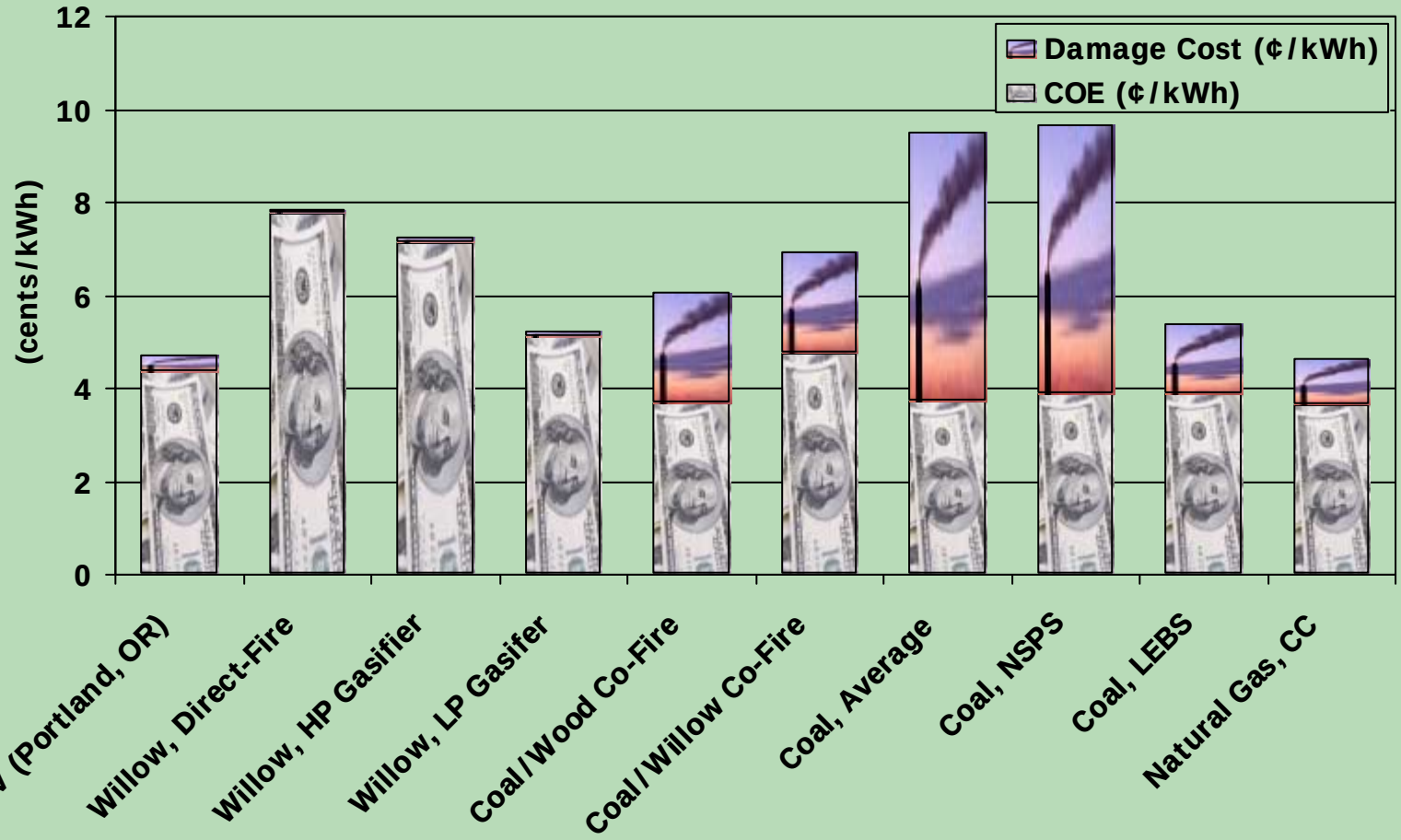
- Life Cycle Area Required to Support Washington State Electricity Consumption (100,436 GWh)(1)

1. BIPV (1.37 ha-yr/GWh)(2)
2. Willow, Direct-Fire (55.3 ha-yr/GWh)
3. Willow, HP Gasifier (42.6 ha-yr/GWh)
4. Willow, LP Gasifier (41.1 ha-yr/GWh)
5. Coal/Wood Co-Fire (1.19 ha-yr/GWh)
6. Coal/Willow Co-Fire (6.26 ha-yr/GWh)
7. Coal, Average (1.16 ha-yr/GWh)
8. Coal, NSPS (1.05 ha-yr/GWh)
9. Coal, LEBS (0.87 ha-yr/GWh)
10. Natural Gas CC (0.07 ha-yr/GWh)



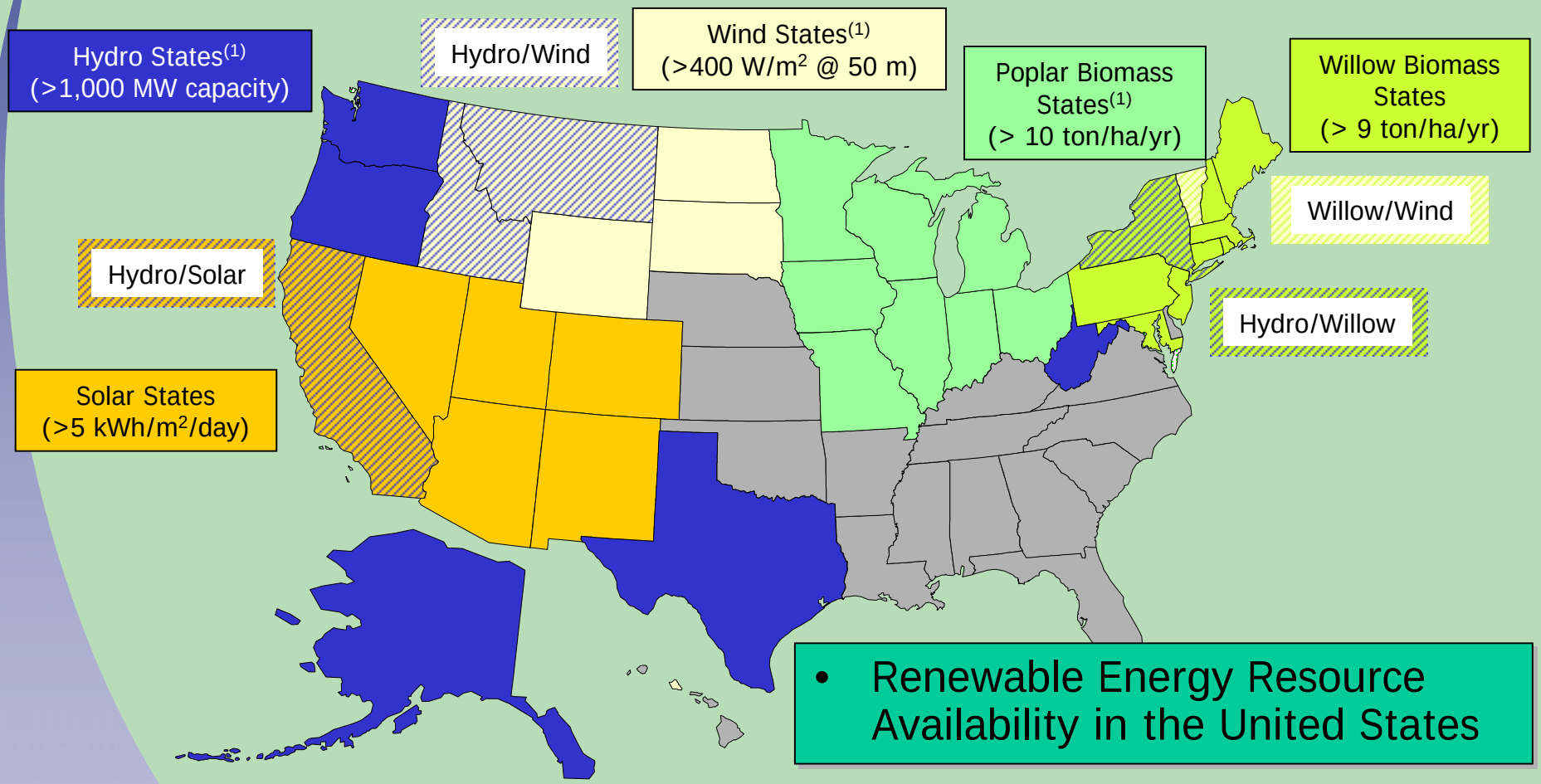
(1) Hypothetical example, does not account for regional differences in all data
(2) Data for Portland ,OR; existing building area required.

Which Technologies Offer the Lowest Costs?



COE = Cost of Electricity, Operating revenue requirement

Where are Generating Resources Available?



- Renewable Energy Resource Availability in the United States

Sources
Hydro: DOE, *U.S. Hydropower Resource Assessment*, 1998
Biomass: Klass, *Biomass for Renewable Energy, Fuels, and Chemicals*, 1998
Solar: NREL, *Solar Atlas, Annual Direct Normal Solar Radiation*, 2002
Wind: NREL, *Wind Resource Map*
(1) To be examined in future study

What's Next?

- Examination of additional electricity generating technologies
  - Hydroelectric
  - Wind
  - Nuclear
  - Poplar Biomass

Key Resources

- Analysis Based On:
  - Spath and Mann (2000) *Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System*, NREL
  - Spath, Mann and Kerr (1999) *Life Cycle Assessment of Coal-fired Power Production*, NREL
  - Mann and Spath (1997) *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System*, NREL
  - EPRI/DOE (1997) *Renewable Energy Technology Characterizations*
  - DOE (1999) *Market-Based Advanced Coal Power Systems*
- Relevant CSS Publications:
  - Heller, et al. (In Press) "Life Cycle Energy and Environmental Benefits of Generating Electricity from Willow Biomass," *Renewable Energy*.
  - Heller, Keoleian and Volk (2003) "Life Cycle Assessment of a Willow Bioenergy Cropping System," *Biomass and Bioenergy*, 25, 147-165.
  - Keoleian and Lewis (2003) "Modeling the Life Cycle Energy and Environmental Performance of Amorphous Silicon BIPV Roofing in the US," *Renewable Energy*, 28, 271-293.

Acknowledgements

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