# Pennsylvania Indigenous Energy Hydrogen Delivery Tradeoff Study

**NHA 2008**

**Sacramento, CA**

**March 31, 2008**

**Hydrogen Regional Infrastructure Program in Pennsylvania**

Eileen M. Schmura and Sarah Largent
Concurrent Technologies Corporation
Paul L. Lemar, Resource Dynamics Corporation

# Presentation Outline

- Phase I Results
- Phase II Work
  - PA Indigenous Energy Resources
  - Hydrogen Production Options
  - Hydrogen Delivered Price

# Phase I Hydrogen Tradeoff Study

- **Objectives**
  - Quantify tradeoffs between alternative hydrogen production and delivery approaches using DOE's H2A model and other analytical methods
  - Investigate commercial and near commercial options
  - Use Pennsylvania as a case study
- **Tradeoff Study Parameters**
  - Assess demand at 1%, 10%, and 30% of light duty vehicle miles
  - Lowest delivered hydrogen cost based on life cycle cost analysis
  - State level feedstock costs

# Key Tradeoffs Analyzed

- **Plant Size**
  - **Large central plants-** better production economics but more intensive distribution costs
  - **Regional central plants-** lower distribution costs
  - **On-site distributive production-** eliminates distribution
- **Feedstock and Technology Options**
  - Natural gas versus coal, biomass, electricity or other feedstocks
  - State level feed stock pricing (Natural Gas: $8.00-$10.00/MMBTU and Coal: $41/ton)
  - Capital investment as well as operating costs
- **Delivery Methods**
  - Compressed truck transport, liquid truck transport, and pipeline delivery were pitted against on-site production

# Phase I Key Feedstock Inputs for Analysis

| Feedstocks, for Central Station | PA Prices | Source | Units |
|---|---|---|---|
| Electricity | **0.0598** | EIA PA Industrial | $/kWh |
| Electricity Central Plant Electrolysis | **0.0295** | PJM 2004 average | $/kWh, wholesale price |
| Natural Gas | **7.82** | EIA PA city gate | $/MMBtu HHV |
| Biomass | **45.0** | ORNL PA average | $/bone dry ton, 8,000 Btu/lb HHV |
| Coal | **41.18** | EIA PA Utility | $/tonne, 12,000 Btu/lb HHV |
| Diesel | **2.20** | Bloomberg | $/gal |

| Feedstocks, for Distributed Production | PA Prices | Source | Units |
|---|---|---|---|
| Electricity | **0.0836** | EIA PA Commercial | $/kWh |
| Natural Gas | **9.82** | EIA PA city gate+$2 for distribution cost | $/MMBtu HHV |
| Gasoline | **1.46** | Bloomberg US Wholesale | $/gal |
| Methanol | **0.95** | Methanex US | $/gal |

Note: EIA=Energy Information Administration, PJM=PJM Interconnection, ORNL=Oak Ridge National Laboratory.

# Impact of Hydrogen Demand on Feedstock Availability

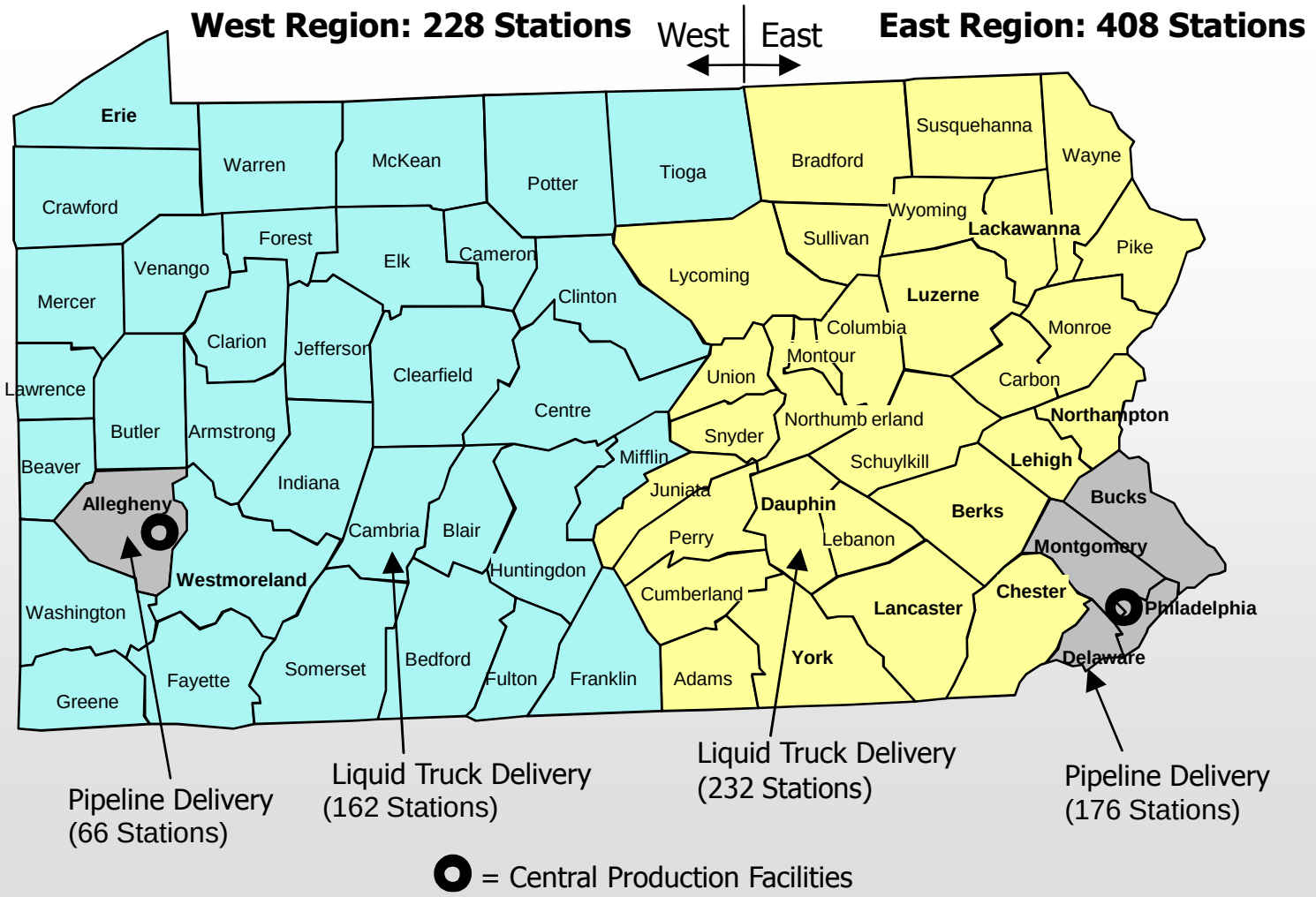
| | | | MMBTU Daily | | | |
|---|---|---|---|---|---|---|
| | **Annual** | **Units** | **Feedstock Production/ Consumption** | **Units** | **30% LDV Penetration Feedstock Requirement** | **Current Share of Feedstock** |
| **Natural Gas** (Production) | 159,800 | Million cuft/yr | 446,600 | MMBtu/day | 360,800 | 81% |
| **Natural Gas** (Consumption) | 651,600 | Million cuft/yr | 1,820,900 | MMBtu/day | 360,800 | 20% |
| **Coal** (Production) | 63,700 | 1000 Short tons/yr | 4,188,500 | MMBtu/day | 464,000 | 11% |
| **Electricity** (Production) | 206,300 | GWh/yr | 1,928,500 | MMBtu/day | 412,800 | 21% |
| **Biomass,** Woody (Available) | 7,430 | 1000 dry tons/yr | 325,700 | MMBtu/day | 494,500 | 152% |

Note: Each feedstock evaluated independently.

Source: Feedstock data from EIA (2003), except biomass from Oak Ridge National Laboratory (1999).

Assumptions: Hydrogen production efficiencies from H2A case studies and SFA Pacific (2002) (pipeline transport). Hydrogen demand for electricity includes electrolysis and compression, and for biomass includes feedstock use for drying feedstock input to gasifier.

# Two Plant Option, Demand Centers
# 30 Percent Demand Scenario



# Phase I Summary of Lowest Delivered Costs for Both Carbon Cases

| | | 1% LDV Penetration | | 10% LDV Penetration | | 30% LDV Penetration | |
|---|---|---|---|---|---|---|---|
| | | East | West | East | West | East | West |
| | Plant Size (kg/day) | 74,000 | 18,000 | 428,000 | 224,000 | 1,283,000 | 718,000 |
| NO CARBON REGULATION | Lowest Delivered Cost ($/kg) | $4.08 | $4.08 | $3.64 | $4.05 | $3.28 | $3.48 |
| | Production and Delivery Method | Distributed NG | Distributed NG | Central Station Coal Gasification; Pipeline/Liquid | Central Station Coal Gasification; Pipeline/Liquid | Central Station Coal Gasification; Pipeline/Liquid | Central Station Coal Gasification; Pipeline/Liquid |
| LOW CARBON | Lowest Delivered Cost ($/kg) | $4.08 | $4.08 | $3.90 | $4.08 | $3.54 | $3.74 |
| | Production and Delivery Method | Distributed NG | Distributed NG | Central Station Coal Gasification w Seq; Pipeline/Liquid | Distributed NG | Central Station Coal Gasification w Seq; Pipeline/Liquid | Central Station Coal Gasification w Seq; Pipeline/Liquid |

**KEY:**

= Central Station Production, Pipeline/Liquid Delivery (Pipeline for Philadelphia and Pittsburgh, Liquid Truck for remaining areas)

= Distributed Natural Gas Production On-Site via Reformation (no Delivery Necessary)

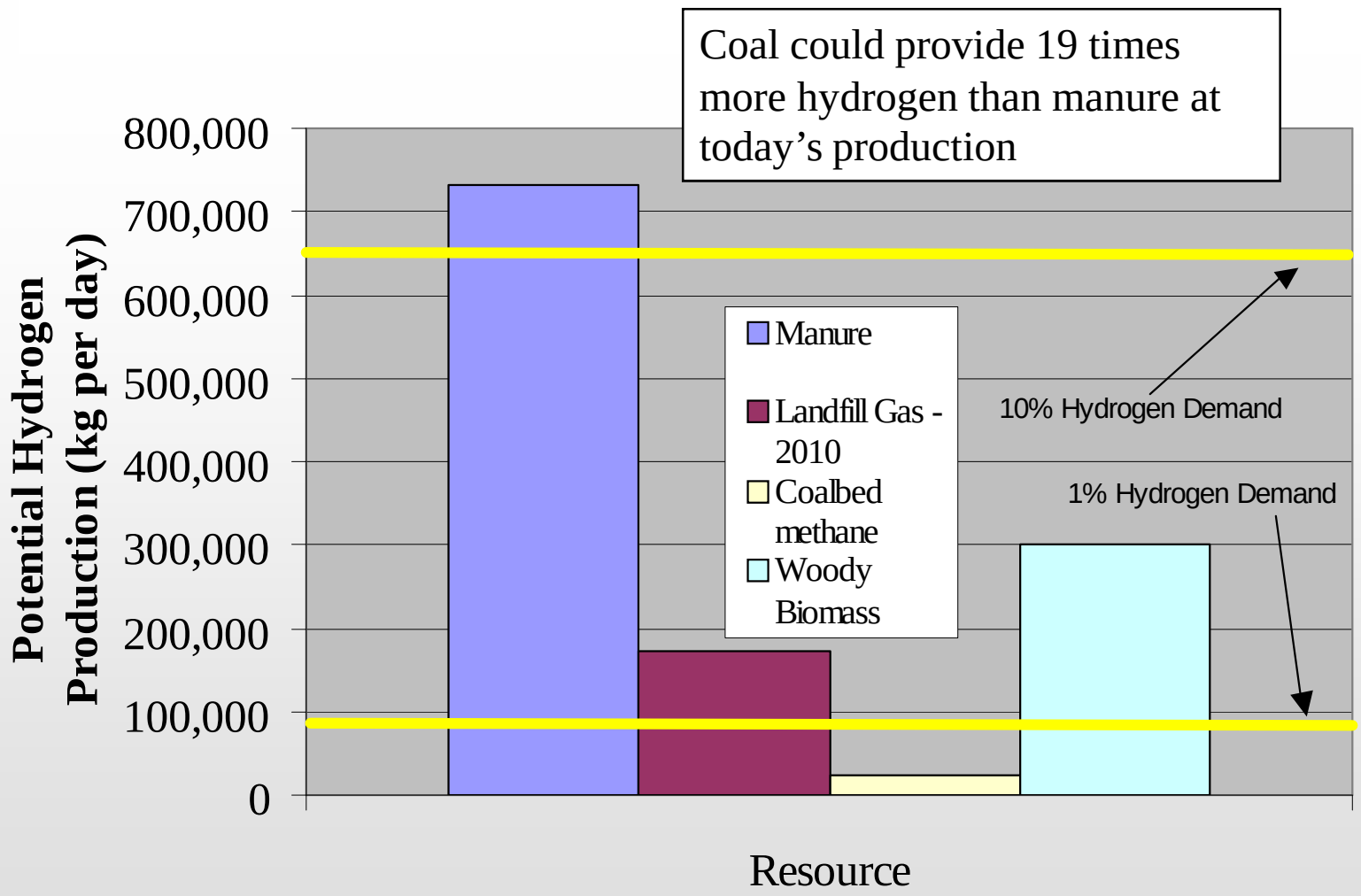
# Phase II Hydrogen Tradeoff Study

- **Objectives**
  - Quantify tradeoffs between alternative hydrogen production and delivery approaches using DOE's H2A model and other analytic methods
  - Investigate commercial and near commercial options
  - Use Pennsylvania as a case study (I-95 Corridor is a focus of a companion effort)
- **Tradeoff Study Parameters**
  - Assess demand at 1%, 10%, and 30% of light duty vehicle miles
  - Analyze lowest delivered hydrogen cost based on life cycle cost
  - **Use location-specific (county basis) PA resources as a feedstock for hydrogen**
- **Key Tradeoffs Analyzed**
  - Feedstocks (coal, coalbed methane, manure, woody biomass)
  - Plant size (distributed vs. central station)
  - Delivery (truck, pipeline, etc.)

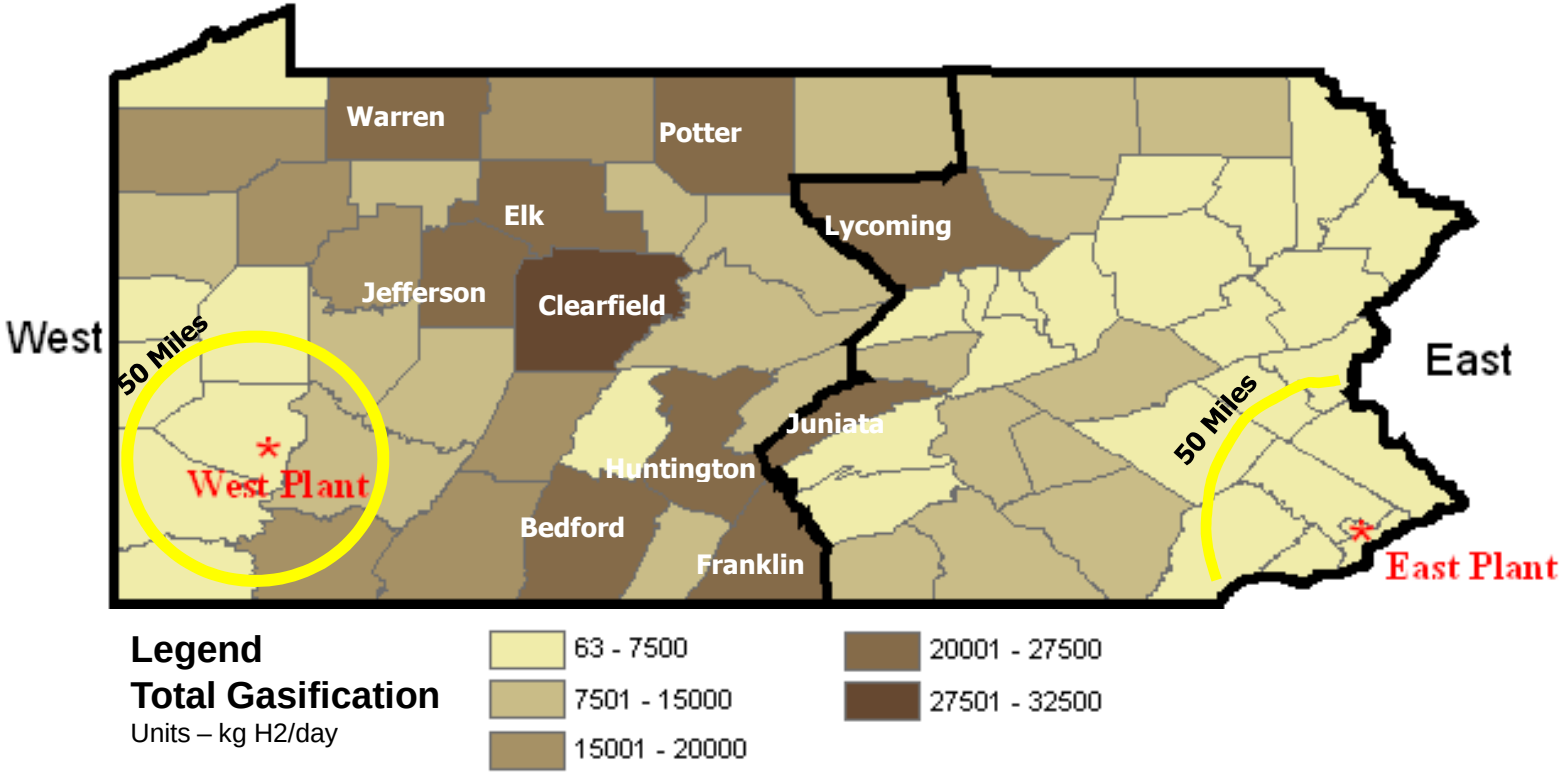
# Pennsylvania's Natural Resources for Potential Hydrogen Production

- Coal
- Coalbed Methane
- Natural Gas
- Electricity
  - Nuclear
  - Renewables
    - Wind
    - Biodiesel
    - Ethanol
- Agricultural Resources
  - Livestock manure
  - Herbaceous biomass
- Forestry & Wood Resources
  - Logging & primary mill residues
  - Secondary mill residues
- Miscellaneous Resources
  - Municipal solid waste (landfill gas)
  - Restaurant-derived waste grease
  - Residual paper waste
- Biomass

# Pennsylvania's Hydrogen Resources

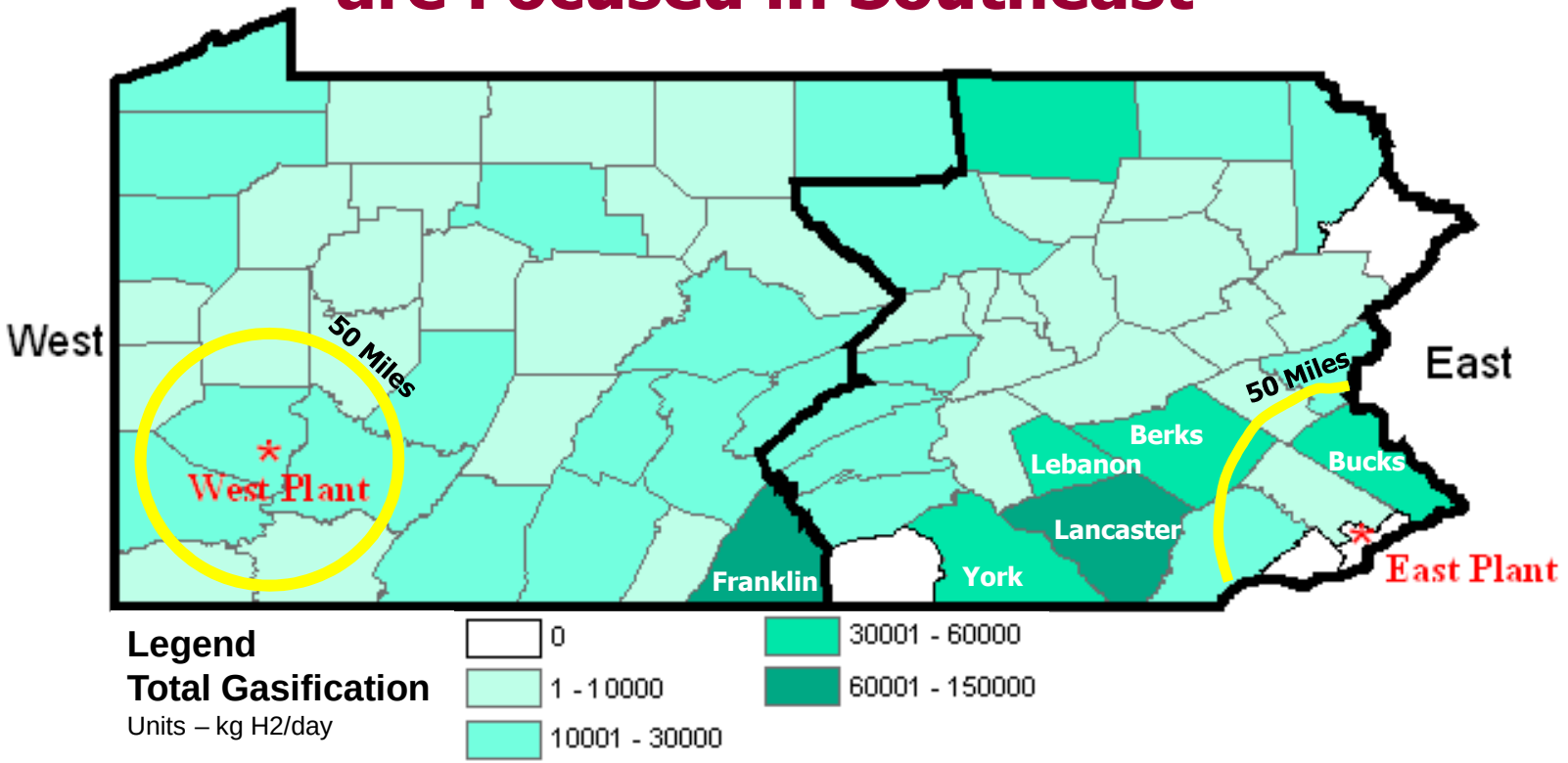


# Woody Biomass Concentrated in Center of State Away From Demand Centers



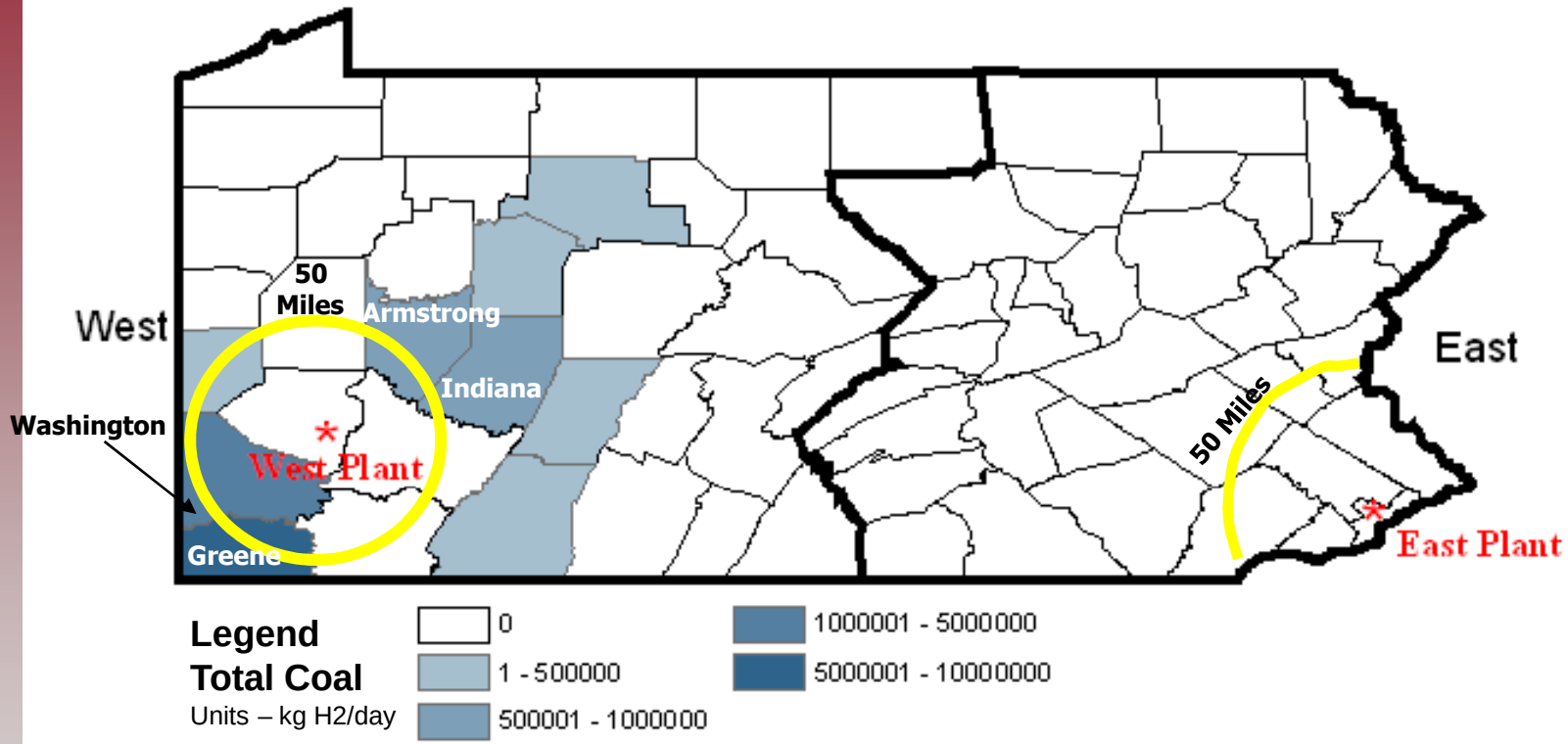

- Top 10 counties comprise 37 % of resources
- Top counties are over 100 mi from East/West hydrogen plant locations (50 mile radius important for biomass power generation)
- Resources based on current production of primary and secondary wood wastes, no harvesting of growing stock
- Entire State can provide 10% of hydrogen demand at $46-$55/ton delivered

# Biogas and Coalbed Methane Resources are Focused in Southeast




- Top 2 counties comprise 22% of resources
- Resources based on
  - digestion of swine and dairy manure (77%)
  - landfill gas production (21%)
  - coal bed methane (2%)
  - no food processing waste or other manure used
- New term: "Green" Natural Gas
- Entire State can provide 15% hydrogen demand, using dedicated pipeline or existing natural gas distribution to deliver biogas

# Ample Coal for Entire State Hydrogen Demand




- Production of underground bituminous = 2 times the hydrogen needed at 100%, does not count surface mining, other coal or reserves
- Greene county provides two-thirds of current production, and is 50 mi from West plant, though coal can be transported 100s of miles
- East Plant remote from major coal reserves, although anthracite mines are closer
- Cost of coal $65-$78/ton delivered

# Phase II: Key Feedstock Inputs for Distributed Production Analysis

| Feedstocks For Distributed Production | Price | Source | Units | Units ($/MMBTU) |
|---|---|---|---|---|
| Electricity | 0.09 | EIA PA commercial (2006 ) | $/kWh | 26.38 |
| Natural Gas | 12.3 | EIA PA Industrial (2006 Annual) | $/MMBTU (1500 kg/day Scenario) | 12.3 |
| Natural Gas | 14.3 | EIA PA commercial (2006 Annual) | $/MMBTU (100 kg/day Scenario) | 14.3 |
| Gasoline | 3.08 | EIA PA (November 2007) | $/gal | 22.21 |
| Biodiesel | 3.86 | US Rack Prices | $/gal | 25.67 |
| Ethanol | 2.45 | US Rack Prices | $/gal | 17.67 |
| Methanol | 1.42 | Methanex US | $/gal | 10.24 |
| Coalbed Methane | 14.3 | (being sold as NG) | $/MMBTU | 14.3 |

Note: EIA=Energy Information Administration, PJM=PJM Interconnection, ORNL=Oak Ridge National Laboratory

# Phase II: Key Feedstock Inputs for Central Station Production Analysis

| Feedstocks For Central Production | PA Prices | Source | Units | Units ($/MMBTU) |
|---|---|---|---|---|
| Electricity | 0.06 | EIA PA Industrial (2006) | $/kWh | 17.58 |
| Electricity Central Plant Electrolysis | 0.03 | PJM Interconnection, off-peak (2006) | $/kWh, wholesale price | 8.79 |
| Natural Gas | 10.3 | EIA PA City Gate (2006) | $/MMBTU | 10.3 |
| Biomass | 46-55 | Penn State University Forest Resources | $/dry ton delivered | 2.67-3.21 |
| Biomass | 45 | ORNL PA average | $/bone dry ton, 8000 btu/lb higher heating value bone dry 50% moist, 41 mile haul | 2.62 |
| Coal | 43-52 | Leonardo Technologies Inc. | $/ton delivered (June 2007) | 2.08-2.51 |
| Coal | 64-78 | Leonardo Technologies Inc. | $/ton delivered (February 2008) | 3.13-3.77 |
| Diesel | 3.4 | EIA PA (November 2007) | $/gal | 24.52 |
| Landfill Gas | 5.91- 7.89 | Montauk | $/MMBTU, with gas cleanup with and 10 miles pipeline added | 5.67 |
| ADG | 4.64-7.08 | Lehman Ag Service Inc. | $/MMBTU based on gas cleanup and $0.20/mile manure delivery charge | 4.64-7.08 |

Note: EIA=Energy Information Administration, PJM=PJM Interconnection, ORNL=Oak Ridge National Laboratory

# Phase II COAL & BIOMASS

## Coal (June 2007)

| Regions | Total Tons Available | Average Distance (Miles) | Transportation Costs ($) | Total cost of coal Delivered ($/short ton delivered) |
|---|---|---|---|---|
| West | 37,704,447 | 91 | 2.72 | 42.97 |
| East | 0 | 387 | 11.61 | 51.86 |
| Southwest | 37,704,447 | 91 | 2.72 | 42.97 |
| Southeast | 0 | 387 | 11.61 | 51.86 |
| South-central | 0 | 208 | 6.24 | 46.49 |
| Northeast | 0 | 277 | 8.31 | 48.56 |
| Northwest | 0 | 127 | 3.81 | 44.06 |

## Biomass

| Region | Total Tons Available | Average Distance (Miles) | Transportation Costs ($) | Total Cost of Biomass Delivered ($/dry ton) |
|---|---|---|---|---|
| Southeast | 1,895,385 | 30 | 6.00 | 46.00 |
| Southcentral | 63,610,314 | 71.45 | 14.29 | 54.29 |
| Southwest | 35,098,901 | 52.2 | 10.44 | 50.44 |
| Northwest | 79,144,153 | 61.65 | 12.33 | 52.33 |
| Northeast | 37,342,775 | 76.45 | 15.29 | 55.29 |

# Impact of Location on Delivered Hydrogen Cost

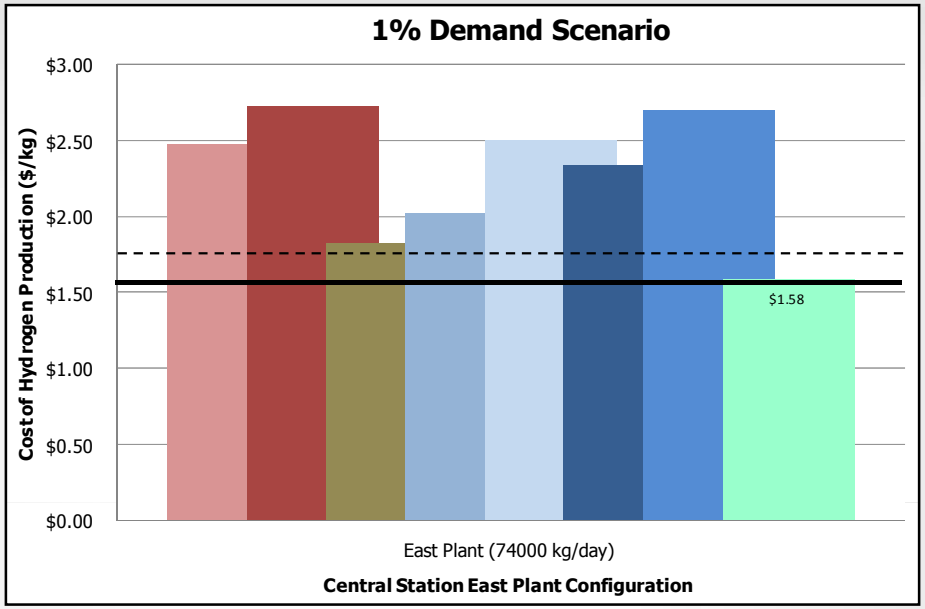
| Coal Pricing Compo | Statewide Average Price (Phase I) | | Regional Pricing (Phase II) | |
|---|---|---|---|---|
| | East Plant | West Plant | East Plant | West Plant |
| **Delivered Coal Price ($/Ton)** | 37.5 | 37.5 | 77.79 | 64.46 |
| **Hydrogen Production Cost ($/kg)** | 1.41 | 1.41 | 2.10 | 1.97 |
| **Hydrogen Delivery Cost ($/kg)** | 1.87 | 2.07 | 1.87 | 2.07 |
| **Delivered Hydrogen Cost ($/kg)** | **3.28** | **3.48** | **3.97** | **4.04** |

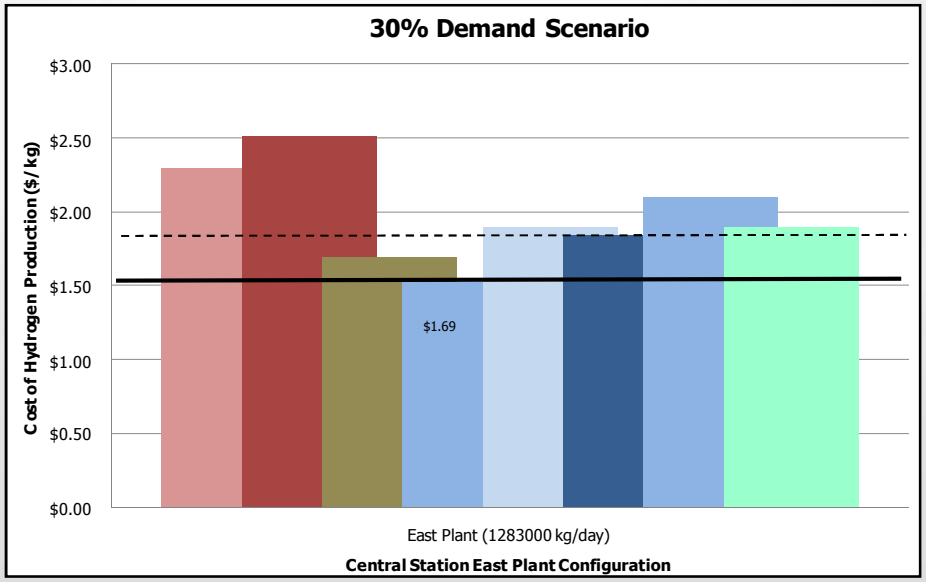
Note: hydrogen production and delivery costs for 30 percent demand scenario

# Screening Tool

| Feedstock | Feedstock Price ($/MMBTU) | Estimated Hydrogen Production Cost ($/kg) | Maximum Cost ($/kg) | Screening Analysis Result |
|---|---|---|---|---|
| Electricity | 19.05 | 5.04 | 2.50 | Fail |
| Electricity incorporating off peak hours | 8.79 | 4.08 | 2.50 | Fail |
| Natural Gas | 10.3 | 2.30 | 2.50 | Pass |
| Biomass | 3.46 | 1.73 | 2.50 | Pass |
| Coal (June 2008) | 1.97 | 1.48 | 2.50 | Pass |
| Coal (February 2008) | 2.95 | 1.70 | 2.50 | Pass |
| ADG | 4.64 | 1.25 | 2.50 | Pass |
| LFG | 5.91 | 1.48 | 2.50 | Pass |
| Wind | 19.05 | 7.96 | 2.50 | Fail |
| Wind incorporating off peak hours | 8.79 | 6.71 | 2.50 | Fail |
| Biodiesel | 15.00 | 7.12 | 2.50 | Fail |
| Ethanol | 31.18 | 6.61 | 2.50 | Fail |
| Gasoline | 23.69 | 5.96 | 2.50 | Fail |
| Methanol | 21.98 | 5.88 | 2.50 | Fail |
| Natural Gas w/ Carbon Seq | 10.3 | $2.49 | 2.50 | Pass |
| Coal (June 2008) w/ Carbon Seq | 1.97 | $1.73 | 2.50 | Pass |
| Coal (February 2008) w/ Carbon Seq | 2.95 | $1.93 | 2.50 | Pass |

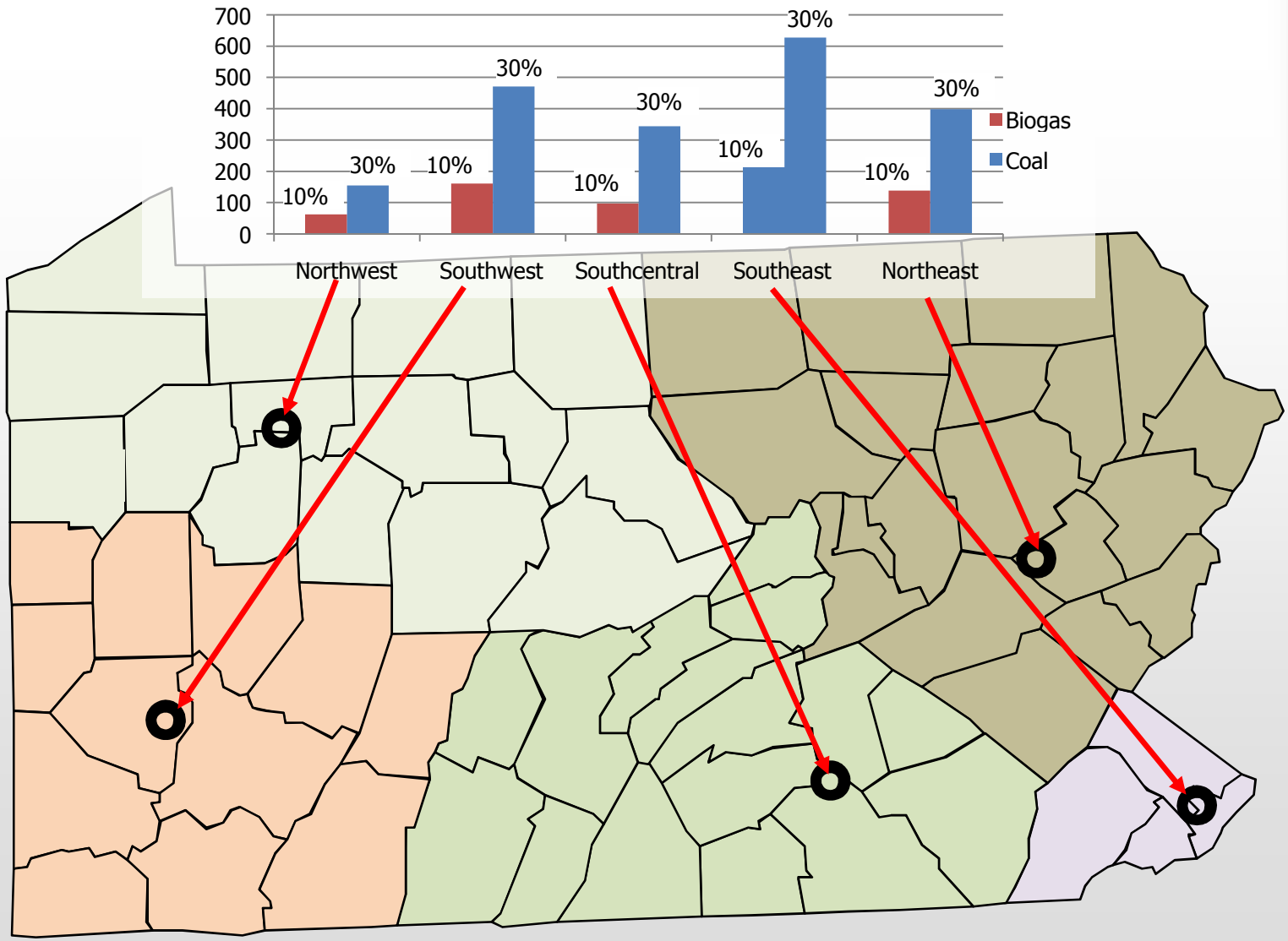
# Central Station East Plant Configuration




- Natural Gas Steam Reformation
- Natural Gas Reformation with Seq
- Biomass Gasification
- Coal Gasification (June 2007)
- Coal Gasification With Seq (June 2007)
- Coal Gasification (February 2008)
- Coal Gasification With Seq (February 2008)
- Biogas (LFG and ADG with Natural Gas) Reformation

# Two Plant Option, Demand Centers
# 30 Percent Demand Scenario



# Summary Delivered Hydrogen, Two Central Plant Option

| | | 1% LDV | | 10% LDV | | 30% LDV | |
|---|---|---|---|---|---|---|---|
| | | East Plant | West Plant | East Plant | West Plant | East Plant | West Plant |
| | Plant Size (kg/day) | 74000 | 19000 | 428000 | 239000 | 1283000 | 718000 |
| NO CARBON REGULATION | Lowest Delivered Cost ($/kg) | 4.28 | 4.61 | 3.64 | 4.13 | 3.4 | 3.57 |
| | Production and Delivery Method | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Biogas (LFG and ADG); Pipeline Distribution | Central Station Coal Gasification; Pipeline/Liquid Distribution | | |
| LOW CARBON | Lowest Delivered Cost ($/kg) | 4.28 | 4.61 | 3.64 | 4.48 | 3.77 | 3.88 |
| | Production and Delivery Method | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Biogas (LFG and ADG); Pipeline Distribution | Central Station Coal Gasification w Seq; Pipeline/Liquid Distribution | | |

# Summary Delivered Hydrogen, Five Regional Plant Option

| | | 10% LDV | | | | | 30% LDV | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Southeast Plant** | **Southwest Plant** | **Northeast Plant** | **Southcentral Plant** | **Northwest Plant** | **Southeast Plant** | **Southwest Plant** | **Northeast Plant** | **South central Plant** | **North west Plant** |
| | Plant Size (kg/day) | 211000 | 161000 | 138000 | 97000 | 62000 | 627000 | 471000 | 398000 | 344000 | 155000 |
| **NO CARBON REGULATION** | Lowest Delivered Cost ($/kg) | 3.60 | 4.27 | 4.61 | 4.33 | 4.61 | 3.21 | 3.64 | 3.78 | 3.76 | 4.31 |
| | Production and Delivery Method | Central Station Coal Gasification; Pipeline/ Liquid Distribution | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Coal Gasification; Pipeline/Liquid Distribution | | | | |
| **LOW CARBON** | Lowest Delivered Cost ($/kg) | 3.95 | 4.27 | 4.61 | 4.33 | 4.61 | 3.58 | 3.95 | 4.10 | 4.08 | 4.61 |
| | Production and Delivery Method | Central Station Coal Gasification w/ Seq; Pipeline/ Liquid Distribution | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Biogas (LFG and ADG); Pipeline Distribution | Distributed Natural Gas | Central Station Coal Gasification w/ Seq; Pipeline/Liquid Distribution | | | | Distributed Natural Gas |

KEY

- Central Station Biogas (LFG and ADG) Production, Pipeline Distribution
- Distributed Natural Gas Production On-Site via Reformation (no Delivery Necessary)
- Central Station Coal Production, Pipeline/Liquid Delivery (Pipeline for Philadelphia and Pittsburgh, Liquid Truck for remaining areas)

Note: The Data for Central Station Coal Gasification with and without Sequestration is based on June 2007 Coal Prices.

# Conclusions

- Indigenous resource do influence the most economical source of hydrogen
  - Central Station emerges earlier in the initial demand scenario
  - Still important in 10% demand option
  - 30 % demand option coal with sequestration is most economical
- Global Energy markets will affect economic choices
- Regional planning may be most prudent along the I95 corridor, not just a state issue

# Contact Information and Acknowledgements

**Concurrent Technologies Corporation**
**Eileen Schmura**
**schmurae@ctc.com**
**(412) 992-5367**

**Sarah Largent**
**largents@ctc.com**
**(937)306-3303**

**Resource Dynamics**
**Paul Lemar Jr., President**
**pll@rdcnet.com**
**703-356-1300 ext. 204**

- U. S. Department of Energy
  - Monterey Gardiner
  - Pete Devlin
  - Paul Bakke
- Air Products and Chemical Inc.
- PA DEP
- Penn State University

**Acknowledgement/Disclaimer**
This material is based on work supported by the Department of Energy under Award Number DE-FC36-04GO14229. This report was prepared as an account of work sponsored by an agency of the United Sates Government.

# Backup Slides