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Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling (FE0049539)

Presentation to Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, March 24 -26, 2009 in Pittsburgh, PA

System Studies and Modeling Efforts – Session 9 – Thursday March 26 @ 8:00-8:30 AM

Richard D. Doctor, Dr. Donald A. Hanson, and Dr. John C. Molburg

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U.S. Department of Energy

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Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling

- **Contractor** — *Argonne National Laboratory — Mark T. Peters, ESE Deputy Assoc. Lab Dir*
- **Contract Number; B&R** — 49539; AA-30-10
- **Principal Investigator** — Richard D. Doctor, Chemical Engineering, P.E.
- **Co-principal Investigator** — Dr. Donald A. Hanson, Economist
- **Investigator** — Dr. John C. Molburg, Engineer/Economist
- **Project Management** — Timothy Fout, Project Manager, Existing Plants Division, NETL, Morgantown, WV
- **Funding FY2008-2010** — DOE: $780K; Cost share: $270K Argonne – University of Chicago Energy Initiative
- **Period of Performance** — October 2007 — September 2009
- **Technical Objective**

FE49539 examined the recovery of CO_2 from pulverized-coal-fired power plants retrofitted for flue-gas recirculation (Oxyfuel). The project focuses on the application Oxyfuels across the existing fleet of domestic PC boilers.

An engineering assessment of Oxyfuels using ASPEN® was linked to cost assessment using the AMIGA (All-Modular Industry Growth Assessment) macroeconomic model. A strategy of retrofitting for Oxyfuels and then converting over the power station site to IGCC also was examined looking at the sensitivity to the timing of policy, price of electricity, cost of CO_2, and timing of the retrofit. This transitional strategy looked at the Net Present Value of retrofitting to Oxyfuels, followed by the later retirement of the system and a repowering of the site for IGCC showed marked benefits with the implementation of Oxyfuels.

The full energy cycle was considered, including mining, coal transportation, coal preparation, power generation, existing environmental regulations, facility water use, pipeline CO_2 conditioning, and pipeline transport of CO_2 to sequestration. Process design conditions and retrofit cost calculations and other criteria used to rank options, including sensitivity AMIGA model runs using these criteria were determined. We examined capacity expansion needed to meet load growth, retirements, and to replace capacity that has been de-rated. In this task we provide fuel demands (gas, coal types), emissions, and investment requirements for the entire power sector.

The Chicago Energy Initiative is an interdisciplinary research program devoted to the study of the economic, environmental and geopolitical impacts of energy use (Total Funding ~$2 MM)

http://research.chicagogsb.edu/energy/index.aspx

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About the Energy Initiative

The Chicago Energy Initiative is an interdisciplinary research program devoted to the study of the economic, environmental and geopolitical impacts of energy use.

The development and distribution of abundant energy is perhaps the most important social problem of our time. Energy is essential to the maintenance of living standards in developed countries, and to the spread of prosperity worldwide. The goal of energy abundance is constrained by three interrelated features of energy use, however.

First, current energy sources are dominantly derived from depleting natural resource stocks. If rising worldwide demands for energy are to be met at reasonable cost, new energy sources must be deployed; either by further developing existing energy sources or inventing new ones, and then providing the means by which these energy sources can be efficiently distributed.

Second, energy use raises environmental concerns both local and global. Most prominently, evidence of anthropogenic climate change from current energy sources is compelling. Energy use on a scale necessary to sustain and spread economic prosperity will require new approaches to both national and international economic policy, along with societal accommodation of climate change and the development of "clean" energy sources.

Third, energy use and commerce create national and international security concerns. Because of the central role of energy in economic activity, developed countries devote substantial resources and political capital to the protection of energy sources. Access to energy supplies remains a prime source of international conflict. The link between nuclear power and nuclear proliferation connects energy policy and international security even more intimately.

Progress on these issues calls for interdisciplinary research that draws on specialties ranging from economics, business and other social sciences to the physical sciences and engineering disciplines, involving the intellectual resources of both the University and Argonne National Lab. The Chicago Energy Initiative serves as a platform for this research. Activities and programs covered by the Initiative include a regularly scheduled Energy Workshop, an annual Energy Research Conference, a Working Paper series, and the provision of seed grants to encourage research on energy issues.

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- **Richard Doctor**, Energy Systems Division, Argonne National Laboratory
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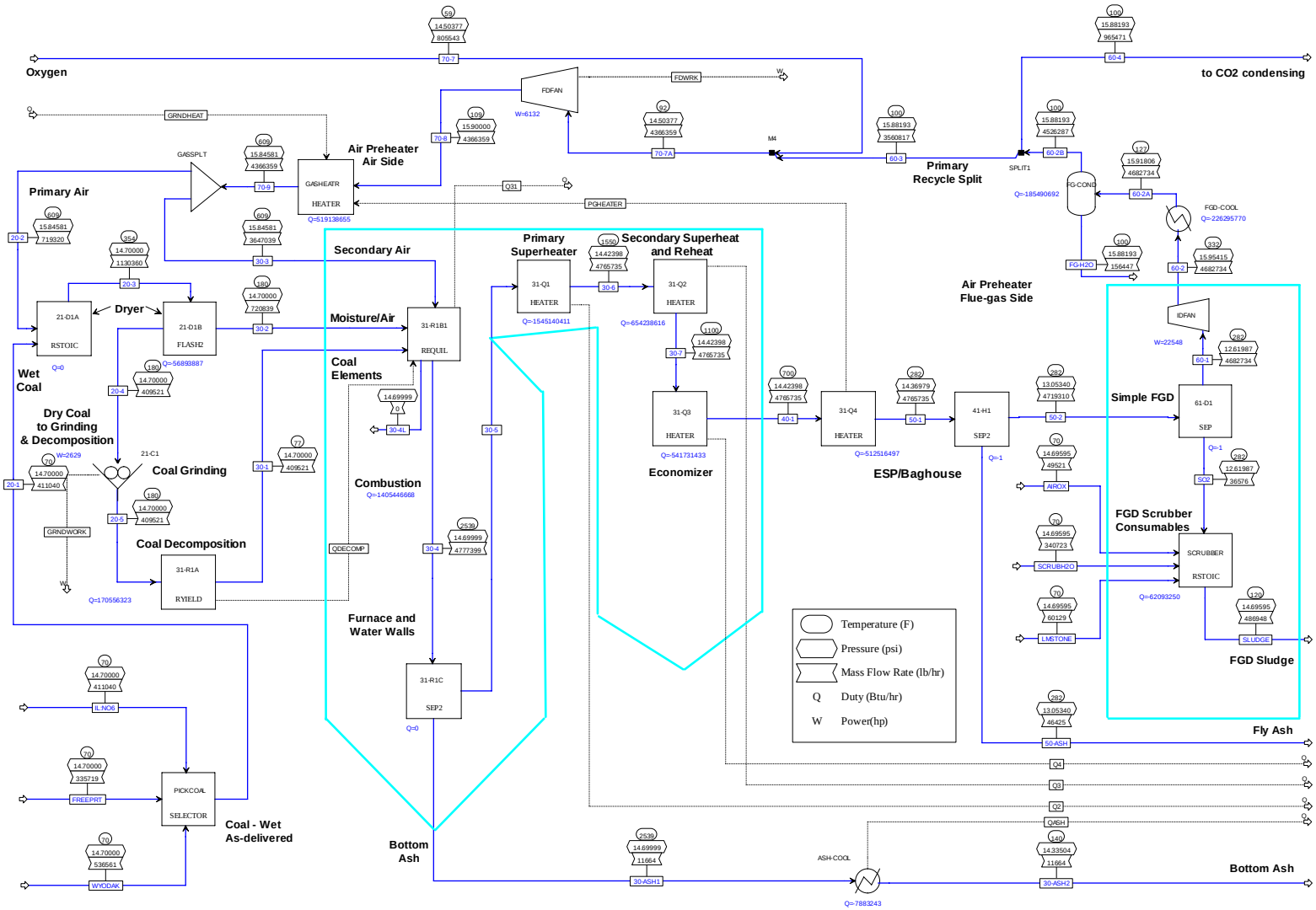
Current Project: Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling *(FE49539 – Tim Fout)*

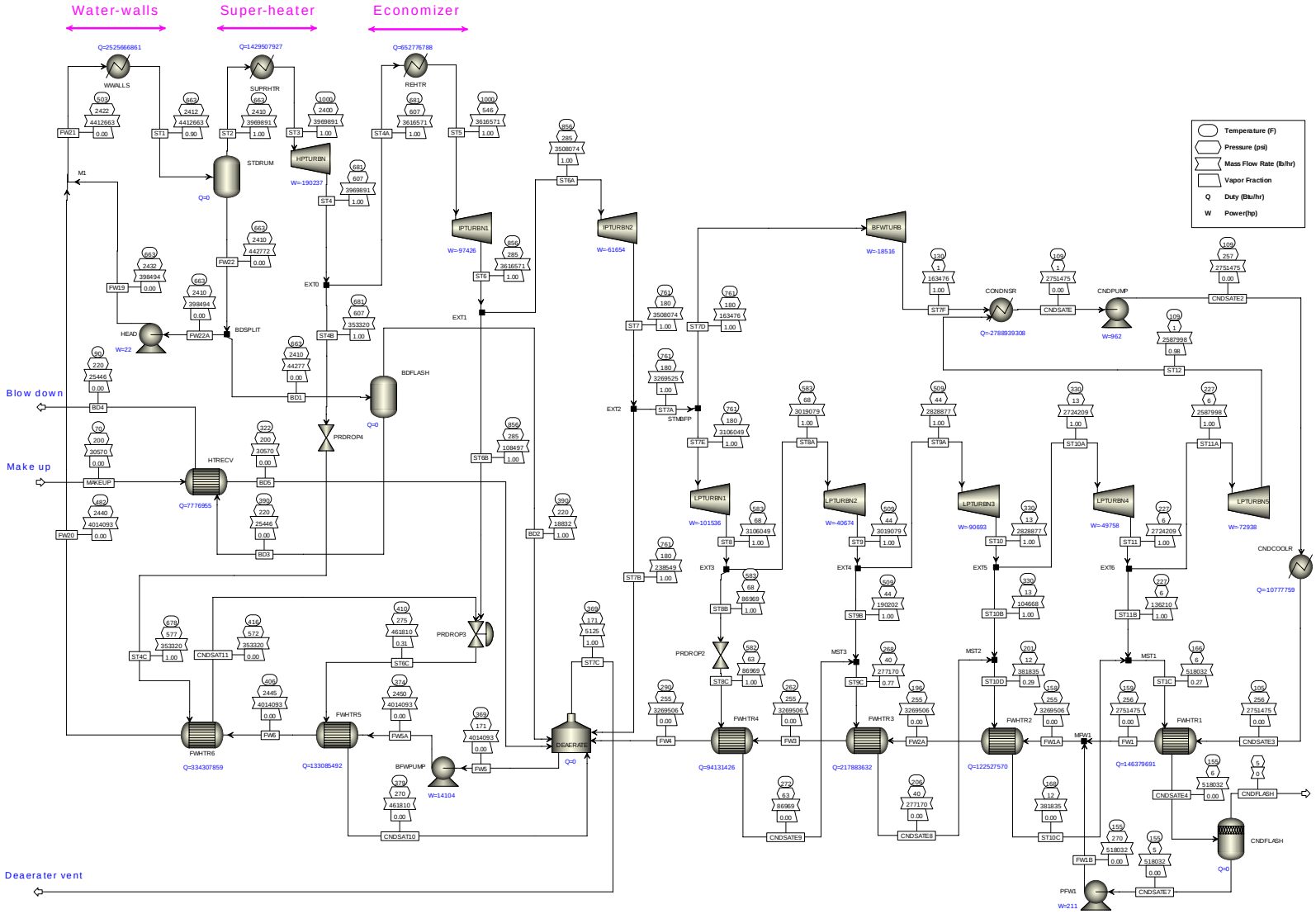
- Use ASPEN to model Oxyfuels retrofit across the existing fleet of domestic PC boilers as a CO_2 Capture and Sequestration (CCS) strategy
- Cost-Engineering for Oxyfuels based on ASPEN
- Recognize that Oxyfuel investment may be a transitional strategy to Integrated Gasification Combined Cycle with CCS
- Link to an ongoing effort with the AMIGA (All-Modular Industry Growth Assessment) as the Computational General Equilibrium (CGE) macroeconomic, sector, & energy model
- Study the sectoral impacts of Oxyfuel CCS with AMIGA
- Limited consideration of site specific issues such as CO_2 transport and water availability

ASPEN: Oxyfuels – Gas Side (with comparison against base)

Aspen Plus 20.0 Run:450 MW-ILNo6 OXY 2009-03-18a 3/18/2009 1:54:58 PM

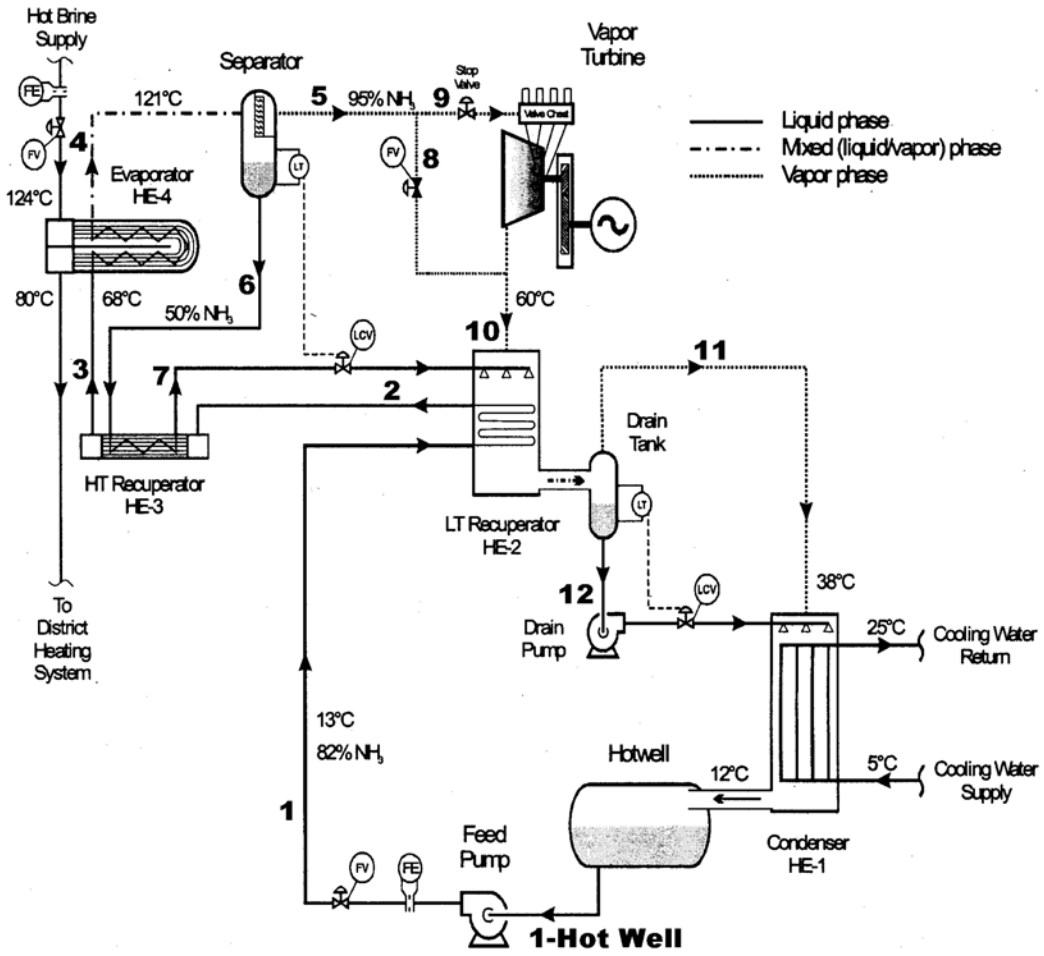


ASPEN: Oxyfuels – Steam-side simulation; also CO_2 condensing; waste heat chilling



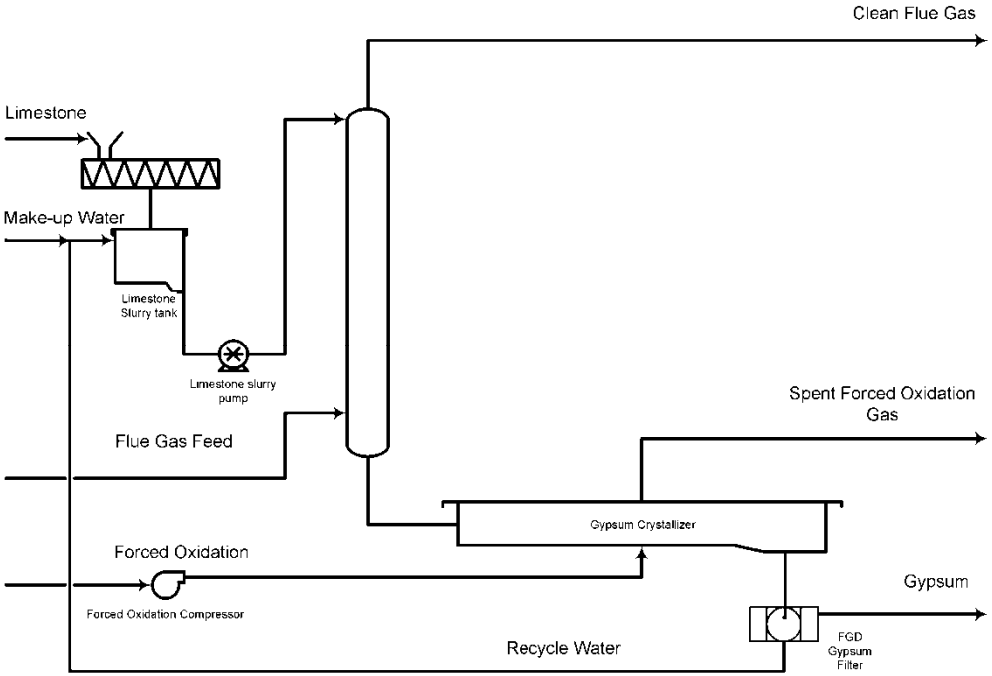
Simulation to validate Kalina

(OMMI Vol. 1, Issue 2; August 2002; "Testing and Operating Experience of the 2 MW Kalina Cycle Geothermal Power Plant in Húsavík, Iceland," Mirolli)



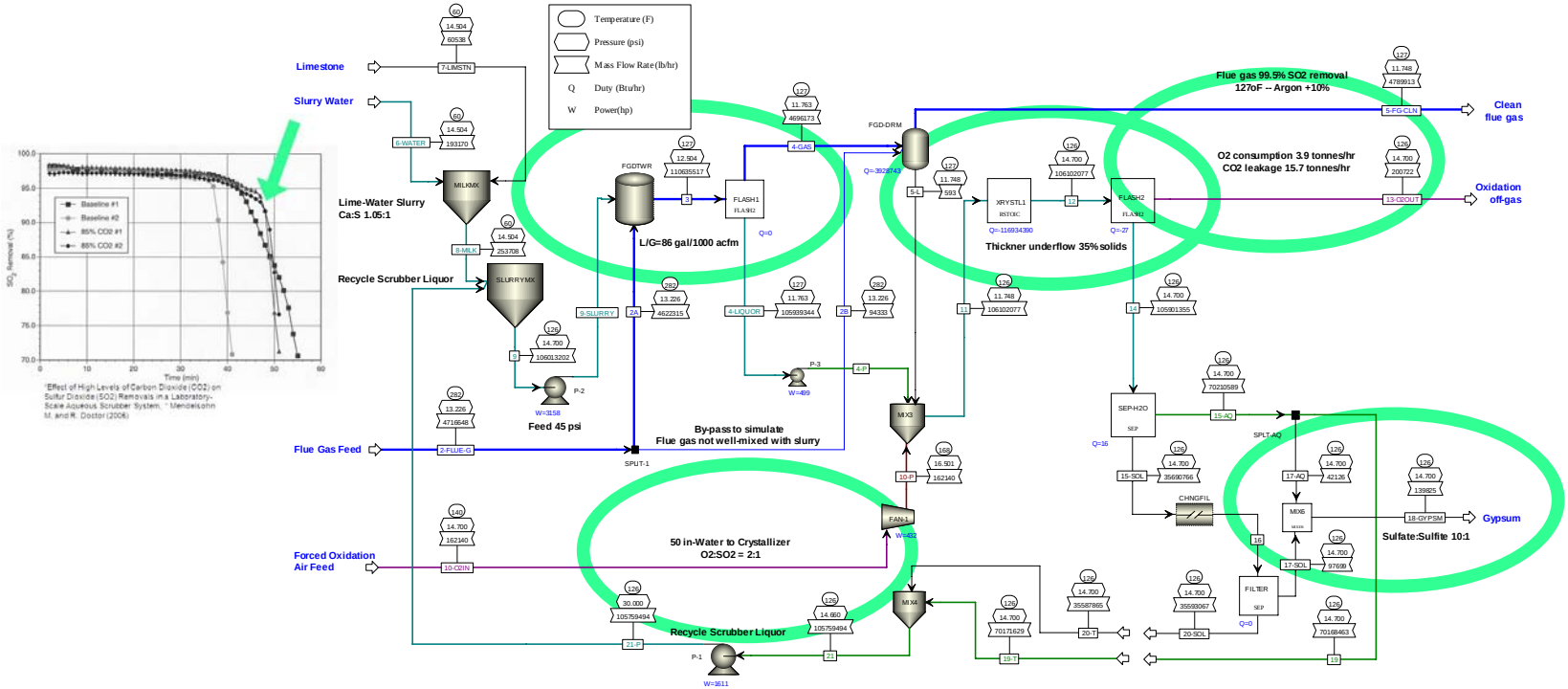
FGD requires special consideration: Electrolytes were modeled

To prevent Argon and N_2 from infiltrating the desulfurized product gas, the ASPEN was run with the electrolyte suite feature and the Forced Oxidation system to examine forced oxidation and Oxygen mixed with an Oxy-fuel-derived CO_2 stream.



Reaction	Type	Stoichiometry
1	Equilibrium	2 H2O <--> H3O+ + OH-
2	Equilibrium	CO2 + 2 H2O <--> H3O+ + HCO3-
3	Equilibrium	HCO3- + H2O <--> H3O+ + CO3--
4	Equilibrium	SO2 + 2 H2O <--> H3O+ + HSO3-
5	Equilibrium	HSO3- + H2O <--> H3O+ + SO3--
6	Equilibrium	CAOH+ <--> CA++ + OH-
CASO3(S)	Salt	CASO3(S) <--> CA++ + SO3--
CASO3*HM	Salt	CASO3*HM <--> CA++ + SO3-- + 0.5 H2O
CA(OH)2	Salt	CA(OH)2 <--> CAOH+ + OH-
CACO3(S)	Salt	CACO3(S) <--> CA++ + CO3--

Oxyfuel 2-tower SO_2 FGD for Air-forced oxidation



- CO_2 leakage justifies O_2 use for Forced Oxidation
- Dilution of CO_2 by non-condensable gases Argon, O_2 and N_2 lowers the temperature required for liquefaction to levels that may not be achievable with evaporative cooling towers alone.
- The concentration of non-condensable gases may violate safe operating specifications for the pipeline.

Economic scoping report for Oxyfuels – simple "Capital charge"

OXYFUELS RETROFIT - PC BOILER	
Gross Power (MW)	473.7
Internal Power (MW)	173.2
Net Power (MW)	300.5
Bituminous coal - IL#6 HHV (Btu/lb)	10,999
HHV (MJ/kg)	25.58
Moisture (as received)	7.97%
Ash (as received)	14.25%
Sulfur (as received)	4.45%

PROJECT COSTS	Capital, $K
Direct Costs	
Base electric@$1,200/kW (capitalized)	$0
Air-Separation Plant-delivery	$153,673
Ducts/Dampers/Air heaters/Controls	$3,297
Feedwater Heater	$507
O_2 Heater	$270
Seal Boiler for 1% in-leakage	$28
Flue Gas Desulfurization @ $125/kW	$59,213
CO_2 Conditioning and Compression	$55,622
Direct Costs Sub-total	*$272,608*
Indirect Costs	
General Facilities	$12,417
Engineering Fees	$28,503
Project Contingency	$62,706
Indirect Costs Sub-total	*$103,625*
Direct + Indirect Costs Sub-total	*$376,234*
Cost ($/kW Gross Power)	$794
Interest & Inflation	$75,247
Total Plant Investment-TPI	*$451,480*
Royalties	$1,636
Initial Inventory	$682
Start-up Costs	$2,726
Commissioning & spare parts	$1,603
Working Capital	$10,904
TOTAL PROJECT COSTS	*$469,031*

PERFORMANCE				
			Gross power heat rate HHV (Btu/kWh)	10,000
			Gross power heat rate HHV (kJ/kWh)	10.56
	Operating hours per year	7,709	Capacity factor	88.00%
			Annual Net Power Production (MW)	2,316,409
	CO_2 Capture	31.45 $/tonne CO_2	CO_2 tonne/yr	3,250,198

OPERATING COSTS		Basis		Unit Cost		Annual, $K
Oxygen (99% purity)		355	tonne/h			
Fuel - Bituminous coal - Illinois #6		186	tonne/h	$1.34	$/10^6 Btu	*$46,484*
Consumables	BFW chemicals			0.0075	$/MWh	$17
	CW chemicals			0.0375	$/MWh	$87
	Ash and FGD sludge disposal	103	tonne/h	$9.00	$/tonne	$7,141
	Limestone	28.0	tonne/h	$15.00	$/tonne	$3,232
	Other chemicals, dessicant, compressor oil					$73
Plant Labor	Operations (w benefits)	3.5	men/shift	$28.00	$/h	$858
	Supervision/support	25%	of above			$215
Maintenance	Base electric plant	1.5%	@	$1,200	$/kW	$8,527
	CO_2 Capture	2.0%	@	$794	$/kW	$7,525
Utilities	Auxiallary, fans, particulates	23.7	MW @ 5%	$0.00	$/MWh	$0
	Air Separation/ CO_2 Compressor	146.4	MW	$0.00	$/MWh	$0
	Flue Gas Desulfurization	3.1	MW	$0.00	$/MWh	$0
	Natural Gas and other utilities	25	10^6 Btu/h	$5.00	$/10^6 Btu	$972
	ConsumptiveWater	0.80	gal/kW	$0.40	$/Mgal	$1,537
Other	Insurance & Local Taxes	0.9%	of Direct + Base			$4,120
	Other - % of Operations labor	12.5%	of above			$134
NET OPERATING COSTS						*$34,439*
CO_2 COSTS AFTER PLANT FENCE		421.6	tonne/h	$7.50	$/tonne	*$24,376*

SUMMARY OF COSTS				
Levelizing Factors		Constant ($)	Basis, $K	
	Capital Charge	0.110	$469,031	
	Fuel	1.025	$46,484	
	Operating & Maintenance	1.000	$34,439	
	Costs after plant fence	1.000	$24,376	
Cost of Electricity - Levelized		mills/kWh		
	Capital Charge	22.27		
	Fuel	20.57		
	Operating & Maintenance	14.87		
	Costs after plant fence	10.52		
BUSBAR COST OF ELECTRICITY		**68.23 mills/kWh**	**Base case**	**24.11 mills/kWh**

Site-specific 300 MW Oxyfuel vs. Amine retrofit advantages for IGCC repowering

Doctor, Molburg, et al, "CO_2 Capture for PC-Boilers Using OXY-FUELS – A Transition Strategy," GHGT-7 (Sept. 2004)

Green highlights – equipment that will retrofit for IGCC

	Oxy-fuel	Amine (MEA)
Air Separation Unit	$101,000	
Amine Scrubber		$67,992
Ducts/Dampers/Air heaters/Controls	$2,571	$1,697
Feed water Heater	$395	
O2 Heater	$193	
Seal Boiler for 1% in-leakage	$22	
Cooling Towers/Cooling Pumps		$35,790
Flue Gas Desulfurization/Caustic	$6,317	$8,423
Chemical Treatment		$8,949
CO2 Conditioning and Compression	$36,828	$33,145
TOTAL DIRECT COSTS	*$147,326*	*$155,995*
RETROFIT CAPABLE for IGCC	*$137,828*	*$68,935*

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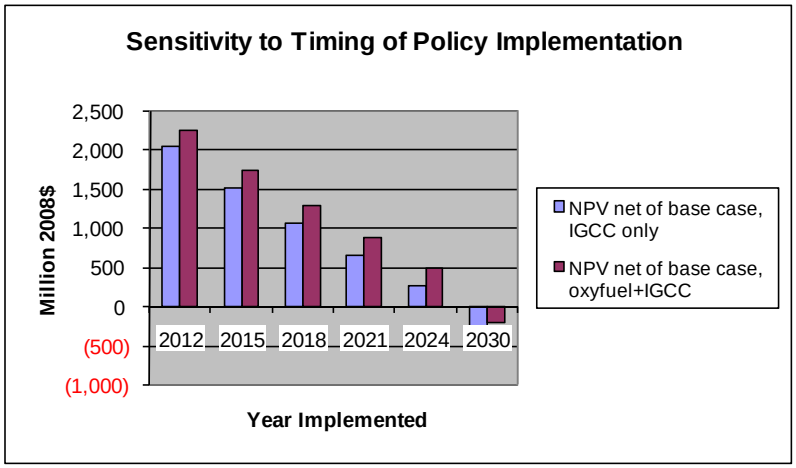
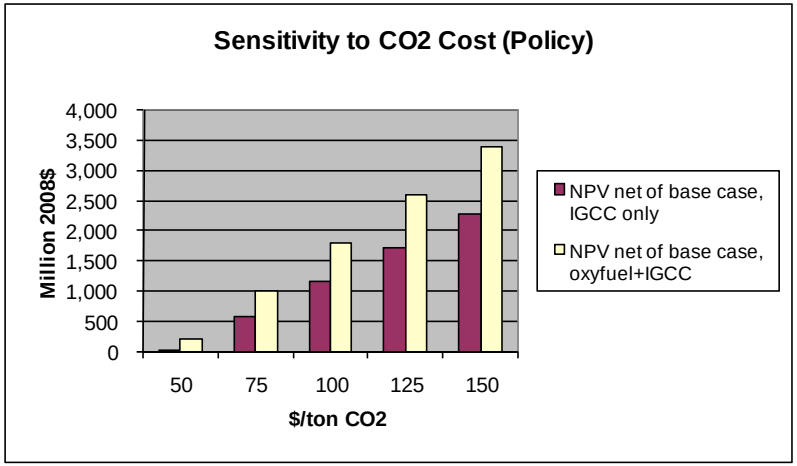
- Limited consideration of site specific issues such as CO_2 transport and water availability

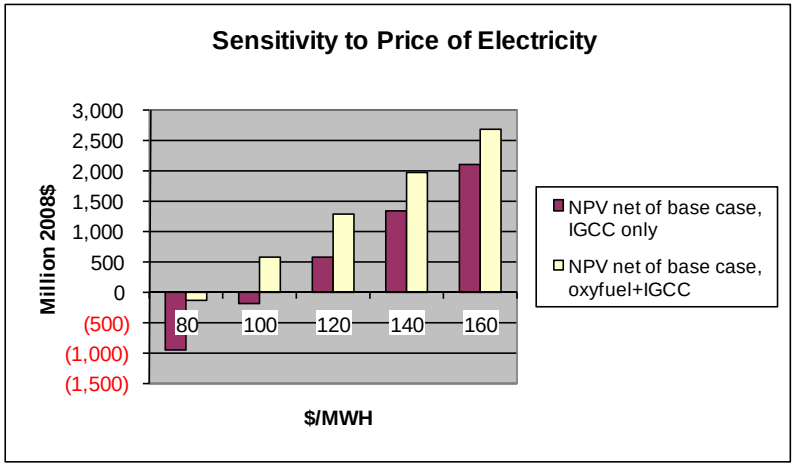
Preliminary results for Oxyfuels as a transitional strategy

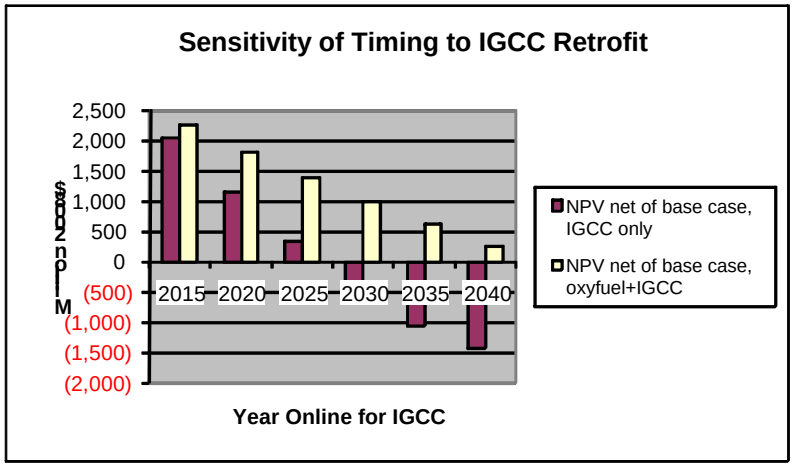
Doctor, R.D., J.C. Molburg, M.H. Mendelsohn, and N.F. Brockmeier, ***CO_2 Capture for PC-Boilers Using Oxy-Fuels – A Transition Strategy***, Proceedings of the 7th International Conference Greenhouse Gas Control Technologies, Vol. II, M. Wilson (*ed.*), Elsevier (2005) p. 1205

Preliminary Results 2008-11; J.C. Molburg







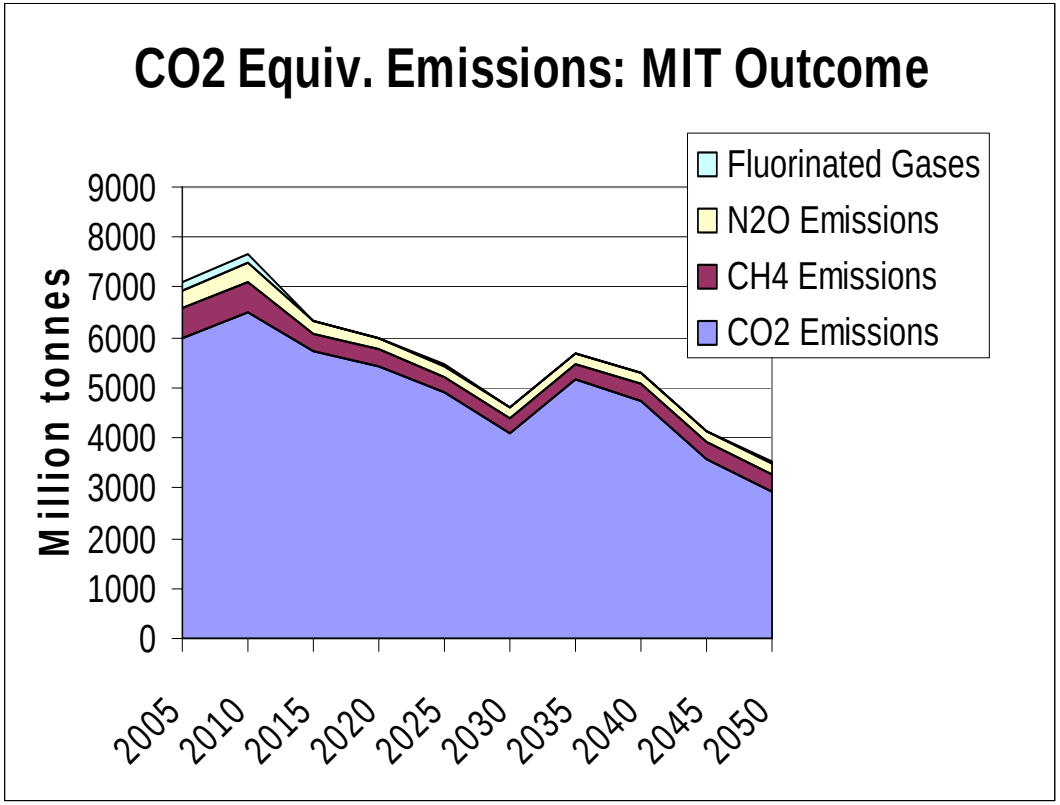


Future Work — ASPEN process design

- Optimize on FGD operation including by-pass for reheat
- Optimize “cold box” condensing using Low-pressure steam—assure all CO_2 pipeline specifications are met
- Plant specific estimates for anticipated pipeline length to candidate reservoir
- Estimate retrofit difficultly
- Load results into detailed cost study
- These features and cost savings will be reported in our forthcoming paper: 8th Annual Conference on Carbon Capture and Sequestration.

Our Analysis is in a Context of a Carbon Constrained World

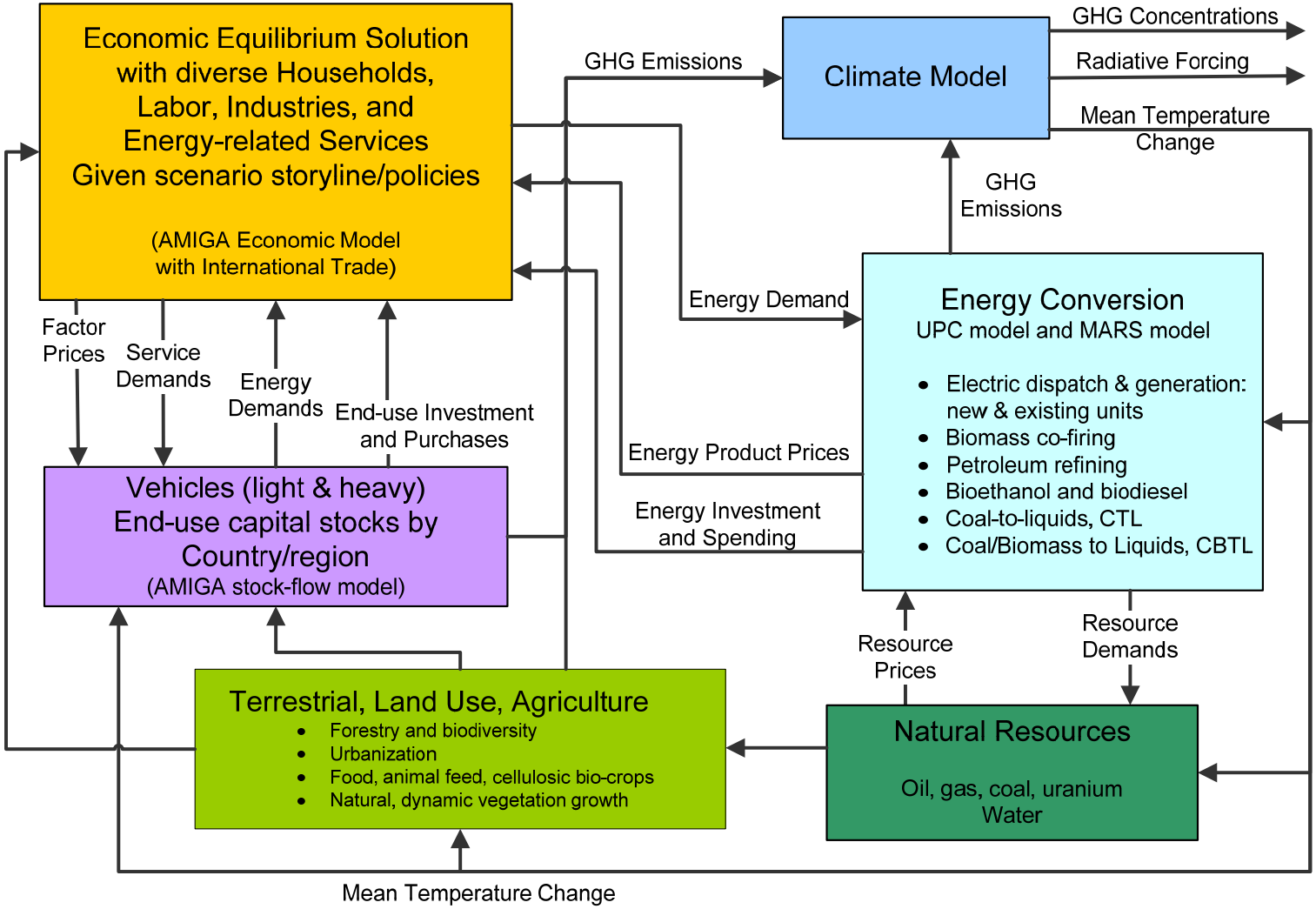
- Here we analyze a scenario with 50% CO_2 equivalent reduction by 2050
- A linear reduction implies 203 bmt cumulative cap from 2012-2050
- See M.I.T. Global Change report #146, April 2007: "Assessment of U.S. Cap-and-Trade Proposals"
- Full banking and borrowing is assumed
- This scenario is the basis for the Stanford University Energy Modeling Forum (EMF-22) Study on climate transitions



Additional Benefits of Oxyfuel Technology

- Early CO_2 reduction from existing PC plants
- Existing plant retrofits can be done in parallel with early penetration of IGCC and CTL/CBTL coproduction plants with CCS
- The retrofit PC plants will provide a needed stream of CO_2 for full scale, long- term experience with CO_2 transport, injection, sequestration, sink reservoir behavior, and monitoring (building confidence in CCS technology)
- When rapid capacity expansion of CCS technologies is needed to meet CO_2 emissions reduction targets, carbon storage technology and related institution-building will be ready.
- Co-benefits of the FGD in the retrofit: lower SO_2, NO_x, & mercury emissions
- These features and cost savings will be reported in our forthcoming paper: 8th Annual Conference on Carbon Capture and Sequestration. We compare scenarios with and without oxyfuel capture technology availability.

The AMIGA Modeling System Integrates Energy Supply Systems and Environmental Emissions Within an Economy-wide Model



The initial retrofits in the 2020's decade help to bring Coal-fired Generation Technologies with CCS to the "n^{th}" Commercial Plant Maturity by Year 2030

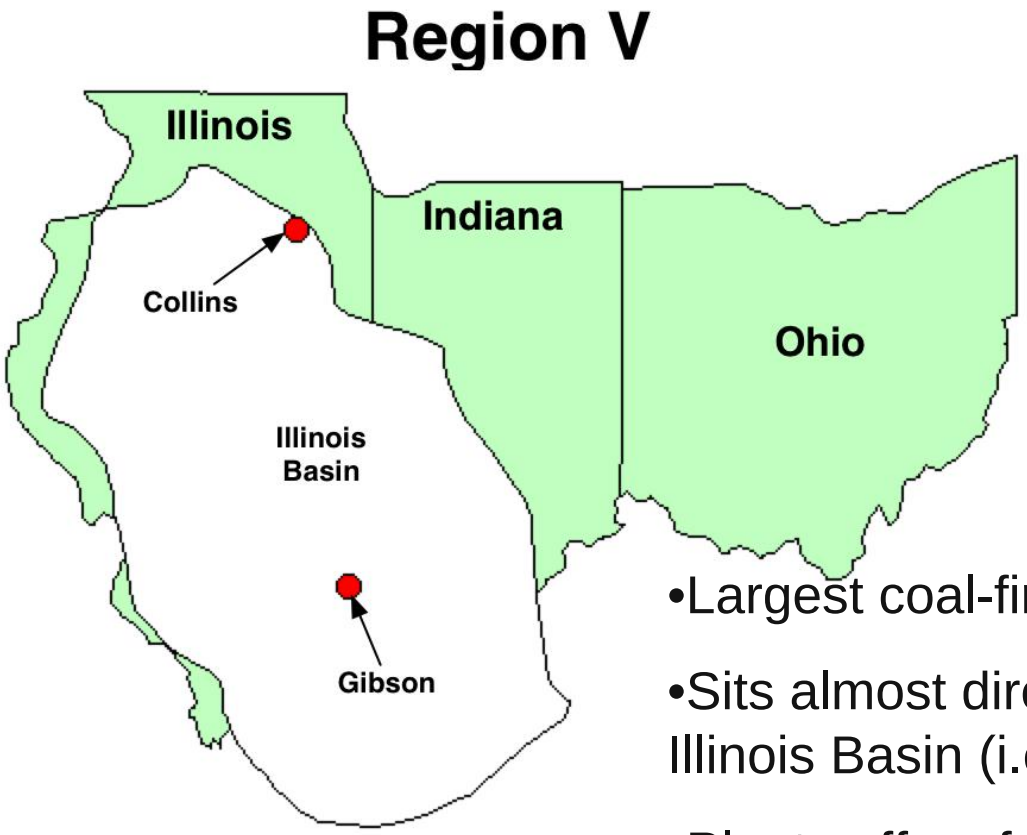
- Technologies with CCS that we include in the AMIGA system
  - Retrofit of existing plants with oxyfuels (based on unit inventory)
  - IGCC
  - CTL & CBTL
  - Biomass co-firing with Texas A&M FASOM biomass supply model

- The economic choice for technology market shares depends on
  - Price of coal (and plant efficiency)
  - Technology cost and performance
  - Relative Price of Oil / Price of Electricity
  - Stringency and implementation of a CO_2 Cap, or
  - Price path of CO_2 in $ per tonne

Plant Selection Process

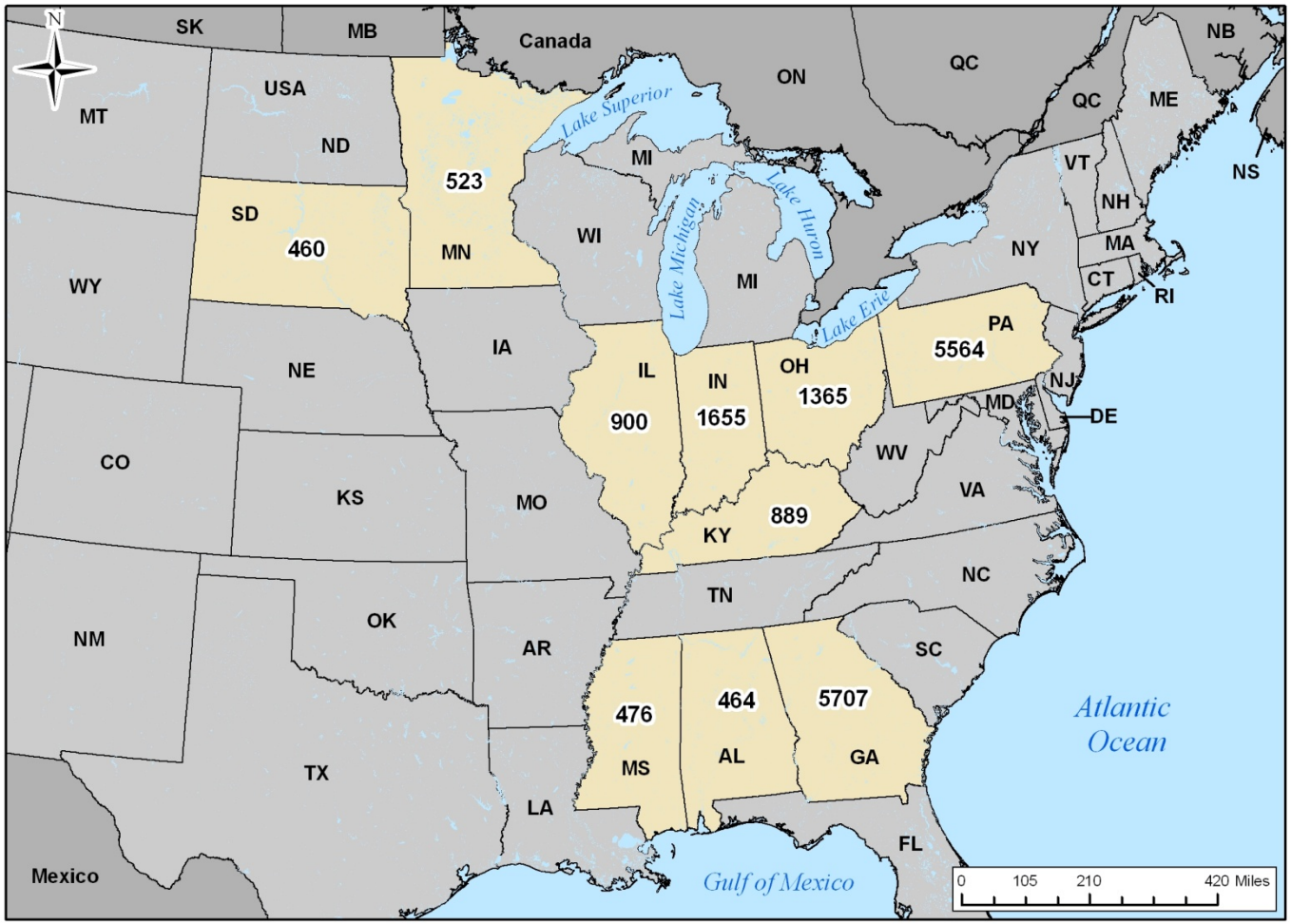
- Selected easily retrofitted units based on EVA study of FGD retrofit feasibility among large coal plants
- For initial retrofit analysis, we select units without FGD, since the presence of an FGD will complicate retrofit process
- Obtained current net capacity, heat rate, and fuel type from eGRID database
- Obtained distance to closest sequestration site from Partnership reports
- Applied these values via retrofit cost model to obtain costs for application in AMIGA model

Power Plant: Gibson, Indiana



- Largest coal-fired plant in the region
- Sits almost directly on the deepest part of the Illinois Basin (i.e. short CO_2 pipelines)
- Plant suffers from pollution issues that could benefit from retooling and sequestration

Aggregate Capacity, MW, by State for Selected Oxyfuel Retrofits with Geologic Sequestration or Enhanced Oil Recovery

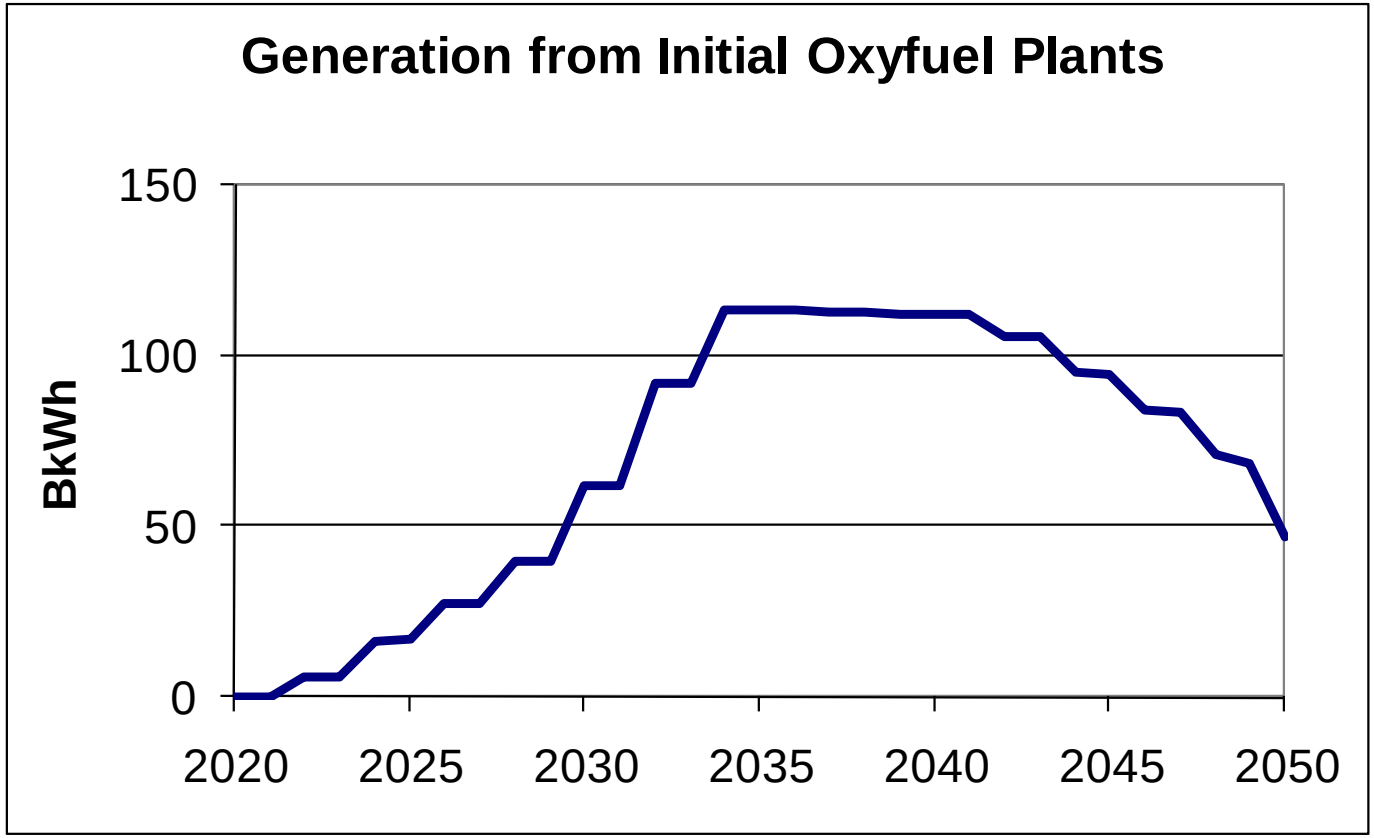


Retrofit Cost Estimates

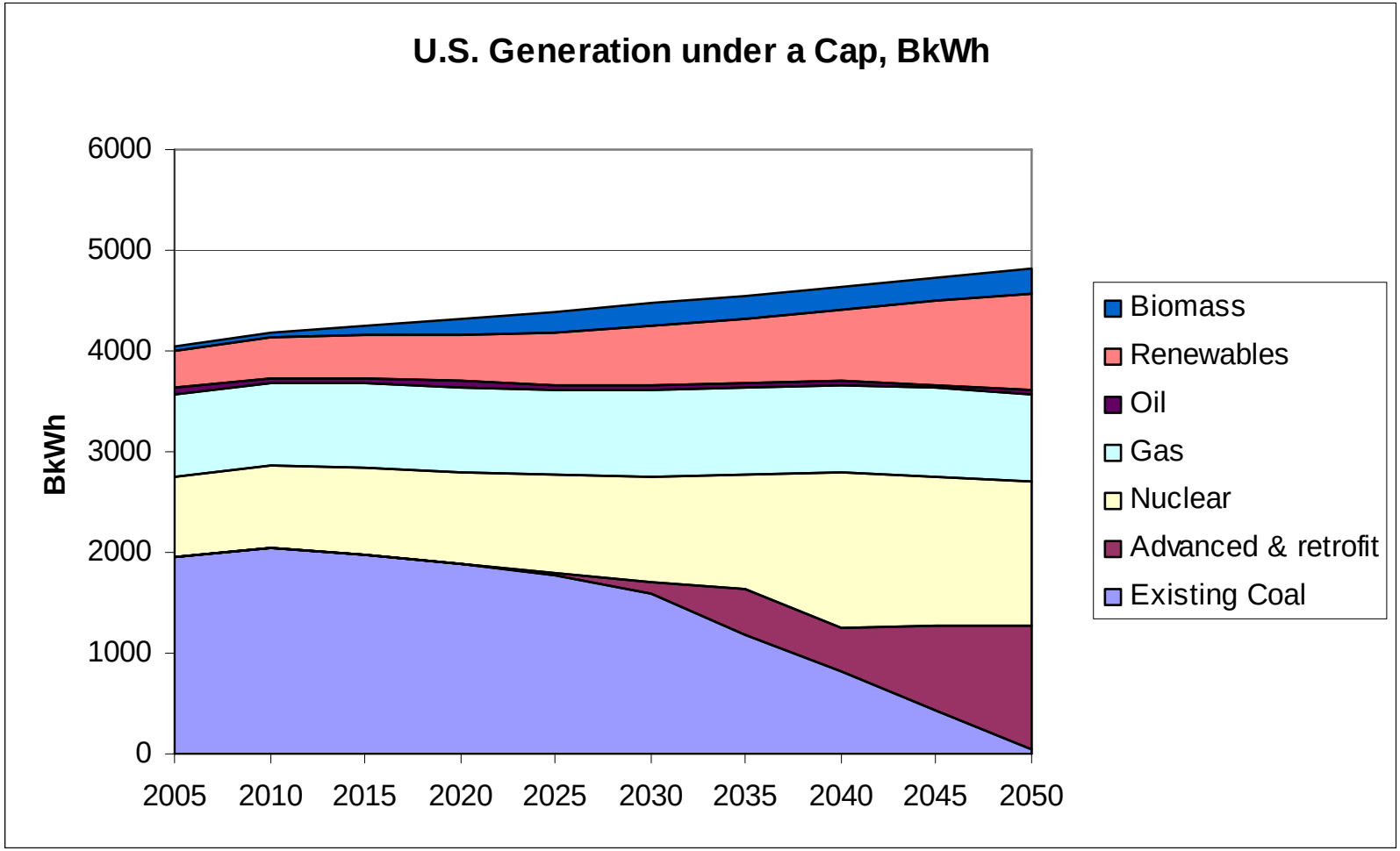
- Capital Costs
  - Air separation unit (ASU) sized to meet oxygen demand
  - CO_2 compression, condensation, purification, and pumping
  - FGD addition
  - Plant modifications, principally recycle loop
- Retrofit Operating Costs are calculated in AMIGA
  - Auxiliary power includes all retrofitted systems
  - Net heat rate penalty
  - Fuel, reagents, water, waste disposal
  - CO_2 transport and sequestration
- Electric System Costs/Implications
  - Retrofit units are high on dispatch loading order (low CO_2 penalty)
  - High emitting existing units are pushed down the loading order
  - Replacement power impacts utilization, coal & gas demand, and new capacity builds

An Oxyfuel Scenario:

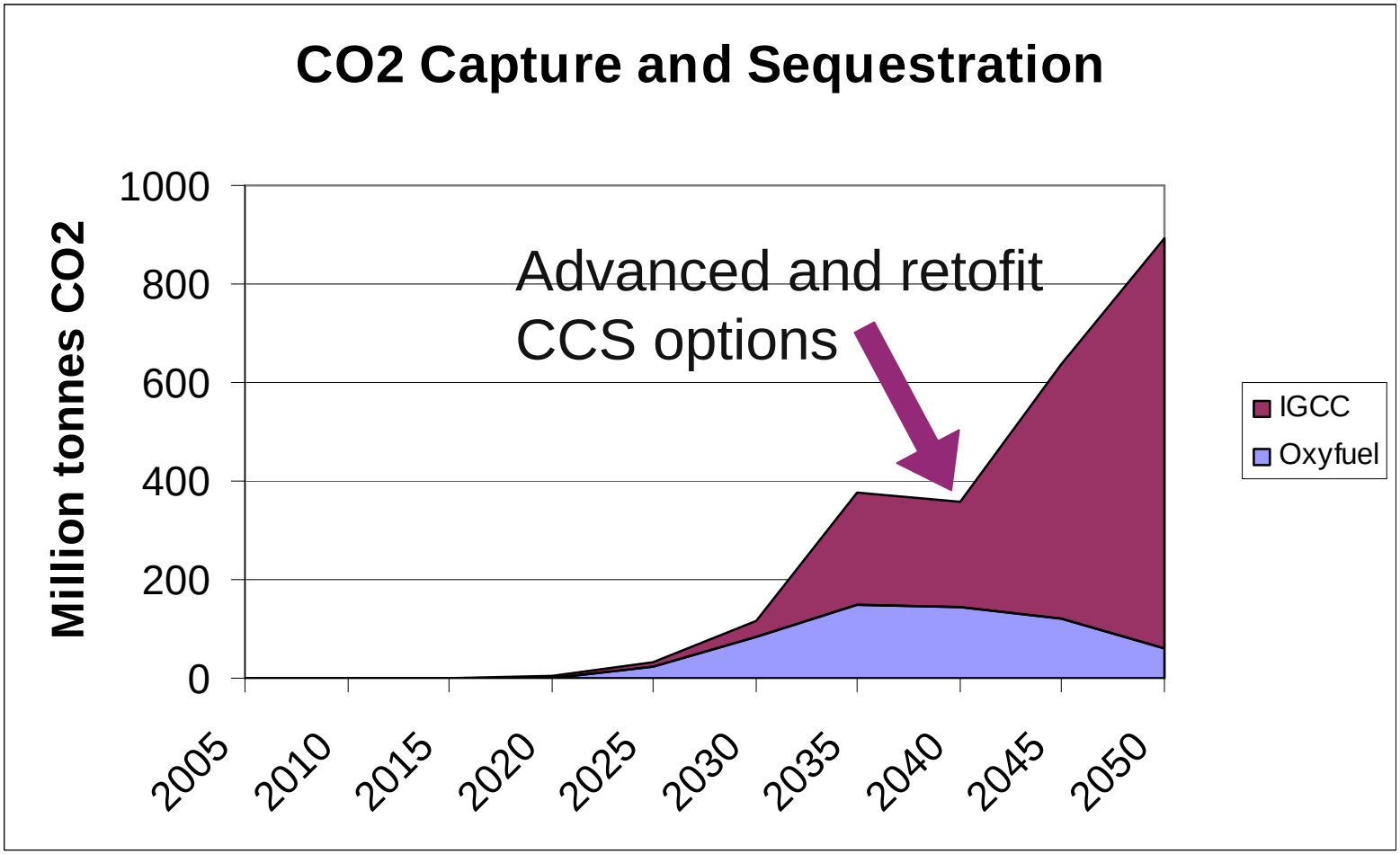
- Commercial construction begins in year 2020 (2 year construction, 6 mo down time)
- In a fourteen year period, 28 units are retrofitted
- 19.8 GW of nameplate capacity is retrofitted
- Units are refurbished for a 20-year life extension



Under a Carbon Cap, Advanced Coal with CCS, Nuclear, Gas, and Renewable Electric Generation have a Role



The Existing Plants Retrofitted with Oxyfuel and Carbon Capture Provide a CO_2 Steam for Enabling Early CCS Deployment and Longer-term Experience

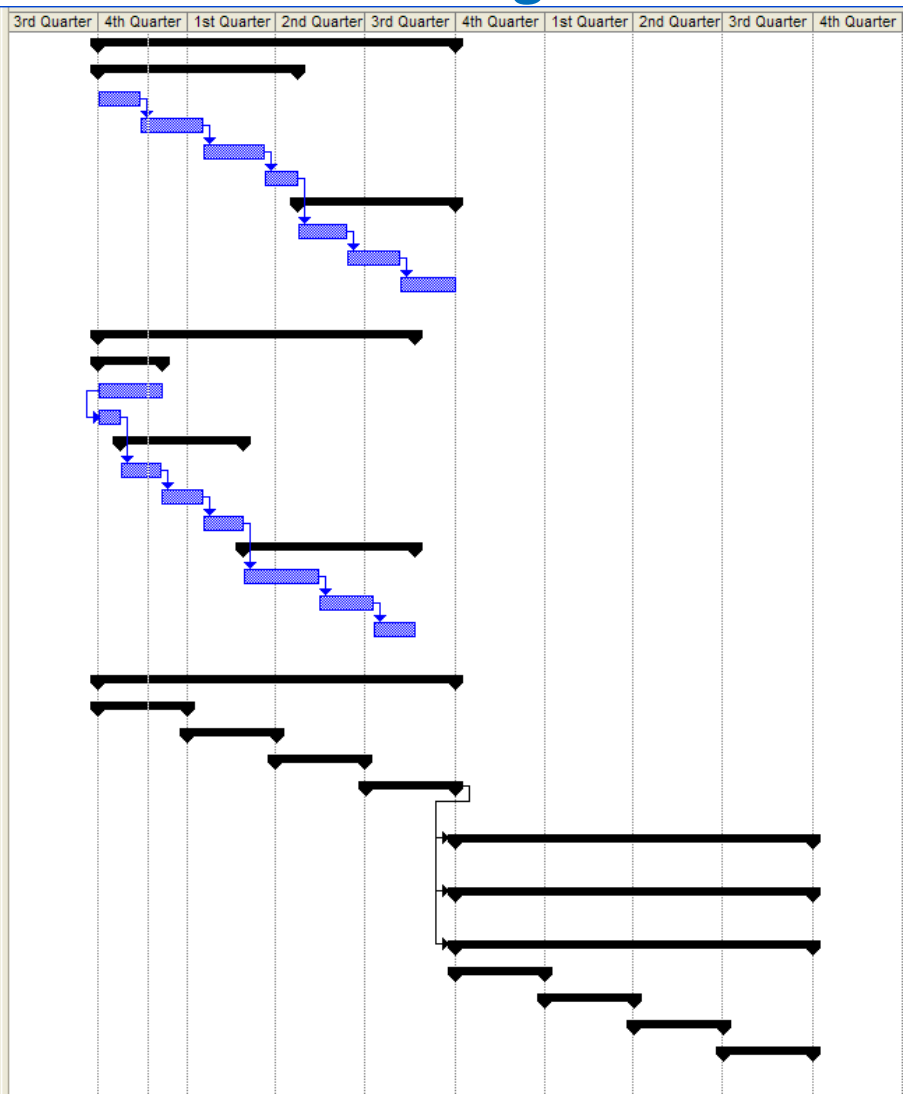


Future Work — Economics and Energy Systems Analysis

- Keep current with regional partnerships and power companies
  - Plant selections for analysis of retrofits
  - Sequestration sites, costs
- Combine into regional and nation-wide analyses of electric power generation
- Compare alternative incentive structures
- Build a user-selected option into the integrated model on retrofit/new plant details within a scenario run
  - Output reports by type of retrofit or new plant
  - Detailed breakdown of engineering, fuel, and other inputs
  - Project finance and performance within electric system
  - Emission sequestration opportunities
  - User friendly interface to select which units to examine with detail
  - Keep current with cost analysis by technology (e.g. NETL, EPRI)

Good hopes — enhanced Process Design – AMIGA Global Economics – Climate Modeling (FE0049539)

	Task Name
1	Task 1 FY2009 Oxyfuel/IGCC design retrofit - Large PC Power Plants
2	Task 1.1 Plant design retrofit
3	ASPEN for existing PC-boilers > 500 MW
4	Oxyfuel retrofit using current coal consumption
5	Flue Gas Desulfurization with sulfur polishing
6	CO2 50-km pipeline to trunk system
7	Task 1.2 Cost Engineering calculations
8	Internal Rates of Return at 15%.
9	Plant dispatch and capacity factor
10	Externals - Water-use, etc
11	
12	Task 2. FY2009 - AMIGA Analysis of Oxyfuel/IGCC Retrofit
13	Task 2.1 AMIGA Least-cost Investment Strategies
14	Dispatch - costs estimates
15	Dispatch - energy impacts
16	Task 2.2 Rank units
17	Proximity to high-quality CO2 reservoir
18	CO2 pipeline cost feasibility
19	Full energy chain considerations
20	Task 2.3 Ordering on the dispatch load curve
21	Capacity expansion
22	Load growth and to replace derated capacity
23	Investment requirements & other considerations
24	
25	Task 3. FY2009 - Reporting & NETL Internal Co-ordination
26	Task 3.1 - Quarter 1
28	Task 3.2 - Quarter 2
30	Task 3.3 - Quarter 3
32	Task 3.4 - Quarter 4
34	
35	Task 4. FY2010 - Oxyfuel retrofit - Intermediate 150-500 MW Units
45	
46	Task 5. FY2010 - AMIGA Analysis of Oxyfuel Retrofit
59	
60	Task 6. FY2010 - Reporting
61	Task 6.1 - Quarter 1
63	Task 6.2 - Quarter 2
65	Task 6.3 - Quarter 3
67	Task 6.4 - Quarter 4
69	



Thank you!

Questions?