Workshop on Carbon Sequestration Science

Economics

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Cost Components

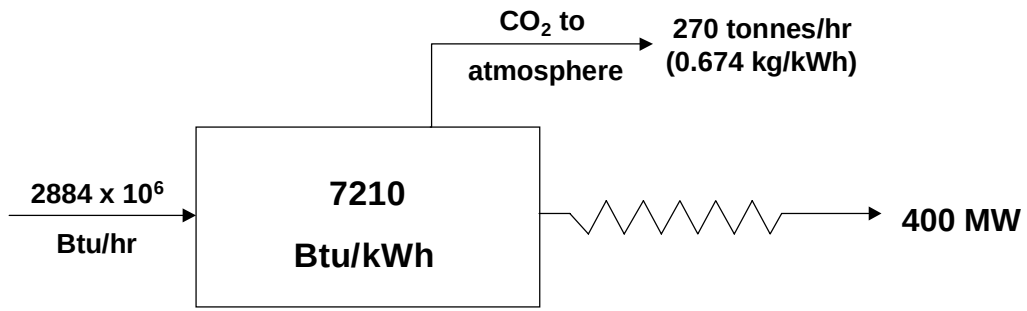
- Capture
  - Separation
  - Compression
- Sequestration
  - Transport
  - Injection

Approach

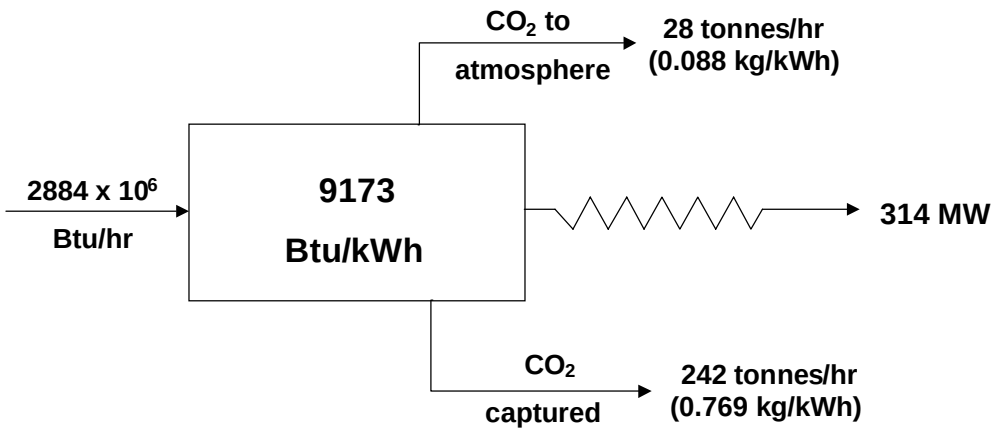
- Extract cost data from literature studies
  - Includes capture and compression
  - Excludes transportation and injection
- Adjust cost data to common economic basis
- Construct composite cost model
- Conduct sensitivity analyses and other studies with the composite cost model

Methodology for Analysis of Economic Studies

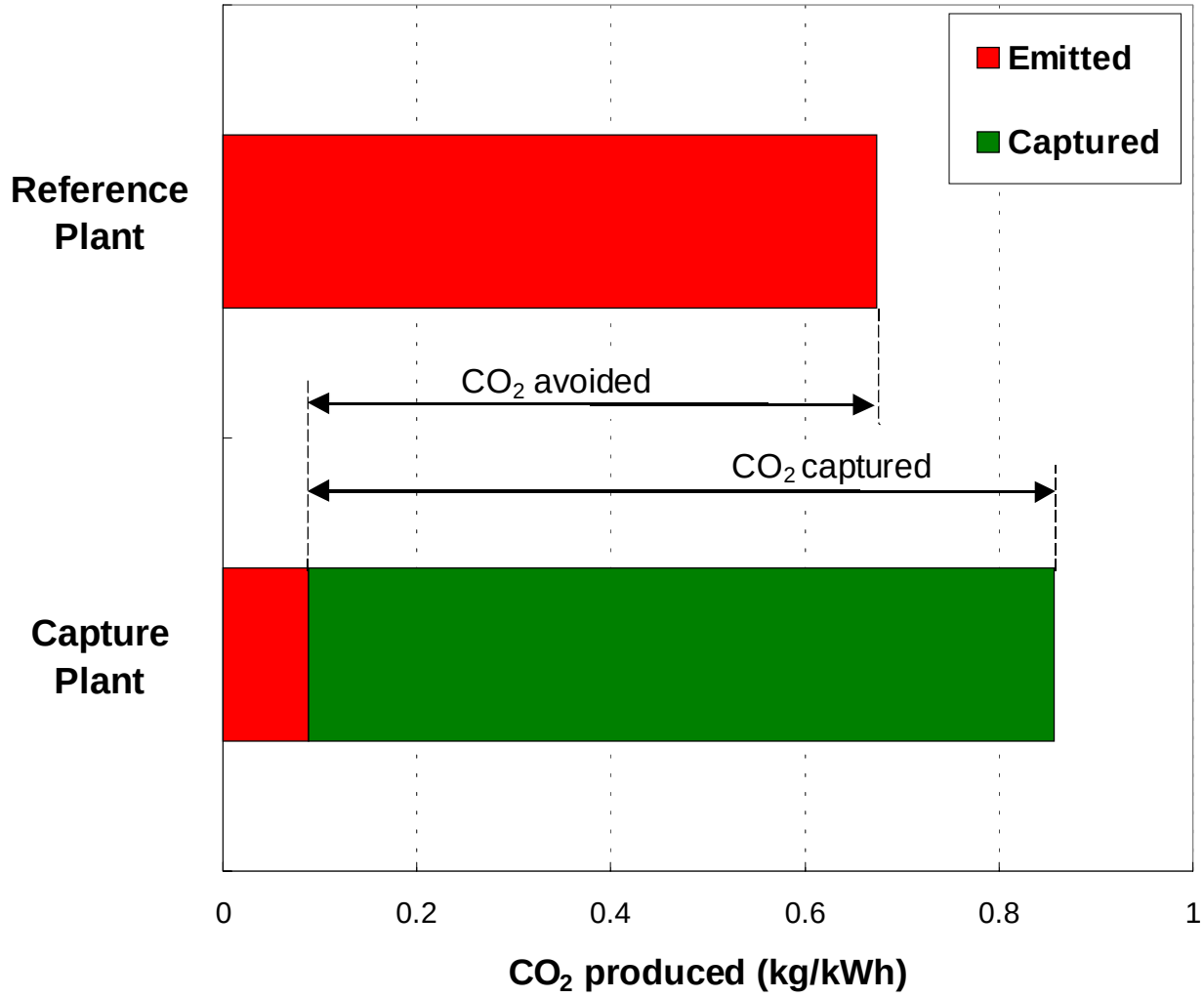
a) Reference Plant (No Capture)



b) Capture Plant



CO_2 Captured vs. CO_2 Avoided



Detailed Reference

- Jeremy David Thesis:
  - David, J., "Economic Evaluation of Leading Technology Options for Sequestration of Carbon Dioxide," M.I.T. Masters Thesis, (2000).
  - http://web.mit.edu/sequestration/JeremyDavid.pdf

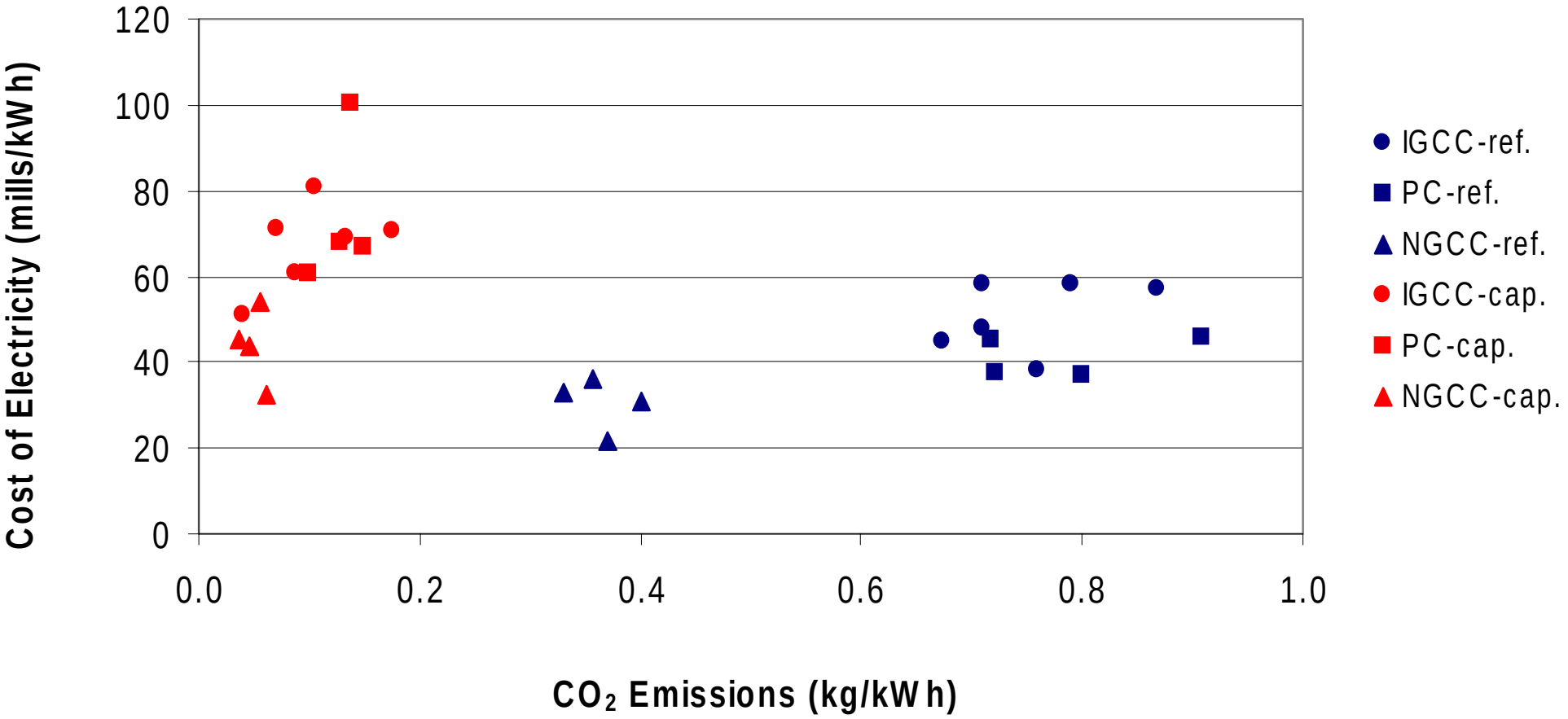
Approaches to CO_2 Separation

Approach	Coal	Gas
Flue Gas	Flue gas clean-up followed by CO_2 separation process (e.g., amines)	CO_2 separation from flue gas (e.g., amines)
Oxygen	Oxygen plus recycled flue gas in place of air Steam turbine	Oxygen plus recycled flue gas in place of air Modified turbine/CC
Hydrogen (or Syn-Gas)	Gasificaton Shift Capture H_2 to turbine/CC	Steam Reforming Shift Capture H_2 to turbine/CC

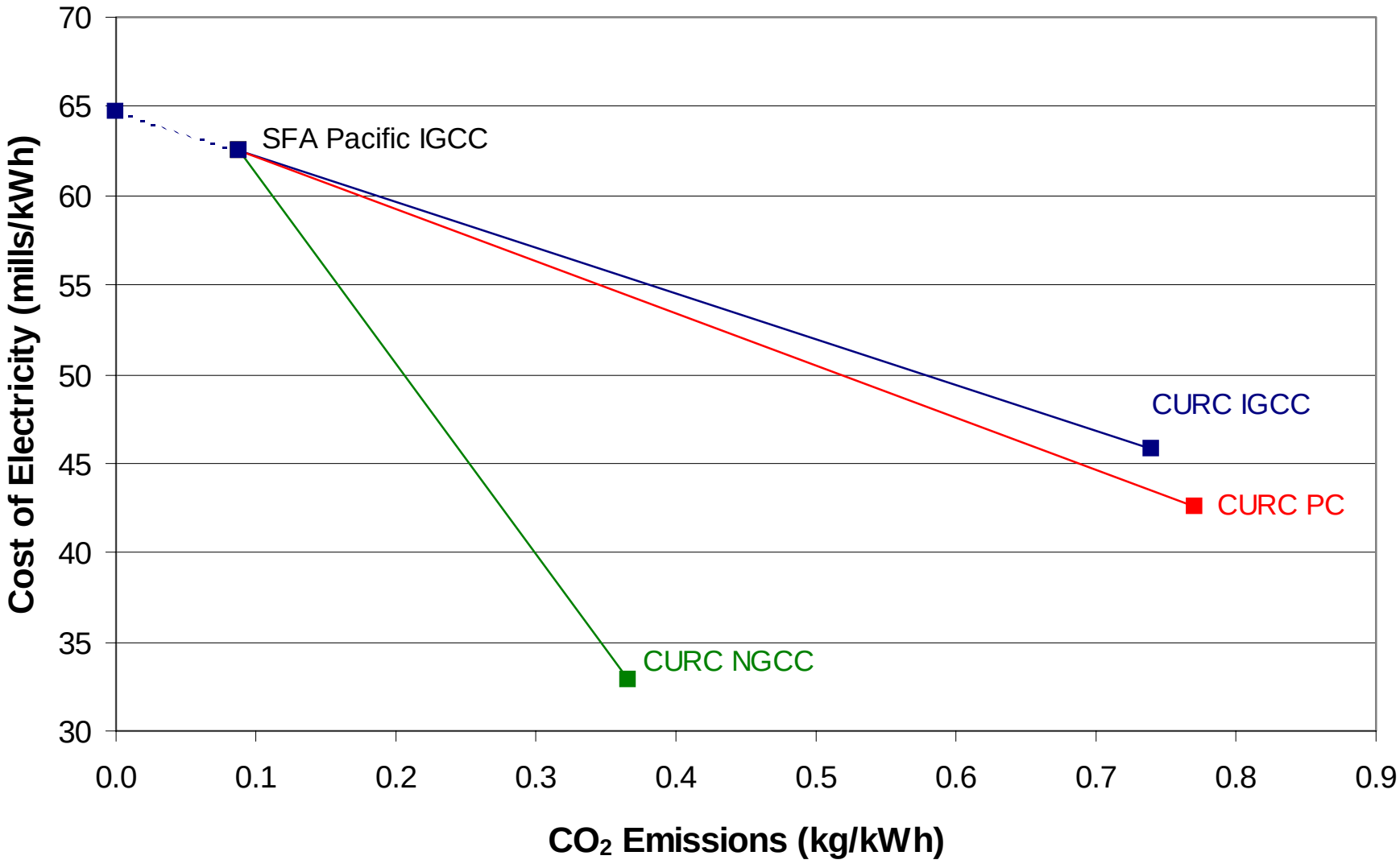
Analysis of IGCC Power Plants Reported Data

Study:		Argonne	Milan	SFA Pacific	Utrecht	EPRI	IEA
Cycle:		IGCC	IGCC	IGCC	IGCC	IGCC	IGCC
Data Description	**Units**						
Reference Plant							
coe: CAPITAL	mills/kWh	33.7	38.3	29.7	15.0	33.4	27.2
coe: FUEL	mills/kWh	14.9	14.0	7.4	16.5	12.2	11.7
coe: O&M	mills/kWh	9.7	5.7	7.9	6.7	11.4	8.9
Capital Cost	$/kW	1332	1536	1300	1265	1600	1471
Net Power Output	MW	413.5	404.1	400.0	600.0	431.6	408
CO_2 emitted	kg/kWh	0.790	0.709	0.674	0.760	0.868	0.710
Thermal Efficiency (LHV)		38.2%	43.7%	47.3%	43.6%	36.8%	46.3%
Heat Rate (LHV)	Btu/kWh	8938	7817	7210	7826	9280	7369
Cost of Electricity	¢/kWh	5.83	5.80	4.50	3.82	5.70	4.78
CO_2 Capture Plant							
coe: CAPITAL	mills/kWh	42.7	47.7	40.3	21.3	44.9	41.1
coe: FUEL	mills/kWh	16.3	16.4	9.4	19.8	15.2	14.2
coe: O&M	mills/kWh	11.7	7.0	10.8	9.7	20.5	13.8
Capital Cost	$/kW	1687	1913	1767	1799.1	2152	2204
Net Power Output	MW	377.5	345.6	314.4	500.0	347.4	382.0
CO_2 emitted	kg/kWh	0.176	0.071	0.088	0.040	0.105	0.134
Thermal Efficiency (LHV)		34.8%	37.3%	37.2%	36.3%	29.6%	38.2%
Heat Rate (LHV)	Btu/kWh	9791	9140	9173	9399	11528	8932
Cost of Electricity	¢/kWh	7.06	7.10	6.06	5.08	8.06	6.91
Comparison							
Incremental coe	¢/kWh	1.23	1.31	1.56	1.27	2.36	2.13
Energy Penalty		8.7%	14.5%	21.4%	16.7%	19.5%	6.4%
Mitigation Cost vs. ref	$/tonne CO2	$20	$20	$27	$18	$31	$37
Mitigation Cost vs. gas	$/tonne CO2	$199	$129	$100	$55	$183	$156
Basis							
Capital Charge Rate		14.4%	17.4%	15.0%	7.1%	11.9%	14.8%
Yearly Operating Hours	hrs/yr	5694	7000	6570	6000	5694	8000
Fuel (Coal) Cost, LHV	$/MMBtu	1.66	1.79	1.03	2.11	1.32	1.58

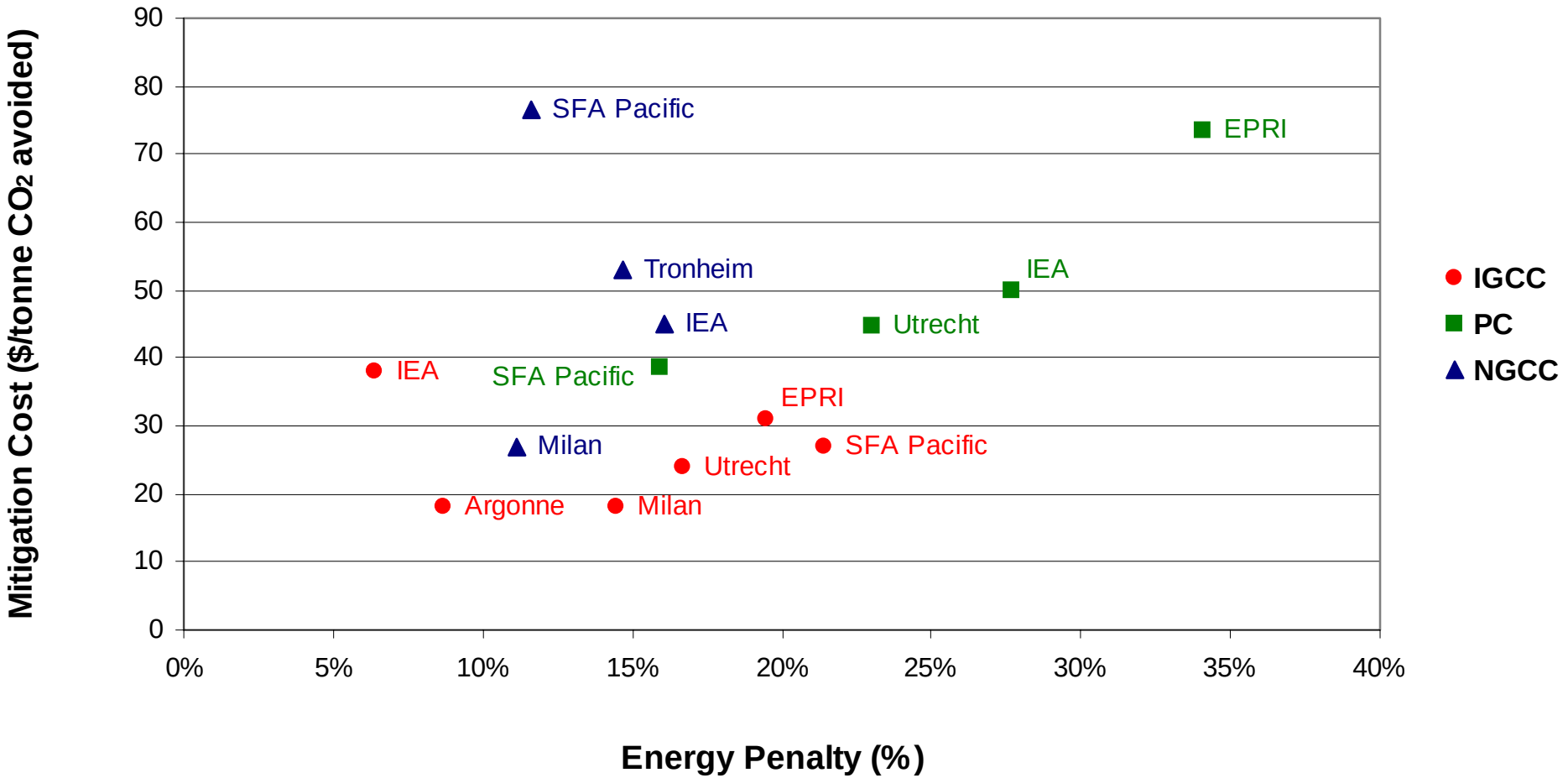
Cost of Electricity vs. CO_2 Emissions Reported Data



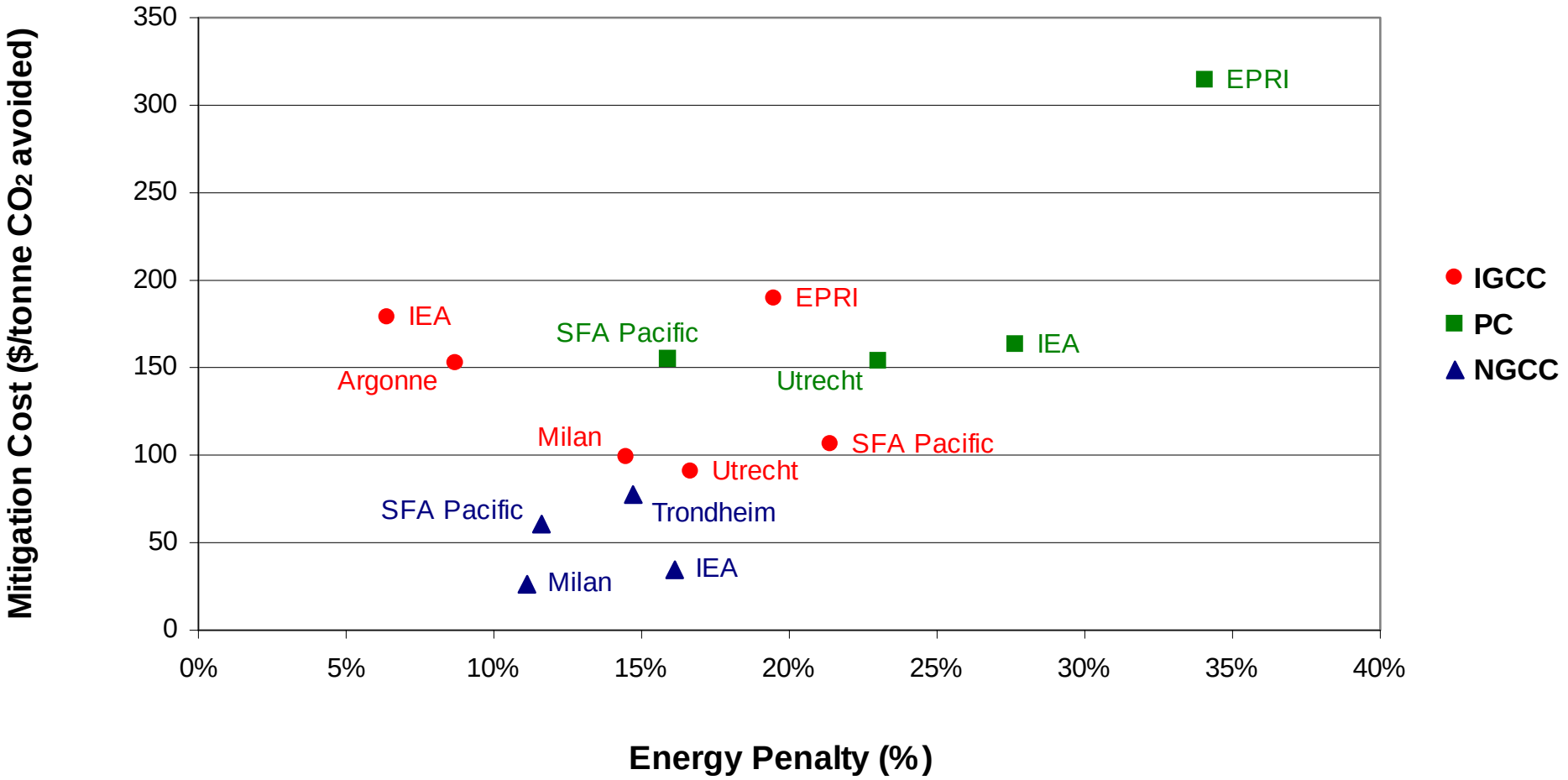
Calculation of Mitigation Costs



Mitigation Costs



Mitigation Costs on an NGCC Basis



Mitigation Costs

- Cost numbers are easily misinterpreted – they must be put in context to be interpreted correctly
- No universal answer – answers depend on the situation
- Discussion question: What do you tell a reporter looking for a single number for the cost of carbon capture and sequestration?

Analysis of IGCC Power Plants Adjusted Data

Study:		Argonne	Milan	SFA Pacific	Utrecht	EPRI	IEA	CURC
Cycle:		IGCC	IGCC	IGCC	IGCC	IGCC	IGCC	IGCC
Data Description	**Units**							
Reference Plant								
coe: CAPITAL	mills/kWh	30.4	35.1	29.7	28.9	36.5	33.6	29.7
coe: FUEL	mills/kWh	11.1	9.7	8.9	9.7	11.5	9.1	10.1
coe: O&M	mills/kWh	9.3	5.8	7.9	6.5	10.4	9.6	6.1
Capital Cost	$/kW	1332	1536	1300	1265	1600	1471	1300
Net Power Output	MW	413.5	404.1	400.0	600.0	431.6	408.0	
CO_2 emitted	kg/kWh	0.790	0.709	0.674	0.760	0.868	0.710	0.762
Thermal Efficiency (LHV)		38.2%	43.7%	47.3%	43.6%	36.8%	46.3%	42.0%
Heat Rate (LHV)	Btu/kWh	8938	7817	7210	7826	9280	7369	8124
Cost of Electricity	¢/kWh	5.08	5.06	4.65	4.50	5.85	5.23	4.58
CO_2 Capture Plant								
coe: CAPITAL	mills/kWh	38.5	43.7	40.3	41.1	49.1	50.3	
coe: FUEL	mills/kWh	12.1	11.3	11.4	11.7	14.3	11.1	
coe: O&M	mills/kWh	11.2	7.2	10.8	9.4	18.8	14.9	
Capital Cost	$/kW	1687	1913	1767	1799	2152	2204	
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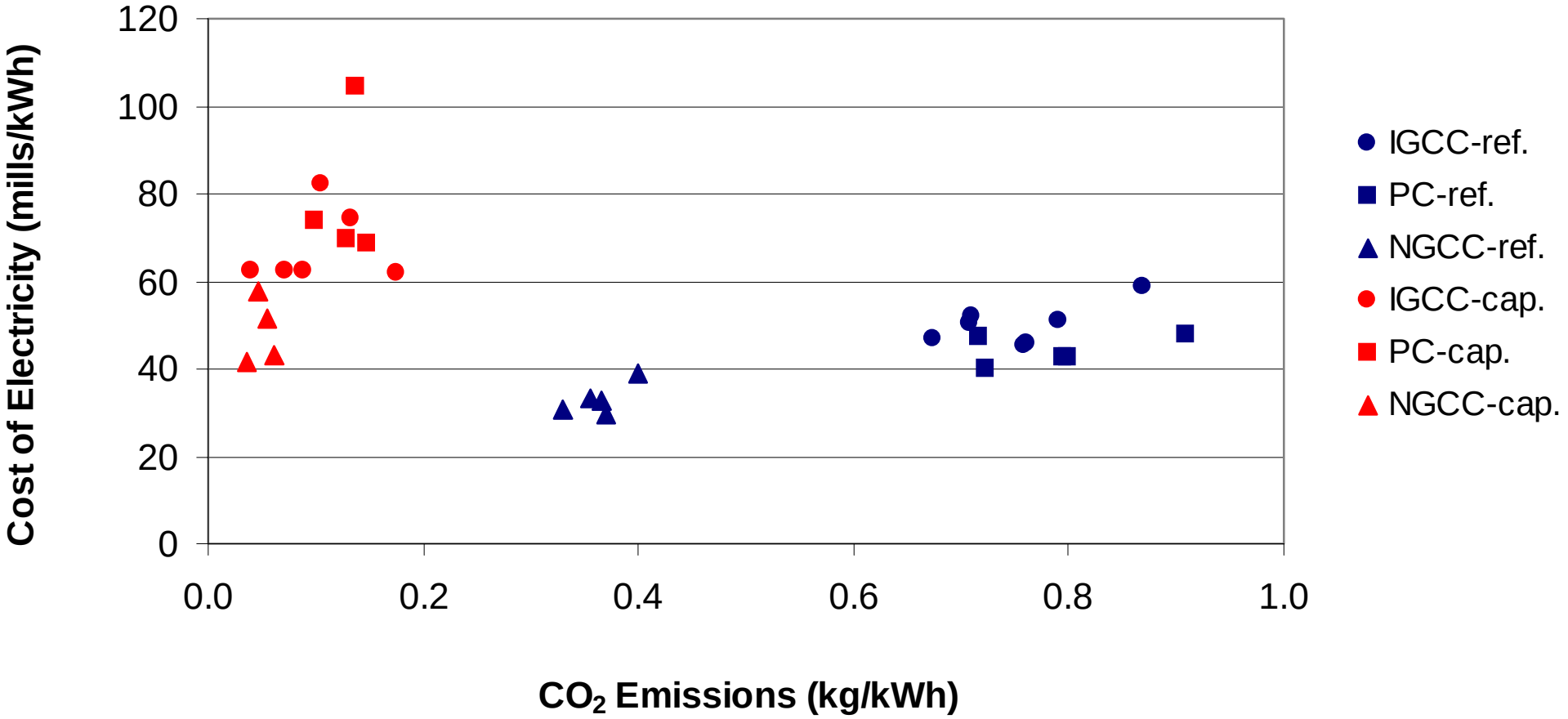
CO_2 emitted	kg/kWh	0.176	0.071	0.088	0.040	0.105	0.134	
Thermal Efficiency (LHV)		34.8%	37.3%	37.2%	36.3%	29.6%	38.2%	
Heat Rate (LHV)	Btu/kWh	9791	9140	9173	9399	11528	8932	
Cost of Electricity	¢/kWh	6.18	6.22	6.25	6.21	8.23	7.63	
Comparison								
Incremental coe	¢/kWh	1.10	1.16	1.59	1.71	2.38	2.39	
Energy Penalty		8.7%	14.5%	21.4%	16.7%	19.5%	6.4%	
Mitigation Cost vs. ref	$/tonne CO2	$18	$18	$27	$24	$31	$42	
Mitigation Cost vs. gas	$/tonne CO2	$152	$99	$106	$90	$189	$187	
Basis								
Capital Charge Rate		15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
Yearly Operating Hours	hrs/yr	6570	6570	6570	6570	6570	6570	6570
Fuel (Coal) Cost, LHV	$/MMBtu	1.24	1.24	1.24	1.24	1.24	1.24	1.24

Cost of Electricity vs. CO_2 Emissions Adjusted Data



Composite Cost Model Inputs

	Reference Plant	Capture Plant
Capital Costs	$/kW	$/(kg/h)
O&M Costs	mills/kWh	mills/kg
Energy Requirements	Btu/kWh	kWh/kg

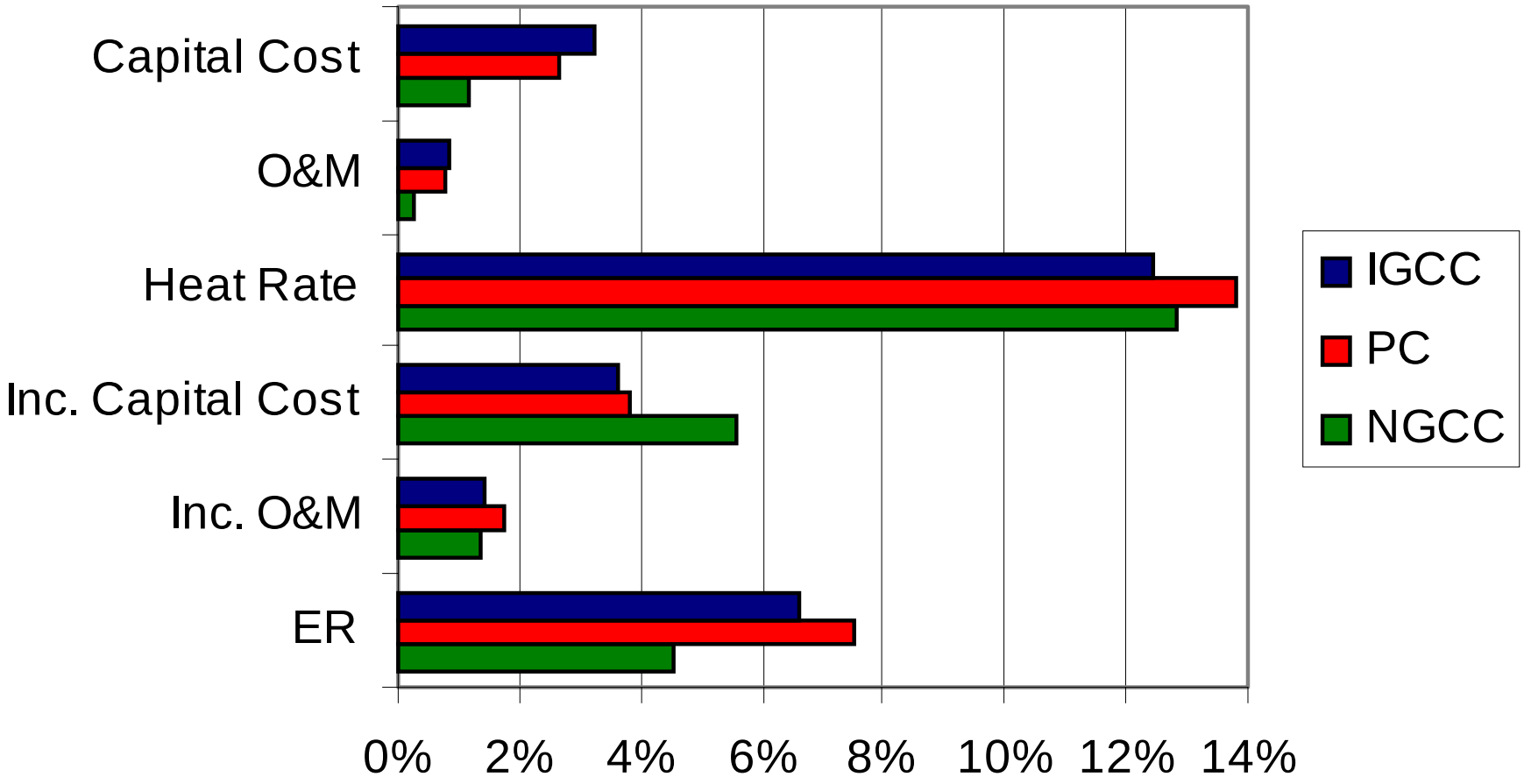
Composite Cost Model Inputs

Cycle	IGCC	IGCC	PC	PC	NGCC	NGCC
Data Description	**2000**	**2012**	**2000**	**2012**	**2000**	**2012**
Input						
Capital Cost, $/kW	1401	1145	1150	1095	542	525
O&M, mills/kWh	7.9	6.1	7.4	6.1	2.5	2.4
Heat Rate (LHV), Btu/kWh	8081	7137	8277	8042	6201	5677
Incremental Capital Cost, $/(kg/h)	305	275	529	476	921	829
Incremental O&M, mills/kg	2.65	2.39	5.56	5.00	5.20	4.68
Energy Requirements, kWh/kg	0.194	0.135	0.317	0.196	0.354	0.297
Basis						
Yearly Operating Hours, hrs/yr	6570	6570	6570	6570	6570	6570
Capital Charge Rate, %/yr	15	15	15	15	15	15
Fuel Cost (LHV), $/MMBtu	1.24	1.24	1.24	1.24	2.93	2.93
Capture Efficiency, %	90	90	90	90	90	90

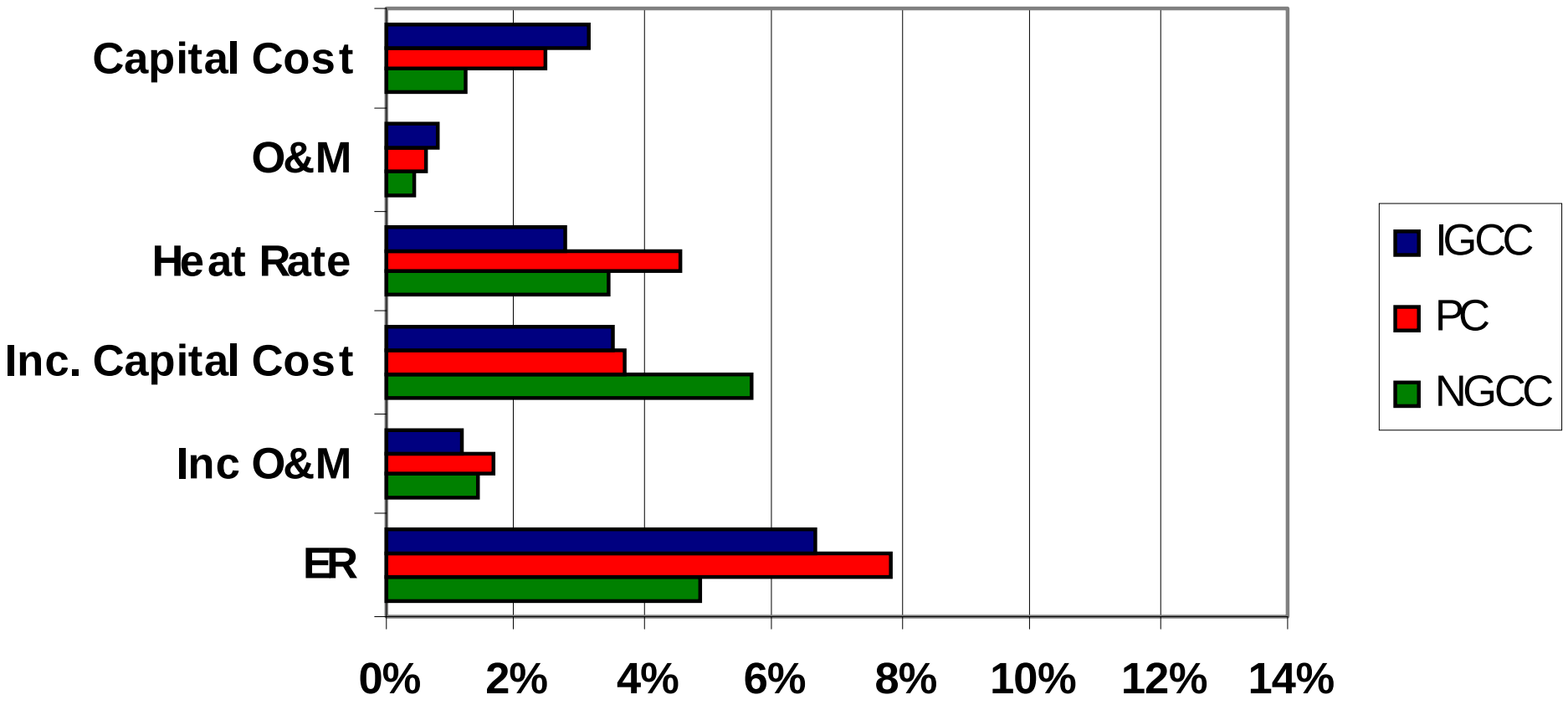
Composite Cost Model Results

Cycle	**IGCC**	**IGCC**	**PC**	**PC**	**NGCC**	**NGCC**
Data Description	**2000**	**2012**	**2000**	**2012**	**2000**	**2012**
REFERENCE PLANT						
Cost of Electricity, ¢/kWh	4.99	4.10	4.39	4.10	3.30	3.10
Thermal Efficiency (LHV), %	42.2	47.8	41.2	42.4	55.0	60.1
CAPTURE PLANT						
Cost of Electricity, ¢/kWh	6.69	5.14	7.71	6.26	4.91	4.33
Thermal Efficiency (LHV), %	36.1	43.5	30.9	36.1	47.8	54.1
COMPARISON						
Incremental coe, ¢/kWh	1.70	1.04	3.32	2.16	1.61	1.23
Energy Penalty, %	14.6	9.0	25.0	15.0	13.0	10.0
Mitigation Cost, Capture vs. Ref., \$/tonne of CO_2 avoided	26	18	49	32	49	41
Mitigation Cost, Capture vs. Gas, \$/tonne of CO_2 avoided	121	77	168	128	49	41

Sensitivity Study
Incremental Cost of Electricity



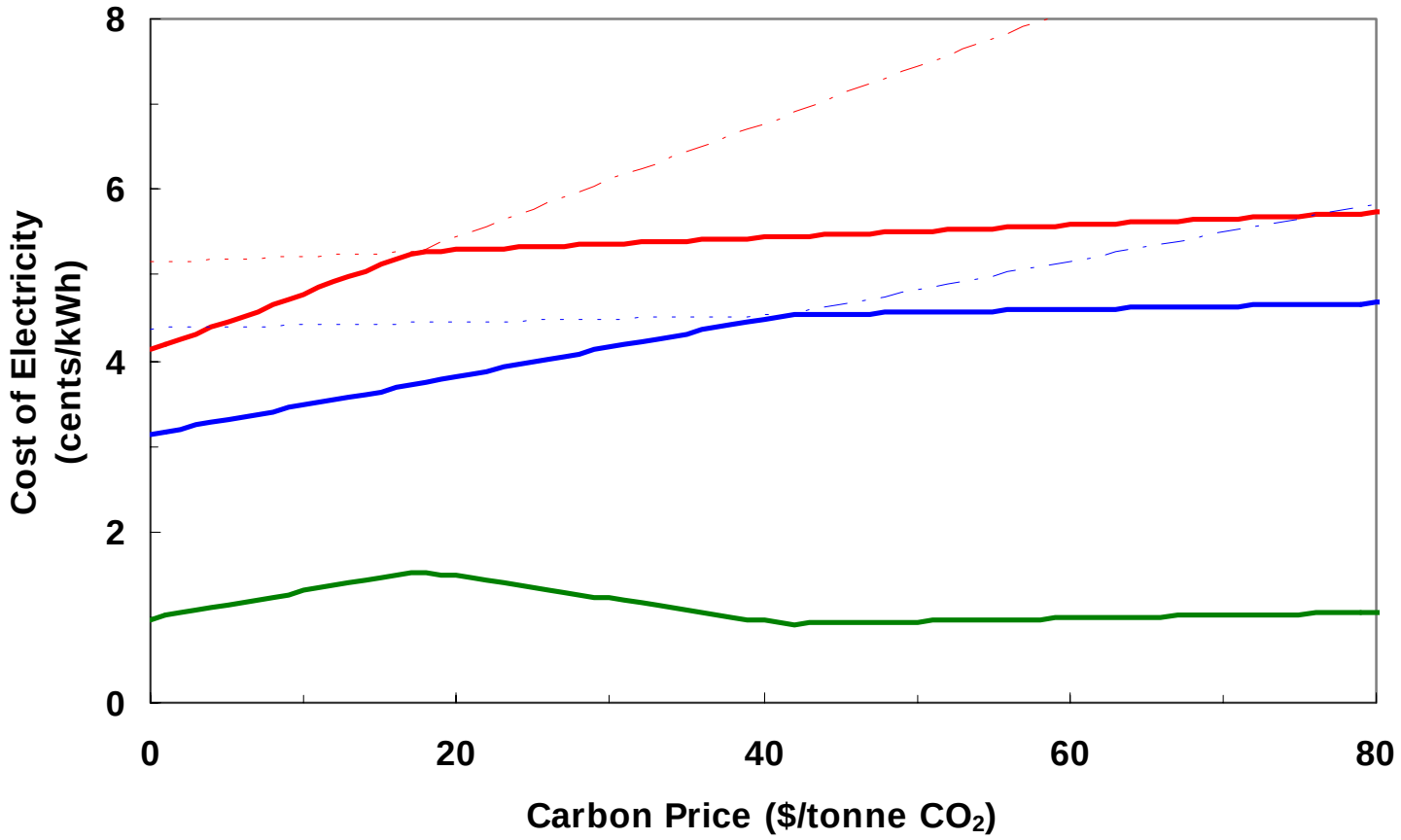
Sensitivity Study
Mitigation Cost



Sensitivity Study
Effect of Heat Rate

Capture Plant	Reference Plant	Incremental COE (cents/kWh)	Mitigation Cost ($/tonne CO_2 avoided)
IGCC Base	IGCC Base	1.7	26
IGCC HR-10%	IGCC HR-10%	1.5	25
IGCC HR-10%	IGCC Base	1.4	21
IGCC Base	NGCC Base	3.4	121
IGCC HR-10%	NGCC Base	3.1	106

Comparing IGCC to NGCC



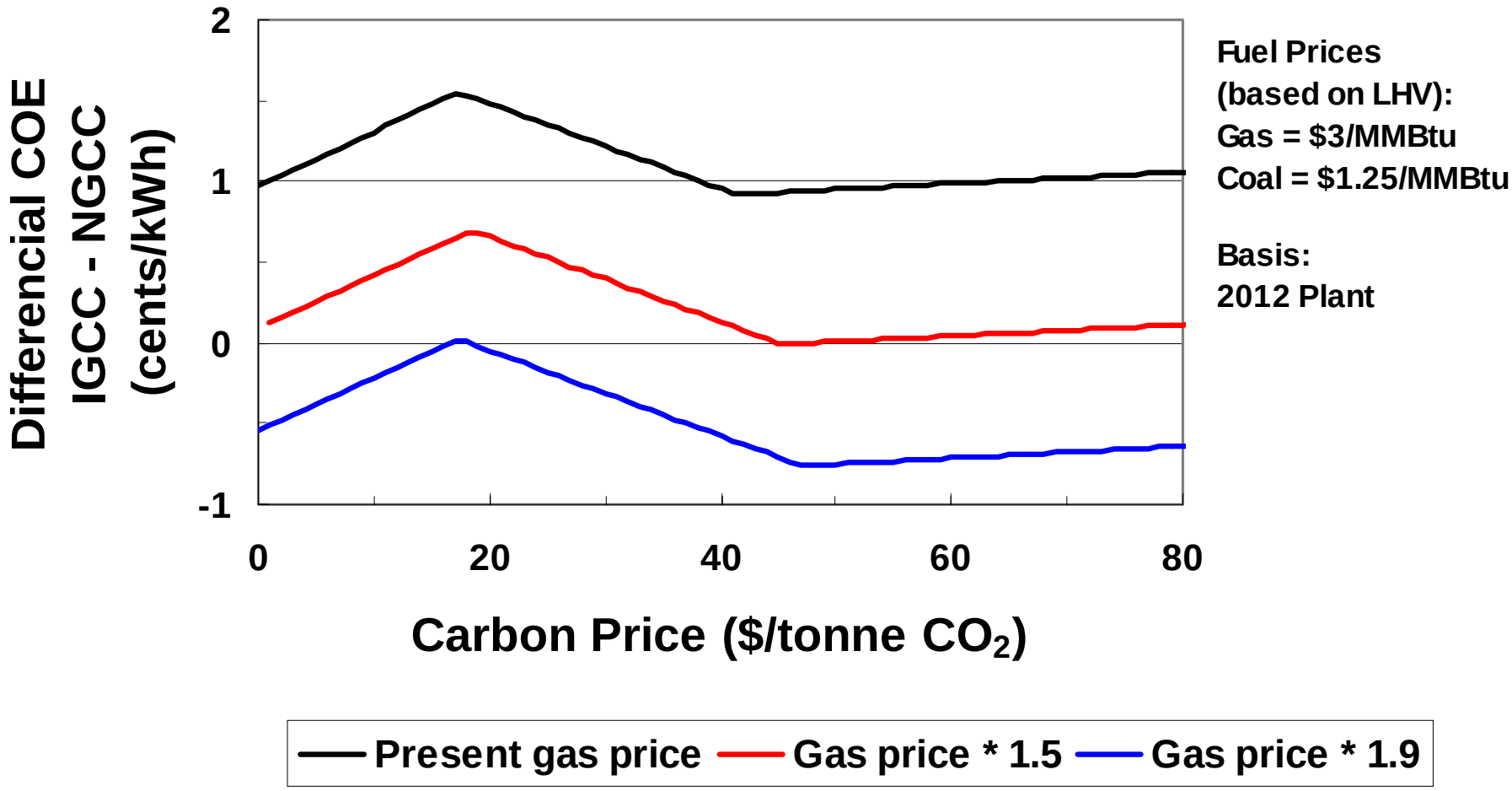
Fuel Prices (based on LHV):
Gas = $3/MMBtu
Coal = $1.25/MMBtu

Basis:
2012 Plant

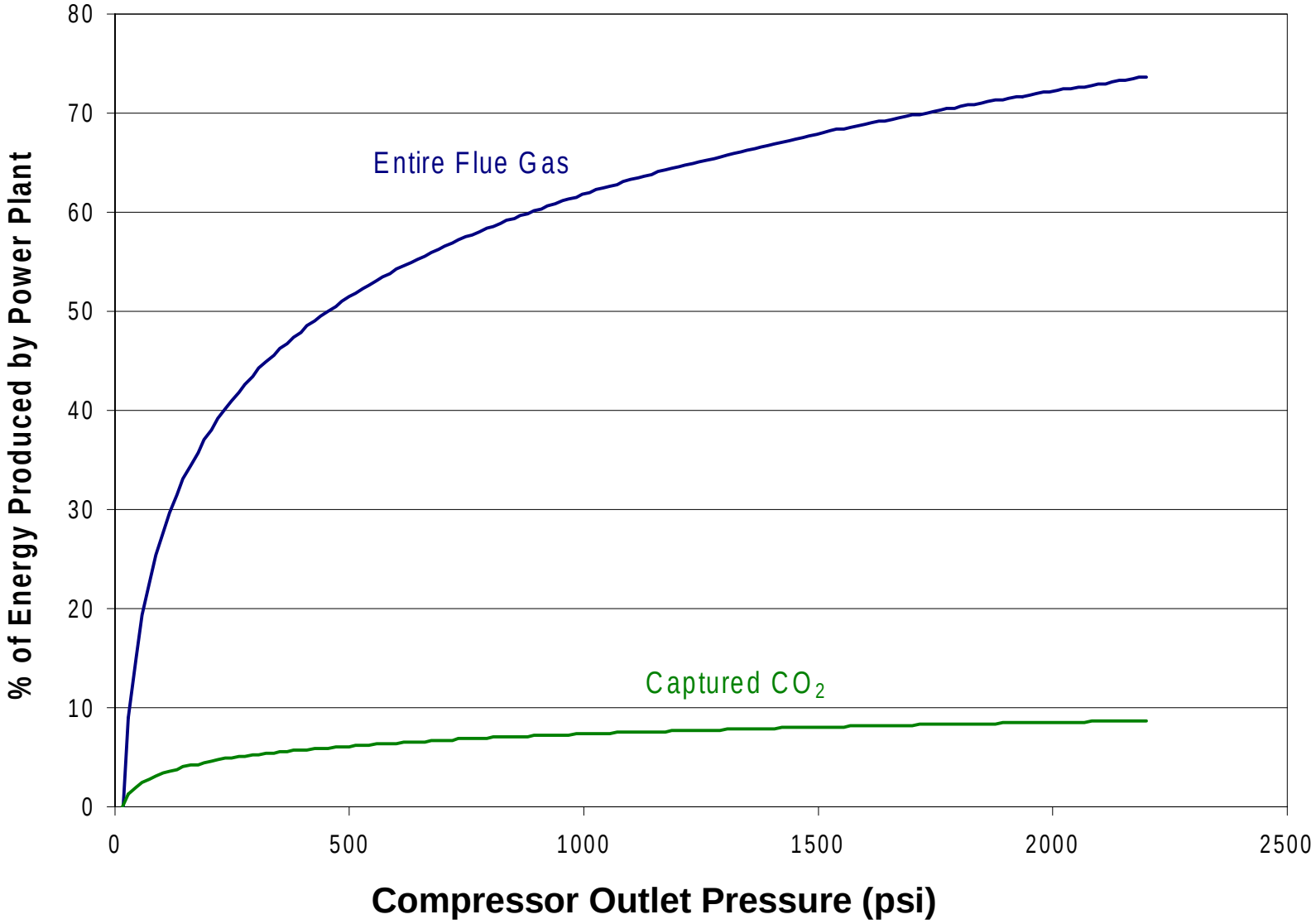
Red = IPCC
Blue = NGCC

Chained = Reference
Dotted = Capture

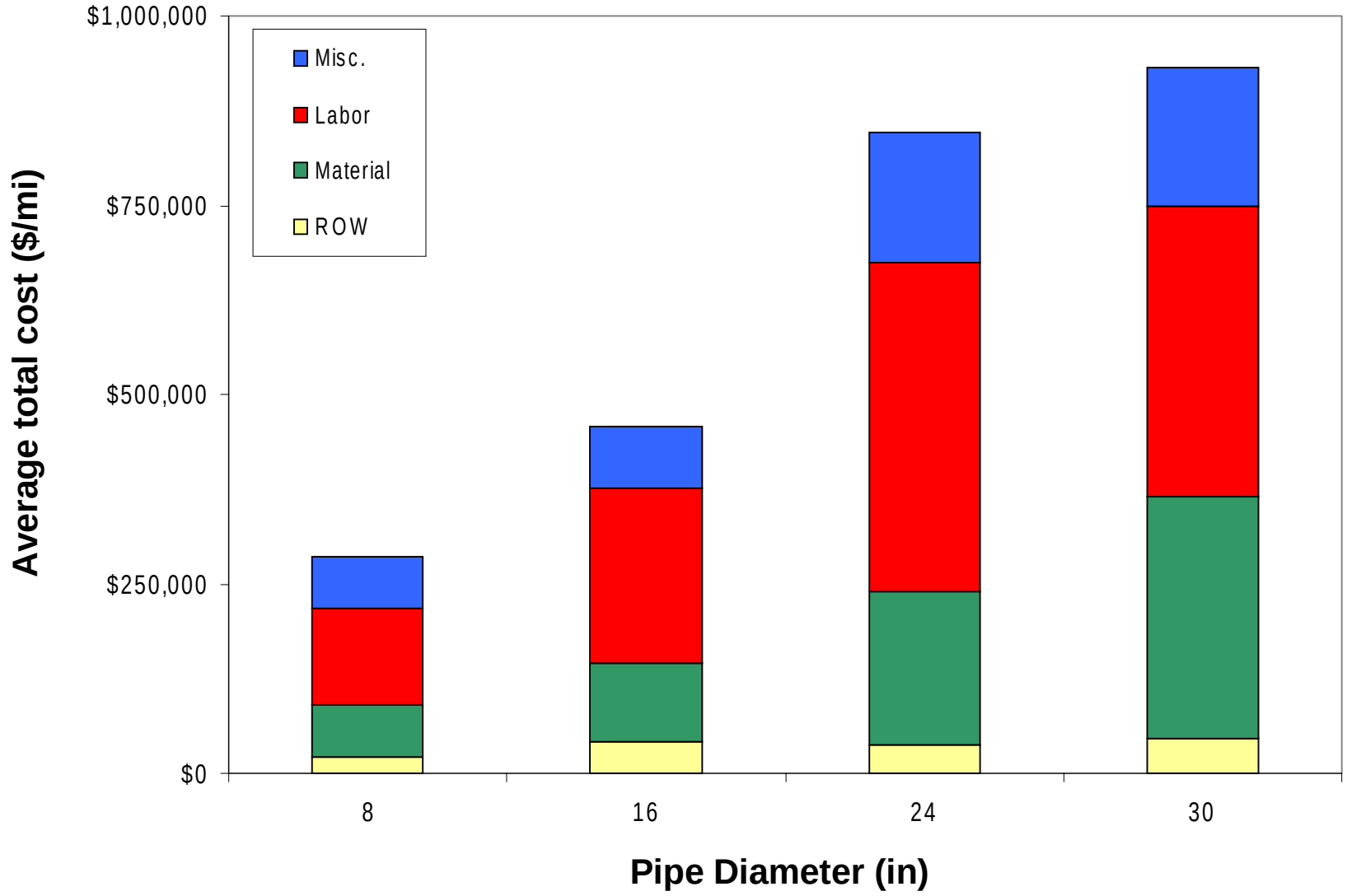
Effect of Gas Price



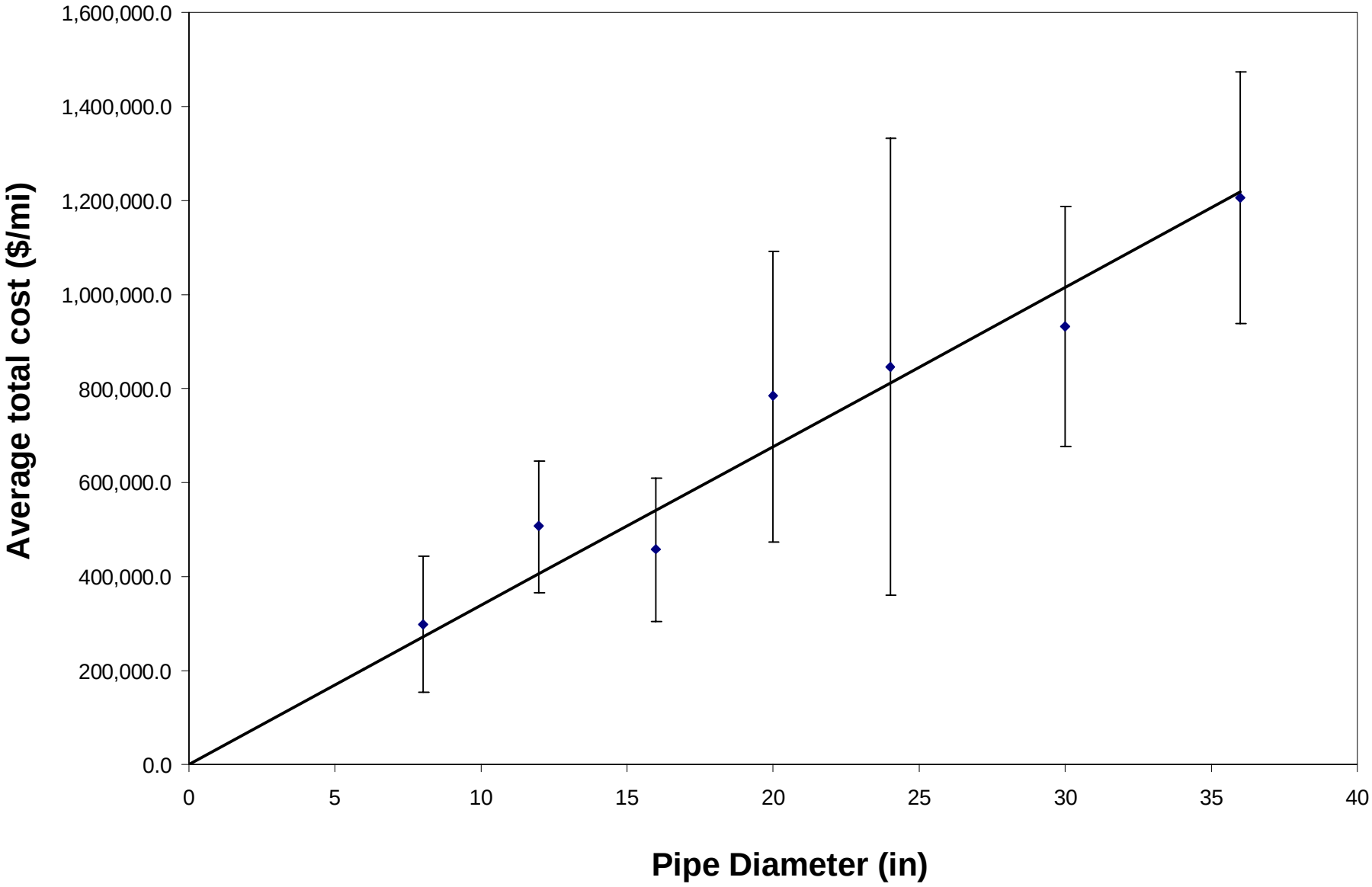
Compression Energy Requirements



Land Construction Costs of Natural Gas Pipelines (1989-1998) Breakdown by Cost Component



Land Construction Costs of Natural Gas Pipeline (1989-1998) versus Pipe Diameter



Cost of CO_2 Pipeline Transport