AC Optimal Power Flow Studies in Reduced-Carbon Electric Power System Operations

Ward Jewell
Wichita State University

Miaolei Shao
GE Energy

Results from the PSERC Project M-21: Technical and Economic Implications of Greenhouse Gas Regulation in a Transmission Constrained Restructured Electricity Market
(Final report at http://tinyurl.com/69ya585)

PSERC Webinar, March 15, 2011

PSERC

WICHITA STATE UNIVERSITY

CO_2 Emission-Incorporated Cost Model

Input-output function

$$H_{fuel\_ij}(P_i) = k_{i0} + k_{i1}P_i + k_{i2}P_i^2$$

Fuel cost function

$$F_{fuel\_ij}(P_i) = C_j(k_{i0} + k_{i1}P_i + k_{i2}P_i^2)$$

CO_2 emission cost function

$$F_{CO_2\_ij}(P_i) = C_{CO_2} \times ef_j \times (k_{i0} + k_{i1}P_i + K_{i2}P_i^2)$$

Fuel + emission cost function

$$F_{fe\_ij}(P_i) = F_{fuel\_ij}(P_i) + F_{CO_2\_ij}(P_i)$$

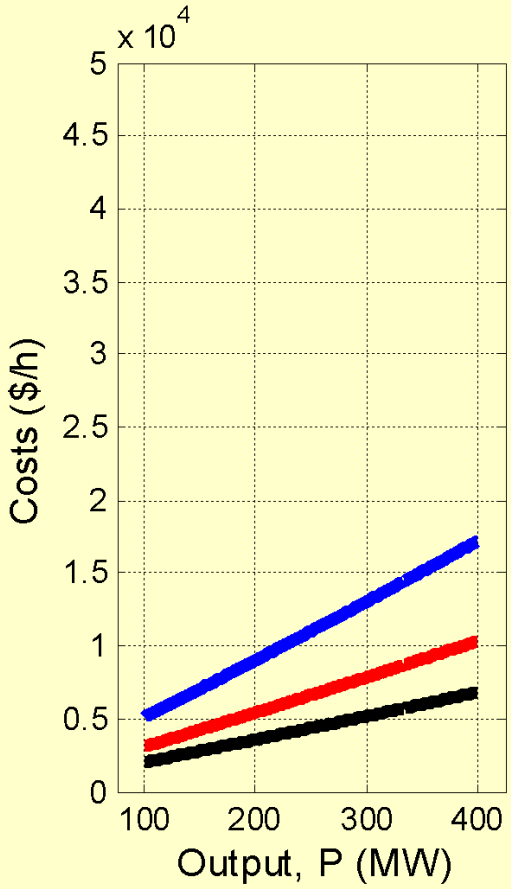
$$= (C_j + C_{CO_2} \times ef_j)(k_{i0} + k_{i1}P_i + k_{i2}P_i^2)$$

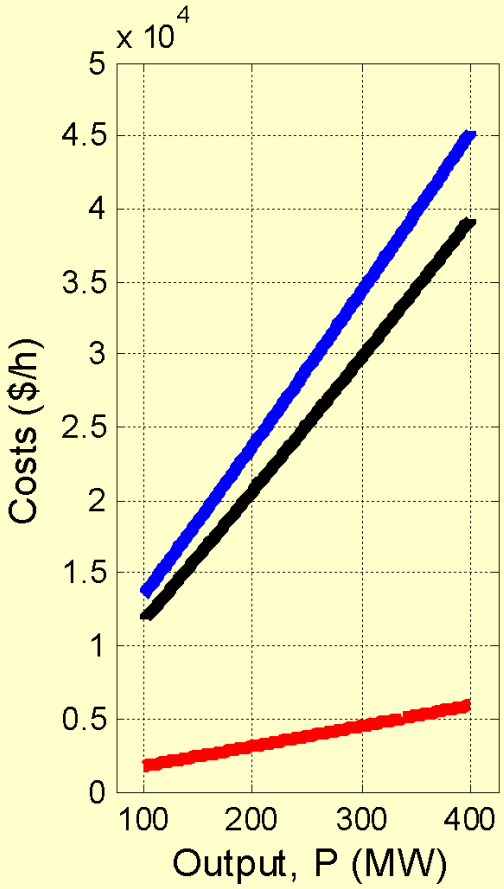
CO_2 Emission Factors (EF) by Type of Fuel (lb CO_2/MBtu)

Coal	EF	Oil	EF	Gas	EF
Bituminous	205	Distillate oil	161	Natural gas	117
Subbituminous	213	Jet fuel	156	Propane	139
Lignite	215	Kerosene	159		
Anthracite	227	Petroleum coke	225		
		Residual	174		

Source: S. Goodman, M. Walker, "Benchmarking air emissions of the 100 largest electric power producers in the united states – 2004", Apr. 2006

Fossil-fired Generation Units' Cost Variation Due to CO_2 Emissions





- *Coal price is 1.90 $/MBtu*
- *CO_2 emission factor of coal is 215 lb/MBtu*
- *Gas price is 10.35 $/MBtu*
- *CO_2 emission factor of gas is 117 lb/MBtu*
- *CO_2 price is 30 $/ton*

Fuel costs

CO_2 emission costs

Fuel-emission costs

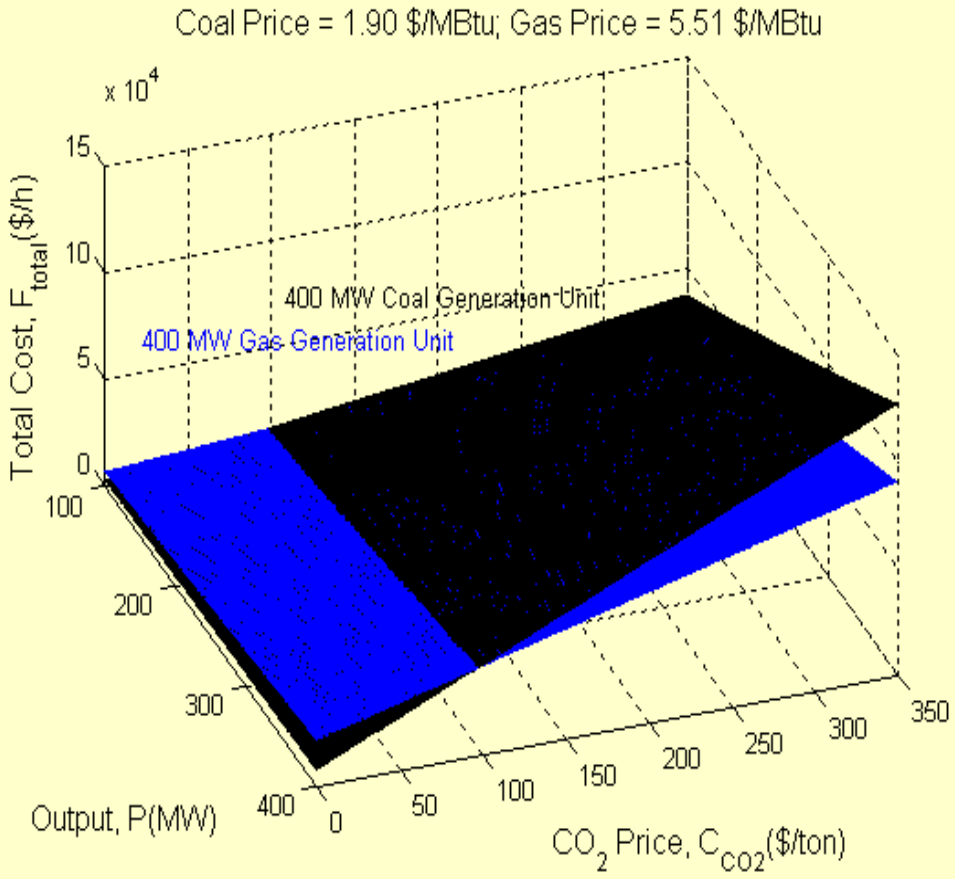
G1 (400 MW coal-fired generation unit)

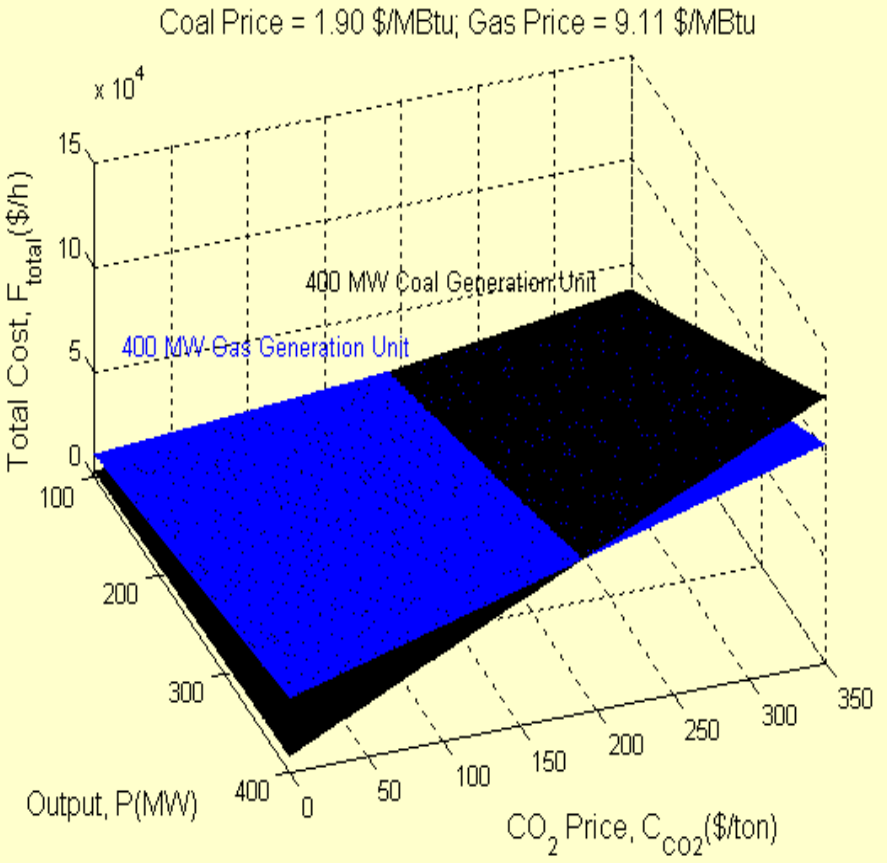
G2 (400 MW gas-fired generation unit)

PSERC

WICHITA STATE UNIVERSITY

Breakeven Price of CO_2





- *Gas: 5.51 $/MBtu*
- *Breakeven CO_2 price: 98 $/ton*

- *Gas: 9.11 $/MBtu*
- *Breakeven CO_2 price: 190 $/ton*

Coal price is 1.90 $/MBtu

PSERC

WICHITA STATE UNIVERSITY

CO_2 Emission-Constrained AC Optimal Power Flow (OPF)

Objective function

$$\min\left\{\sum_{i=1}^{N_g} F_{total\_ij}(P_i)\right\}$$

Equality constraints

$$P_i = P_{gi} - P_{li} \qquad Q_i = Q_{gi} + Q_{li}$$

Inequality constraints

$$P_{gi}^{-} < P_{gi} < P_{gi}^{+} \qquad Q_{gi}^{-} < Q_{gi} < Q_{gi}^{+}$$

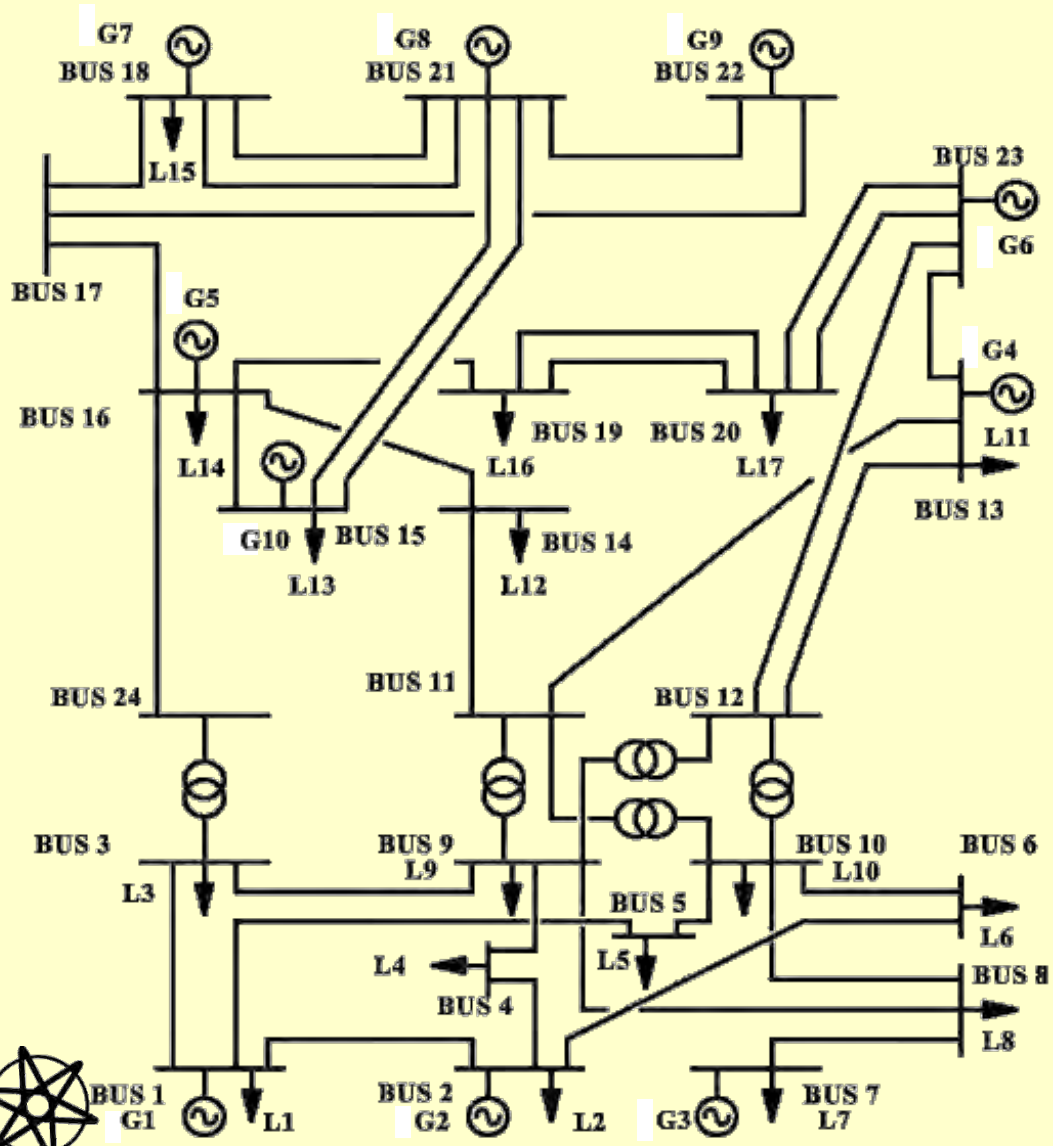
$$E_i^{-} < E_i < E_i^{+} \qquad \delta_i^{-} < \delta_i < \delta_i^{+}$$

$$MVA_{mn}^{-} < MVA_{mn} < MVA_{mn}^{+}$$

PowerWorld Simulator Linear Programming OPF

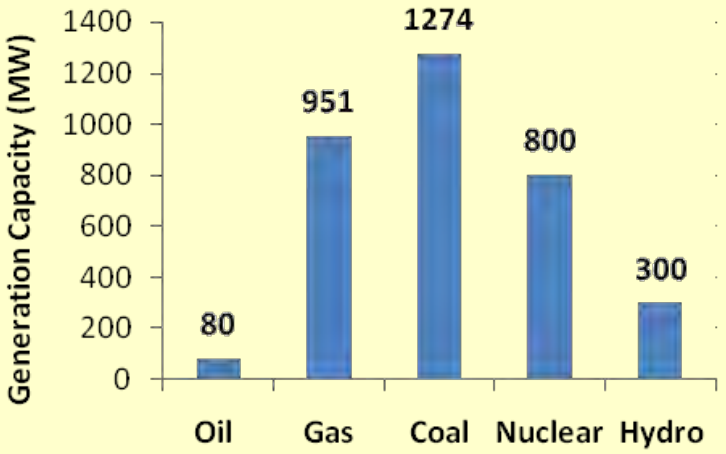
IEEE Reliability Test System (RTS)

Modified for this study



2850 MW load

3405 MW generation



PSERC

WICHITA STATE UNIVERSITY

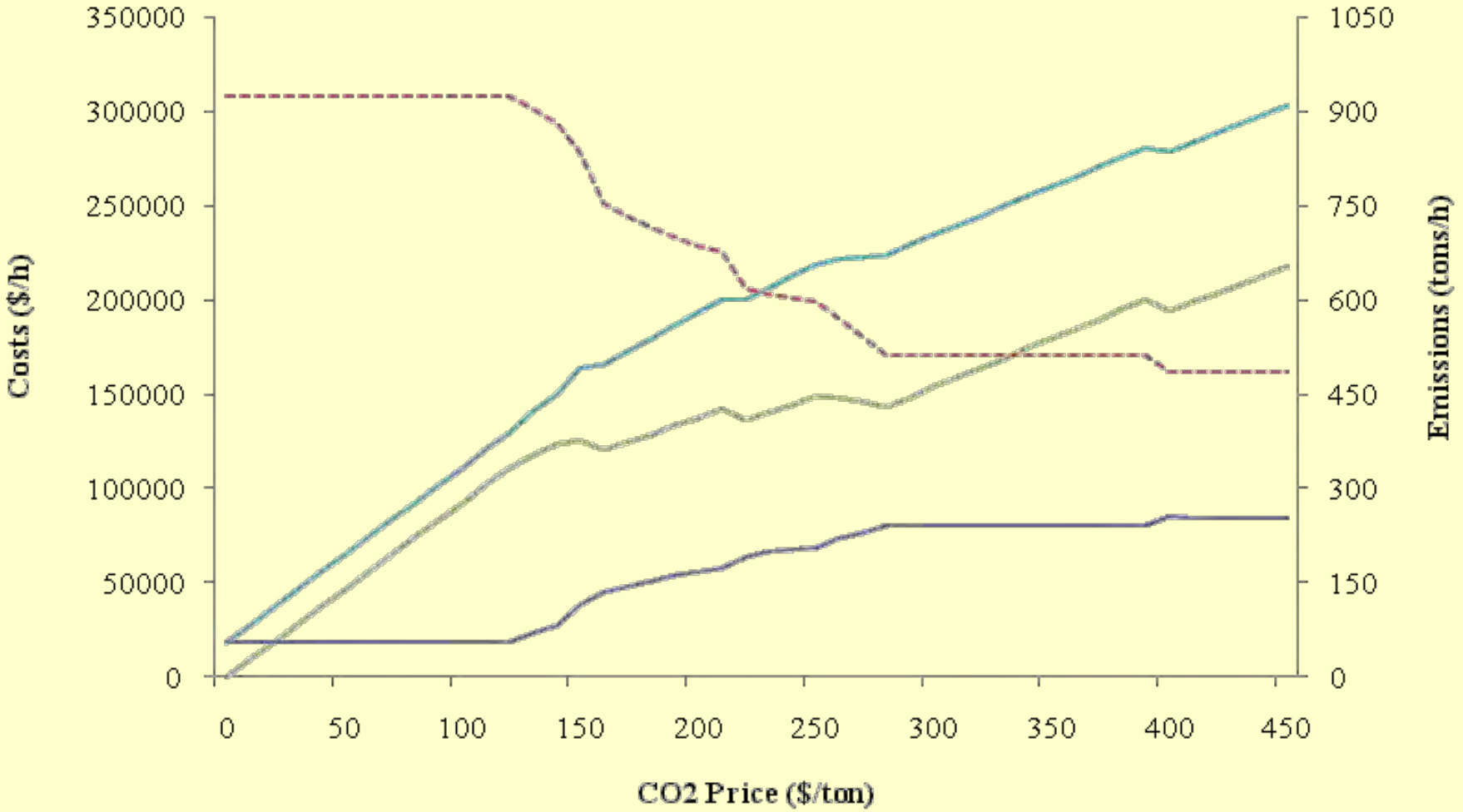
Simulation Cases and Description

Case #	Description	Fuel Prices ($/MBtu)			System Load (MW)
		Coal	Gas	Oil	
1	Medium fuel price and normal system load	1.88	9.09	12.00	1995
2	Medium fuel price and peak system load	1.88	9.09	12.00	2850

Case 1: 70% of peak load, 59% of generation capacity

Case 2: 100% of peak load, 84% of generation capacity)

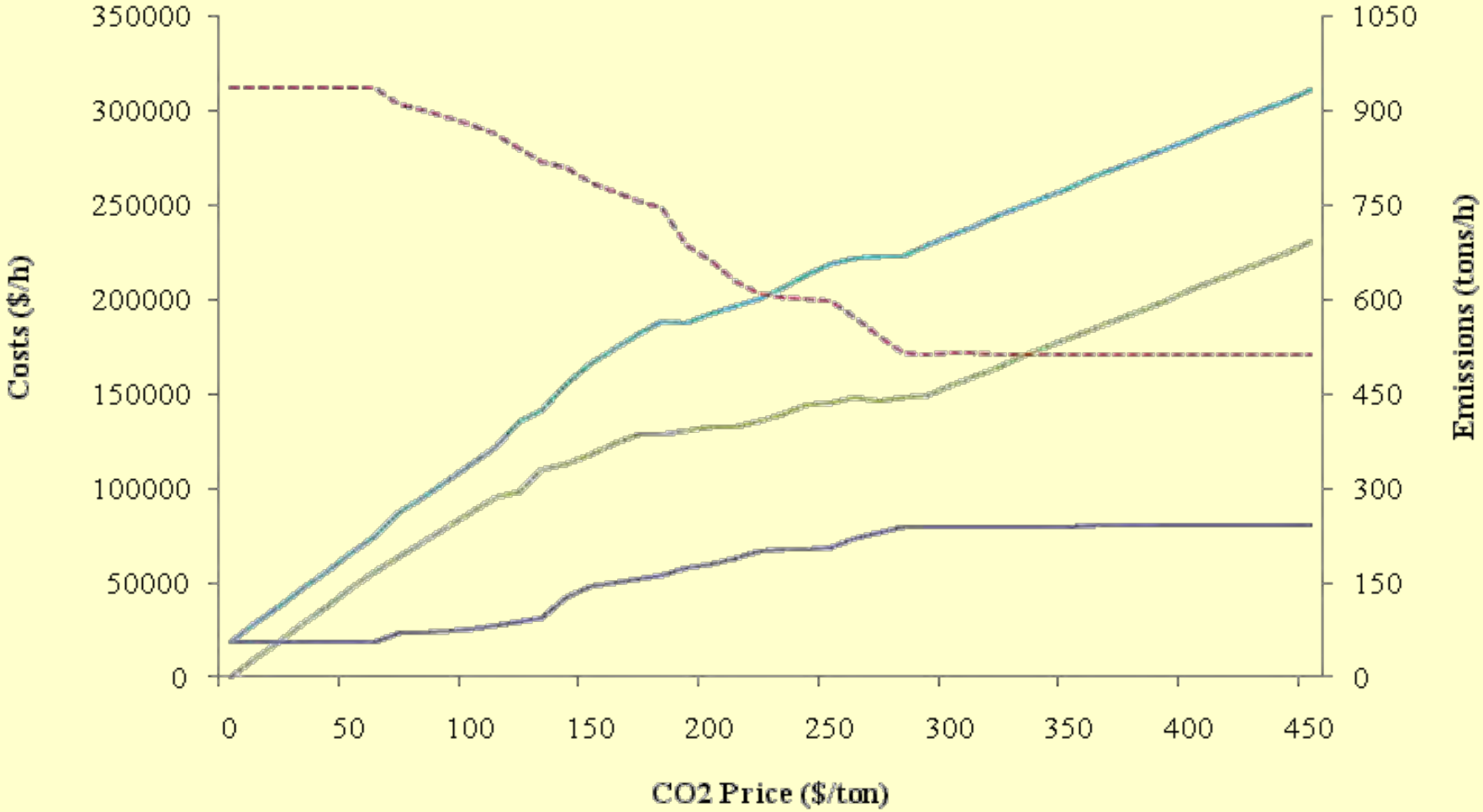
Economic Dispatch Results for Case 1



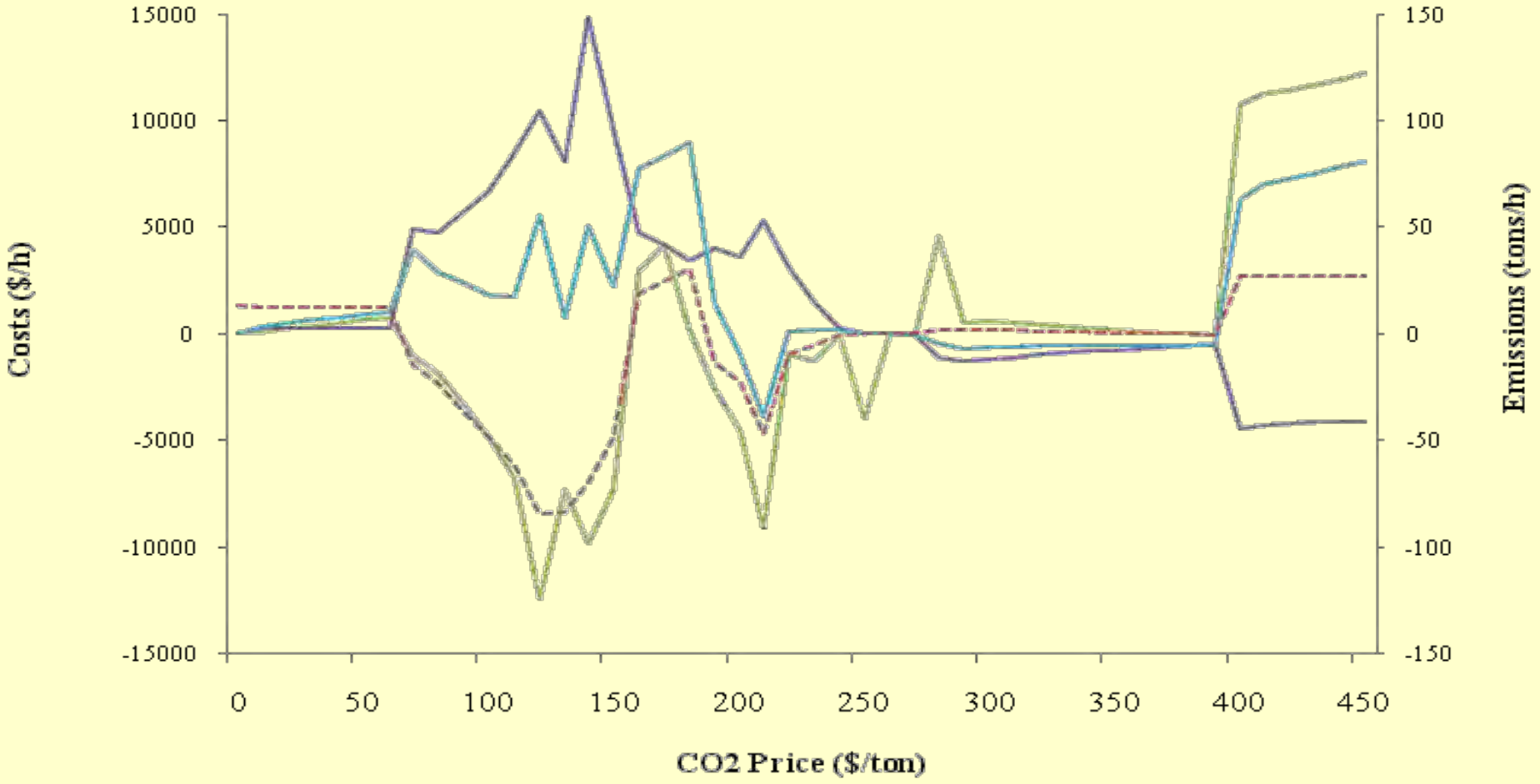
PSERC

Wichita State University

OPF Results for Case 1



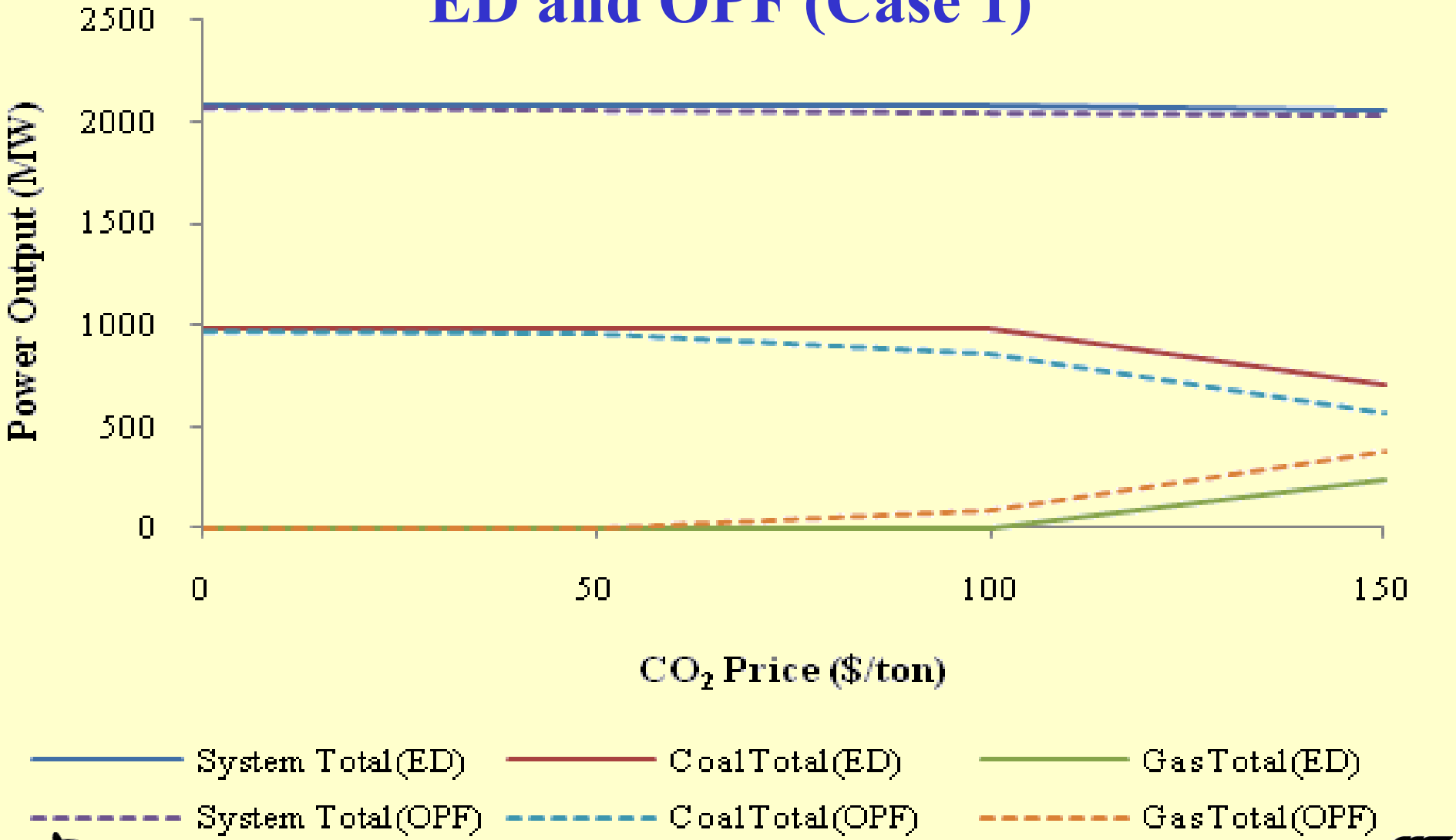
Difference Between Economic Dispatch and OPF
Case 1



PSERC

WICHITA STATE UNIVERSITY

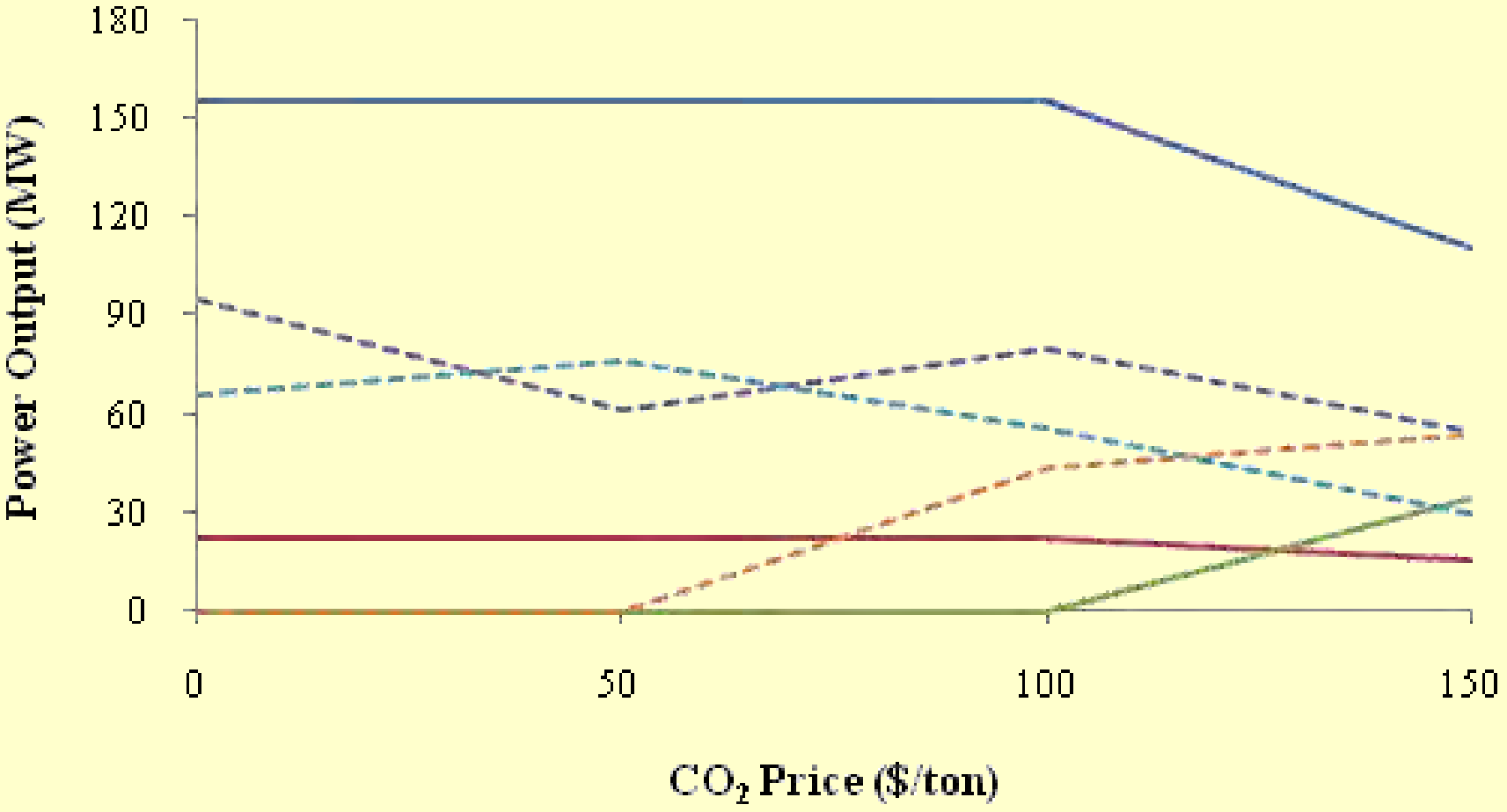
Generation Dispatch Comparison
ED and OPF (Case 1)



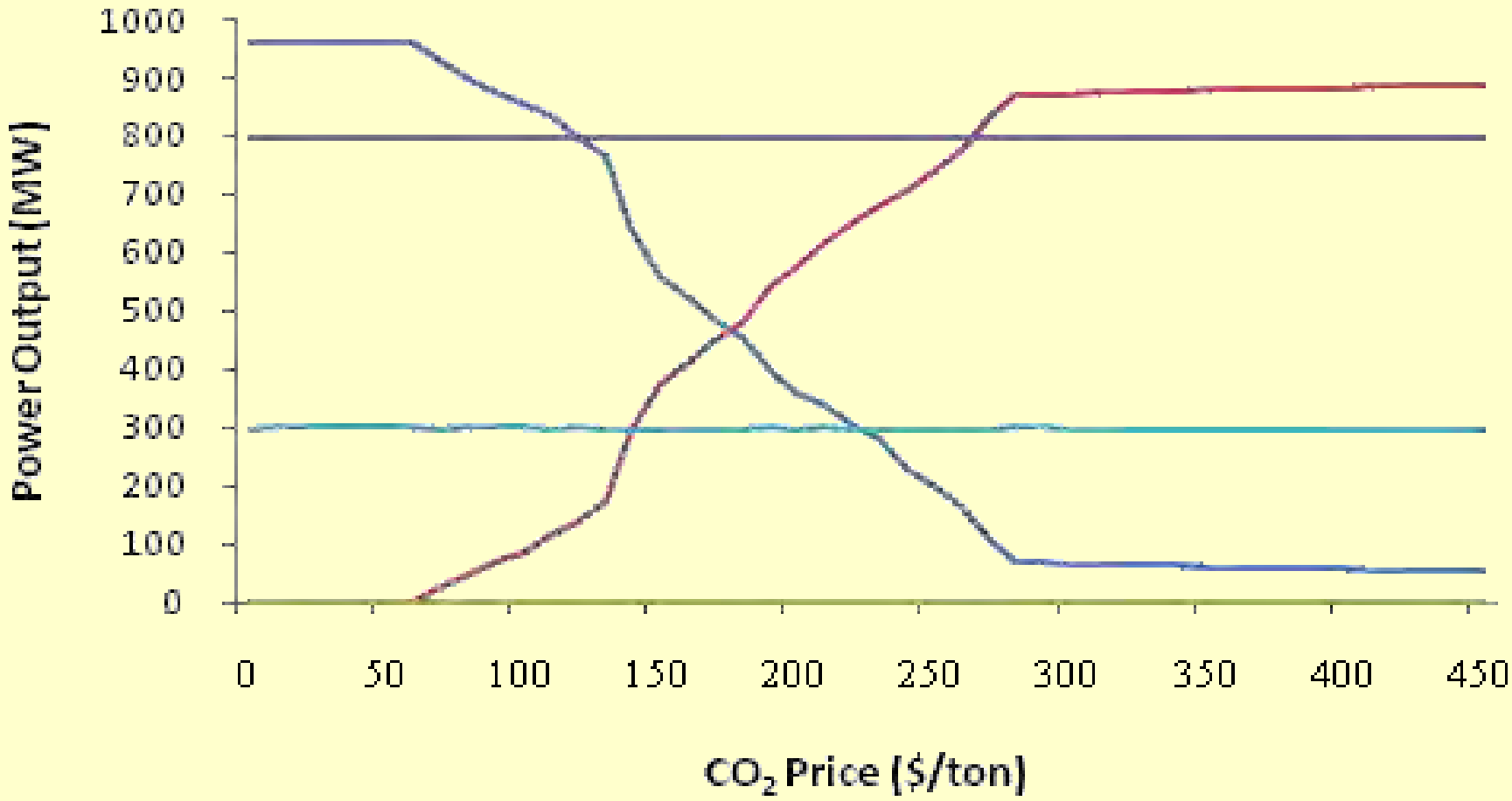
PSERC

WICHITA STATE UNIVERSITY

Selected Units Loading Comparison ED and OPF (Case 1)



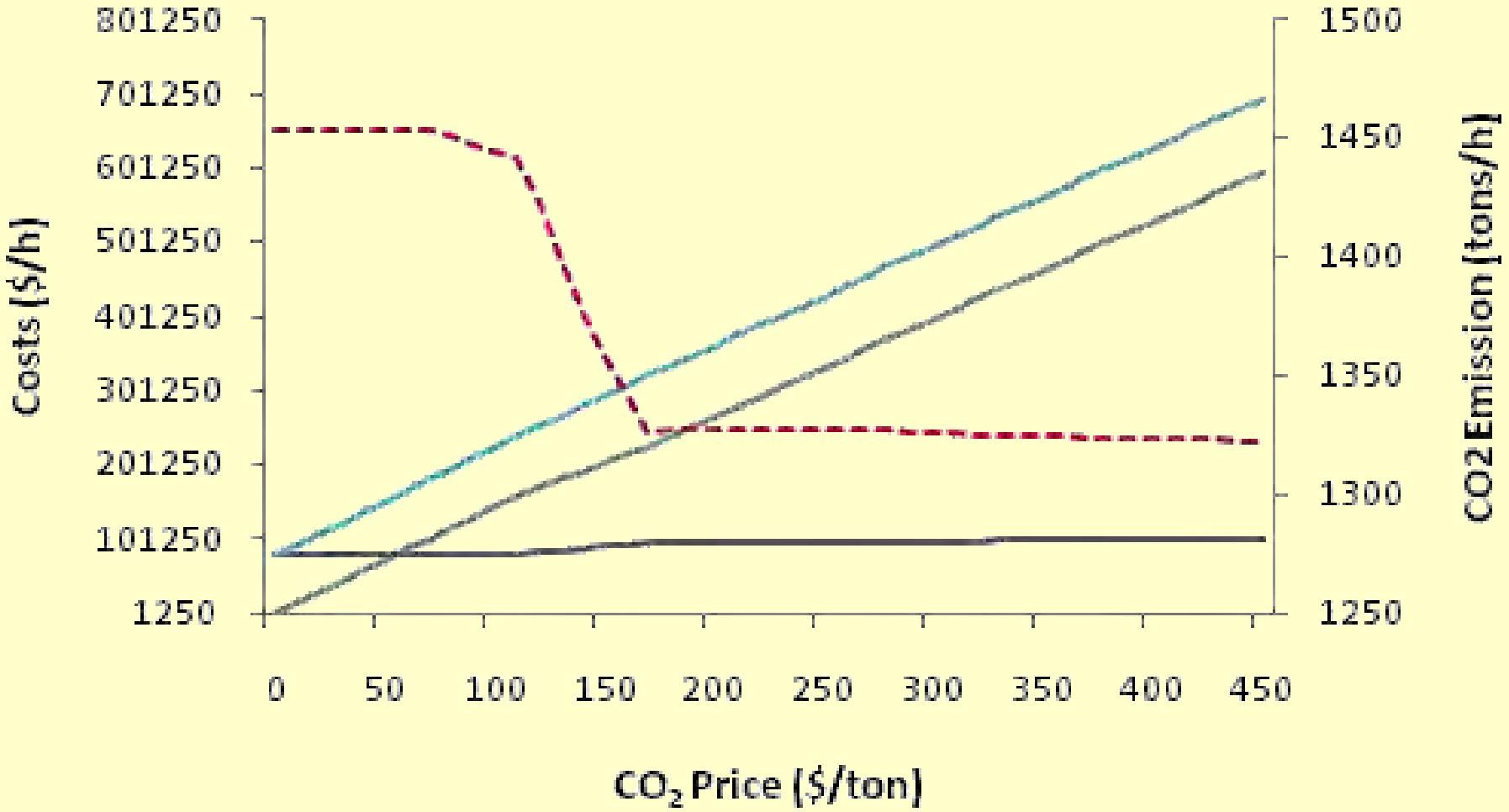
Dispatch by Fuel, Case 1 (OPF)



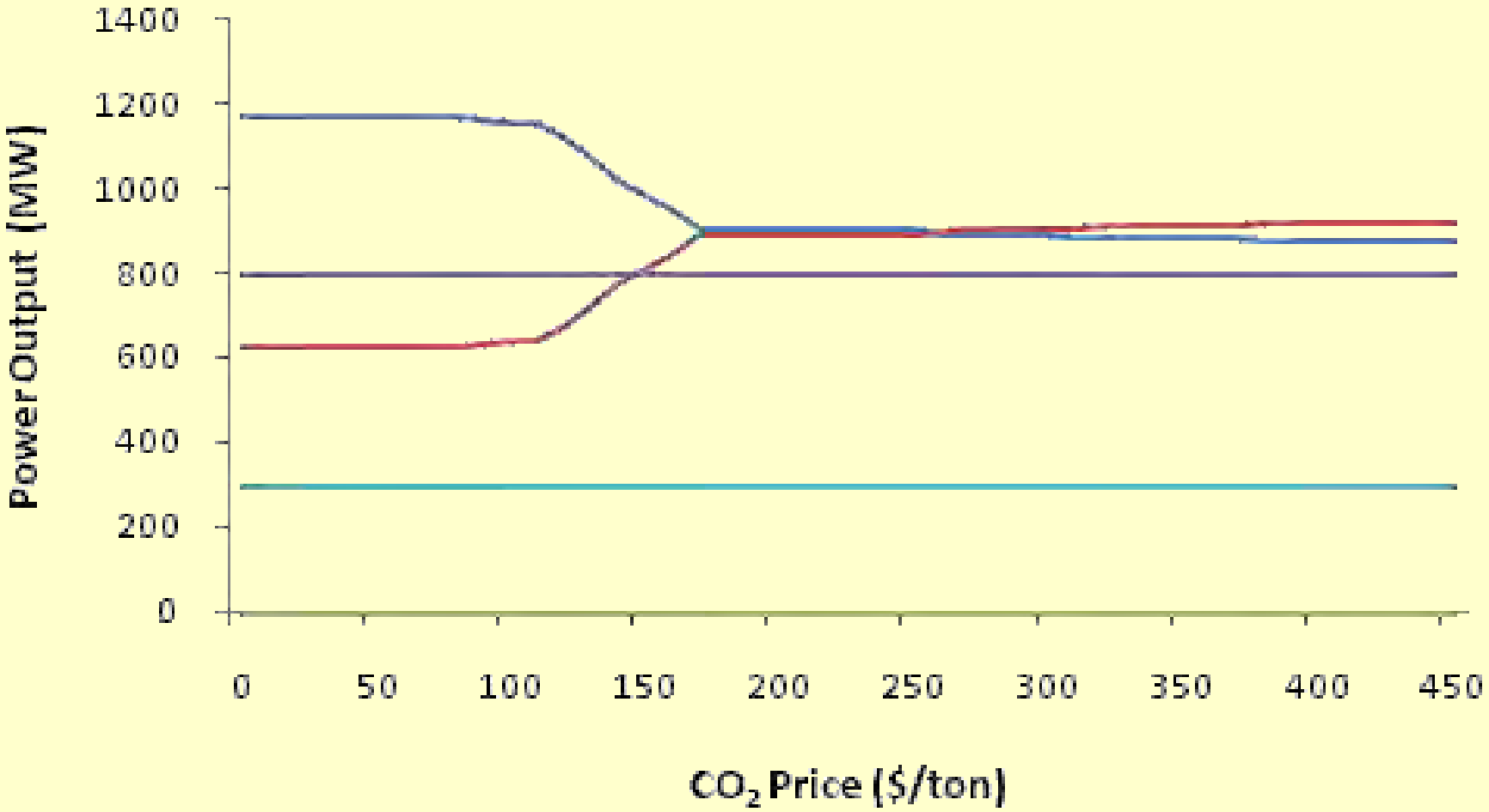
PSERC

Wichita State University

OPF Results for Case 2



Dispatch by Fuel, Case 2 (OPF)



Discussion

- Line congestion has a significant effect on CO_2 emissions.
- For the modified RTS system:
  - At low CO_2 price, redispatch will be among units of same fuel, resulting in little effect on costs and CO_2 emission
  - At high CO_2 price, redispatch will be from coal to natural gas, resulting in lower emissions but high cost.
- CO_2 emissions and costs are sensitive to system load.
- Results will be system-dependent, due to different generation mixes and transmission constraints.

Discussion

- Wind and solar were also simulated by Piyasak Poonpun (now at CAISO); results are in final report (http://tinyurl.com/69ya585)
- Technique will be applied to the WECC system when model is ready.
- PSERC M-24, Interactions of Multiple Market-Based Energy and Environmental Policies in a Transmission-Constrained Competitive National Electricity Market, (Bill Schulze, Cornell) continues this work.