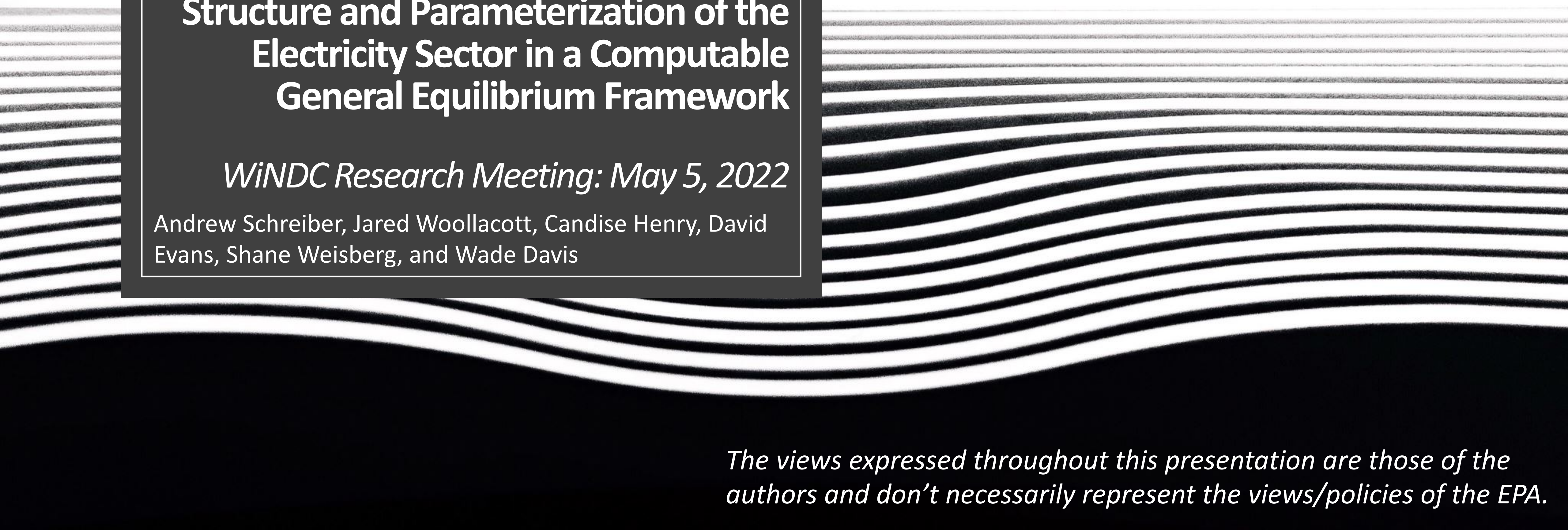


Constructing MEEDE Version 2

Structure and Parameterization of the Electricity Sector in a Computable General Equilibrium Framework

WiNDC Research Meeting: May 5, 2022

Andrew Schreiber, Jared Woollacott, Candise Henry, David Evans, Shane Weisberg, and Wade Davis

Introduction

- EPA-OP/NCEE efforts for electricity sector representations
- SAB guidance
- Consideration of other electricity modeling options

MEEDE Version 2

01

Sources: what's included?

02

Outputs: what's provided?

03

Applications: how to use MEEDE?

Sources

Version 2

- Engineering
  - EIA: Forms 860, 923
- Environmental
  - EPA: AMPD emissions data
  - IPMv6: Pollution control cost data
- Economic
  - NREL: ATB cost data
  - FERC: Form 714 wholesale price data

Updates

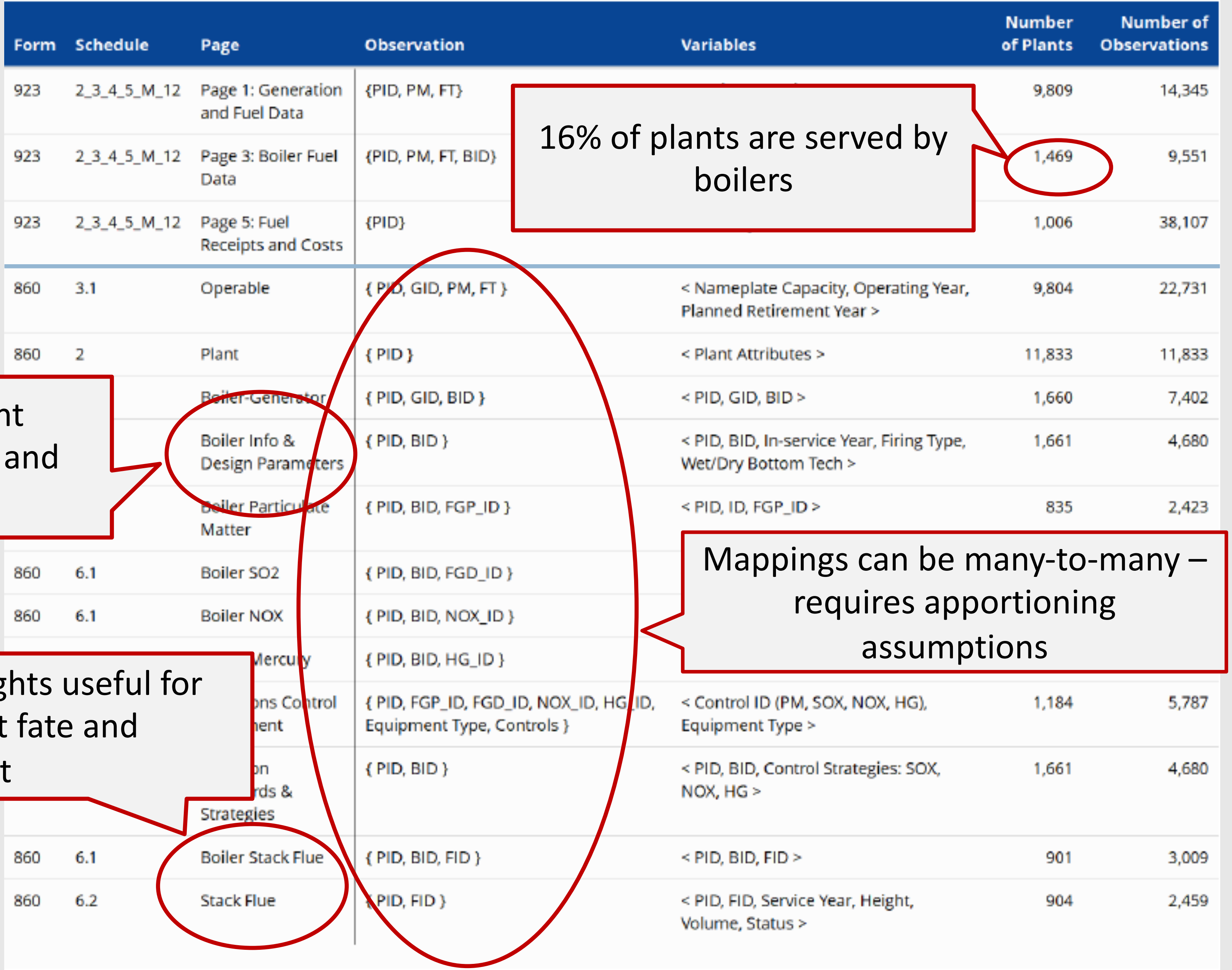
- Historical and projected technology costs
- Historical fuel prices
- Hourly wholesale prices (FERC 714)

Coverage

- 97% of grid generation (≥ 1 MW)
- Annual representation 2013-2019
- 14,347 EGU-level obs. (2019)
- 133 variables describing each unit
- 38 fuel types → 15 fuel codes
- 18 prime movers (79% steam, 2019)
- 33 pollution control types
- > 1,000 plant configurations

Sources

- EIA-923: Activity levels
- EIA-860: Unit attributes



Form	Schedule	Page	Observation	Variables	Number of Plants	Number of Observations
923	2_3_4_5_M_12	Page 1: Generation and Fuel Data	{PID, PM, FT}		9,809	14,345
923	2_3_4_5_M_12	Page 3: Boiler Fuel Data	{PID, PM, FT, BID}		1,469	9,551
923	2_3_4_5_M_12	Page 5: Fuel Receipts and Costs	{PID}		1,006	38,107
860	3.1	Operable	{ PID, GID, PM, FT }	< Nameplate Capacity, Operating Year, Planned Retirement Year >	9,804	22,731
860	2	Plant	{ PID }	< Plant Attributes >	11,833	11,833
		Boiler-Generator	{ PID, GID, BID }	< PID, GID, BID >	1,660	7,402
		Boiler Info & Design Parameters	{ PID, BID }	< PID, BID, In-service Year, Firing Type, Wet/Dry Bottom Tech >	1,661	4,680
		Boiler Particulate Matter	{ PID, BID, FGP_ID }	< PID, ID, FGP_ID >	835	2,423
860	6.1	Boiler SO2	{ PID, BID, FGD_ID }			
860	6.1	Boiler NOX	{ PID, BID, NOX_ID }			
		Mercury	{ PID, BID, HG_ID }			
		ons Control ent	{ PID, FGP_ID, FGD_ID, NOX_ID, HG_ID, Equipment Type, Controls }	< Control ID (PM, SOX, NOX, HG), Equipment Type >	1,184	5,787
		on rds & Strategies	{ PID, BID }	< PID, BID, Control Strategies: SOX, NOX, HG >	1,661	4,680
860	6.1	Boiler Stack Flue	{ PID, BID, FID }	< PID, BID, FID >	901	3,009
860	6.2	Stack Flue	{ PID, FID }	< PID, FID, Service Year, Height, Volume, Status >	904	2,459

16% of plants are served by boilers

Boiler cooling equipment useful for water quality and quantity

Mappings can be many-to-many – requires apportioning assumptions

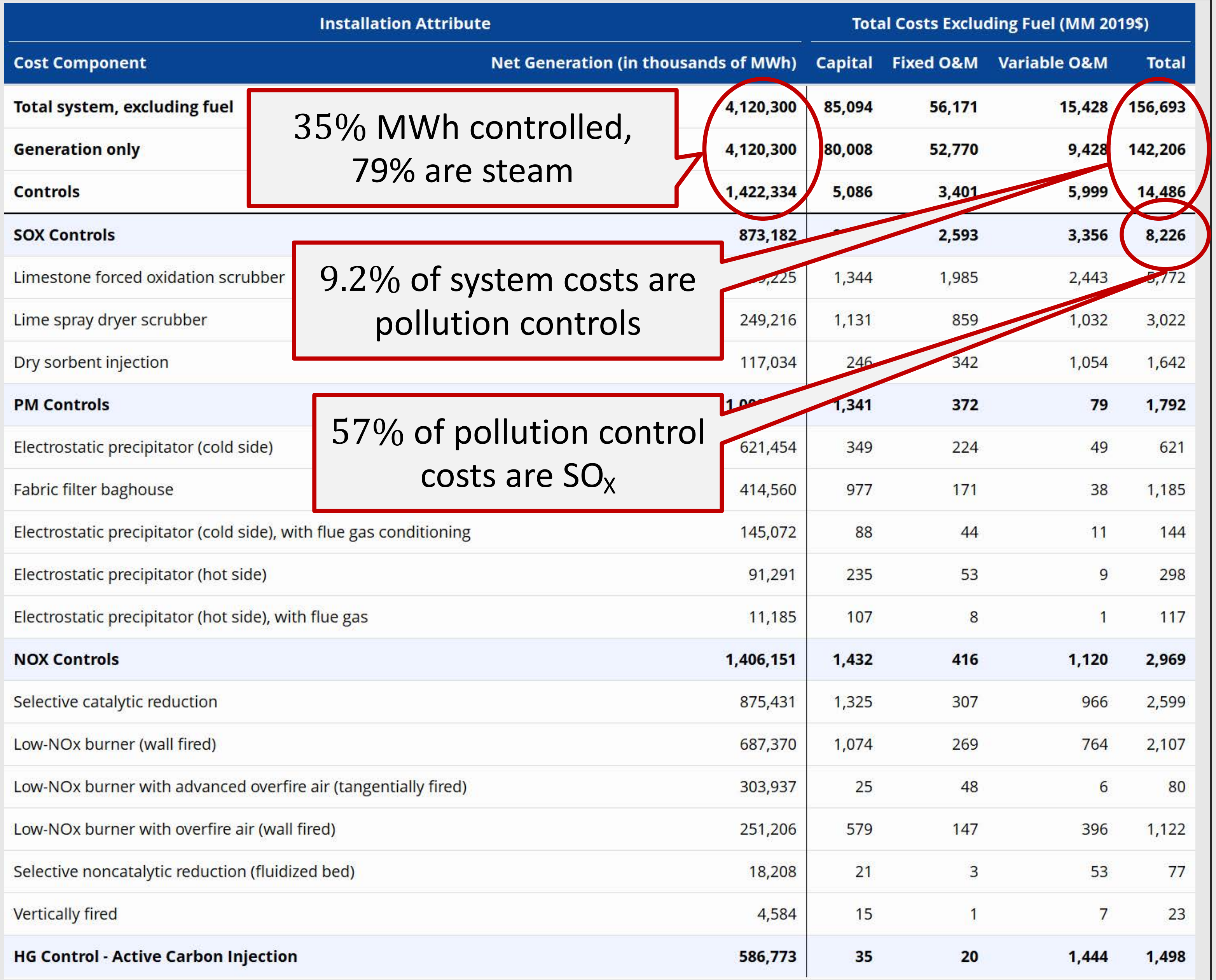
Flue heights useful for pollutant fate and transport

Coverage detail varies on
- Plant (PID)
- Prime mover (PM)
- Fuel type (FT)
- Boiler (BID)
- Generator (GID)
- Pollution control units (FGP_ID, FGD_ID, NOX_ID, HG_ID)

Outputs: Controls

- Unit engineering specs: EIA-923 × EIA-860
- Merged to cost assumptions: ATB & IPMv6
- Generation cost = ATB capital – IPMv6 control costs

Pollution Controls
- Mix of change-in-process and end-of-pipe controls
- Sources have multiple controls
- Costs are not historical, require coarse mapping
- ATB controls assumed



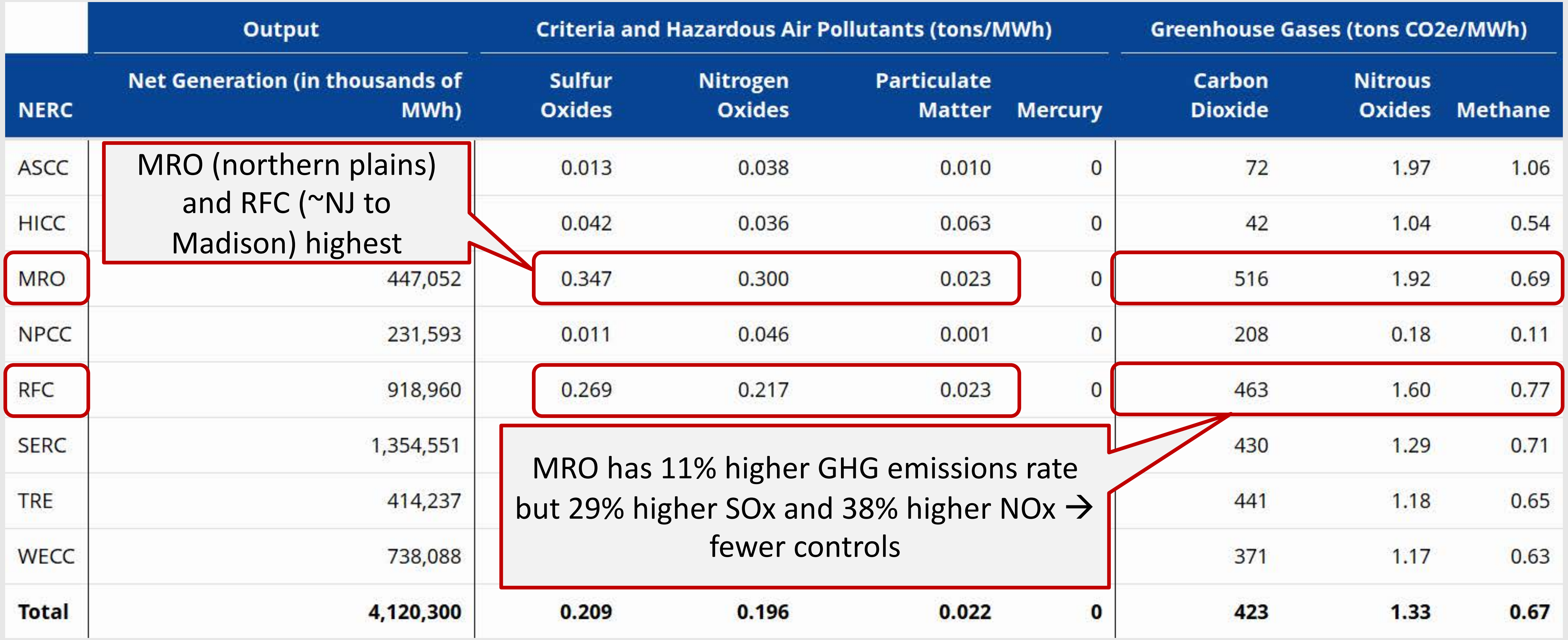
Installation Attribute		Total Costs Excluding Fuel (MM 2019$)			
Cost Component	**Net Generation (in thousands of MWh)**	**Capital**	**Fixed O&M**	**Variable O&M**	**Total**
Total system, excluding fuel	**4,120,300**	**85,094**	**56,171**	**15,428**	**156,693**
Generation only	**4,120,300**	**80,008**	**52,770**	**9,428**	**142,206**
Controls	**1,422,334**	**5,086**	**3,401**	**5,999**	**14,486**
SOX Controls	**873,182**	[illegible]	**2,593**	**3,356**	**8,226**
Limestone forced oxidation scrubber	[illegible]	1,344	1,985	2,443	5,772
Lime spray dryer scrubber	249,216	1,131	859	1,032	3,022
Dry sorbent injection	117,034	246	342	1,054	1,642
PM Controls	[illegible]	**1,341**	**372**	**79**	**1,792**
Electrostatic precipitator (cold side)	621,454	349	224	49	621
Fabric filter baghouse	414,560	977	171	38	1,185
Electrostatic precipitator (cold side), with flue gas conditioning	145,072	88	44	11	144
Electrostatic precipitator (hot side)	91,291	235	53	9	298
Electrostatic precipitator (hot side), with flue gas	11,185	107	8	1	117
NOX Controls	**1,406,151**	**1,432**	**416**	**1,120**	**2,969**
Selective catalytic reduction	875,431	1,325	307	966	2,599
Low-NOx burner (wall fired)	687,370	1,074	269	764	2,107
Low-NOx burner with advanced overfire air (tangentially fired)	303,937	25	48	6	80
Low-NOx burner with overfire air (wall fired)	251,206	579	147	396	1,122
Selective noncatalytic reduction (fluidized bed)	18,208	21	3	53	77
Vertically fired	4,584	15	1	7	23
HG Control - Active Carbon Injection	**586,773**	**35**	**20**	**1,444**	**1,498**

35% MWh controlled, 79% are steam

9.2% of system costs are pollution controls

57% of pollution control costs are SO_X

Outputs: Emissions



	Output	Criteria and Hazardous Air Pollutants (tons/MWh)				Greenhouse Gases (tons CO2e/MWh)		
NERC	Net Generation (in thousands of MWh)	Sulfur Oxides	Nitrogen Oxides	Particulate Matter	Mercury	Carbon Dioxide	Nitrous Oxides	Methane
ASCC		0.013	0.038	0.010	0	72	1.97	1.06
HICC		0.042	0.036	0.063	0	42	1.04	0.54
MRO	447,052	0.347	0.300	0.023	0	516	1.92	0.69
NPCC	231,593	0.011	0.046	0.001	0	208	0.18	0.11
RFC	918,960	0.269	0.217	0.023	0	463	1.60	0.77
SERC	1,354,551					430	1.29	0.71
TRE	414,237					441	1.18	0.65
WECC	738,088					371	1.17	0.63
Total	**4,120,300**	**0.209**	**0.196**	**0.022**	**0**	**423**	**1.33**	**0.67**

MRO (northern plains) and RFC (~NJ to Madison) highest

MRO has 11% higher GHG emissions rate but 29% higher SOx and 38% higher NOx → fewer controls

Regions: ASCC = Alaska Systems Coordinating Council; HICC = Hawaiian Islands Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = ReliabilityFirst Corporation; SERC = Southeastern Electric Reliability Council; TRE = Texas Reliability Entity; WECC = Western Electricity Coordinating Council.

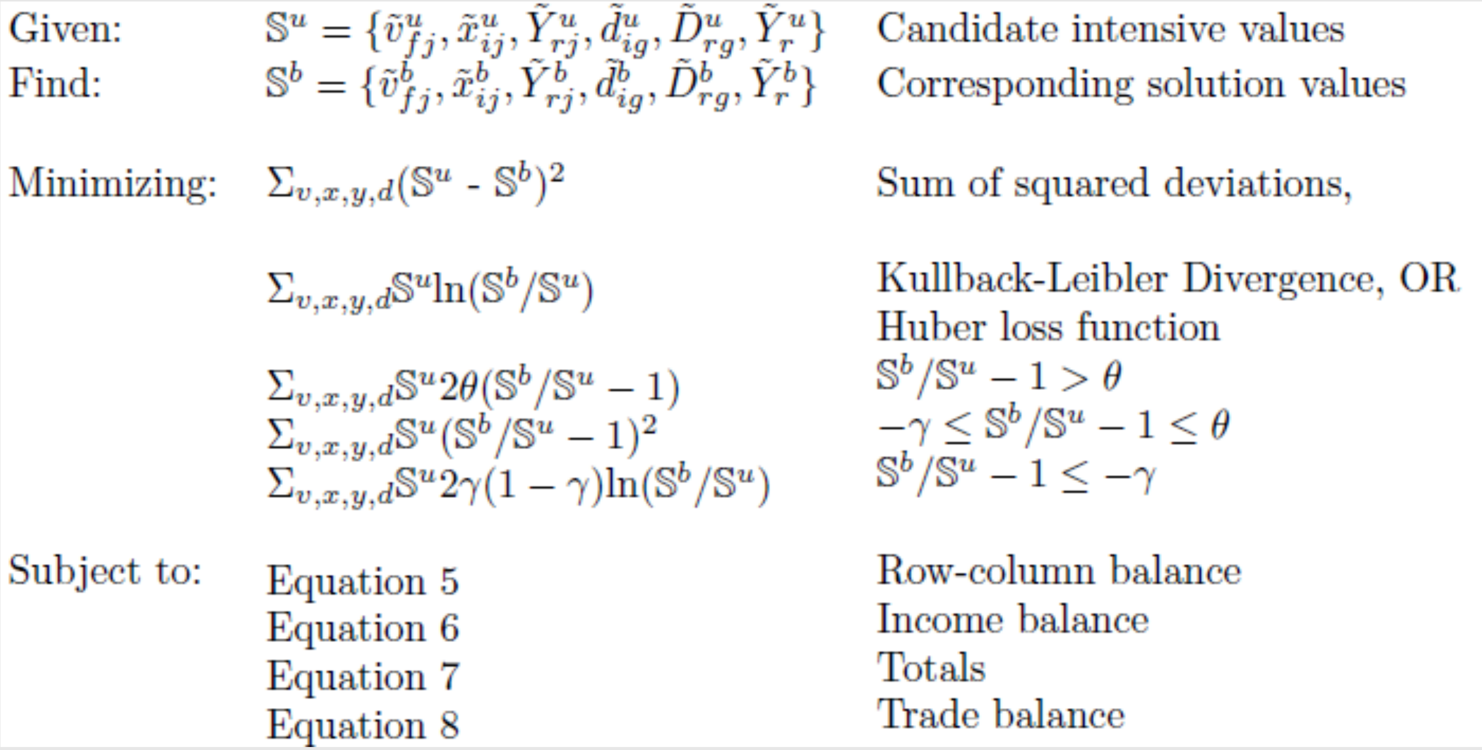
MEEDE vs. Public Utilities Data Liberation (PUDL) Data

- For CGE context:
  - MEEDE includes capital and O&M cost estimations for all generators (including solar, wind, other renewables) and their control techs (for fossil plants) using ATB and IPM data, while PUDL only includes costs for steam, gas turbine, and hydro generators (because it uses FERC Form 1 which doesn’t require the same level of reporting for solar, wind, and other renewables)
  - Because PUDL relies on FERC Form 1, does not allow for projections of future costs. Since MEEDE is integrated with ATB, MEEDE can seamlessly use ATB cost projections.
  - MEEDE includes wholesale price estimates from FERC assigned to each generator, which PUDL does not include
- MEEDE fills in missing data using regional averages so that aggregated data are not skewed, and PUDL does not make assumptions about missing data.
- The format of MEEDE (with plant ID-prime mover-fuel type-boiler ID mappings) makes it easy to aggregate up to higher levels relevant to CGE modeling (e.g., capex by all coal, NG, or oil).

Applications: SAM Integration

1. Form priors
    a. Aggregate MEEDE to 8 technologies
    b. ID labor from QCEW
    c. Assign materials total and distribute using IMPLAN
2. Rebalance SAM
    a. Swap SAM data with priors
    b. Form MP with SAM and macro constraints, variable bounds
    c. Fix generation shares, energy efficiencies, and zeroes
    d. Solve MP using PATHNLP (cross entropy, least squares) or DNLP (Huber)

Input Cost	Generation Value	T&D Value
Capital	MEEDE	IMPLAN - MEEDE
Labor	QCEW	QCEW
Energy	MEEDE	IMPLAN - MEEDE (ex. coal = 0)
Materials	VOM + FOM + Fuel Margins - QCEW	IMPLAN - MEEDE



Given:	$\mathbb{S}^u = \{\tilde{v}^u_{fj}, \tilde{x}^u_{ij}, \tilde{Y}^u_{rj}, \tilde{d}^u_{ig}, \tilde{D}^u_{rg}, \tilde{Y}^u_r\}$	Candidate intensive values
Find:	$\mathbb{S}^b = \{\tilde{v}^b_{fj}, \tilde{x}^b_{ij}, \tilde{Y}^b_{rj}, \tilde{d}^b_{ig}, \tilde{D}^b_{rg}, \tilde{Y}^b_r\}$	Corresponding solution values
Minimizing:	$\Sigma_{v,x,y,d}(\mathbb{S}^u - \mathbb{S}^b)^2$	Sum of squared deviations,
	$\Sigma_{v,x,y,d}\mathbb{S}^u \ln(\mathbb{S}^b/\mathbb{S}^u)$	Kullback-Leibler Divergence, OR Huber loss function
	$\Sigma_{v,x,y,d}\mathbb{S}^u 2\theta(\mathbb{S}^b/\mathbb{S}^u - 1)$	$\mathbb{S}^b/\mathbb{S}^u - 1 > \theta$
	$\Sigma_{v,x,y,d}\mathbb{S}^u (\mathbb{S}^b/\mathbb{S}^u - 1)^2$	$-\gamma \leq \mathbb{S}^b/\mathbb{S}^u - 1 \leq \theta$
	$\Sigma_{v,x,y,d}\mathbb{S}^u 2\gamma(1-\gamma)\ln(\mathbb{S}^b/\mathbb{S}^u)$	$\mathbb{S}^b/\mathbb{S}^u - 1 \leq -\gamma$
Subject to:	Equation 5	Row-column balance
	Equation 6	Income balance
	Equation 7	Totals
	Equation 8	Trade balance

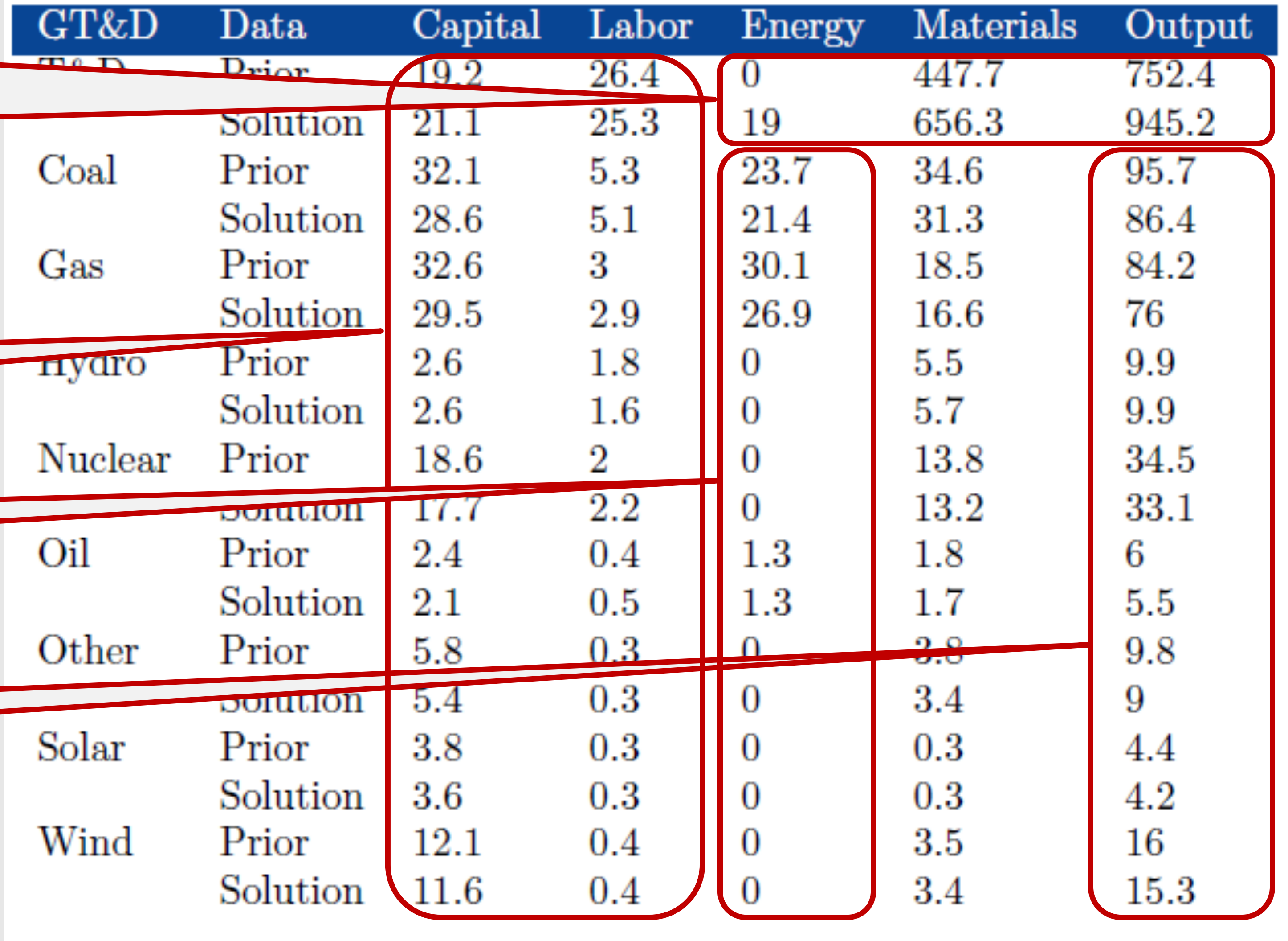
Applications: SAM Integration Results

T&D priors, held weakly (no bottom-up data), travel more.
Total output double counts gen; i.e., gen plus (gen +T&D)

K&L don’t travel much

Energy efficiencies fixed

Gen outputs don’t travel much



GT&D	Data	Capital	Labor	Energy	Materials	Output
T&D	Prior	19.2	26.4	0	447.7	752.4
	Solution	21.1	25.3	19	656.3	945.2
Coal	Prior	32.1	5.3	23.7	34.6	95.7
	Solution	28.6	5.1	21.4	31.3	86.4
Gas	Prior	32.6	3	30.1	18.5	84.2
	Solution	29.5	2.9	26.9	16.6	76
Hydro	Prior	2.6	1.8	0	5.5	9.9
	Solution	2.6	1.6	0	5.7	9.9
Nuclear	Prior	18.6	2	0	13.8	34.5
	Solution	17.7	2.2	0	13.2	33.1
Oil	Prior	2.4	0.4	1.3	1.8	6
	Solution	2.1	0.5	1.3	1.7	5.5
Other	Prior	5.8	0.3	0	3.8	9.8
	Solution	5.4	0.3	0	3.4	9
Solar	Prior	3.8	0.3	0	0.3	4.4
	Solution	3.6	0.3	0	0.3	4.2
Wind	Prior	12.1	0.4	0	3.5	16
	Solution	11.6	0.4	0	3.4	15.3

Applications: PE Modeling

- ACCESS (Accessible Capacity and Cost optimization Electric Sector Simulation) Model
  - Reduced form partial equilibrium model representing the electricity sector
  - Developed in Python with Gurobi solver
  - Internal R&D effort at RTI for now
  - Testing state-level simulations for an environment NGO

- Benefits of a reduced form modeling approach
  - Allows for Monte Carlo simulations of a range of scenarios
  - Users have more flexibility and control over input assumptions; e.g.,
    - Demand profiles at various temporal resolutions,
    - Technology specifications such as capacity factors and ramp rates,
    - Regionality and trade assumptions
  - Can be run with hourly resolution to capture renewable resource variability

Electricity Structure in CGE

01

Functional forms: estimating and simulating dispatch

02

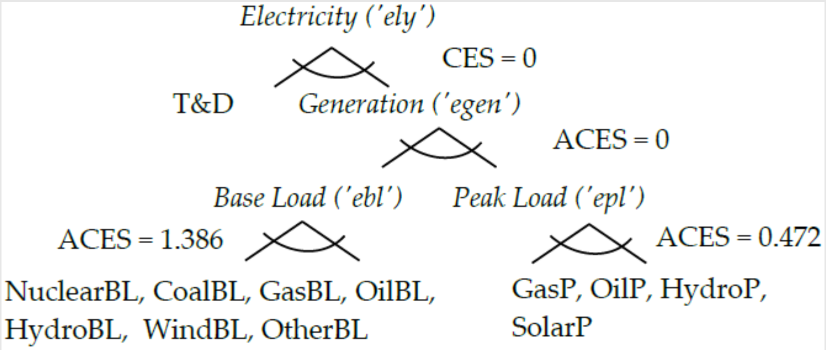
Bottom-up elasticities: how reliable are they?

03

CGE Structure: do we need elasticities?

Functional Forms: Prod.

- CGE models often highly stylized
- Not all separate T&D
- Wide range of elasticity assumptions
- Forms: CES, CRESH, Translog, ACES



(Peters, 2016)

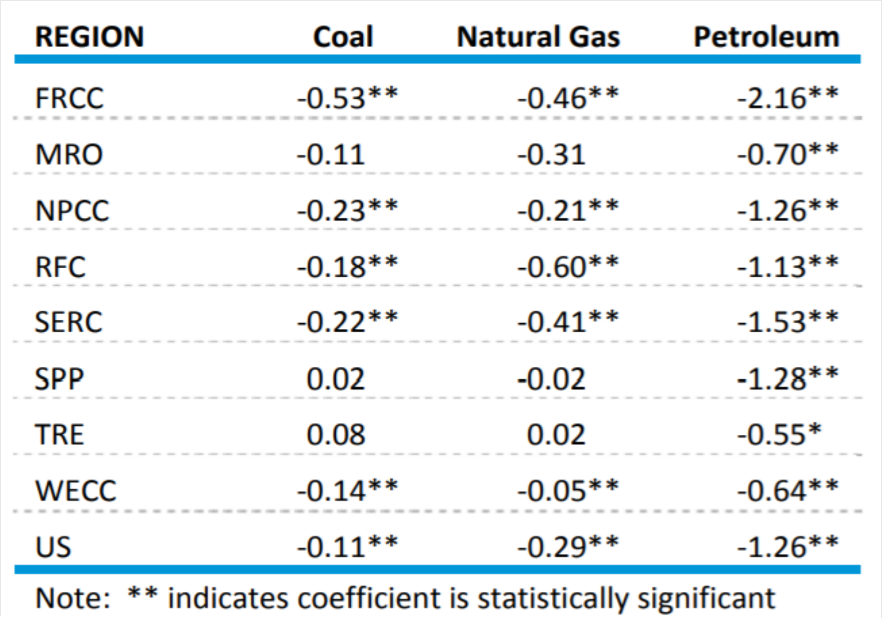
Model	Base	Peak	Gen	Gen-TD	VA – E	Other	No. Tech.
ADAGE (Yongxia Cai et al., 2021)	--	--	0.3		0.4		Small
ARTIMAS (Woollacott, 2020)	2	2	0.4	0	No	No	Large
ENV-Linkages (Jean Château et al., 2014)		--	--	5	N/A		
EPPA (Paltsev et al., 2005)			∞	>0			Small
GEM-E3 (Capros et al., 2013)	--	--	0	0			
GTAP-E-Power (Jeffrey Peters, 2016)	1.39*	0.47*	0	0	Yes	?	Varies
GTEM-CTEM (Yiyong Cai & Arora, 2015)		--	--	CRESH	0	Yes	
IGEM (Goettle et al., 2007)	--	--	--	--	Yes		Small
Phoenix (Sue Wing et al., 2011)	4	4	1	0.7			Small
USREP (Yuan et al., 2019)	∞	∞	Varies				Small

* Represents empirically estimated values.

(2014) have capital-energy and interfuel substitution rather than substituting technologies.

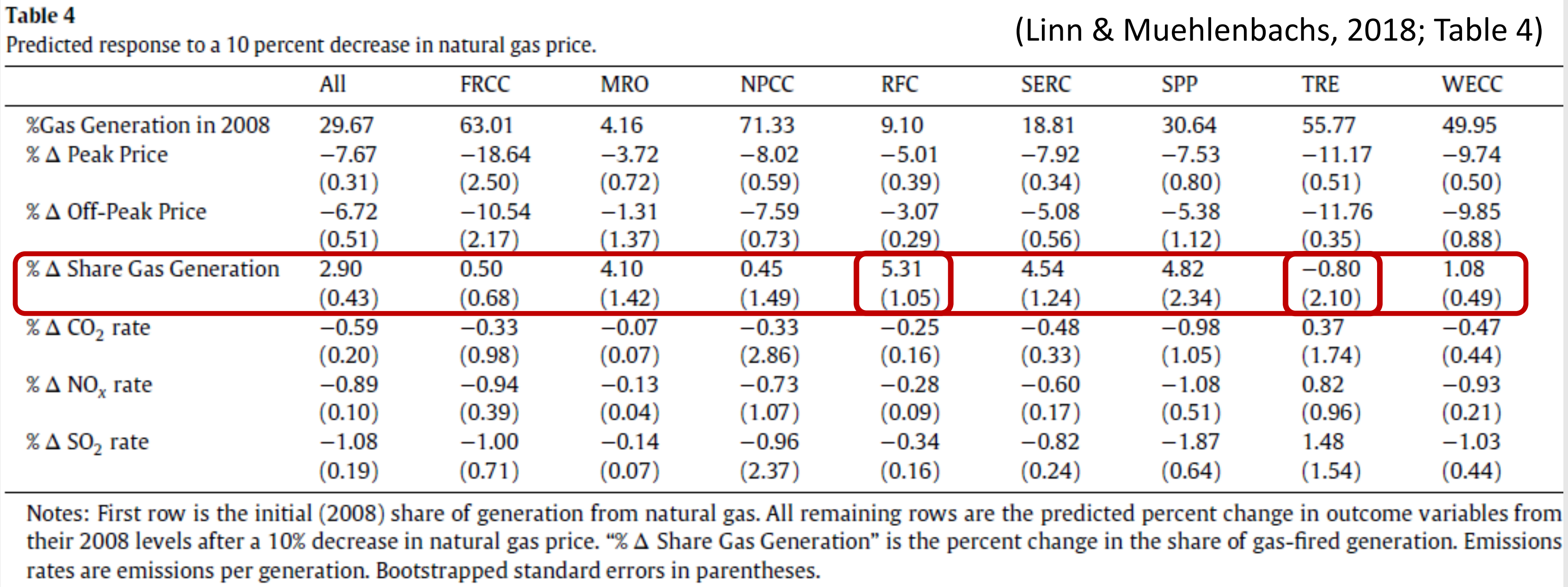
Functional Forms: Estimation

- Elasticity estimates: vary widely across regions
- Common estimation forms: OLS, translog, linear logit
- Recent papers: Linn & Muehlenbachs (2018), Fell & Kaffine (2018), Knittel et al. (2019)



REGION	Coal	Natural Gas	Petroleum
FRCC	-0.53**	-0.46**	-2.16**
MRO	-0.11	-0.31	-0.70**
NPCC	-0.23**	-0.21**	-1.26**
RFC	-0.18**	-0.60**	-1.13**
SERC	-0.22**	-0.41**	-1.53**
SPP	0.02	-0.02	-1.28**
TRE	0.08	0.02	-0.55*
WECC	-0.14**	-0.05**	-0.64**
US	-0.11**	-0.29**	-1.26**

Note: ** indicates coefficient is statistically significant



(Linn & Muehlenbachs, 2018; Table 4)

Table 4
Predicted response to a 10 percent decrease in natural gas price.

	All	FRCC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC
%Gas Generation in 2008	29.67	63.01	4.16	71.33	9.10	18.81	30.64	55.77	49.95
% Δ Peak Price	−7.67	−18.64	−3.72	−8.02	−5.01	−7.92	−7.53	−11.17	−9.74
	(0.31)	(2.50)	(0.72)	(0.59)	(0.39)	(0.34)	(0.80)	(0.51)	(0.50)
% Δ Off-Peak Price	−6.72	−10.54	−1.31	−7.59	−3.07	−5.08	−5.38	−11.76	−9.85
	(0.51)	(2.17)	(1.37)	(0.73)	(0.29)	(0.56)	(1.12)	(0.35)	(0.88)
% Δ Share Gas Generation	2.90	0.50	4.10	0.45	5.31	4.54	4.82	−0.80	1.08
	(0.43)	(0.68)	(1.42)	(1.49)	(1.05)	(1.24)	(2.34)	(2.10)	(0.49)
% Δ CO_2 rate	−0.59	−0.33	−0.07	−0.33	−0.25	−0.48	−0.98	0.37	−0.47
	(0.20)	(0.98)	(0.07)	(2.86)	(0.16)	(0.33)	(1.05)	(1.74)	(0.44)
% Δ NO_x rate	−0.89	−0.94	−0.13	−0.73	−0.28	−0.60	−1.08	0.82	−0.93
	(0.10)	(0.39)	(0.04)	(1.07)	(0.09)	(0.17)	(0.51)	(0.96)	(0.21)
% Δ SO_2 rate	−1.08	−1.00	−0.14	−0.96	−0.34	−0.82	−1.87	1.48	−1.03
	(0.19)	(0.71)	(0.07)	(2.37)	(0.16)	(0.24)	(0.64)	(1.54)	(0.44)

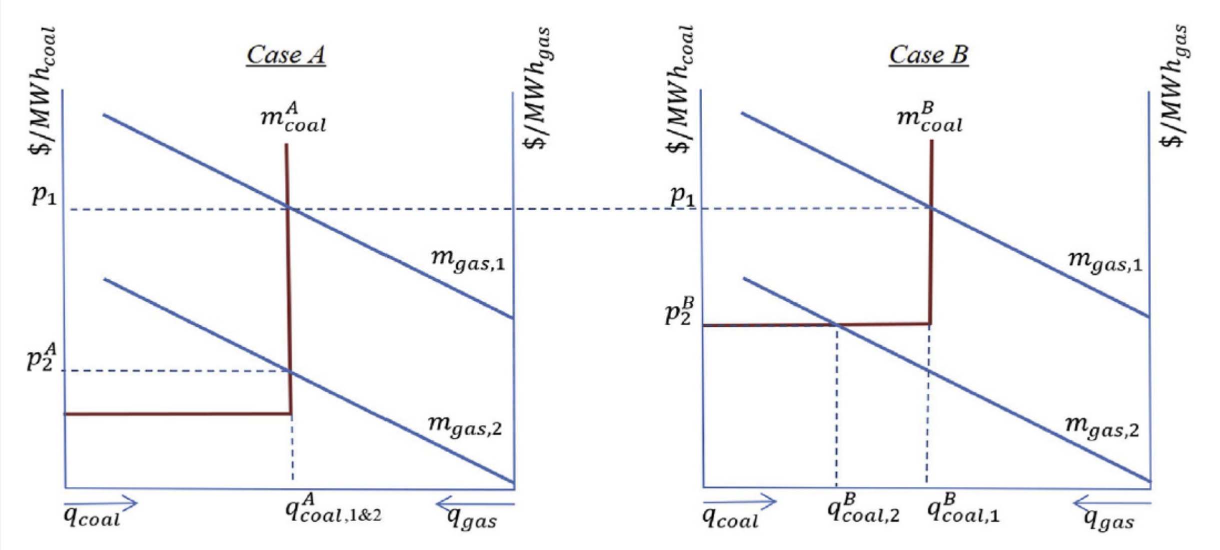
Notes: First row is the initial (2008) share of generation from natural gas. All remaining rows are the predicted percent change in outcome variables from their 2008 levels after a 10% decrease in natural gas price. "% Δ Share Gas Generation" is the percent change in the share of gas-fired generation. Emissions rates are emissions per generation. Bootstrapped standard errors in parentheses.

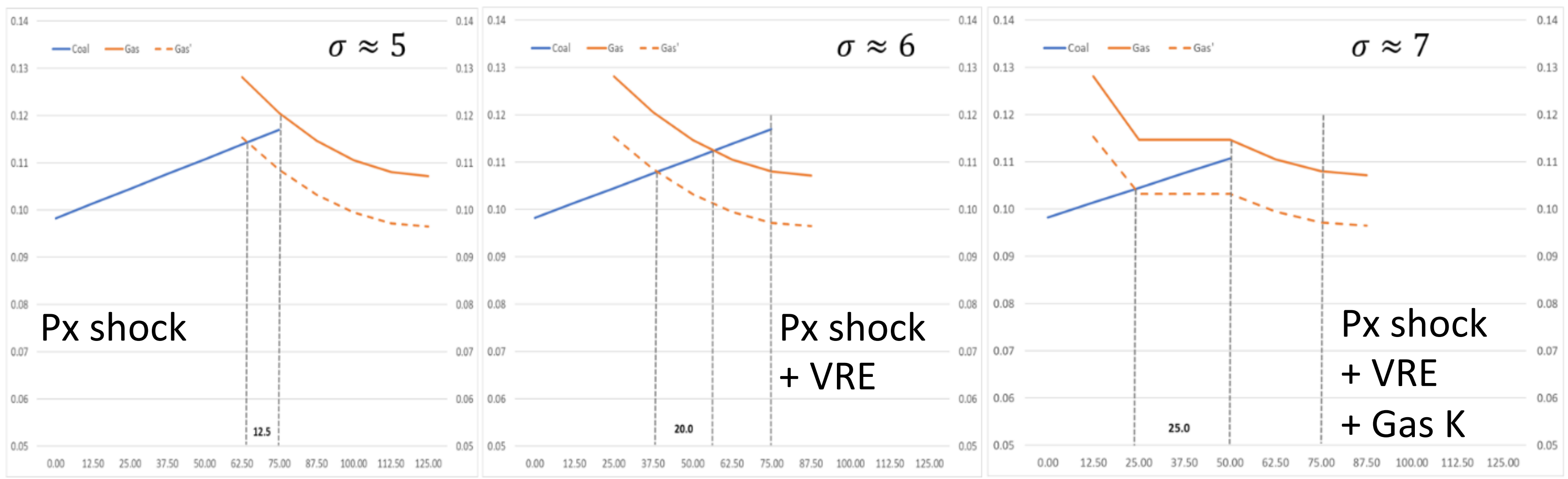
Bottom-Up Elasticities: Theory

(Linn & Muehlenbachs, 2018; Table 4)

- Linn and Muehlenbachs (2018) motivate regional heterogeneity with stylized supply curve analysis (top)

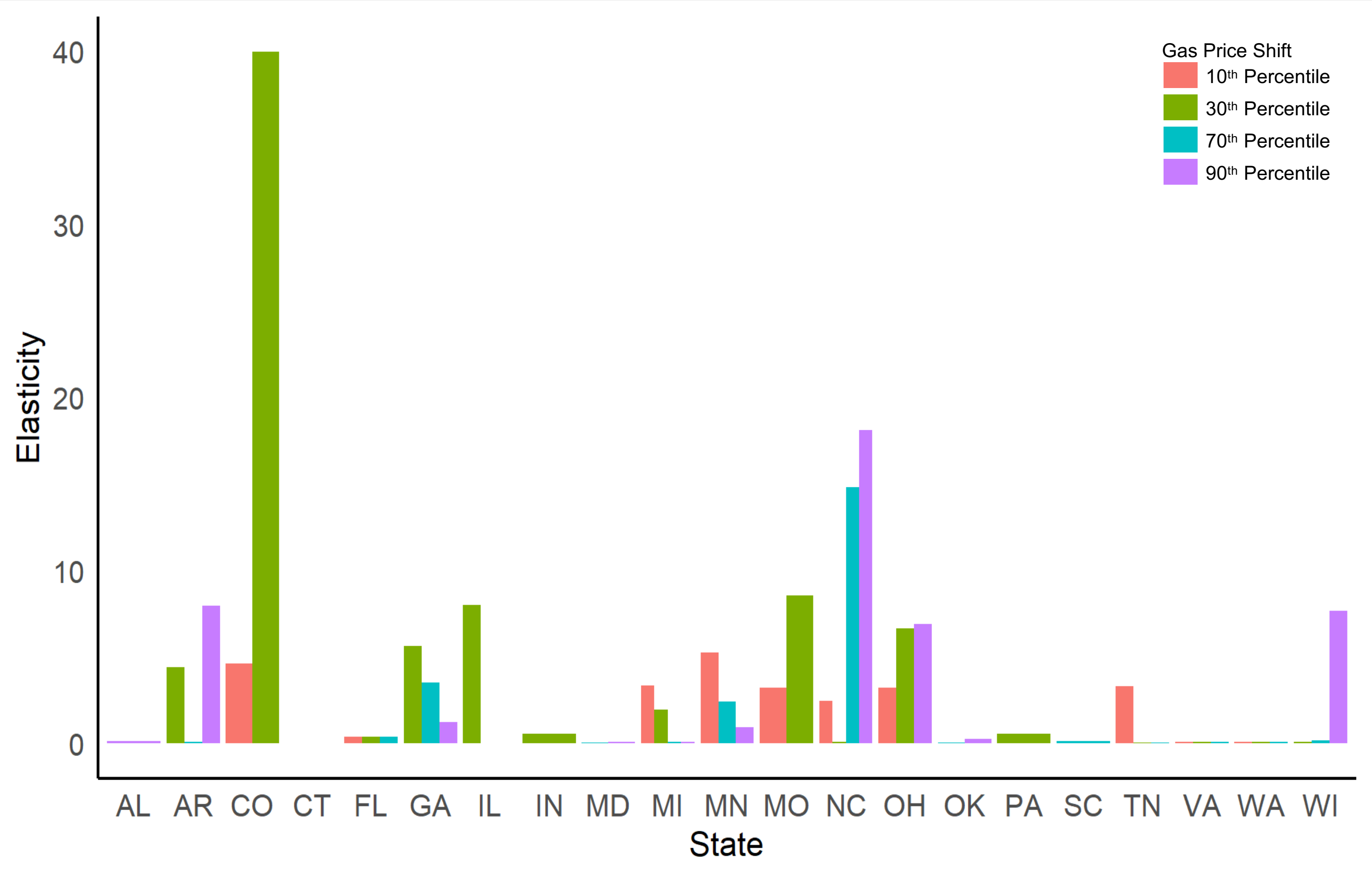
- Worked example (bottom) shows how elasticities change with increased VRE and gas capacity





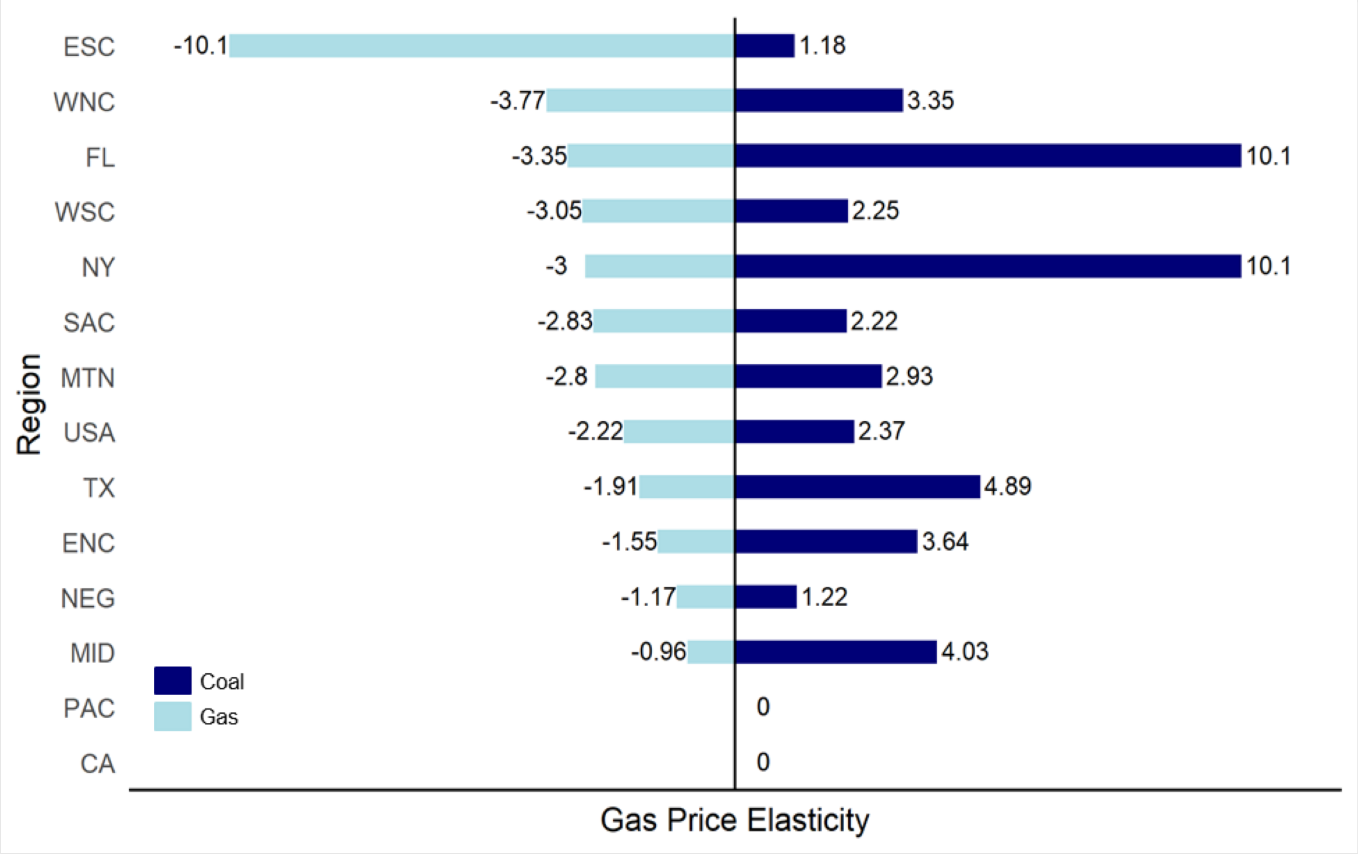
Bottom-Up Elasticities: Discrete Approximation

- Supply curves built from MEEDE data
- Considerable regional variation consistent with lit.
- Not all cross, but annual average distorts hourly reality
- Gas crosses on steep part of coal supply → small elasticity



Bottom-Up Elasticities: Monte Carlo Simulation

- Simple dispatch model replicates MEEDE, gives ~linear behavior
- More complex model may need more sophisticated estimation form
- Elasticity not constant given linearity
- Results may differ significantly with a more complex PE model
- Implied elasticities vary widely by region as in empirical work



Bottom-Up Elasticities: Theory

- What does a ‘bottom-up elasticity’ look like? Is it well-defined?
- Not well defined for ZMC technologies (i.e., $c^m_{gh} = 0$)
- Not constant across or within regions

γ_{gh}:	Capacity utilization	d_h:	Period demand	π_{gh}:	Operating profit
ν_g:	Dispatchable capacity	N_g:	Installed capacity	h:	Periods
c^m_{gh}:	Marginal cost of generation	u_{gh}:	Capacity bounds	g:	Generators

Costs Supply=Demand Utilization Bounds

Lagrangian: $$\mathcal{L}_h = \boxed{\textstyle\sum_g \gamma_{gh}\nu_g c^m_{gh}} + \boxed{\lambda^0_h\left(d_h - \textstyle\sum_g \gamma_{gh}\nu_g\right)} +$$

Capacity $$\boxed{\lambda^1_{gh}\left(N_g - \nu_g\right)} + \boxed{\lambda^2_{gh}\left(u^{Hi}_{gh} - \gamma_{gh}\right) + \lambda^3_{gh}\left(\gamma_{gh} - u^{Lo}_{gh}\right)}$$

FOCs:

$$\mathcal{L}_{\gamma_{gh}}: \nu_g\left(c^m_{gh} - \lambda^0_h\right) - \lambda^2_{gh} + \lambda^3_{gh} = 0 \Rightarrow \nu_g = \frac{\lambda^2_{gh} - \lambda^3_{gh}}{-\pi_{gh}} \quad \forall g$$

$$\mathcal{L}_{\nu_g}: \gamma_{gh}\left(c^m_{gh} - \lambda^0_h\right) - \lambda^1_{gh} = 0 \Rightarrow \gamma_{gh} = \frac{\lambda^1_{gh}}{-\pi_{gh}} \quad \forall g$$

$$\mathcal{L}_{\lambda^0_h}: \textstyle\sum_g \gamma_{gh}\nu_g - d_h \geq 0$$

$$\mathcal{L}_{\lambda^1_{gh}}: \left(N_g - \nu_g\right) \geq 0$$

$$\mathcal{L}_{\lambda^2_{gh}}: \left(u^{Hi}_{gh} - \gamma_{gh}\right) \geq 0$$

$$\mathcal{L}_{\lambda^3_{gh}}: \left(\gamma_{gh} - u^{Lo}_{gh}\right) \geq 0$$

Capacity Rents

Operating Profit

$$\sigma_{gg'} = \frac{\dfrac{\partial \gamma^*_{gh}}{\partial c^m_{gh}} \dfrac{c_{gh}}{\gamma^*_{gh}}}{\dfrac{\partial \gamma^*_{g'h}}{\partial c^m_{gh}} \dfrac{c^m_{gh}}{\gamma^*_{g'h}}} = \boxed{\frac{\lambda^1_{gh}}{\lambda^1_{g'h}}} \left(\frac{\pi_{gh}}{\pi_{g'h}}\right)^2 \frac{c^m_{gh}}{c^m_{g'h}} \frac{\gamma^*_{g'h}}{\gamma^*_{gh}}$$

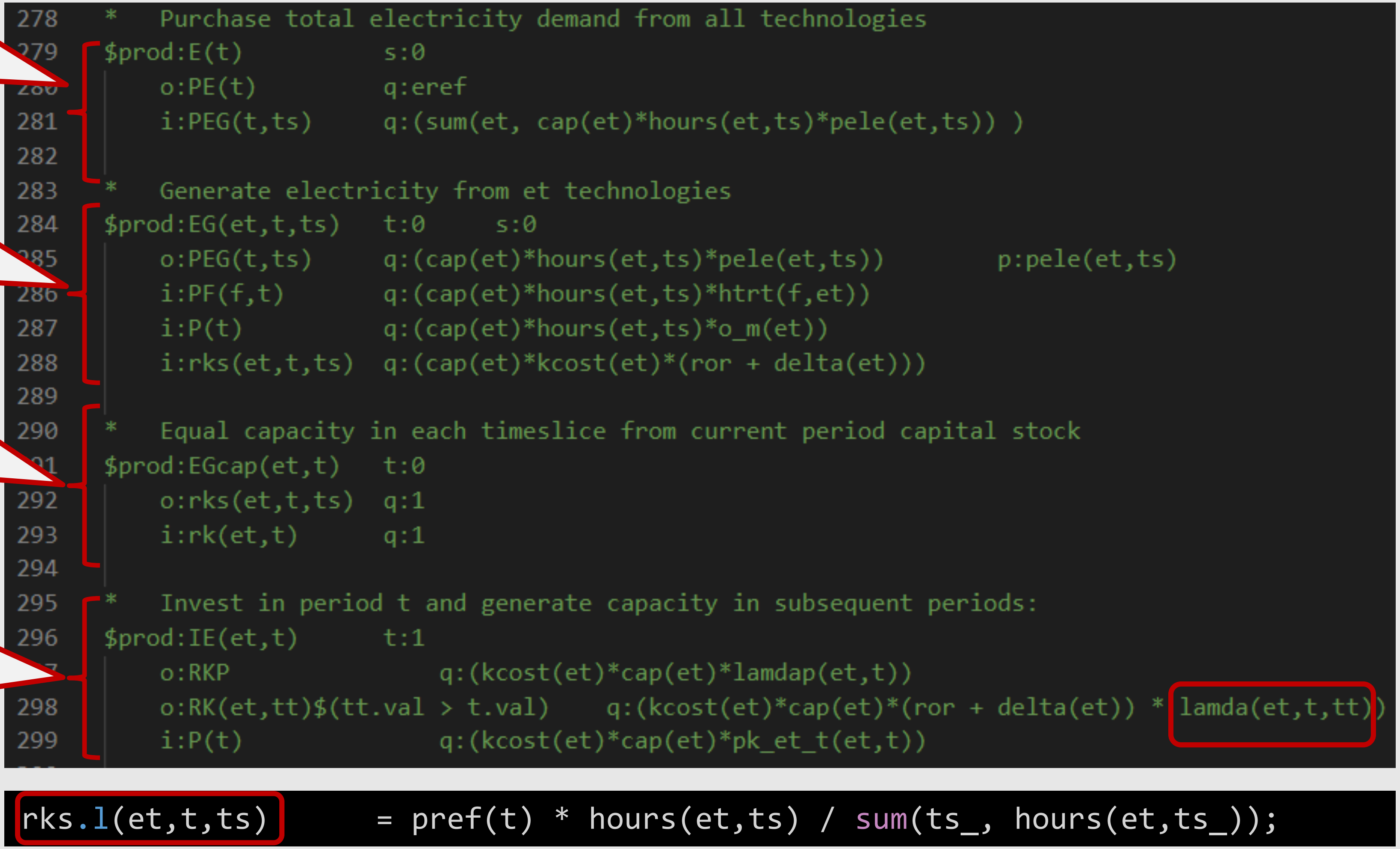
General Equilibrium Structure

Demand fixed load profile from all technologies

Generate in ts given capacity factor hours(et,ts) / card(ts)

Capacity available in all time slices earning rk(et,t) = sum(ts, rks(et,t,ts))

Invest in higher-rent capacity that survives on schedule lambda



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*   Purchase total electricity demand from all technologies
$prod:E(t)          s:0
    o:PE(t)         q:eref
    i:PEG(t,ts)     q:(sum(et, cap(et)*hours(et,ts)*pele(et,ts)) )

*   Generate electricity from et technologies
$prod:EG(et,t,ts)   t:0     s:0
    o:PEG(t,ts)     q:(cap(et)*hours(et,ts)*pele(et,ts))        p:pele(et,ts)
    i:PF(f,t)       q:(cap(et)*hours(et,ts)*htrt(f,et))
    i:P(t)          q:(cap(et)*hours(et,ts)*o_m(et))
    i:rks(et,t,ts)  q:(cap(et)*kcost(et)*(ror + delta(et)))

*   Equal capacity in each timeslice from current period capital stock
$prod:EGcap(et,t)   t:0
    o:rks(et,t,ts)  q:1
    i:rk(et,t)      q:1

*   Invest in period t and generate capacity in subsequent periods:
$prod:IE(et,t)      t:1
    o:RKP                   q:(kcost(et)*cap(et)*lamdap(et,t))
    o:RK(et,tt)$(tt.val > t.val)    q:(kcost(et)*cap(et)*(ror + delta(et)) * lamda(et,t,tt))
    i:P(t)                  q:(kcost(et)*cap(et)*pk_et_t(et,t))
```

```
rks.l(et,t,ts)       = pref(t) * hours(et,ts) / sum(ts_, hours(et,ts_));
```

Research Needs

- Develop and test CGE formulation
    - Develop capacity factor specification
    - Vary time slice representation

- Robust Monte Carlo PE Simulation → response surface for CGE validation
    - Build up toy model
    - Multi-model comparisons