This online appendix provides additional information supporting Gillingham and Huang (2019) "Is Abundant Natural Gas a Bridge to a Low-carbon Future or a Dead-end," published in the *Energy Journal*.

APPENDIX A

This appendix presents the derivation of comparative statics for the two models in Section 3 and the proof for Proposition 1.

Abundant natural gas without carbon pricing

We first derive the comparative static results for a firm profit maximization problem represented in equation (1), which are then used to prove Proposition 1. We take total derivatives of the FOCs (2) plus the inverse demand function $p = p(Q)$ and the output condition $Q = x_L + x_M + x_H$ with respect to natural gas supply S and solve the set of equations, yielding the following equations:

$$\frac{\partial p}{\partial S} = \frac{p'\tau' C_L'' C_H''}{\Delta} \leq 0, \tag{A.1}$$

$$\frac{\partial x_L}{\partial S} = \frac{p'\tau' C_H''}{\Delta} \leq 0, \tag{A.2}$$

$$\frac{\partial x_M}{\partial S} = \frac{\tau' C_L'' C_H'' - p'\tau'\left(C_L'' + C_H''\right)}{\Delta} \geq 0, \tag{A.3}$$

$$\frac{\partial x_H}{\partial S} = \frac{p'\tau' C_L''}{\Delta} \leq 0, \tag{A.4}$$

$$\frac{\partial Q}{\partial S} = \frac{1}{p'} \frac{\partial p}{\partial S} \geq 0, \quad \text{(A.5)}$$

where $\Delta = C_L'' C_M'' C_H'' - p' \left(C_M'' C_H'' + C_L'' C_H'' + C_L'' C_M'' \right) > 0$. The equations (A.1)-(A.5) represent the comparative statics results of abundant natural gas impacts on prices and quantities, and the equation signs indicate the direction of impact. For instance, an increase in natural gas supply results in higher total output (e.g., electricity) and output from natural gas, and lower market price and output from renewables and coal.

The following is the derivations of the conditions in Proposition 1. For the case of emissions increase due to abundant natural gas such that $\partial E_c / \partial S \geq 0$ and $\partial E_j / \partial S \geq 0$ for each j, solve the RHS of equations (3) and (4), which yields:

$$1 \leq \beta \leq \overline{H},$$

$$1 \leq \theta_j \leq \overline{H},$$

where $\overline{H} \equiv -\left(\partial x_M / \partial S \right) / \left(\partial x_H / \partial S \right)$ and the left side of inequality in the above two inequalities are by definition. The marginal products for defining the threshold $\overline{H}$ are represented by equations (A.3) and (A.4), and thus $\overline{H} = \left(p' \left(C_L'' + C_H'' \right) - C_L'' C_H'' \right) / p' C_L''$.

Similarly, for the case of emissions decrease due to abundant natural gas such that $\partial E_c / \partial S \leq 0$ and $\partial E_j / \partial S \leq 0$ for each j, we obtain the conditions for emissions rates:

$$\beta \geq \overline{H},$$

$$\theta_j \geq \overline{H},$$

where $\overline{H}$ is defined above.

Abundant natural gas with carbon pricing

This section presents the derivation of the comparative static results for a firm profit maximization problem that internalizes CO_2 externalities represented in equation (6), and shows the same conditions for emissions implication as in Proposition 1. Again, take total derivatives of (7) plus three additional equations $p = p(Q)$ and $Q = x_L + x_M + x_H$ with respect to S, which yields the following comparative statics results:

$$\frac{\partial p}{\partial S} = \frac{p'\tau_t' C_L'' C_H''}{\Delta} \leq 0, \tag{A.6}$$

$$\frac{\partial x_L}{\partial S} = \frac{p'\tau_t' C_H''}{\Delta} \leq 0, \tag{A.7}$$

$$\frac{\partial x_M}{\partial S} = \frac{\tau_t' C_L'' C_H'' - p'\tau_t'\left(C_L'' + C_H''\right)}{\Delta} \geq 0, \tag{A.8}$$

$$\frac{\partial x_H}{\partial S} = \frac{p'\tau_t' C_L''}{\Delta} \leq 0, \tag{A.9}$$

$$\frac{\partial Q}{\partial S} = \frac{1}{p'}\frac{\partial p}{\partial S} \geq 0. \tag{A.10}$$

The equations (A.6)-(A.10) show that the effects of abundant natural gas under carbon pricing on fuel consumptions and output electricity price and quantities are the same as the previous case without carbon pricing, but in different magnitude, indicated by τ_t'.

The conditions determining the change in emissions are derived in the same logic as the previous case, in which the marginal products deriving the threshold are from equations (A.8) and (A.9), which results in the same threshold $\overline{H}$ as in Proposition 1.

APPENDIX B

This appendix presents the raw numbers behind several of the key figures in the paper for our reader's reference.

Table B.1: Projected Henry Hub prices for natural gas (unit: 2016$/MMBtu)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	2.99	2.83	2.99	2.84
2018	3.41	3.13	3.37	3.12
2019	3.92	3.49	3.97	3.51
2020	4.48	3.64	4.49	3.68
2021	4.42	3.48	4.41	3.48
2022	4.36	3.43	4.28	3.47
2023	4.39	3.46	4.34	3.56
2024	4.45	3.60	4.44	3.73
2025	4.47	3.75	4.53	3.90
2026	4.53	3.85	4.61	3.97
2027	4.65	3.95	4.70	4.03
2028	4.77	4.05	4.79	4.07
2029	4.85	4.05	4.93	4.06
2030	4.85	3.97	5.03	4.00
2031	4.97	3.90	5.15	3.97
2032	5.00	3.82	5.15	3.90
2033	4.99	3.83	5.12	3.93
2034	4.97	3.83	5.08	3.97
2035	5.03	3.88	5.17	4.06
2036	5.01	3.87	5.22	4.03
2037	4.99	3.83	5.23	4.00
2038	4.98	3.80	5.27	3.96
2039	5.02	3.81	5.33	3.96
2040	5.01	3.81	5.31	3.92
2041	5.01	3.83	5.37	3.91
2042	5.14	3.85	5.48	3.96
2043	5.19	3.90	5.52	3.95
2044	5.22	4.06	5.52	4.06
2045	5.28	4.12	5.56	4.10
2046	5.35	4.14	5.61	4.10
2047	5.44	4.16	5.63	4.09
2048	5.54	4.23	5.71	4.13
2049	5.64	4.31	5.73	4.20
2050	5.66	4.33	5.78	4.34

Table B.2: Projected U.S. natural gas consumption (unit: trillion Btus)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	28.77	28.76	28.77	28.76
2018	29.05	29.78	28.99	29.80
2019	28.69	30.05	28.77	30.07
2020	28.24	29.92	28.27	30.22
2021	28.08	30.17	28.22	30.52
2022	28.12	30.56	28.18	31.10
2023	28.34	30.89	28.41	31.58
2024	28.57	31.20	28.75	32.19
2025	28.96	31.61	29.19	32.79
2026	29.18	31.98	29.66	33.31
2027	29.34	32.05	29.79	33.65
2028	29.42	32.25	29.95	34.10
2029	29.48	32.48	30.19	34.55
2030	29.48	32.72	30.50	35.00
2031	29.57	33.06	30.71	35.48
2032	29.78	33.43	31.09	35.99
2033	29.99	33.78	31.51	36.40
2034	30.37	34.19	31.96	36.98
2035	30.81	34.63	32.42	37.49
2036	31.12	35.05	32.85	37.95
2037	31.40	35.43	33.27	38.30
2038	31.75	35.92	33.70	38.60
2039	32.10	36.33	34.06	38.86
2040	32.33	36.70	34.31	39.06
2041	32.53	37.04	34.49	39.29
2042	32.71	37.34	34.65	39.46
2043	32.87	37.72	34.79	39.66
2044	33.17	38.19	34.95	39.92
2045	33.47	38.66	35.18	40.21
2046	33.73	39.21	35.33	40.46
2047	34.01	39.72	35.45	40.65
2048	34.24	40.07	35.48	40.83
2049	34.46	40.38	35.53	40.97
2050	34.79	40.76	35.72	41.19

Table B.3: Projected U.S. coal consumption (unit: trillion Btus)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	14.12	13.97	14.12	13.97
2018	14.07	13.42	14.01	13.36
2019	14.91	13.58	14.21	13.05
2020	15.37	13.78	14.32	12.60
2021	15.24	13.27	13.74	11.71
2022	15.41	13.04	13.32	10.67
2023	15.50	13.19	12.81	10.07
2024	15.65	13.48	12.54	9.54
2025	15.58	13.54	12.25	9.08
2026	15.50	13.61	11.79	8.56
2027	15.54	13.68	11.37	7.92
2028	15.56	13.63	10.94	7.11
2029	15.61	13.52	10.51	6.53
2030	15.64	13.36	9.93	5.92
2031	15.53	13.13	9.43	5.28
2032	15.46	12.93	8.80	4.71
2033	15.39	12.79	8.17	4.31
2034	15.37	12.78	7.70	3.92
2035	15.35	12.82	7.24	3.65
2036	15.31	12.73	6.71	3.27
2037	15.32	12.65	6.26	2.99
2038	15.30	12.42	5.76	2.79
2039	15.25	12.26	5.44	2.61
2040	15.19	12.01	5.07	2.45
2041	15.15	11.82	4.94	2.40
2042	15.13	11.73	4.83	2.32
2043	15.17	11.74	4.72	2.28
2044	15.18	11.74	4.63	2.28
2045	15.24	11.87	4.58	2.25
2046	15.25	11.81	4.60	2.22
2047	15.27	11.86	4.64	2.20
2048	15.26	11.90	4.59	2.22
2049	15.25	11.88	4.51	2.18
2050	15.30	11.90	4.53	2.18

Table B.4: Projected U.S. renewable consumption (unit: trillion Btus)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	7.69	7.72	7.69	7.71
2018	8.19	8.20	8.30	8.22
2019	8.56	8.55	9.07	8.96
2020	9.09	9.06	9.89	9.67
2021	9.74	9.66	10.69	10.42
2022	10.18	10.05	11.66	11.13
2023	10.48	10.27	12.39	11.61
2024	10.58	10.33	12.57	11.72
2025	10.61	10.37	12.62	11.77
2026	10.66	10.38	12.66	11.85
2027	10.72	10.45	12.79	12.05
2028	10.79	10.50	13.01	12.26
2029	10.87	10.56	13.18	12.36
2030	10.95	10.60	13.37	12.44
2031	11.02	10.63	13.52	12.55
2032	11.12	10.69	13.74	12.62
2033	11.21	10.73	13.93	12.73
2034	11.32	10.77	14.22	12.81
2035	11.45	10.82	14.56	12.93
2036	11.55	10.85	14.76	13.08
2037	11.64	10.89	14.98	13.28
2038	11.70	10.92	15.26	13.50
2039	11.76	10.96	15.46	13.72
2040	11.83	10.99	15.70	13.81
2041	11.97	11.07	15.88	13.90
2042	12.12	11.16	16.08	14.08
2043	12.29	11.22	16.38	14.28
2044	12.36	11.26	16.77	14.43
2045	12.43	11.30	17.08	14.58
2046	12.56	11.34	17.37	14.82
2047	12.69	11.36	17.74	15.12
2048	12.82	11.38	18.11	15.40
2049	13.01	11.44	18.43	15.72
2050	13.15	11.49	18.59	15.98

Table B.5: Projected energy-related carbon dioxide emissions (unit: million metric tons)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing	Reference with CPP
2017	5182.74	5162.78	5182.63	5162.58	5182.85
2018	5217.46	5194.24	5209.37	5189.78	5221.66
2019	5277.00	5224.39	5213.78	5173.88	5272.05
2020	5286.98	5229.86	5186.87	5130.90	5271.66
2021	5259.66	5189.91	5121.69	5055.09	5229.85
2022	5267.07	5178.10	5065.17	4976.46	5168.35
2023	5272.39	5195.25	5011.84	4927.97	5137.50
2024	5279.01	5220.57	4982.34	4889.63	5108.49
2025	5266.10	5225.91	4950.83	4854.45	5067.96
2026	5245.96	5230.72	4904.88	4810.74	5020.81
2027	5237.15	5223.08	4850.25	4746.50	4965.17
2028	5226.10	5210.42	4796.50	4674.90	4922.14
2029	5221.14	5196.69	4751.34	4623.83	4884.13
2030	5209.61	5176.02	4696.15	4569.24	4849.43
2031	5187.81	5159.78	4643.44	4522.03	4831.64
2032	5179.41	5150.69	4587.02	4484.58	4818.00
2033	5176.70	5151.80	4538.71	4461.96	4815.28
2034	5191.38	5171.89	4513.37	4453.05	4820.34
2035	5212.42	5199.52	4492.35	4453.68	4827.43
2036	5225.43	5213.18	4464.20	4441.04	4835.37
2037	5244.76	5229.62	4446.94	4435.36	4845.97
2038	5267.65	5240.56	4426.85	4436.00	4856.95
2039	5288.12	5250.97	4419.43	4435.92	4869.27
2040	5299.79	5251.23	4399.04	4435.69	4880.16
2041	5311.86	5258.22	4403.93	4448.81	4892.75
2042	5332.22	5274.59	4411.31	4458.72	4909.24
2043	5354.65	5309.47	4419.55	4477.92	4928.91
2044	5387.46	5347.70	4432.77	4503.92	4950.81
2045	5422.25	5397.67	4453.51	4528.97	4972.52
2046	5450.17	5433.72	4474.81	4550.51	4995.82
2047	5478.38	5477.64	4496.64	4568.05	5016.37
2048	5500.97	5511.39	4504.76	4590.75	5034.62
2049	5526.80	5540.42	4513.10	4605.68	5056.85
2050	5566.92	5578.90	4539.68	4632.95	5085.03

Table B.6: Projected SO_2 emissions from the electric power sector (unit: million short tons)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	1.09	1.07	1.09	1.07
2018	1.10	1.03	1.06	1.02
2019	1.13	1.00	1.07	0.98
2020	1.21	1.08	1.13	1.01
2021	1.18	1.03	1.07	0.95
2022	1.23	1.06	1.10	0.86
2023	1.28	1.08	1.09	0.84
2024	1.30	1.10	1.07	0.80
2025	1.31	1.09	1.05	0.74
2026	1.30	1.12	1.00	0.71
2027	1.30	1.10	0.98	0.65
2028	1.29	1.08	0.95	0.61
2029	1.29	1.10	0.91	0.67
2030	1.35	1.10	0.84	0.59
2031	1.33	1.09	0.82	0.45
2032	1.35	1.08	0.77	0.37
2033	1.33	1.07	0.75	0.34
2034	1.33	1.06	0.71	0.29
2035	1.34	1.10	0.68	0.27
2036	1.36	1.12	0.62	0.23
2037	1.37	1.10	0.55	0.21
2038	1.37	1.10	0.51	0.26
2039	1.38	1.09	0.48	0.28
2040	1.38	1.09	0.49	0.25
2041	1.36	1.07	0.47	0.23
2042	1.37	1.07	0.46	0.22
2043	1.41	1.05	0.46	0.22
2044	1.40	1.06	0.46	0.22
2045	1.39	1.07	0.45	0.22
2046	1.40	1.08	0.46	0.21
2047	1.43	1.09	0.46	0.21
2048	1.46	1.09	0.46	0.23
2049	1.45	1.09	0.44	0.22
2050	1.47	1.09	0.44	0.22

Table B.7: Projected NO_x emissions from the electric power sector (unit: million short tons)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	1.07	1.03	1.02	0.99
2018	1.06	1.02	1.06	1.01
2019	1.13	1.02	1.05	0.96
2020	1.13	1.03	1.03	1.05
2021	1.10	0.98	0.96	0.81
2022	1.11	0.97	0.90	0.72
2023	1.11	0.98	0.86	0.69
2024	1.12	0.99	0.85	0.66
2025	1.12	1.00	0.82	0.63
2026	1.12	1.01	0.79	0.61
2027	1.13	1.03	0.76	0.57
2028	1.13	1.02	0.74	0.54
2029	1.13	1.02	0.71	0.49
2030	1.14	1.01	0.68	0.46
2031	1.13	1.00	0.64	0.42
2032	1.13	0.99	0.60	0.39
2033	1.12	0.99	0.55	0.37
2034	1.13	1.00	0.52	0.36
2035	1.13	1.01	0.49	0.35
2036	1.13	1.01	0.46	0.33
2037	1.13	1.01	0.44	0.32
2038	1.13	1.00	0.41	0.30
2039	1.13	0.99	0.40	0.29
2040	1.12	0.98	0.37	0.29
2041	1.12	0.97	0.37	0.29
2042	1.12	0.97	0.37	0.29
2043	1.13	0.97	0.37	0.29
2044	1.13	0.98	0.36	0.29
2045	1.13	0.98	0.36	0.29
2046	1.13	0.98	0.36	0.29
2047	1.14	0.98	0.36	0.29
2048	1.15	0.98	0.37	0.29
2049	1.14	0.98	0.36	0.29
2050	1.14	0.99	0.37	0.29

Table B.8: Projected mercury emissions from the electric power sector (unit: short tons)

	Reference	Abundant Gas	Carbon Pricing	Abundant Gas & Carbon Pricing
2017	5.08	4.97	5.07	4.99
2018	4.85	4.59	4.89	4.61
2019	5.15	4.65	4.91	4.43
2020	5.48	4.92	5.06	4.42
2021	5.41	4.72	4.84	4.13
2022	5.54	4.66	4.75	3.69
2023	5.54	4.67	4.53	3.41
2024	5.60	4.75	4.41	3.18
2025	5.60	4.78	4.30	3.02
2026	5.58	4.81	4.11	2.81
2027	5.61	4.84	3.85	2.58
2028	5.62	4.86	3.70	2.29
2029	5.61	4.85	3.52	2.10
2030	5.60	4.79	3.33	1.89
2031	5.57	4.71	3.13	1.68
2032	5.58	4.63	2.96	1.48
2033	5.54	4.51	2.74	1.34
2034	5.49	4.46	2.56	1.17
2035	5.45	4.48	2.38	1.08
2036	5.43	4.47	2.23	0.95
2037	5.41	4.40	2.06	0.83
2038	5.39	4.35	1.85	0.69
2039	5.36	4.31	1.74	0.62
2040	5.35	4.22	1.56	0.59
2041	5.28	4.15	1.54	0.58
2042	5.29	4.10	1.53	0.53
2043	5.32	4.09	1.49	0.52
2044	5.32	4.08	1.45	0.52
2045	5.36	4.17	1.43	0.51
2046	5.36	4.17	1.45	0.50
2047	5.39	4.20	1.45	0.48
2048	5.34	4.19	1.41	0.51
2049	5.33	4.17	1.39	0.52
2050	5.35	4.19	1.40	0.52

Table B.9: Changes in consumer and producer surplus due to abundant natural gas in 2030 and 2050 (unit: billion 2016$)

	Abundant Gas vs. Reference				Abundant Gas & Carbon Pricing vs. Carbon Pricing			
	2030		2050		2030		2050	
	CS	PS	CS	PS	CS	PS	CS	PS
New England	2.01	0.03	8.76	0.06	2.18	0.03	9.12	0.08
Middle Atlantic	1.21	-1.02	8.83	-3.05	1.18	0.51	11.22	-4.72
Upper Midwest	2.43	-1.27	6.91	-0.19	-0.41	-1.13	10.50	-0.20
West North Central	4.65	-0.69	5.31	-0.09	4.52	-0.93	4.38	-0.78
South Atlantic	1.07	-0.70	9.09	0.72	3.95	-0.42	17.50	0.05
East South Central	0.36	-0.16	2.56	0.05	1.02	-0.11	4.38	-0.07
West South Central	25.31	-3.81	37.02	-6.61	26.37	-2.39	41.29	-7.98
Mountain	3.05	-1.39	5.78	-1.58	2.85	-1.41	6.80	-3.44
West Coast	13.02	-0.01	22.64	-0.08	13.67	0.00	23.69	-0.15

Table B.10: Savings on monetized pollutant damages due to abundant natural gas in 2030 and 2050 (unit: billion 2016$)

	Abundant Gas vs. Reference		Abundant Gas & Carbon Pricing vs. Carbon Pricing	
	2030	2050	2030	2050
New England	0.00	0.00	0.00	0.00
Middle Atlantic	0.56	0.75	0.93	0.51
Upper Midwest	1.48	2.21	3.84	1.96
West North Central	0.14	0.22	0.20	0.47
South Atlantic	0.40	0.68	0.56	0.31
East South Central	0.20	0.40	-0.05	0.40
West South Central	0.37	0.45	-0.12	0.00
Mountain	0.03	0.03	0.12	0.03
West Coast	0.00	0.00	0.01	0.00

Table B.11: Changes in total welfare due to abundant natural gas in 2030 and 2050 (unit: billion 2016$)

	Abundant Gas vs. Reference		Abundant Gas & Carbon Pricing vs. Carbon Pricing	
	2030	2050	2030	2050
New England	2.26	8.72	2.67	8.86
Middle Atlantic	0.97	6.42	3.08	6.66
Upper Midwest	2.86	8.82	2.76	11.91
West North Central	4.31	5.33	4.26	3.73
South Atlantic	1.00	10.38	4.55	17.51
East South Central	0.61	2.91	1.32	4.36
West South Central	22.09	30.76	24.32	32.96
Mountain	1.90	4.12	2.01	3.04
West Coast	13.23	22.45	14.14	23.19

APPENDIX C

This appendix presents the methods that are applied to estimating consumer and producer surplus. Figure C.1 shows the change in consumer and producer surplus in the natural gas market due to abundant natural gas (panel A) and carbon tax (panel B). Although the figures in Figure C.1 display linear curves, we estimate linear demand curve and supply curve is obtained directly from Yale-NEMS. Note that abundant natural gas shifts the supply curve downwards, but carbon pricing shifts it upwards. Under both abundant natural gas and carbon pricing, the change in supply curve compared to the reference depends on the relative forces of abundant gas and carbon policy. The changes in consumer and producer surplus are calculated based on equations (9) and (10).

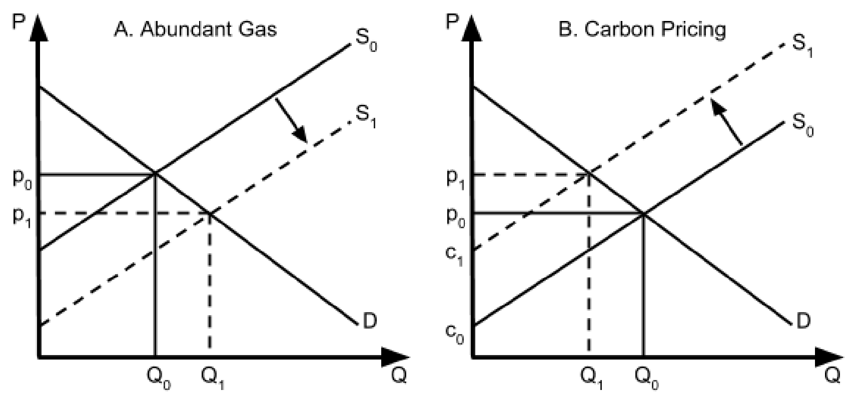

Figure C.1: Graphical representation of change in welfare for natural gas market under the abundant natural gas and carbon pricing scenarios relative to the reference case

Figure C.2 displays the graphical analysis of calculating changes in consumer and producer surplus in coal and liquid fuels markets. We use variations in data owing to market shocks (i.e. carbon pricing) to estimate linear demand and supply curves. In particular, we assume that carbon pricing shifts the supply curves for coal or liquid fuels, and thus the demand curve (D) can be estimated by the two pairs of price and quantity output data, (p_0, Q_0) and (p_1, Q_1) in Figure C.2.

For the supply curve estimation, we obtain additional data on cost change caused by carbon pricing, as indicated by $p_1 - c_1$. Thus, the slope of supply curve can be estimated by the data $Q_0 - Q_1$ and $p_0 - c_1$, as shown in Figure C.2.

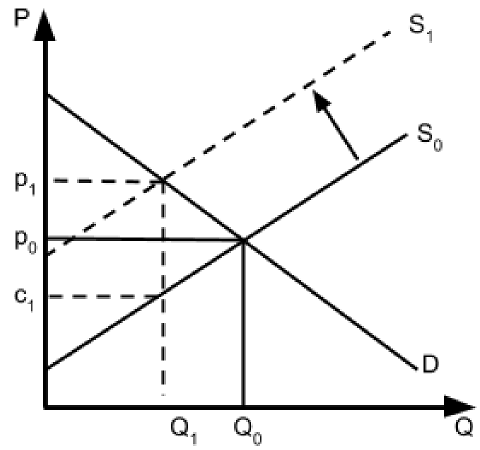

Figure C.2: Graphical representation of change in welfare for coal and liquid fuel markets under the carbon pricing scenario relative to the reference case

With the estimated slopes, we estimate the shifted demand and supply curves that pass through the new price-quantity combinations under the scenarios. Thus, the changes in consumer and producer surplus are estimated with the triangle method according to the pre- and post-shifted demand and supply curves.

APPENDIX D

This appendix provides additional regional results, in particular comparing the carbon pricing scenario to the reference case.

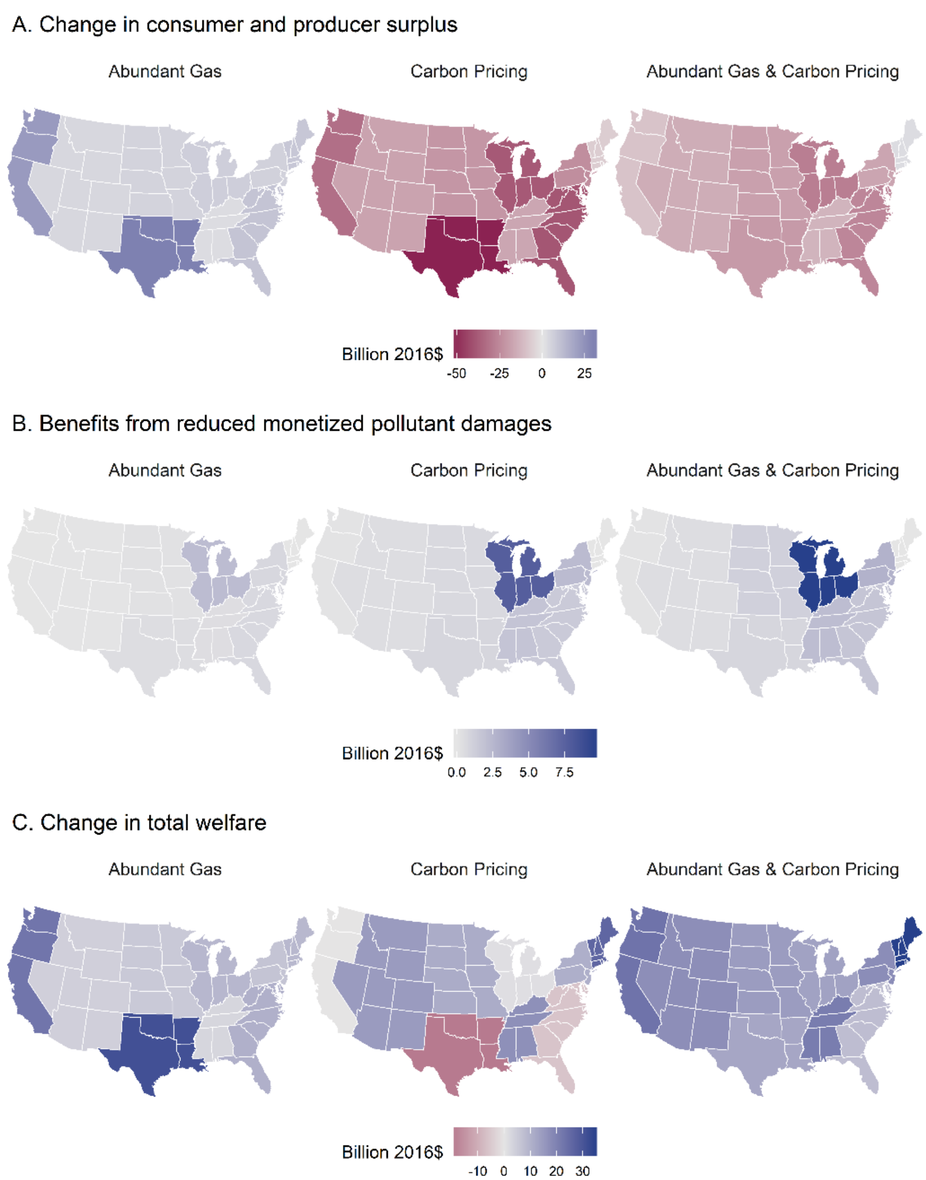

Figure D.1: Change in (A) consumer and producer surplus, (B) benefits from reduced monetized pollutant damage, and (C) total welfare across the abundant gas, carbon pricing, and abundant gas with carbon pricing scenarios compared to the reference in 2050

APPENDIX E

This appendix provides the primary results for sensitivity analysis. We selected five factors that potentially impact natural gas demand and supply, each of which has a high and a low case by varying the relevant parameters. The factors related to natural gas demand are fossil fuel efficiency, renewable learning rates, and international demand for U.S. LNG. Fossil fuel efficiency is a factor that is related to fuel substitution. The average natural gas boiler efficiency in the industrial sector is assumed to be 0.78 for AEO2017. We adjust the parameter for the high and low fuel efficiency cases, in which the high case has an efficiency parameter 0.83 and the low case has a parameter 0.73. Similarly, the learning rates for renewables specify the relative substitution ability of renewables for fossil fuels. Learning rates for the renewables (conventional wind, offshore wind, solar thermal, and solar photovoltaic) in Yale-NEMS is set for three steps, from which the first step of rates is set at the level 0.2 for the reference case. We made them to be 0.1 for the low case and 0.3 for the high case. In addition, natural gas demand from other countries also affect domestic demand. For this factor, we adjust 20% of future LNG export capacity up and down for the high and low cases respectively apart from AEO2017.

We also investigate factors that potentially affect the supply of natural gas. Technology improvement over time is believed to be important for natural gas production. The parameter governing technology advancement is a percentage adjustment that impacts natural gas production costs and productivity in Yale-NEMS. Again, we create a high and a low case by adjusting the parameter 50% higher and lower, respectively. Another factor is domestic capacity for transporting natural gas. In this case, we allow the average capital cost of expanding new capacity to be adjusted 20% higher and lower for the high and low cases.

The selected set of results (natural gas production, consumption, CO_2 emissions, and other pollutant emissions) for sensitivity analysis are shown in Figures E.1-4. Broadly, we see that the technology advancement is the most influential factor across the four figures, followed by the future LNG export capacity expansion (in dashed lines). The rest of factors seem no impact compared to the abundant gas scenario. For example, the high natural gas technology advancement case results in 12% more natural gas production, 20% more gas consumption, 0.3% less CO_2 emissions, and 21% less SO_2 emissions by 2050. We see that the impact of production technology advancement on natural gas production, consumption, and pollutant emissions increases towards 2050, due largely to increase in productivity and substitution for coal over the projected years. We also see in Figure E.3 that the impact of factors on CO_2 emissions declines after 2045 because of the interaction with renewables. For example, as more natural gas produced associated with high technology, less renewable energy capacity is invested.

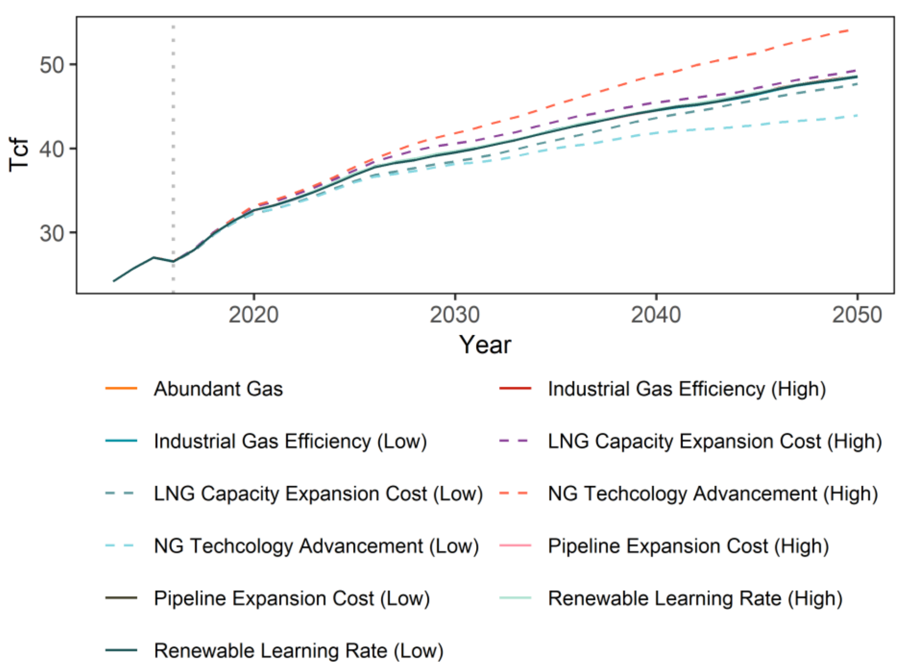

Figure E.1: Sensitivity results of natural gas production

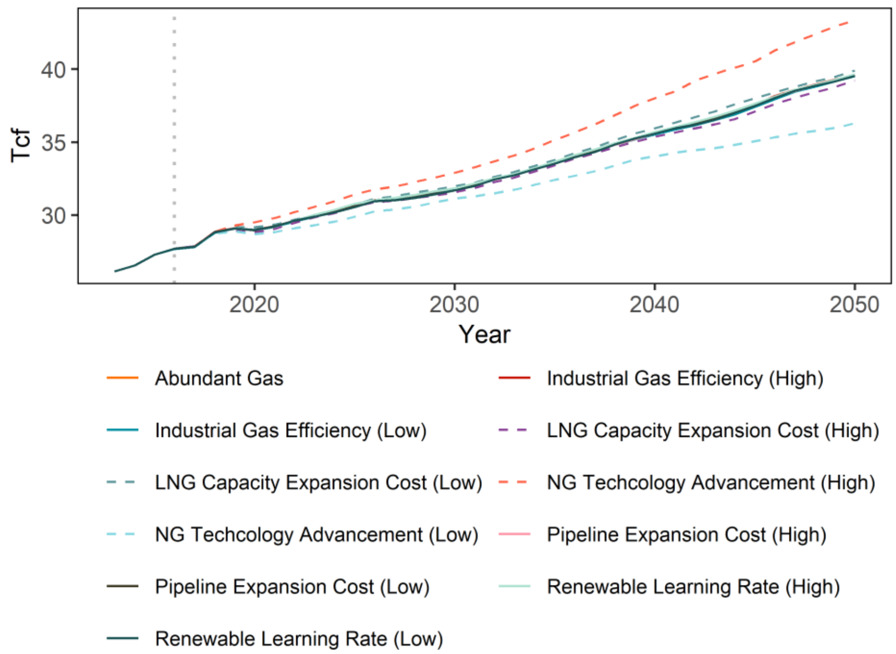

Figure E.2: Sensitivity results of natural gas consumption

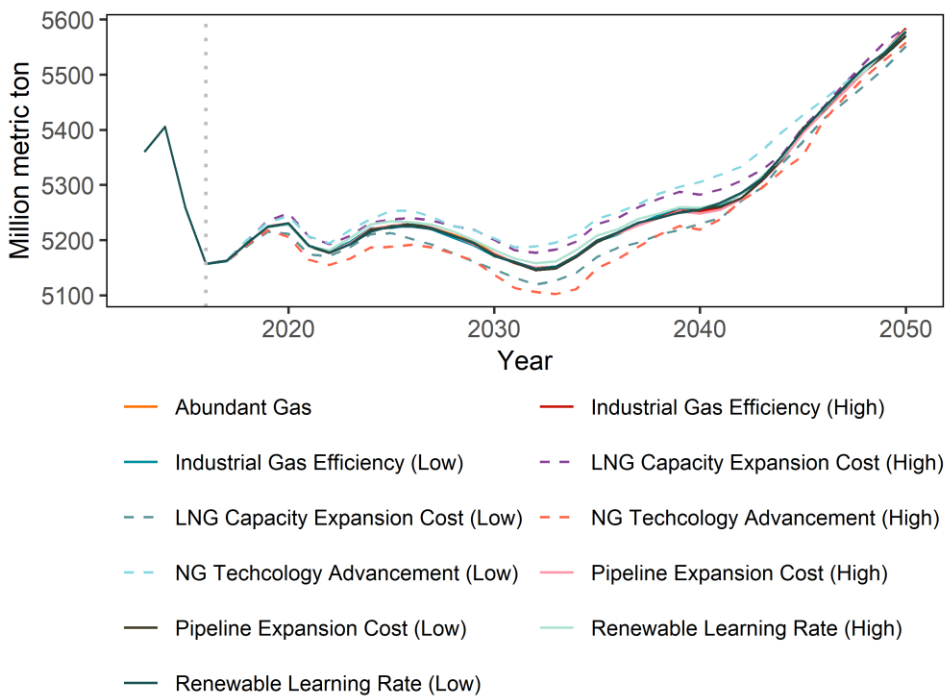

Figure E.3: Sensitivity results of energy-related CO_2 emissions

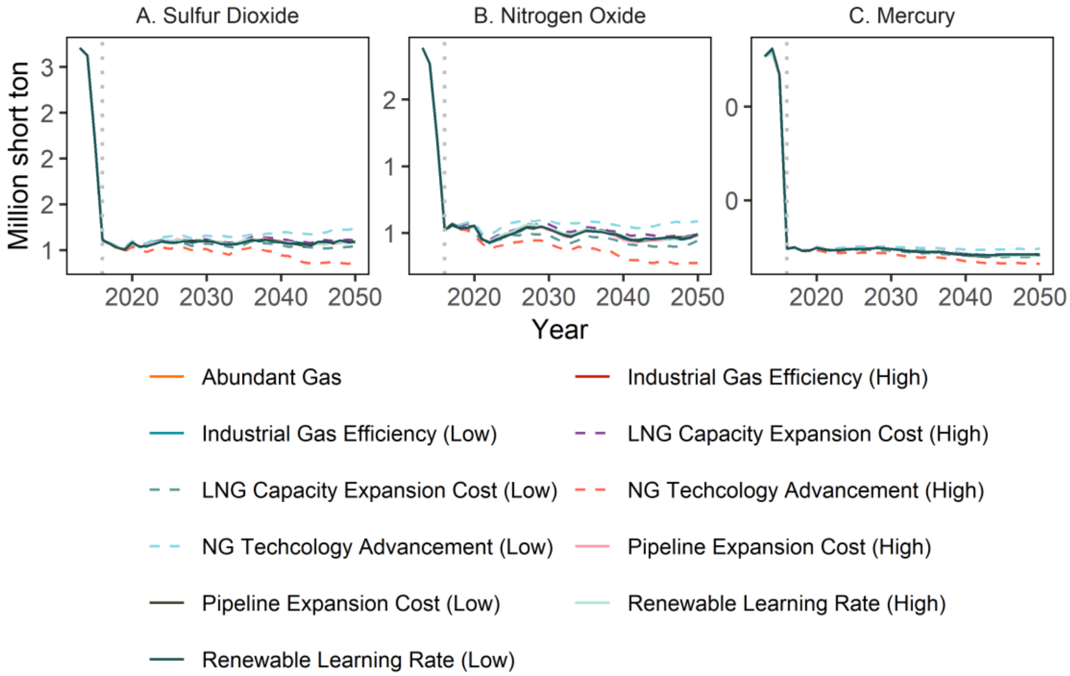

Figure E.4: Sensitivity results of air pollutant emissions