

SUPPORTING INFORMATION

Regional Air Quality Management Aspects of Climate Change: Impact of Climate Mitigation Options on Regional Air Emissions

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MARKAL DESCRIPTION

The MARKAL energy system model responds to prescribed demand for regionally-based energy services, specifically the energy required to meet the associated energy service demands of the residential, commercial, industrial, and transportation sectors. MARKAL selects from available technologies (characterized by their costs, efficiencies, lifetimes, and maximum utilization rates, along with any user imposed constraints on market penetration, availability, etc.) to determine the least-cost path that satisfies the specified demands and constraints. MARKAL can examine technology choices made over a span of 20 to 50 years that shape the evolution of an energy system in meeting specific environmental or other goals. The model allows the implications of specific policy options to be examined and compared. Owing to its solid basis in energy economics, MARKAL makes choices based upon the relative costs of technology options and overall system constraints. Thus, it serves to identify the key technologies that will be needed to realize air quality, climate, and energy objectives cost-effectively.

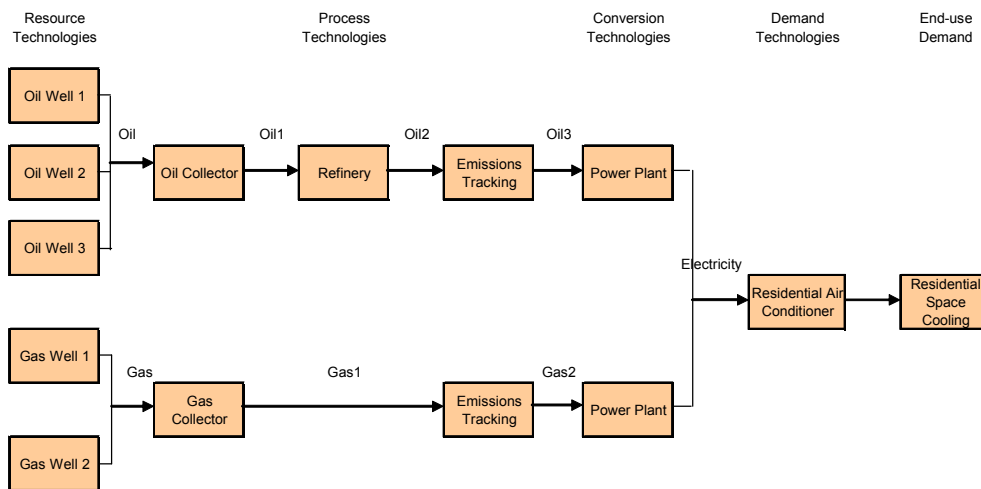


Figure S1. Example of a Simple Reference Energy System

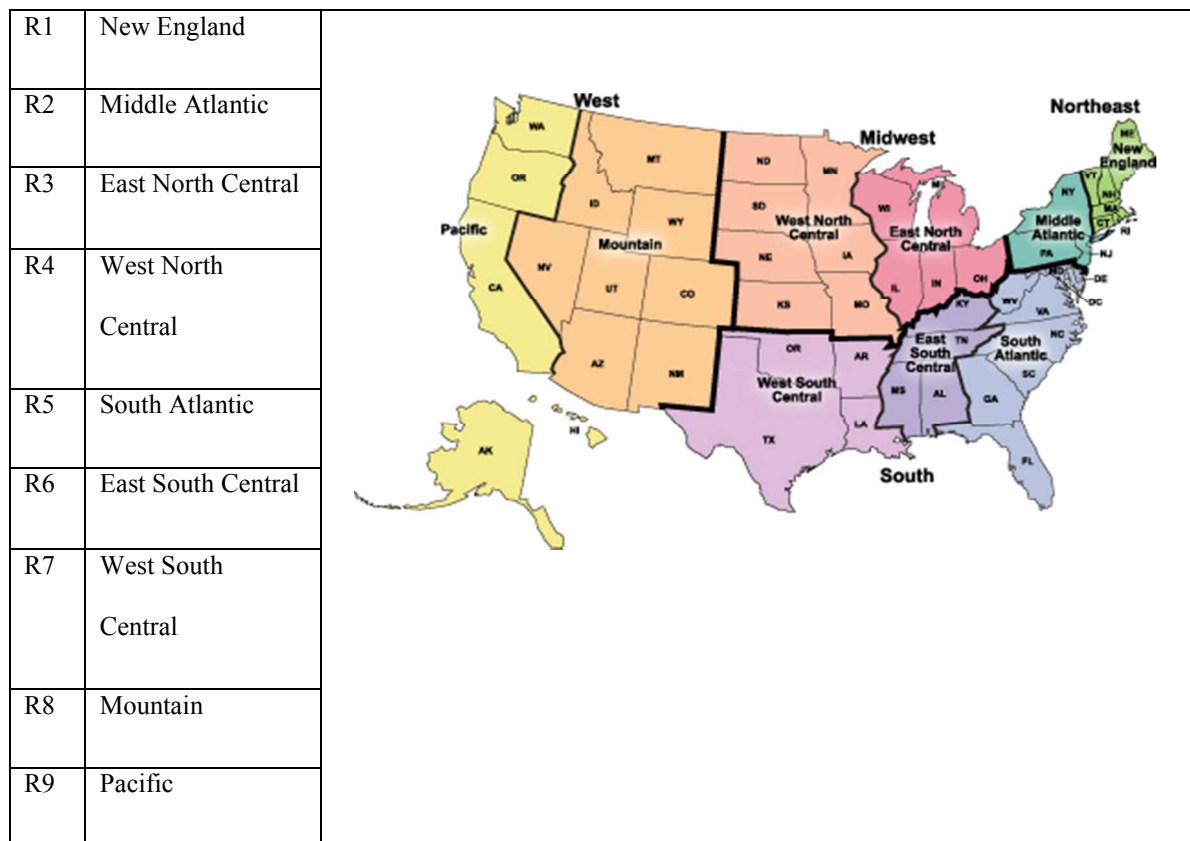


Figure S2. Map of EPAUS9R Regions

FIGURES AND TABLES

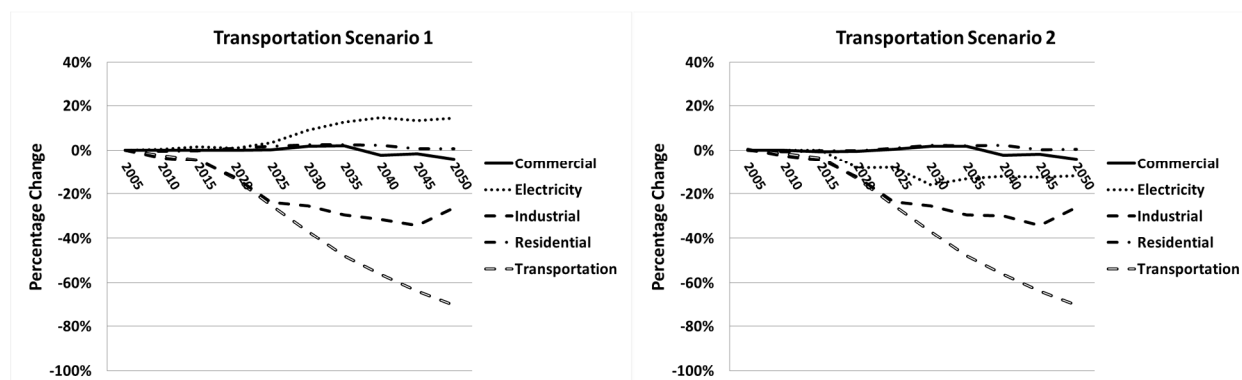


Figure S3. Percentage Change in U.S. CO₂ Emissions under Transportation Scenarios
Base Year 2005 Emissions (Million Tons), Commercial: 217, Electricity: 2,367, Industrial: 322, Residential: 416, Transportation: 2,171.

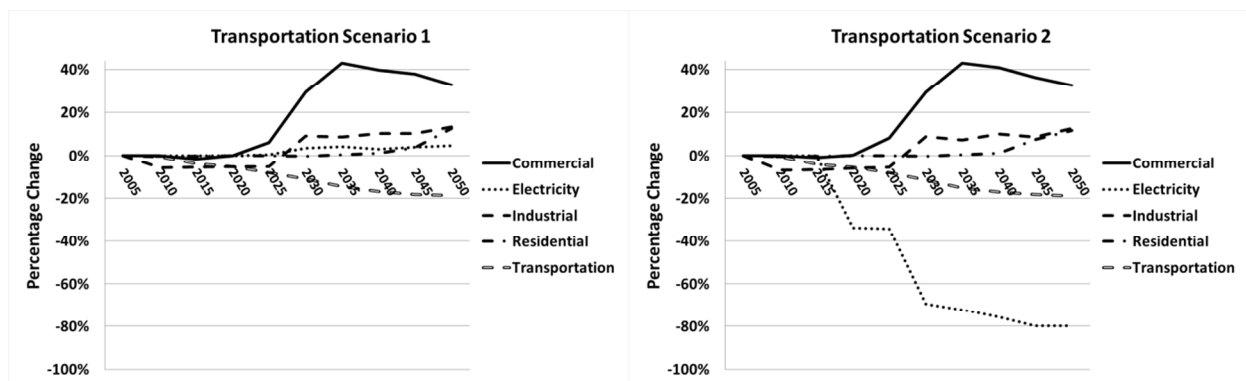


Figure S4. Percentage Change in U.S. SO₂ Emissions under Transportation Scenarios

Base Year 2005 Emissions (Million Tons), Commercial: 187, Electricity: 9,296, Industrial: 1,248, Residential: 143, Transportation: 1,362.

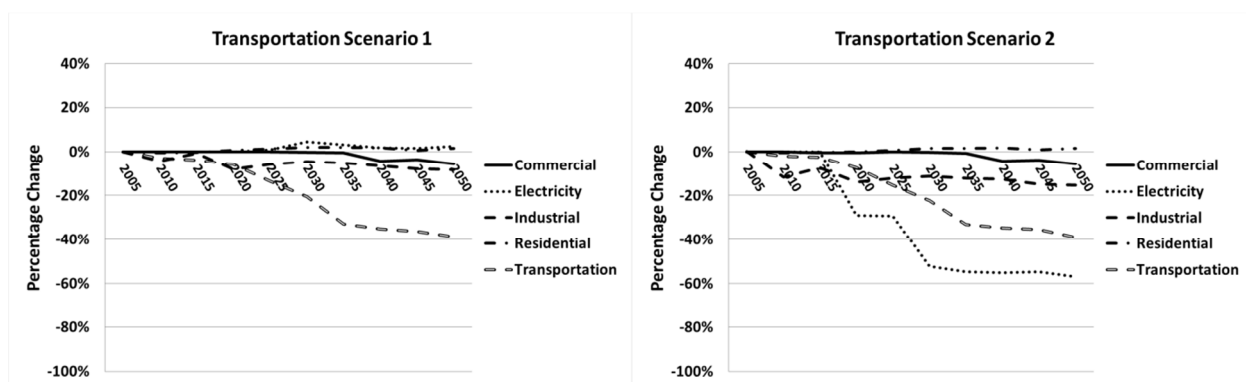


Figure S5. Percentage Change in U.S. NO_x Emissions under Transportation Scenarios

Base Year 2005 Emissions (Million Tons), Commercial: 170, Electricity: 3,317, Industrial: 1,179, Residential: 170, Transportation: 11,106.

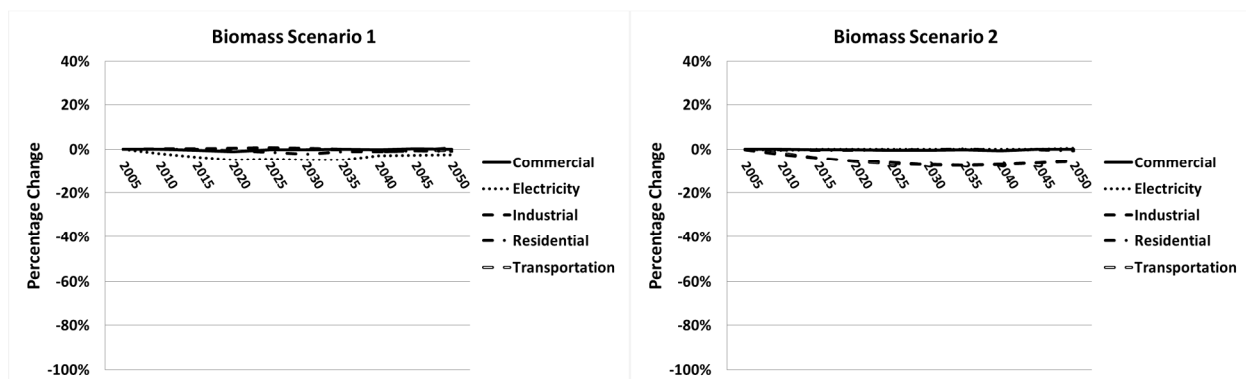


Figure S6. Percentage Change in U.S. CO₂ Emissions under Biomass Scenarios

Base Year 2005 Emissions (Million Tons), Commercial: 217, Electricity: 2,367, Industrial: 322, Residential: 416, Transportation: 2,171.

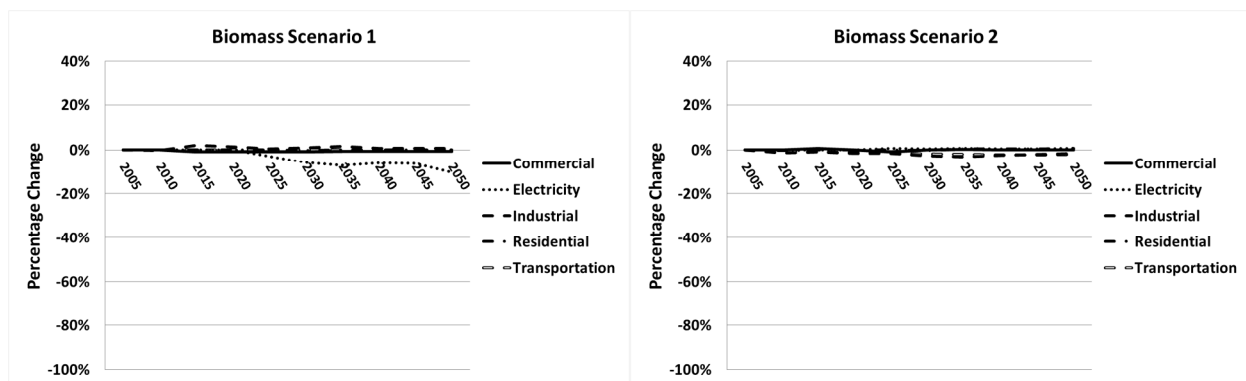


Figure S7. Percentage Change in U.S. SO₂ Emissions under Biomass Scenarios

Base Year 2005 Emissions (Million Tons), Commercial: 187, Electricity: 9,296, Industrial: 1,248, Residential: 143, Transportation: 1,362.

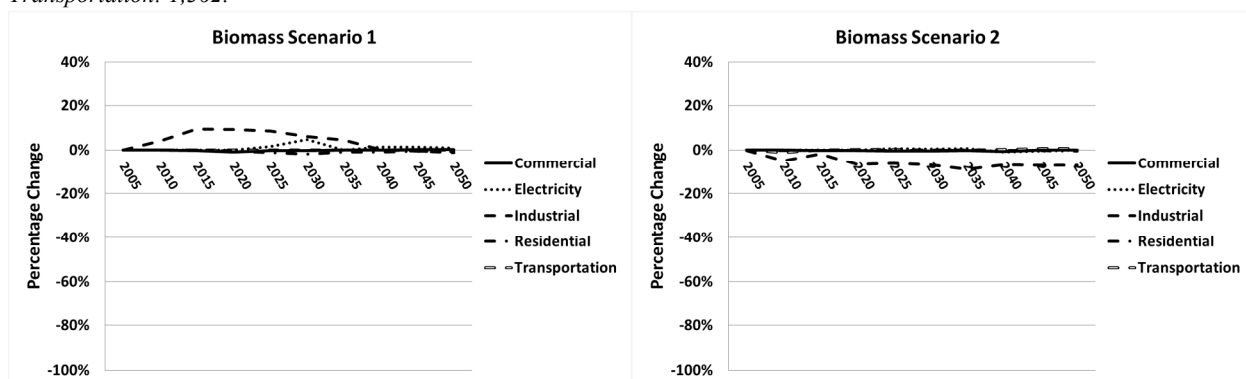


Figure S8. Percentage Change in U.S. NO_x Emissions under Biomass Scenarios

Base Year 2005 Emissions (Million Tons), Commercial: 170, Electricity: 3,317, Industrial: 1,179, Residential: 170, Transportation: 11,106.

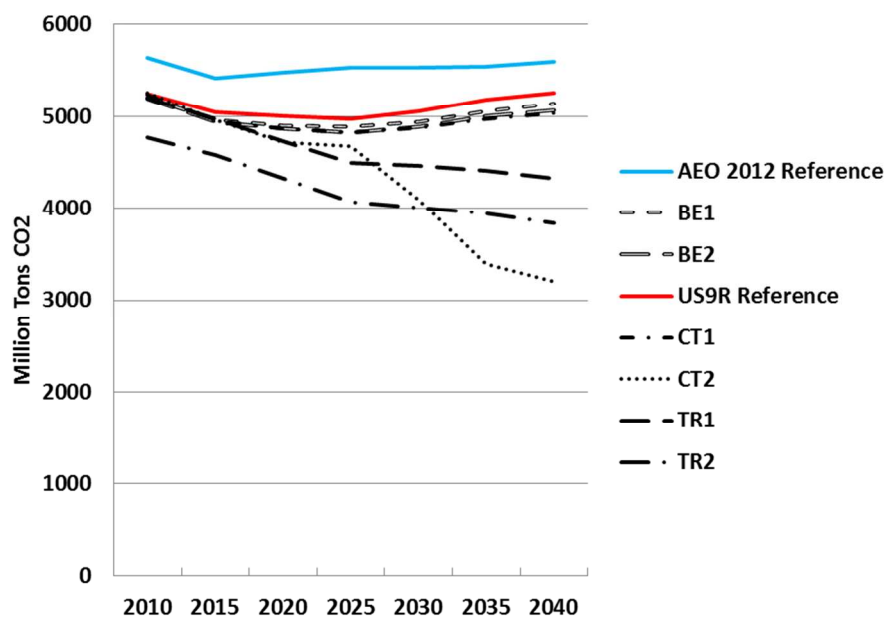


Figure S9. EPAUS9r CO₂ Emissions Results Compared to AEO 2012 Reference Case

Region	2005, Million Tons	2050, Million Tons (Reference)	2050, Million Tons (CT1)	2050, Million Tons (CT2)	2050, Million Tons (TR1)	2050, Million Tons (TR2)	2050, Million Tons (BE1)	2050, MillionTons (BE2)
R1	62	34	39	8	35	31	33	43
R2	206	169	156	25	186	148	165	158
R3	521	468	428	44	479	362	462	470
R4	276	265	231	31	283	212	256	262
R5	528	442	409	78	546	456	421	449
R6	189	165	153	15	194	153	161	165
R7	342	425	401	50	526	438	412	430
R8	181	178	145	16	254	212	185	181
R9	63	162	166	17	139	130	158	164
Total	2,367	2,308	2,127	285	2,642	2,141	2,253	2,323

Table S1. CO₂ Emissions by Region

Region	2005, Million Tons	2050, Million Tons (Reference)	2050, Million Tons (CT1)	2050, Million Tons (CT2)	2050, Million Tons (TR1)	2050, Million Tons (TR2)	2050, Million Tons (BE1)	2050, MillionTons (BE2)
R1	131	6	12	3	6	-5	1	12
R2	1,104	52	39	63	73	-122	48	49
R3	2,544	512	571	188	585	23	614	562
R4	778	311	235	98	302	180	56	314
R5	2,484	160	202	171	229	-336	204	162
R6	1,180	214	123	61	145	123	83	198
R7	734	339	141	74	299	314	363	296
R8	304	124	87	18	149	147	163	135
R9	36	27	40	2	40	26	35	29
Total	9,296	1,746	1,452	679	1,828	351	1,567	1,757

Table S2. SO₂ Emissions by Region

Region	2005, Million Tons	2050, Million Tons (Reference)	2050, Million Tons (CT1)	2050, Million Tons (CT2)	2050, Million Tons (TR1)	2050, Million Tons (TR2)	2050, Million Tons (BE1)	2050, MillionTons (BE2)
R1	34	22	29	75	23	6	17	33
R2	228	137	137	137	137	75	137	137
R3	698	396	396	396	396	188	396	396
R4	462	381	381	381	381	63	380	381
R5	700	268	268	268	268	222	268	268
R6	402	145	145	145	145	67	145	145
R7	328	234	234	246	243	117	234	235
R8	416	269	215	470	295	57	297	266
R9	48	44	56	99	54	23	49	47
Total	3,317	1,897	1,862	2,217	1,943	817	1,923	1,906

Table S3. NO_x Emissions by Region

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	25	304	127	325	-55	181
R2	9	-46	590	1,781	-191	-827
R3	-3,180	-9,993	2,187	3,131	-715	302
R4	-2,855	-3,585	2,327	3,880	1,285	214
R5	-1,440	-3,589	3,668	3,415	-1,558	172
R6	-363	-1,691	1,799	2,368	911	87
R7	-261	1,329	6,138	7,005	-713	272
R8	-2,476	-2,339	3,874	7,802	771	257
R9	-112	363	264	142	-64	-45
Total	-10,653	-19,249	20,974	29,848	-329	612

Table S4. Cumulative Change in Coal Generation Relative to Reference Case

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	500	3,512	811	606	-159	2,930
R2	-458	-643	97	598	-419	-1,646
R3	-736	-2,089	-271	99	-192	-168
R4	-1,538	-3,805	-885	-489	-704	-1,602
R5	-1,992	-5,963	6,169	4,611	-2,354	215
R6	-298	-1,680	1,804	1,621	829	74
R7	-345	837	8,617	9,585	-898	388
R8	-2,151	-7,631	3,499	3,364	185	-129
R9	2,324	2,615	3,248	3,845	-988	-296
Total	-4,694	-14,849	23,090	23,839	-4,699	-235

Table S5. Cumulative Change in Natural Gas Generation Relative to Reference Case

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	-56	-179	45	51	-151	179
R2	-149	-189	176	231	185	-7
R3	1	1	22	78	-1	0
R4	-244	-244	-244	-244	-8	-8
R5	-7	-7	447	942	-7	-2
R6	0	0	0	0	0	0
R7	-141	-552	-9	69	-49	-13
R8	-451	-451	-295	-451	50	-86
R9	153	-3	325	193	0	0
Total	-894	-1,624	465	870	20	64

Table S6. Cumulative Change in Municipal Solid Waste Generation Relative to Reference Case

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	0	0	0	0	0	-2,678
R2	0	0	0	0	0	-68
R3	-448	-2,050	267	323	-119	-360
R4	0	0	0	0	0	0
R5	0	0	0	0	0	0
R6	0	0	0	0	0	0
R7	-45	16	492	494	-122	-44
R8	0	0	0	0	0	0
R9	0	0	0	0	0	0
Total	-493	-2,035	758	817	-242	-3,150

Table S7. Cumulative Change in Nuclear Generation Relative to Reference Case

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	-19	-7	196	-89	6	-13
R2	-6	10	202	142	-24	-16
R3	-8	-22	5	-8	-2	1
R4	-12	-10	0	0	1	0
R5	-5	-12	24	-855	8	-2
R6	0	0	0	0	0	0
R7	0	1	4	-6	0	0
R8	-2	-4	5	9	1	1
R9	1	8	20	87	-3	1
Total	-51	-37	455	-720	-15	-27

Table S8. Cumulative Change in Oil Generation Relative to Reference Case

Region	Cumulative Change, Petajoules (CT1)	Cumulative Change, Petajoules (CT2)	Cumulative Change, Petajoules (TR1)	Cumulative Change, Petajoules (TR2)	Cumulative Change, Petajoules (BE1)	Cumulative Change, Petajoules (BE2)
R1	354	2,325	67	-24	57	1,210
R2	270	784	172	426	-309	-408
R3	-663	-824	409	836	59	196
R4	108	1,369	1,424	1,060	-3	19
R5	-156	1,448	254	306	-100	0
R6	17	-414	542	538	54	41
R7	40	2,117	1,682	1,892	-122	91
R8	244	7,061	1,774	2,354	-13	122
R9	695	14,854	3,635	3,779	-548	115
Total	909	28,720	9,958	11,167	-926	1,387

Table S9. Cumulative Change in Renewable Generation Relative to Reference Case

	Energy Density: Petajoules / Million Tons
Corn Grain	0.33
Corn Stover	13.50
Alfalfa Stalks	13.50
Rice Husks	13.50
Wheat Straw	13.50
Switchgrass	13.08
Poplar	15.00
Spruce Wood	15.00
Sawdust	15.00
Urban Wood Waste	15.00

Table S10. Energy Density of Biomass Feedstocks Represented in the EPAUS9r Database

Sector	2005, Million Tons	2050, Million Tons (Reference)	2050, Million Tons (CT1)	2050, Million Tons (CT2)	2050, Million Tons (TR1)	2050, Million Tons (TR2)	2050, Million Tons (BE1)	2050, Million Tons (BE2)
Commercial	217	284	268	219	272	272	287	287
Residential	416	382	384	305	384	384	380	380
Industrial	322	327	312	271	241	242	319	300
Electricity	2,367	2,308	2,127	285	2,642	2,034	2,253	2,323
Transportation	2,171	2,198	2,148	1,853	659	659	2,165	2,047
Total	5,494	5,499	5,239	2,933	4,199	3,590	5,404	5,337

Table S11. Emissions of CO₂ (million tons) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	187	140	138	124	186	186	139	140
Residential	143	55	55	50	62	61	55	55
Industrial	1,248	1,264	1,197	1,019	1,432	1,424	1,250	1,223
Electricity	9,296	1,746	1,452	679	1,828	351	1,567	1,757
Transportation	1,362	106	105	99	86	86	106	104
Total	12,235	3,311	2,946	1,970	3,594	2,109	3,117	3,279

Table S12. Emissions of SO₂ (thousand tons) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	170	219	207	172	206	206	221	221
Residential	366	335	337	290	340	340	333	334
Industrial	1,179	2,319	2,355	2,420	2,124	1,966	2,299	2,158
Electricity	3,317	1,897	1,862	2,217	1,943	817	1,923	1,906
Transportation	11,106	3,389	3,389	2,933	2,080	2,071	3,358	3,376
Total	16,137	8,158	8,150	8,032	6,693	5,400	8,135	7,994

Table S13. Emissions of NO_x (thousand tons) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	16	20	19	15	20	20	20	20
Residential	363	329	334	378	351	351	329	329
Industrial	51	83	93	107	114	112	103	75
Electricity	3,729	3,455	3,120	4,032	3,890	3,847	3,377	3,467
Transportation	656	307	307	293	249	249	305	306
Total	4,814	4,194	3,873	4,825	4,624	4,579	4,134	4,197

Table S14. Particulate Matter Less Than 10 Micrometers in Diameter (PM₁₀) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	14	17	16	13	17	17	17	17
Residential	312	283	288	325	302	302	283	283
Industrial	110	138	145	150	135	133	150	125
Electricity	1,027	991	900	1,164	1,121	1,056	970	995
Transportation	558	211	211	199	173	172	211	211
Total	2,021	1,640	1,560	1,850	1,747	1,681	1,630	1,631

Table S15. Fine Particulate Matter Less Than 2.5 Micrometers in Diameter (PM_{2.5}) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	8	11	10	8	10	10	11	11
Residential	595	547	556	626	582	583	547	547
Industrial	28	93	98	131	92	84	78	82
Electricity	192	197	184	229	220	211	195	198
Transportation	5,937	3,080	3,080	3,010	2,727	2,725	3,077	3,078
Total	6,761	3,927	3,928	4,004	3,631	3,612	3,907	3,915

Table S16. Volatile Organic Compounds (VOC) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	116	161	152	124	142	142	164	163
Residential	2,725	2,504	2,545	2,851	2,664	2,666	2,504	2,504
Industrial	400	834	802	878	790	732	749	763
Electricity	2,232	2,183	2,047	2,532	2,486	1,509	2,169	2,194
Transportation	54,495	35,034	35,032	33,736	28,918	28,859	35,014	35,013
Total	59,967	40,686	40,578	40,121	35,001	33,907	40,599	40,637

Table S17. Carbon Monoxide (CO) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	3	5	4	4	4	4	5	5
Residential	131	121	122	128	126	127	120	120
Industrial	58	482	468	409	371	317	425	469
Electricity	2,514	2,335	2,102	2,688	2,622	2,642	2,281	2,342
Transportation	70	53	53	48	29	28	53	53
Total	2,775	2,995	2,749	3,276	3,151	3,118	2,884	2,990

Table S18. Methane (CH₄) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	3	4	4	4	4	4	4	4
Residential	3	3	3	3	3	3	3	3
Industrial	12	22	23	23	21	20	27	22
Electricity	22	25	32	54	28	28	30	26
Transportation	85	38	38	34	22	22	38	38
Total	125	92	100	117	78	77	102	93

Table S19. Nitrous oxide (N₂O) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	2	2	2	1	2	2	2	2
Residential	25	22	22	25	23	23	22	22
Industrial	4	9	12	18	14	13	13	7
Electricity	12	12	11	14	13	13	11	12
Transportation	306	78	78	74	73	72	78	78
Total	348	122	125	132	125	124	126	120

Table S20. Black Carbon (BC) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Sector	2005, Thousand Tons	2050, Thousand Tons (Reference)	2050, Thousand Tons (CT1)	2050, Thousand Tons (CT2)	2050, Thousand Tons (TR1)	2050, Thousand Tons (TR2)	2050, Thousand Tons (BE1)	2050, Thousand Tons (BE2)
Commercial	3	5	5	4	4	4	5	5
Residential	122	113	115	128	120	120	113	113
Industrial	12	21	22	22	20	19	22	21
Electricity	48	44	41	53	49	50	44	44
Transportation	155	61	61	58	54	54	61	61
Total	339	244	244	265	248	248	244	244

Table S21. Organic Carbon (OC) by Sector and Total for 2005 and 2050 under Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

Scenario	Percentage Change in Total System Cost Relative to Reference
CT1	0.1%
CT2	2.4%
TR1	7.1%
TR2	n/a
BE1	0.4%
BE2	2.5%

Table S22. Total System Cost Relative to Reference Case for Carbon Tax (CT), Transportation (TR), and Biomass Energy (BE) Scenarios.

In the EPAUS9r MARKAL framework, the decision making objective is to minimize the total discounted cost of the energy system over the modeling horizon. Total system cost is an internal accounting and decision making criteria used within the MARKAL modeling framework to choose between the alternative portfolios of energy sources and technologies represented in the EPAUS9r database. The total system cost in the EPAUS9r framework includes annualized

investments in technologies; fixed and variable operations and maintenance of technologies; cost of energy imports and domestic energy production; revenue from energy exports; fuel delivery costs; taxes and subsidies associated with energy sources, technologies and emissions.