GCAM-USA v5.3_water_dispatch: Integrated modeling of subnational U.S. energy, water, and land systems within a global framework

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Supplementary Materials

Supplementary Note 1: Electricity trade in GCAM-USA

In GCAM-USA, states are grouped into 15 grid-regions representing electricity market and planning areas which roughly correspond to the North American Electric Reliability Corporation (NERC) Assessment Areas. Within these grid-regions, investment in new generation capacity in GCAM-USA is driven by economic competition (based on the cost of new power plants in each state) but influenced by the historical pattern of power-sector infrastructure investments. Electricity supplies and demands are resolved at the grid-region level; states within a given grid region are assumed to trade electricity freely (without constraint) and pay a common electricity price. By default, the load profile is fixed over time, and generation in each sub-annual load segment is met from generators across all states within that grid on the basis of least cost competition.

At a national level, electricity trade between grid regions occurs but is assumed to be limited by the availability of long-distance transmission infrastructure. In the GCAM-USA Reference scenario, development of new long-distance transmission infrastructure is assumed to be limited by numerous institutional constraints; inter-grid electricity trade is not expected to deviate significantly from historical levels. Inter-grid electricity trade is represented only at the annual temporal scale – the sub-annual load profile of imports or exports is not represented. Net interregional trade is calibrated to historical levels to reflect existing economic conditions as well as implied physical transmission capability. Although inter-grid electricity trade can change from calibrated levels in future modeling periods as relative regional electricity prices change, the nonlinear formulation means that the relative ease or elasticity of expanding these imports in a region tightens as the share of imports increases from the calibrated historical shares. In other words, an increasing differential in regional prices is required to expand trade, reflecting an increasing marginal cost of building and maintaining expanded transmission infrastructure.

Supplementary Note 2: Variable energy integration – capacity factors

An important factor affecting the construction and operation of variable (non-dispatchable) generating units is that their resource bases within a given state are heterogeneous (wind and solar potentials are represented at the state level in GCAM-USA). Some areas have higher quality resources which translate to higher capacity factors, while other less sunny or windy areas are still potentially suitable for development but will sustain operation for fewer hours of the year.

Variable resource potentials, specifically onshore wind, offshore wind, photovoltaic (PV) solar, and concentered solar power (CSP), are represented by resource supply curves in GCAM-USA. These resource curves are comprised of various grades, each containing a quantity of resource available and the capacity factor at which that resource is capable of operating. As deployment of these variable energy technologies increases, utilization moves up the resource supply curve to grades with lower capacity factors (sites with the highest capacity factors are assumed to be utilized first). The capacity factor derived from the resource curve is then used to inform both investment and operation decisions in the GCAM-USA power sector.

On the investment side, the capacity factor passed from the resource curve is used to levelize all fixed costs (capital costs, fixed O&M) for the current period's technology vintage. Thus, as deployment of a given variable energy technology increases, the levelized cost of electricity from that technology becomes marginally more expensive (assuming constant cost and efficiency characteristics) because the new capacity is expected to have a lower capacity factor, and thus produce less electricity per unit of capacity, than generation units invested at lower levels of deployment. This dynamic is also reflected on the operation (dispatch) side of the power sector, where the generation potential of VRE capacity is depreciated to reflect this diminishing capacity factor. Thus, technology vintages invested in later periods will tend to have lower generation per unit of capacity because these newer generating units are installed in locations with lower quality wind or solar resources.

Table SM1: GCAM-USA Reference scenario Socioeconomic Assumptions

GCAM-USA Reference scenario Population (thousand persons)

Region	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
AK	0.74	0.73	0.73	0.75	0.76	0.78	0.8	0.81	0.83	0.84	0.85	0.85	0.86	0.87	0.88	0.88	0.88	0.88
AL	4.85	4.92	5.02	5.15	5.28	5.4	5.5	5.6	5.7	5.79	5.88	5.96	6.01	6.07	6.08	6.1	6.09	6.08
AR	2.98	3.04	3.1	3.18	3.25	3.32	3.37	3.43	3.48	3.53	3.57	3.62	3.64	3.67	3.67	3.68	3.67	3.66
AZ	6.83	7.41	7.91	8.29	8.56	8.84	9.09	9.33	9.57	9.8	10.02	10.23	10.39	10.54	10.64	10.73	10.77	10.81
CA	38.95	39.91	41.06	42.58	44.11	45.64	47	48.36	49.68	51	52.2	53.41	54.31	55.21	55.78	56.36	56.64	56.93
CO	5.45	5.85	6.19	6.46	6.66	6.87	7.05	7.23	7.41	7.58	7.74	7.9	8.02	8.13	8.2	8.27	8.3	8.33
CT	3.59	3.58	3.63	3.75	3.87	4	4.11	4.22	4.32	4.43	4.53	4.62	4.7	4.77	4.81	4.85	4.87	4.89
DC	0.68	0.71	0.74	0.78	0.81	0.84	0.86	0.89	0.92	0.94	0.97	0.99	1.01	1.03	1.04	1.05	1.06	1.07
DE	0.94	0.99	1.03	1.07	1.11	1.14	1.17	1.2	1.23	1.26	1.29	1.31	1.33	1.35	1.36	1.37	1.38	1.38
FL	20.22	21.91	23.27	24.31	25.12	25.93	26.63	27.34	28.04	28.73	29.35	29.98	30.44	30.9	31.19	31.47	31.6	31.73
GA	10.18	10.72	11.2	11.61	11.94	12.27	12.55	12.83	13.1	13.37	13.61	13.85	14.02	14.18	14.26	14.34	14.36	14.38
HI	1.42	1.42	1.42	1.46	1.5	1.55	1.58	1.62	1.66	1.69	1.73	1.76	1.78	1.8	1.82	1.83	1.84	1.84
IA	3.12	3.18	3.26	3.35	3.43	3.51	3.58	3.64	3.7	3.77	3.82	3.88	3.91	3.95	3.96	3.97	3.97	3.96
ID	1.65	1.82	1.96	2.04	2.1	2.15	2.19	2.24	2.28	2.33	2.37	2.4	2.43	2.45	2.47	2.48	2.48	2.48
IL	12.86	12.69	12.75	13.12	13.55	13.98	14.37	14.74	15.12	15.49	15.82	16.15	16.4	16.64	16.79	16.94	17.01	17.07
IN	6.61	6.76	6.95	7.18	7.39	7.59	7.77	7.94	8.12	8.29	8.44	8.59	8.7	8.8	8.85	8.91	8.92	8.93
KS	2.91	2.92	2.96	3.04	3.13	3.21	3.28	3.35	3.42	3.49	3.55	3.61	3.65	3.69	3.71	3.73	3.74	3.74
KY	4.43	4.5	4.59	4.72	4.83	4.94	5.03	5.11	5.2	5.29	5.36	5.43	5.48	5.52	5.54	5.55	5.54	5.53
LA	4.66	4.65	4.68	4.8	4.93	5.06	5.17	5.28	5.38	5.49	5.58	5.68	5.74	5.81	5.84	5.87	5.88	5.88
MA	6.8	6.98	7.22	7.49	7.75	8.02	8.25	8.48	8.71	8.94	9.15	9.35	9.51	9.66	9.76	9.85	9.9	9.95
MD	5.99	6.09	6.24	6.46	6.68	6.9	7.1	7.29	7.48	7.67	7.84	8.02	8.14	8.27	8.35	8.42	8.46	8.5
ME	1.33	1.34	1.37	1.4	1.43	1.45	1.47	1.49	1.51	1.53	1.54	1.56	1.57	1.58	1.58	1.57	1.57	1.56
MI	9.93	10.05	10.25	10.56	10.88	11.19	11.45	11.72	11.97	12.23	12.46	12.69	12.86	13.02	13.1	13.19	13.21	13.23
MN	5.48	5.7	5.9	6.1	6.27	6.44	6.58	6.72	6.86	6.99	7.11	7.24	7.32	7.4	7.44	7.49	7.49	7.5
MO	6.07	6.17	6.3	6.49	6.68	6.86	7.02	7.17	7.32	7.47	7.61	7.74	7.83	7.92	7.97	8.01	8.02	8.03
MS	2.99	2.99	3.01	3.07	3.14	3.2	3.25	3.29	3.34	3.39	3.43	3.47	3.49	3.51	3.51	3.51	3.5	3.49
MT	1.03	1.08	1.12	1.15	1.17	1.2	1.21	1.23	1.25	1.26	1.28	1.29	1.3	1.3	1.3	1.31	1.3	1.3
NC	10.03	10.6	11.09	11.48	11.78	12.08	12.32	12.57	12.81	13.05	13.26	13.47	13.61	13.74	13.8	13.86	13.86	13.85
ND	0.75	0.77	0.79	0.82	0.83	0.85	0.87	0.88	0.89	0.91	0.92	0.93	0.94	0.94	0.95	0.95	0.95	0.94
NE	1.89	1.95	2.01	2.08	2.14	2.19	2.24	2.29	2.34	2.38	2.42	2.46	2.49	2.52	2.53	2.55	2.55	2.55
NH	1.34	1.37	1.4	1.44	1.48	1.51	1.54	1.56	1.59	1.62	1.64	1.66	1.68	1.69	1.69	1.7	1.7	1.69
NJ	8.87	8.96	9.17	9.48	9.81	10.14	10.44	10.73	11.01	11.3	11.55	11.81	12.01	12.2	12.32	12.44	12.5	12.56
NM	2.09	2.1	2.14	2.2	2.26	2.32	2.37	2.42	2.46	2.51	2.56	2.6	2.63	2.66	2.67	2.69	2.69	2.69
NV	2.87	3.15	3.4	3.57	3.69	3.81	3.92	4.02	4.13	4.23	4.32	4.42	4.48	4.55	4.6	4.64	4.66	4.67
NY	19.66	19.49	19.66	20.23	20.91	21.58	22.17	22.76	23.33	23.91	24.42	24.94	25.32	25.71	25.94	26.17	26.27	26.38
OH	11.62	11.75	12	12.38	12.77	13.15	13.48	13.81	14.13	14.46	14.74	15.03	15.24	15.44	15.56	15.68	15.71	15.76
OK	3.91	3.97	4.05	4.16	4.27	4.38	4.47	4.56	4.64	4.73	4.81	4.88	4.93	4.98	5.01	5.03	5.03	5.03
OR	4.02	4.28	4.48	4.65	4.79	4.93	5.05	5.17	5.29	5.4	5.51	5.62	5.69	5.76	5.8	5.85	5.86	5.87
PA	12.79	12.86	13.1	13.49	13.9	14.3	14.65	14.99	15.33	15.67	15.97	16.27	16.48	16.69	16.8	16.92	16.95	16.99
RI	1.06	1.06	1.08	1.12	1.16	1.2	1.23	1.26	1.3	1.33	1.36	1.39	1.41	1.43	1.45	1.46	1.47	1.48
SC	4.89	5.2	5.47	5.67	5.82	5.97	6.1	6.22	6.34	6.46	6.57	6.68	6.75	6.82	6.85	6.88	6.88	6.89
SD	0.85	0.9	0.94	0.96	0.98	1	1.02	1.03	1.05	1.06	1.07	1.08	1.09	1.09	1.1	1.1	1.09	1.09
TN	6.59	6.89	7.17	7.42	7.61	7.81	7.98	8.14	8.3	8.46	8.61	8.75	8.85	8.94	8.98	9.03	9.03	9.04
TX	27.49	29.43	31.07	32.4	33.45	34.51	35.43	36.34	37.23	38.12	38.92	39.72	40.3	40.88	41.22	41.55	41.69	41.82
UT	2.98	3.27	3.5	3.67	3.78	3.9	4	4.1	4.2	4.29	4.38	4.47	4.54	4.6	4.64	4.68	4.69	4.71
VA	8.36	8.63	8.91	9.21	9.48	9.76	9.99	10.22	10.44	10.67	10.87	11.07	11.21	11.35	11.42	11.49	11.51	11.53
VT	0.62	0.63	0.64	0.65	0.66	0.67	0.67	0.68	0.68	0.69	0.69	0.7	0.7	0.7	0.7	0.7	0.69	0.68
WA	7.16	7.75	8.21	8.57	8.84	9.11	9.35	9.58	9.81	10.04	10.25	10.46	10.61	10.76	10.85	10.94	10.97	11.01
WI	5.76	5.86	6	6.17	6.33	6.49	6.62	6.74	6.87	7	7.11	7.22	7.29	7.37	7.4	7.43	7.43	7.43
WV	1.84	1.79	1.78	1.8	1.84	1.87	1.89	1.92	1.94	1.97	1.99	2.01	2.02	2.02	2.02	2.02	2.01	2
WY	0.59	0.58	0.58	0.6	0.61	0.62	0.64	0.65	0.66	0.67	0.68	0.69	0.7	0.7	0.71	0.71	0.71	0.71

GCAM-USA Reference scenario GDP (billion 2015 USD)

Region	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
AK	56	55	56	61	66	72	79	87	94	102	109	116	124	131	137	143	148	153
AL	197	214	239	269	295	326	359	396	428	461	494	526	557	586	612	637	658	677
AR	118	124	133	147	162	177	195	213	232	251	270	289	306	323	337	351	363	373
AZ	292	348	412	474	531	593	660	733	813	897	980	1066	1146	1225	1295	1361	1416	1466
CA	2536	2989	3455	3886	4299	4753	5260	5804	6374	6967	7561	8169	8737	9304	9806	10292	10704	11086
CO	322	376	438	501	560	624	694	770	854	940	1027	1116	1199	1281	1353	1422	1479	1530
CT	253	259	281	316	355	402	454	509	569	631	693	757	817	876	929	978	1019	1055
DC	122	135	150	165	181	199	217	237	256	276	296	316	336	355	372	390	404	419
DE	69	67	71	77	84	91	99	107	115	124	132	140	148	156	163	170	176	182
FL	874	1023	1176	1307	1427	1557	1695	1838	1978	2124	2269	2418	2556	2695	2819	2942	3049	3153
GA	501	573	640	704	765	831	900	972	1042	1115	1186	1260	1327	1394	1454	1512	1562	1610
HI	81	86	93	102	112	123	135	148	162	176	191	205	218	232	244	255	265	274
IA	176	184	200	220	241	265	291	319	342	366	390	415	437	459	478	496	512	527
ID	66	79	93	107	119	132	146	161	177	194	212	229	245	261	274	287	298	307
IL	775	834	928	1034	1136	1250	1376	1509	1648	1793	1938	2085	2222	2359	2480	2597	2696	2789
IN	324	354	391	433	474	520	570	622	678	735	791	849	902	955	1001	1046	1083	1117
KS	152	165	182	202	222	245	270	297	319	343	366	390	412	434	453	471	487	502
KY	189	201	220	246	270	298	329	362	391	421	450	480	507	534	557	580	598	615
LA	242	248	268	298	329	363	400	441	482	524	566	609	648	687	721	754	781	805
MA	491	552	630	720	808	917	1037	1165	1303	1447	1593	1741	1882	2021	2143	2259	2355	2441
MD	360	397	433	475	519	567	617	670	722	776	829	884	935	986	1032	1077	1116	1154
ME	56	62	68	77	85	95	106	117	129	141	154	166	177	188	198	206	213	219
MI	460	516	583	651	712	781	857	937	1020	1107	1193	1280	1361	1442	1512	1580	1637	1690
MN	325	362	402	445	490	540	596	655	705	757	808	861	909	957	1000	1041	1076	1110
MO	288	309	345	383	421	465	513	564	608	653	698	743	785	827	864	900	930	959
MS	104	109	118	131	144	158	174	191	206	221	236	251	264	278	289	300	310	318
MT	47	48	52	57	63	70	77	84	92	100	109	117	125	132	138	145	149	153
NC	489	548	618	680	738	799	864	930	996	1063	1129	1197	1259	1320	1374	1427	1473	1516
ND	57	56	63	69	76	83	91	100	107	115	122	129	136	142	148	154	159	163
NE	115	121	132	145	160	176	194	214	230	247	264	281	297	312	326	340	351	362
NH	74	83	93	104	116	130	146	162	179	197	215	233	250	266	281	294	304	313
NJ	558	603	669	747	832	926	1031	1145	1266	1392	1519	1648	1769	1890	1997	2099	2185	2264
NM	95	100	111	125	139	155	171	189	209	229	249	270	289	307	324	339	352	363
NV	141	163	188	215	241	269	299	333	369	407	445	484	520	557	589	619	644	667
NY	1431	1567	1745	1948	2167	2407	2677	2968	3278	3600	3924	4253	4562	4868	5138	5396	5612	5808
OH	604	652	718	797	873	959	1054	1153	1258	1366	1474	1583	1685	1786	1875	1961	2033	2101
OK	203	209	232	259	285	314	346	381	416	452	488	524	557	590	618	645	668	688
OR	200	238	274	306	337	371	408	448	490	533	576	620	661	702	737	771	800	826
PA	709	777	864	963	1068	1183	1312	1450	1597	1749	1902	2057	2201	2343	2468	2587	2685	2773
RI	55	57	62	69	78	88	99	112	125	138	152	167	180	193	205	216	225	233
SC	198	219	238	260	282	305	330	356	381	407	433	459	482	506	527	548	565	582
SD	47	49	53	58	64	70	77	84	89	95	101	107	112	117	122	127	130	134
TN	314	358	410	467	514	569	629	694	753	812	872	932	987	1042	1090	1137	1175	1211
TX	1662	1863	2146	2434	2701	2996	3321	3678	4034	4405	4775	5152	5502	5851	6157	6452	6699	6926
UT	148	178	212	244	273	304	338	375	415	457	499	542	582	622	657	691	718	743
VA	475	525	591	651	708	770	835	902	968	1036	1104	1173	1237	1301	1357	1412	1460	1506
VT	30	32	35	39	43	48	53	58	64	70	76	81	87	92	96	100	103	105
WA	463	587	722	824	908	1000	1102	1212	1327	1446	1565	1686	1799	1911	2010	2105	2186	2260
WI	298	329	369	410	447	488	534	581	631	682	733	785	832	879	920	960	993	1023
WV	73	78	86	94	101	109	117	125	133	141	149	157	165	172	178	184	189	194
WY	41	41	43	48	53	59	65	71	79	86	93	101	108	115	121	126	131	135

Table SM2: GCAM-USA Grid Regions

Grid Region	States in Grid
Alaska grid	AK
California grid	CA
Central East grid	IN, KY, MI, OH, WV
Central Northeast grid	IL, MO, WI
Central Northwest grid	IA, MN, ND, NE, SD
Central Southwest grid	KS, OK
Florida grid	FL
Hawaii grid	HI
Mid-Atlantic grid	DC, DE, MD, NJ, PA
New England grid	CT, MA, ME, NH, RI, VT
New York grid	NY
Northwest grid	ID, MT, NV, OR, UT, WA
Southeast grid	AL, AR, GA, LA, MS, NC, SC, TN, VA
Southwest grid	AZ, CO, NM, WY
Texas grid	TX

Table SM3: Thermal power plant cooling systems

	once through	seawater	recirculating	cooling pond	dry cooling	dry hybrid
coal (conv pul)	historical only	coastal only	available	available	available	NA
coal (conv pul CCS)	historical only	coastal only	available	NA	available	NA
coal / biomass (IGCC) / (IGCC CCS)	historical only	coastal only	available	NA	available	NA
gas / refined liquids (steam/CT)	historical only	coastal only	available	available	available	NA
gas / refined liquids (CC) / (CC CCS)	historical only	coastal only	available	NA	available	NA
biomass (conv)	historical only	coastal only	available	available	available	NA
nuclear	historical only	coastal only	available	available	NA	NA
geothermal	NA	NA	available	NA	NA	available
CSP	NA	NA	available	NA	NA	available

- Historical only: New fresh water once-through cooling systems are not available for future installation, consistent with EPA regulation.
- Coastal only: Seawater cooling systems are only available in coastal states.
- Available: Available for future installation, with the following conditions. For generation technologies which are deployed historically in a given state, generation technology / cooling system combinations which do not exist historically will not be built in the future (e.g. a state with conventional coal but no coal + cooling pond plants won't build that combination in the future). For generation technology types which did not deploy historically in a given state, all available cooling technologies.
- NA: Not available for future installation.

Table SM4: Key Input Data Sources for GCAM-USA Calibration

File Name	**Description**
AEO_2020_elec_gen_hydro.csv	AEO 2020 Hydropower Electricity Generation (case = Reference case; region = United States)
AEO_2019_regional_pcGDP_ratio.csv	AEO 2019 Change in Per-Capita Gross Regional Product by US Census Division from 1990-2050
BEA_GDP_87_96_97USD_state.csv	Bureau of Economic Analysis Real GDP by State from 1987-1996
BEA_GDP_97_18_12USD_state.csv	Bureau of Economic Analysis Real GDP by State from 1997-2018
CBECS_2012.csv	U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey 2012
Census_pop.csv	U.S. Census Bureau Population by State from 1970-2018
EIA_860_generators_existing_2018.csv	EIA Form 860 Data for 2018 - Generators 2018 capacity data
EIA_860_generators_retired_2018.csv	EIA Form 860 Data for 2018 - Schedule 3; 'Generator Data' (Retired & Canceled Units Only)
EIA_923_generator_gen_fuel_2018.csv	EIA Form 923 Data for 2018 - Plant-Level Electricity Generation Data in MWh
EIA_AEO_Tab4.csv	EIA Annual Energy Outlook Table 4 (1996-2018 editions): Residential energy use for 1993-2015 base years
EIA_AEO_Tab5.csv	EIA Annual Energy Outlook Table 5 (2002-2018 editions) - Floorspace and building energy consumption for 1999-2015 base years
EIA_biodiesel_Mgal.yr.csv	Biodiesel producers and production capacity by state in March 2014, from EIA
EIA_elec_gen_hydro.csv	U.S. EIA Historical Electricity Generation from Hydropower by State, from 1990-2016
EIA_elect_td_ownuse.csv	EIA State Electricity Profiles 2018
EIA_state_energy_prices.csv	EIA State Electricity Profiles 2012 - Table E1. Primary Energy Electricity and Total Energy Price Estimates
EIA_use_all_Bbtu.csv	EIA State Energy Data System (SEDS) Energy Consumption Data (in BBTU) from 1960-2017
RECS_2015.csv	U.S. Energy Information Administration's Residential Energy Consumption Survey 2015
SEDS_refining_feedstock_prod.csv	Coal production and Natural gas marketed production for 2017 in Billion BTU

Supplementary Figure SF1: Energy System CO2 Emissions by Scenario

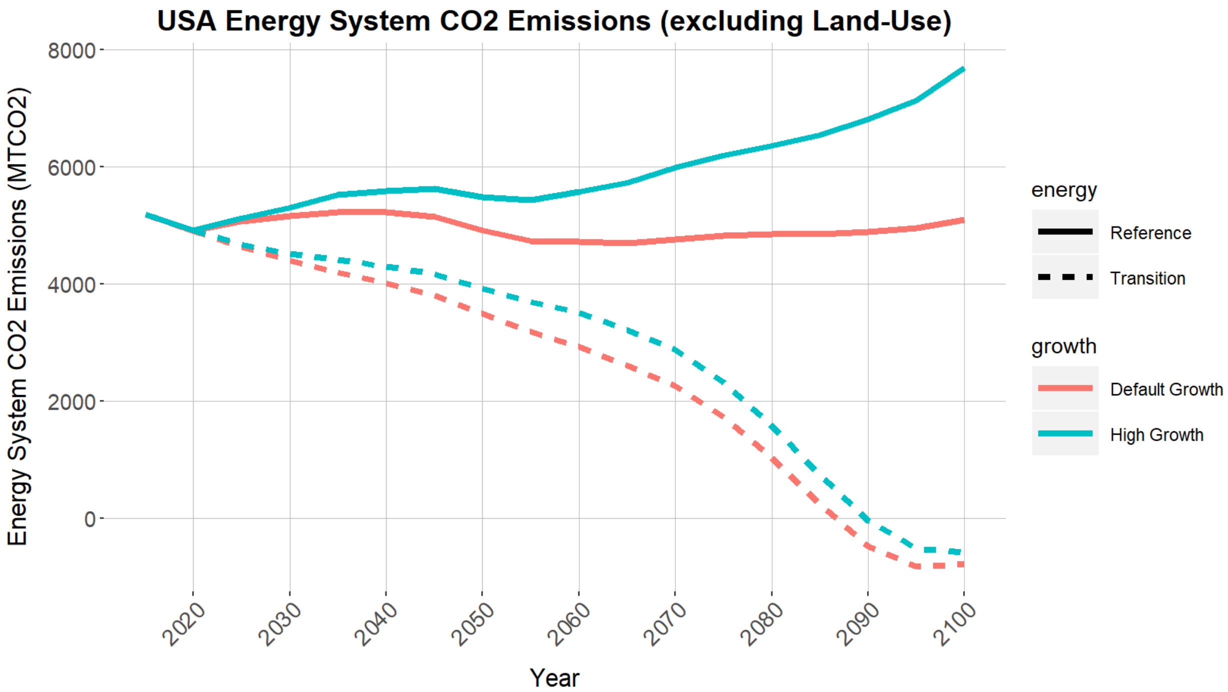

Figure SF1. Energy system CO2 emissions by scenario.

Supplementary Figure SF2: Passenger Transportation Electrification Rate (Percent of Passenger Miles Traveled)

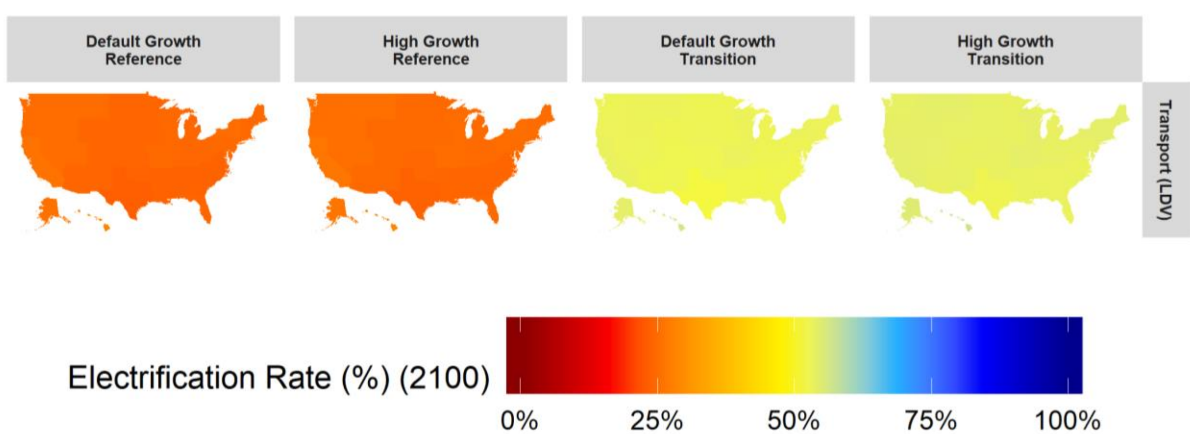

Figure SF2. Battery electric vehicle (BEV) share of passenger vehicle transportation service (passenger miles traveled) by scenario in 2100.