Appendix A – The GCAM-USA Advanced Technology Scenario

Note: Along with the “Advanced Technology” assumptions developed for use in this report, GCAM-USA also has “Reference Technology” assumptions, described below. The Reference Technology assumptions were not used in this report but are presented to provide a reference point for the magnitude of technological advancement envisioned in the U.S. Mid-Century Strategy scenarios. The assumptions in this document were informed by U.S. Department of Energy data, but changes were made as the data were translated into GCAM model inputs.

I. Electricity Sector Assumptions

Both the Reference and Advanced Technology scenarios use capital cost assumptions that were developed for selected electricity technologies. All other technologies used default GCAM values (Table 1). The updated technology assumptions were developed specifically for 2010 to 2040 and were assumed to be constant after 2040.

The Advanced Technology scenario uses a set of updated capital and O&M cost assumptions for the following technologies: coal (IGCC CCS), gas (CC CCS), Gen III nuclear, CSP, PV, and wind. Relative to the Reference scenario, costs were higher in 2020 for coal (IGCC CCS) and CSP technologies and lower for all other technologies. In subsequent years, the advanced capital cost assumptions were uniformly lower for all technologies relative to the reference (Table 1).

In the Reference scenario, default GCAM fixed and variable operating and maintenance (O&M) costs are used. These costs are given for 2005 to 2015 and assumed to decrease by a constant percentage from 2015 until they reach a maximum improvement threshold. In the Advanced Technology scenario, data for fixed O&M costs was developed for this report for 2010 to 2040. Values after 2040 were assumed to equal those in 2040. With the exception of gas (CC CCS), fixed O&M costs declined under the Advanced Technology scenario relative to the reference. In addition, variable O&M costs were provided for coal (IGCC CCS) and gas (CC CCS) technologies. These cost assumptions are higher than in the Reference scenario (Table 2).

Efficiency and capacity factors assumptions did not change between the Reference and Advanced Technology scenarios, but are presented in Table 3 for reference. For intermittent wind and solar technologies without storage, capacity factors are assumed to be dependent on renewable supply curves.

Table A.1: Capital Cost Assumptions for Reference and Advanced Technology scenarios (2010$/kW)

	Reference Technology					**Advanced Technology**			
	2005	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Biomass (conv)[1]	3999	3951	3818	3702		Same as reference			
Biomass (IGCC)[1]	6000	5745	5180	4819		Same as reference			

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[1] GCAM allows biomass production to compete with land carbon storage on a carbon price basis, fully accounting for CO2 emissions resulting from bioenergy use and any trade-offs with potential to increase carbon storage through forests. GCAM assumes protection of 90% of natural forests from conversion to other land uses and across MCS scenarios forest land area increases. As such, biomass produced under the MCS scenarios is limited to forms that result in net reductions of CO2 emissions to the atmosphere

Biomass (conv CCS)[1]	7701	7317	6568	6167		Same as reference			
Biomass (IGCC CCS)[1]	8850	837	7298	6720		Same as reference			
Coal (conv pul)	2344	2337	2242	2196		Same as reference			
Coal (IGCC)	3073	3061	2855	2769		Same as reference			
Coal (conv pul CCS)	5800	5503	4925	4618		Same as reference			
Coal (IGCC CCS)	4315	4020	3607	3448		4315	4310	3464	3103
Gas (CC)	856	859	824	807		Same as reference			
Gas (steam/CT)	915	912	875	857		Same as reference			
Gas (CC CCS)	1931	1864	1677	1605		1931	1766	1577	1466
Refined liquids (steam/CT)	749	742	717	694		Same as reference			
Refined liquids (CC)	1049	1036	1003	972		Same as reference			
Refined liquids (CC CCS)	2498	2356	2079	1937		Same as reference			
Gen_II_LWR (Nuclear)	5326	5500	5500	5500		Same as reference			
Gen III (Nuclear)	4400	4400	4044	3901		4400	3952	3275	2710
CSP	3442	3415	3077	2946		3442	4278	2470	2343
CSP_storage	8001	7430	6329	5771		Same as reference			
PV	2053	1855	1534	1514		2053	1247	684	641
PV_storage	4399	4212	3799	3534		Same as reference			
Wind	1682	1662	1526	1481		1682	1331	1200	1201
Wind_storage	2956	5555	5006	4661		Same as reference			
Rooftop_PV	4699	4499	4057	3776		Same as reference			
Geothermal[2]	4399	4348	4199	4073		Same as reference			

Table A.2: Fixed and Variable O&M Assumptions, Reference and Advanced Technology scenarios (2010$)[3]

		Reference Technology					**Advanced Technology**			
		2005	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Biomass (conv)	Fixed	29.3	94.1	91.3	88.6		Same as reference			
	Variable	4.8	9.9	9.6	9.3		Same as reference			
Biomass (IGCC)	Fixed	41.2	135.8	123.9	113.1		Same as reference			
	Variable	3.1	14.6	13.3	12.1		Same as reference			
Biomass (conv CCS)	Fixed	116.1	110.3	94.5	81.1		Same as reference			
	Variable	13.4	12.7	10.9	9.3		Same as reference			
Biomass (IGCC CCS)	Fixed	46.3	161.0	138.0	118.4		Same as reference			
	Variable	5.2	17.1	14.6	12.5		Same as reference			
Coal (conv pul)	Fixed	28.5	24.8	24.0	23.3		Same as reference			
	Variable	4.7	4.0	3.8	3.7		Same as reference			
Coal (IGCC)	Fixed	40.0	34.0	31.0	28.3		Same as reference			
	Variable	3.0	6.3	5.8	5.3		Same as reference			
Coal (conv pul CCS)	Fixed	50.0	47.5	40.7	34.9		Same as reference			
	Variable	8.0	7.6	6.5	5.6		Same as reference			
Coal (IGCC CCS)	Fixed	45.9	66.5	57.0	48.9		42.5	42.5	36.3	34.0
	Variable	5.6	9.5	8.1	7.0		14.2	14.2	12.1	11.3
Gas (CC)	Fixed	12.5	9.9	9.6	9.3		Same as reference			
	Variable	2.1	3.5	3.4	3.3		Same as reference			

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[2] Geothermal is assumed to be carbon-free.

[3] Reference scenario data is from GCAM; Advanced Technology data is specifically developed for this report.

Gas (steam/CT)	Fixed	11.7	5.9	5.8	5.6		Same as reference			
	Variable	3.5	9.9	9.6	9.3		Same as reference			
Gas (CC CCS)	Fixed	13.8	19.0	16.3	14.0		30.1	30.1	26.9	25.9
	Variable	2.7	6.7	5.7	4.9		6.4	6.4	5.7	5.5
Refined liquids (steam/CT)	Fixed	11.7	5.9	5.8	5.6		Same as reference			
	Variable	3.5	9.9	9.6	9.3		Same as reference			
Refined liquids (CC)	Fixed	36.0	9.9	9.6	9.3		Same as reference			
	Variable	2.7	3.5	3.4	3.3		Same as reference			
Refined liquids (CC CCS)	Fixed	38.8	22.6	19.4	16.6		Same as reference			
	Variable	3.9	7.9	6.8	5.8		Same as reference			
Gen_II_LWR (Nuclear)	Fixed	71.1	105.0	105.0	105.0		Same as reference			
	Variable	0.2	2.2	2.2	2.2		Same as reference			
Gen III (Nuclear)	Fixed	70.3	94.1	91.3	88.5		80.4	80.4	80.4	80.4
	Variable	0.5	2.0	1.9	1.9		Same as reference			
CSP	Fixed	53.6	52.3	44.8	38.4		56.8	52.2	37.3	37.3
CSP_storage	Fixed	53.6	63.1	57.5	52.5		Same as reference			
PV	Fixed	28.8	38.8	35.4	32.3		17.5	9.3	9.3	9.3
PV_storage	Fixed	56.2	46.6	42.5	38.8		Same as reference			
Wind	Fixed	12.1	48.5	44.3	40.4		47.4	44.2	39.0	37.6
Wind_storage	Fixed	27.9	58.2	53.1	48.5		Same as reference			
Rooftop_PV	Fixed	151.0	58.2	53.1	48.5		Same as reference			
Geothermal	Fixed	76.0	99	96.1	93.2		Same as reference			

Table A.3: Electricity Sector Efficiency and Capacity Factor Assumptions

	Efficiency					**Capacity Factor**
	2005	**2020**	**2035**	**2050**		
Biomass (conv)	38%	28%	31%	33%		0.85
Biomass (IGCC)	42%	34%	38%	41%		0.8
Biomass (conv CCS)	20%	23%	30%	34%		0.8
Biomass (IGCC CCS)	36%	30%	37%	41%		0.8
Coal (conv pul)[4]	39%	41%	44%	47%		0.85
Coal (IGCC)[4]	43%	43%	47%	51%		0.8
Coal (conv pul CCS)	29%	34%	42%	48%		0.8
Coal (IGCC CCS)	36%	37%	45%	50%		0.8
Gas (steam/CT)	33%	39%	41%	43%		0.8
Gas (CC)	50%	58%	61%	63%		0.85
Gas (CC CCS)	49%	50%	58%	63%		0.8
Refined liquids (steam/CT)	38%	37%	40%	42%		0.8
Refined liquids (CC)	43%	57%	60%	63%		0.85
Refined liquids (CC CCS)	36%	47%	56%	62%		0.8
Gen_II_LWR (nuclear)	33%	33%	33%	33%		0.9
Gen_III (nuclear)	33%	33%	33%	33%		0.9
Wind	variable	variable	variable	variable		0.37 + variable
Wind_storage	variable	variable	variable	variable		0.37
PV	variable	variable	variable	variable		0.20 + variable

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[4] Coal-fired power plants without CCS do not meet the minimum requirements for New Source Performance Standards, as such no new plants come online under all MCS scenarios.

PV_storage	variable	variable	variable	variable		0.2
CSP	variable	variable	variable	variable		0.25 + variable
CSP_storage	variable	variable	variable	variable		0.65
Rooftop_PV	variable	variable	variable	variable		0.20 + variable
Geothermal	10%	10%	10%	10%		0.9

II. Buildings Sector Assumptions

The buildings sector in GCAM is divided into residential and commercial sectors that model a set of services including heating, lighting, hot water and appliances. Each service contains a set of technologies that compete with one another for market share. Among these technologies are low and high-efficiency alternatives that are powered by both electricity and direct fuel use. Demand for services grows as a function of floorspace, per-capita GDP, and exogenous growth factors.

The Reference scenario uses floorspace, exogenous demand, shell efficiency, and service technology cost, efficiency, and retirement assumptions developed for this report. The Advanced Technology scenario builds on these assumptions, but contains altered building shell efficiency trajectories and technology cost and efficiency assumptions. Building shell efficiency is modeled as watts of energy consumption per square meter. Improved shell efficiency trajectories were assumed for both the residential and commercial sectors under the Advanced Technology scenario, as shown by reduced consumption per square meter (Figure 1). Since residential and commercial trajectories converge after 2010, only commercial efficiency trajectories are shown in Figure 1. Floorspace is presented for residential and commercial buildings in Figure 2, and is the same under both Reference and Advanced Technology scenarios.

Cost and efficiency assumptions for a subset of residential and commercial technologies were developed for this report. In general, both cost and efficiency increased for these technologies, reflecting a set of standards under which raised minimum efficiency standards are applied to the market place. These assumptions are described in tables 4 to 7.

Figure A.1: Commercial Shell Efficiency Trajectories, Reference and Advanced Technology

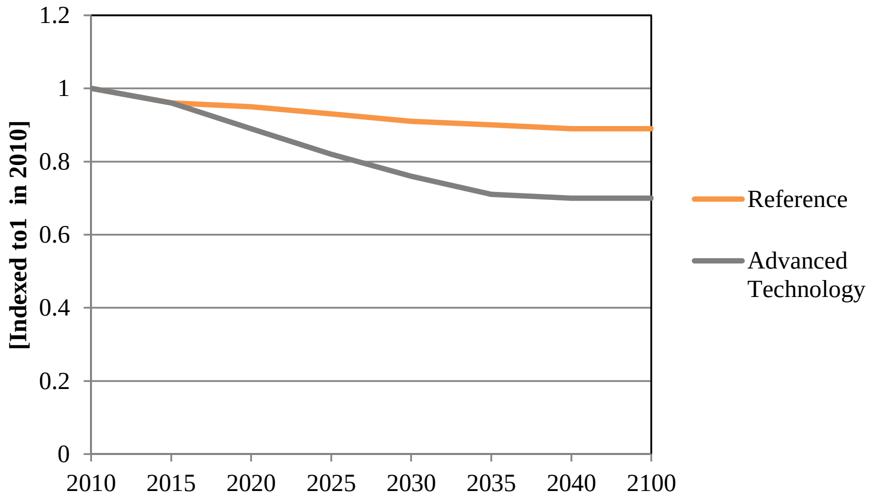

Figure A.2: Residential and Commercial Floorspace Assumptions, Reference, Advanced Technology and Smart Growth

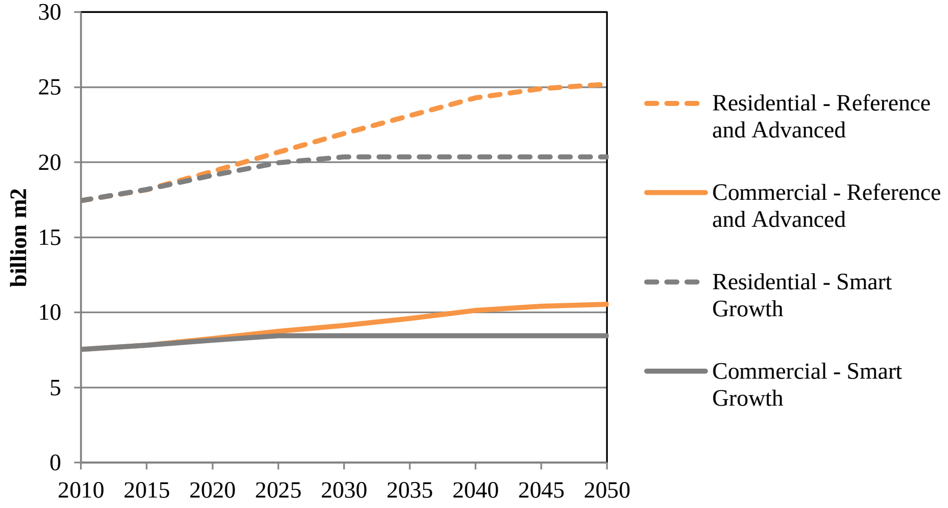

Table A.4: Technology Cost Assumptions under Reference and Advanced Technology Scenarios, Residential Buildings Sector (2010$/GJ)

		Reference Technology					Advanced Technology			
Service	**Technology**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Heating	Wood furnace	4.4	4.2	4.2	4.1		Same as reference			
	Coal furnace	4.4	4.2	4.2	4.1		Same as reference			
	Gas furnace	7.3	7.3	7.3	7.3		7.3	9.8	11.4	11.4
	Gas furnace hi-eff	11.3	11.3	11.3	11.3		Same as reference			
	Electric furnace	4.2	4.2	4.2	4.2		Same as reference			
	Electric heat pump	6.3	6.5	7.0	7.2		6.1	6.1	7.0	7.2
	Fuel furnace	11.2	12.7	12.7	12.7		11.2	15.0	15.0	15.0
	Fuel furnace hi-eff	18.7	18.7	18.7	18.7		Same as reference			
Cooling	Air conditioning	17.8	17.8	17.8	17.8		17.8	22.0	24.5	24.5
	Air conditioning hi-eff	43.3	43.3	43.3	43.3		Same as reference			
Water Heating	Gas	31.8	32.0	32.0	32.0		31.8	32.0	53.6	53.6
	Gas hi-eff	53.6	53.6	53.6	53.6		87.0	49.9	49.9	49.9
	Electric resistance	17.8	17.8	17.8	17.8		17.8	18.5	18.5	18.5
	Electric resistance hi-eff	21.1	21.1	21.1	21.1		Same as reference			
	Electric heat pump	56.9	54.0	54.0	54.0		Same as reference			
	Fuel	31.8	32.0	32.0	32.0		31.9	42.2	53.6	53.6
	Fuel hi-eff	53.6	53.6	53.6	53.6		87.0	88.2	83.2	81.5
Lighting	Incandescent	0.5	2.4	2.4	2.4		Same as reference			
	Fluorescent	0.79	0.59	0.57	0.56		Same as reference			
	Solid state	13.8	0.81	0.49	0.49		Same as reference			
Kitchen appliances	Refrigerator	29.2	32.1	32.1	32.1		29.2	37.8	41.1	41.1
	Refrigerator hi-eff	29.2	39.4	39.4	39.4		29.2	45.2	45.2	45.2
	Freezer	51.4	58.0	58.0	58.0		51.4	61.2	63.2	63.2
	Freezer hi-eff	58.0	61.2	61.2	61.2		58.0	94.2	94.2	94.2

	Dishwasher	0.60	0.60	0.60	0.60		0.60	0.60	0.65	0.65
	Dishwasher hi-eff	0.66	0.66	0.66	0.66		Same as reference			
	Electric oven	41.8	41.8	41.8	41.8		71.7	71.7	71.7	71.7
	Gas oven	41.8	41.8	41.8	41.8		Same as reference			
	Gas oven hi-eff	47.8	47.8	47.8	47.8		Same as reference			
	LPG oven	41.8	41.8	41.8	41.8		Same as reference			
	LPG oven hi-eff	47.8	47.8	47.8	47.8		Same as reference			
Clothes appliances	Electric clothes dryer	0.09	0.12	0.12	0.12		0.09	0.12	0.15	0.15
	Electric clothes dryer hi-eff	0.11	0.15	0.15	0.15		Same as reference			
	Gas clothes dryer	0.09	0.10	0.10	0.10		0.09	0.10	0.13	0.13
	Clothes washer	0.37	0.40	0.40	0.40		0.37	0.40	0.55	0.55
	Clothes washer hi-eff	0.38	0.55	0.55	0.55		Same as reference			
Other	Television	64.6	64.5	64.5	64.5		Same as reference			
	Computer	64.6	64.5	64.5	64.5		Same as reference			
	Furnace fan	64.6	64.5	64.5	64.5		Same as reference			
	Gas other	64.5	62.6	61.7	60.5		Same as reference			
	Electric other	64.6	64.5	64.5	64.5		Same as reference			
	Liquids other	64.5	62.6	61.7	60.5		Same as reference			

Table A.5: Technology Cost Assumptions under Reference and Advanced Technology Scenarios, Commercial Buildings Sector (2010$/GJ)

		Reference Technology					**Advanced Technology**			
Service	**Technology**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Heating	Wood furnace	4.3	4.2	4.2	4.1		Same as reference			
	Coal furnace	4.4	4.2	4.2	4.1		Same as reference			
	Gas furnace	3.3	3.8	3.8	3.8		3.4	3.5	4.0	4.0
	Gas furnace hi-eff	5.6	5.6	5.6	5.6		Same as reference			
	Electric furnace	5.4	6.2	6.2	6.2		5.4	5.4	5.4	5.4
	Electric heat pump	22.1	22.1	22.1	22.1		22.1	27.5	27.5	27.5
	Fuel furnace	3.6	3.7	3.7	3.7		3.6	3.8	3.8	3.8
Cooling	Gas cooling	49.4	49.4	49.4	49.4		Same as reference			
	Air conditioning	5.4	7.4	7.4	7.4		5.4	7.8	10.9	10.9
	Air conditioning hi-eff	13.1	13.1	13.1	13.1		Same as reference			
Water Heating	Gas	4.1	4.1	4.1	4.1		4.1	4.6	4.6	4.6
	Electric resistance	4.6	4.6	4.6	4.6		4.6	4.6	38.5	38.5
	Electric heat pump	45.3	40.9	40.9	40.9		40.9	38.7	38.7	38.7
	Fuel	7.1	9.7	9.7	9.7		Same as reference			
Ventilation	Ventilation	166.5	175.4	175.4	175.4		Same as reference			
	Ventilation hi-eff	235.2	235.2	235.2	235.2		Same as reference			
Lighting	Solid state	23.8	2.3	1.7	1.7		23.8	2.5	2.0	2.0
	Incandescent	6.4	5.5	5.2	5.2		Same as reference			
	Fluorescent	1.2	1.2	1.1	1.1		Same as reference			
Kitchen Appliances	Gas range stove	7.9	7.9	7.9	7.9		Same as reference			
	Gas range hi-eff stove	10.6	10.6	10.6	10.6		Same as reference			

	Electric range stove	10.9	10.9	10.9	10.9		Same as reference			
	Electric range hi-eff stove	12.6	12.6	12.6	12.6		Same as reference			
	Refrigeration	138.5	144.5	144.5	144.5		138.5	140.3	140.3	140.3
	Refrigeration hi-eff	138.5	158.9	158.9	158.9		156.8	156.9	156.9	156.9
Other	Office equipment	142.6	138.4	136.3	133.6		Same as reference			
	Gas other	64.6	62.6	61.7	60.5		Same as reference			
	Electricity other	129.3	125.4	123.6	121.2		Same as reference			
	Liquids other	64.5	62.6	61.7	60.5		Same as reference			

Table A.6: Technology Efficiency Assumptions under Reference and Advanced Technology Scenarios, Residential Buildings Sector

			Reference Technology					**Advanced Technology**			
Service	**Technology**	**Units**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Heating	Wood furnace	Out/in	0.40	0.40	0.40	0.40		Same as reference			
	Coal furnace	Out/in	0.40	0.40	0.40	0.40		Same as reference			
	Gas furnace	Out/in	0.78	0.80	0.80	0.80		0.78	0.92	0.98	0.98
	Gas furnace hi-eff	Out/in	0.98	0.98	0.98	0.98		Same as reference			
	Electric Heat Pump	Out/in	2.26	2.67	2.75	2.77		2.26	2.45	2.74	2.77
	Electric furnace	Out/in	0.99	0.99	0.99	0.99		Same as reference			
	Fuel furnace	Out/in	0.80	0.83	0.83	0.83		0.80	0.85	0.86	0.86
	Fuel furnace hi-eff	Out/in	0.97	0.97	0.97	0.97		Same as reference			
Cooling	Air Conditioning	Out/in	3.04	3.81	3.81	3.81		3.04	4.54	4.84	4.84
	Air conditioning hi-eff	Out/in	7.03	7.03	7.03	7.03		Same as reference			
Water Heating	Gas	Out/in	0.59	0.62	0.62	0.62		0.59	0.62	0.82	0.82
	Gas hi-eff	Out/in	0.82	0.82	0.82	0.82		0.80	1.20	1.20	1.20
	Electric resistance	Out/in	0.89	0.90	0.90	0.90		0.89	0.95	0.95	0.95
	Electric resistance hi-eff	Out/in	0.95	0.96	0.96	0.96		Same as reference			
	Electric heat pump	Out/in	2.00	2.30	2.45	2.50		Same as reference			
	Fuel	Out/in	0.59	0.62	0.62	0.62		0.59	0.67	0.82	0.82
	Fuel hi-eff	Out/in	0.82	0.82	0.82	0.82		0.8	0.85	0.85	0.85
Lighting	Incandescent	mil lumen-hours/GJ	4.03	5.50	5.50	5.50		Same as reference			

	Fluorescent	mil lumen-hours/GJ	18.67	19.17	19.64	20.14		Same as reference			
	Solid state	mil lumen-hours/GJ	12.22	43.61	56.11	56.11		Same as reference			
Kitchen appliances	Refrigerator	Out/in	1.92	2.53	2.53	2.53		1.92	2.87	3.10	3.10
	Refrigerator hi-eff	Out/in	2.00	2.97	2.97	2.97		2.00	5.13	5.13	5.13
	Freezer	Out/in	1.00	1.39	1.39	1.39		1.00	1.46	1.52	1.52
	Freezer hi-eff	Out/in	1.39	1.46	1.46	1.46		1.39	2.61	2.61	2.61
	Dishwasher	cycles/GJ	194.44	194.44	194.44	194.44		194.44	194.44	202.78	202.78
	Dishwasher hi-eff	cycles/GJ	333.33	333.33	333.33	333.33		Same as reference			
	Electric oven	Out/in	0.62	0.621	0.62	0.62		Same as reference			
	Gas oven	Out/in	0.40	0.40	0.40	0.40		Same as reference			
	Gas oven hi-eff	Out/in	0.42	0.42	0.42	0.42		Same as reference			
	LPG oven	Out/in	0.40	0.40	0.40	0.40		Same as reference			
	LPG oven hi-eff	Out/in	0.42	0.42	0.42	0.42		Same as reference			
Clothes appliances	Electric clothes dryer	kg/GJ	447.69	480.48	480.48	480.48		447.69	480.48	683.52	683.52
	Electric clothes dryer hi-eff	kg/GJ	480.48	683.52	683.52	683.52		Same as reference			
	Gas clothes dryer	kg/GJ	395.98	416.17	416.17	416.17		395.99	416.17	455.26	455.26
	Clothes washer	cycles/GJ	1262.6	2777.8	2777.8	2777.8		1262.6	2777.8	3086.4	3086.4
	Clothes washer hi-eff	cycles/GJ	2525.3	3086.4	3086.4	3086.4		Same as reference			
Other	Television	Indexed to 1 in 2005	1.00	1.25	1.35	1.35		Same as reference			
	Computer	Indexed to 1 in 2005	1.00	1.50	3.00	3.80		Same as reference			
	Furnace fan	Indexed to 1 in 2005	1.00	1.33	1.83	2.00		Same as reference			
	Gas other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference			
	Electricity other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference			

	Liquids other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference

Table A.7: Technology Efficiency Assumptions under Reference and Advanced Technology Scenarios, Commercial Buildings Sector

			Reference Technology					**Advanced Technology**			
Service	**Technology**	**Units**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Heating	Wood furnace	Out/in	0.65	0.65	0.65	0.65		Same as reference			
	Coal furnace	Out/in	0.65	0.65	0.65	0.65		Same as reference			
	Gas furnace	Out/in	0.76	0.78	0.78	0.78		0.76	0.80	0.88	0.88
	Gas furnace hi-eff	Out/in	0.88	0.88	0.89	0.89		Same as reference			
	Electric heat pump	Out/in	3.30	3.30	3.30	3.30		3.30	3.40	3.40	3.40
	Fuel furnace	Out/in	0.79	0.80	0.80	0.80		0.79	0.81	0.81	0.81
Cooling	Gas cooling	Out/in	0.87	0.98	1.05	1.08		Same as reference			
	Air conditioning	Out/in	2.87	3.22	3.22	3.22		2.87	3.37	3.81	3.81
	Air conditioning hi-eff	Out/in	5.80	6.06	6.28	6.28		Same as reference			
Water heating	Gas	Out/in	0.79	0.80	0.80	0.80		0.79	0.99	0.99	0.99
	Gas hi-eff	Out/in	0.99	0.99	0.99	0.99		Same as reference			
	Electric resistance	Out/in	0.98	0.98	0.98	0.98		0.98	0.98	2.00	2.00
	Electric HP	Out/in	2.45	2.45	2.45	2.45		2.45	2.45	4.10	4.10
	Fuel	Out/in	0.79	0.80	0.80	0.80		0.79	0.80	0.80	0.80
Ventilation	Ventilation	Million m3/GJ	0.61	0.73	0.77	0.82		Same as reference			
	Ventilation hi-eff	Million m3/GJ	2.42	2.57	2.74	2.93		Same as reference			
Lighting	Incandescent	mil lumen-hours/ GJ	3.75	5.65	5.93	5.93		Same as reference			
	Fluorescent	mil lumen-hours/ GJ	19.33	19.81	20.13	20.13		Same as reference			
	Solid state	mil lumen-hours/ GJ	17.50	47.22	56.11	56.11		Same as reference			

Kitchen Appliances	Gas range stove	Out/in	0.45	0.45	0.45	0.45		Same as reference			
	Gas range hi-eff stove	Out/in	0.60	0.60	0.60	0.60		Same as reference			
	Electric range stove	Out/in	0.70	0.70	0.70	0.70		Same as reference			
	Electric range hi-eff stove	Out/in	0.80	0.80	0.80	0.80		Same as reference			
	Refrigeration	Out/in	2.06	3.32	3.32	3.32		2.06	2.65	2.65	2.65
	Refrigeration hi-eff	Out/in	3.76	4.12	4.12	4.12		3.32	5.41	5.41	5.41
Other	Office equipment	Indexed to 1 in 2005	1.00	1.45	1.45	1.45		Same as reference			
	Gas other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference			
	Electricity other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference			
	Liquids other	Indexed to 1 in 2005	1.00	1.00	1.00	1.00		Same as reference			

III. Industrial Sector Assumptions

The industrial sector in GCAM is an aggregate representation of many diverse sectors. Specific industries such as cement and nitrogen fertilizer production are separated from the aggregate, while others are grouped into an ‘industrial energy use’ sector. The industrial energy use sector is organized by fuel consumption, with each subsector containing a set of technologies that consume a particular fuel.

Technology assumptions in the reference scenario are taken from the core GCAM assumptions. The Advanced Technology scenario uses altered efficiency assumptions for a subset of technologies (Table 8).

Table A.8: Selected industrial sector technology efficiency assumptions under Reference and Advanced Technology scenarios (Indexed to 1 in 2005)

	Reference Technology					**Advanced Technology**			
Technology	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Biomass	1.000	0.997	1.006	1.014		1.000	1.002	1.030	1.019
Coal	1.000	1.030	1.042	1.051		1.000	1.013	1.041	1.030
Electricity	1.000	1.015	1.030	1.046		1.000	1.008	1.101	1.156
Gas	1.000	1.016	1.033	1.048		1.000	1.008	1.057	1.110
Hydrogen	1.000	1.000	1.015	1.030		1.000	1.024	1.088	1.088
Refined liquids	1.000	1.019	1.037	1.052		1.000	1.009	1.059	1.112

IV. Transportation Sector Assumptions

The transportation sector is divided into freight and passenger classes, each of which contains on-road technologies such as cars, trucks, and motorcycles and off-road technologies such as trains. Intensity and capital expenditure assumptions were developed for this report for a suite of on-road technologies in the passenger and freight classes. These include liquid, hybrid liquid, and battery-electric vehicle (BEV) technologies. The reference scenario adds electric vehicles to the freight sector in GCAM. Capital cost, vehicle intensity, and load factor assumptions for these vehicles are presented in Table 9, alongside conventional liquid-fueled vehicles for comparison. In addition, the Smart Growth scenario assumes significantly lower transportation demand in the passenger and freight sectors. These assumptions, and the Reference assumptions, are presented in Figures 3 and 4.

The Advanced Technology scenario alters efficiency and capital cost parameters for selected on-road freight and passenger vehicle technologies. For liquid and hybrid liquid-fueled vehicles, capital expenditures tend to increase relative to the reference, while fuel intensity (an inverse measure of efficiency) declines (Tables 10 and 11). BEVs are assumed to have lower capital costs than in the Reference scenario.

In order to calibrate BEV deployment to expected levels, preference weights are utilized. Preference weights alter the competition between technologies within a sector for market share. If two technologies have equal preference weights, competition will occur on the basis of cost. Preference weights may be altered in order to calibrate to observed technology shares, or to emulate the role of unquantified factors in competition, such as public acceptance and legal and institutional barriers. In the passenger sector, default preference weights are set to 1 for conventional liquid technologies. Under the Reference scenario, preference weights for passenger and freight BEVs are linearly interpolated to 1 in 2050. Under the Advanced Technology scenario, passenger and freight BEV preference weights are linearly interpolated to 5 in 2050, in order to represent a high BEV future that is consistent with current trends and projections.

Figure A.3: Passenger VMT trajectories for Reference and Smart Growth scenarios

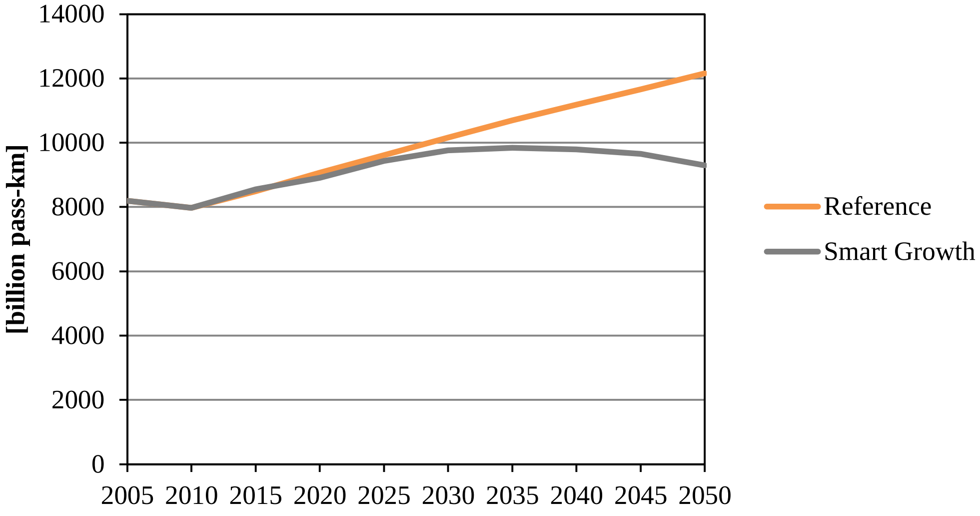

Figure A.4: Freight VMT trajectories for Reference and Smart Growth Scenarios

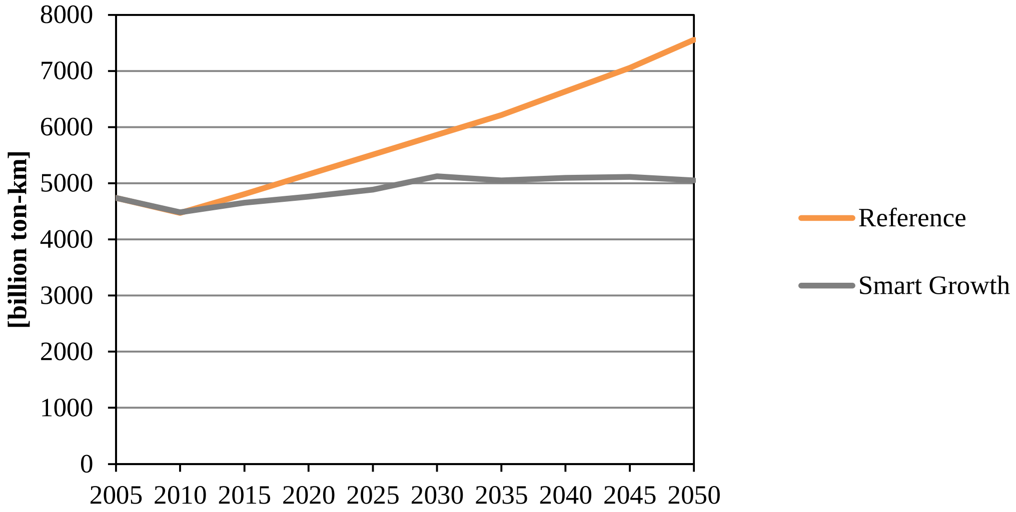

Table A.9: Electric and conventional (liquid-fueled) freight vehicle assumptions, Reference Scenario

Parameter	**Class**	**Technology**	**2005**	**2020**	**2035**	**2050**
CAPEX and non-fuel OPEX (2010$/vkt)	Truck (0-2.7t)	Liquids	1.14	1.14	1.14	1.14
	Truck (0-2.7t)	BEV	3.04	1.74	1.65	1.56
	Truck (2.7-4.5t)	Liquids	1.25	1.25	1.25	1.25
	Truck (2.7-4.5t)	BEV	3.31	1.89	1.79	1.70
	Truck (4.5-12t)	Liquids	1.35	1.35	1.35	1.35
	Truck (4.5-12t)	BEV	3.60	2.05	1.95	1.84
	Truck (>12t)	Liquids	1.37	1.37	1.37	1.37
	Truck (>12t)	BEV	3.63	2.07	1.97	1.86
Intensity (MJ/vkm)	Truck (0-2.7t)	Liquids	4.74	3.45	2.93	2.81
	Truck (0-2.7t)	BEV	1.42	1.40	1.38	1.36
	Truck (2.7-4.5t)	Liquids	5.36	4.61	4.18	4.02
	Truck (2.7-4.5t)	BEV	1.61	1.58	1.56	1.54
	Truck (4.5-12t)	Liquids	10.79	9.34	8.48	8.14
	Truck (4.5-12t)	BEV	3.24	3.19	3.14	3.10
	Truck (>12t)	Liquids	13.32	11.53	10.46	10.05
	Truck (>12t)	BEV	4.00	3.94	3.88	3.82
Load factor (tons/vehicle)	Truck (0-2.7t)	Liquids	0.27	0.27	0.27	0.27
	Truck (0-2.7t)	BEV	Same as liquids			

	Truck (2.7-4.5t)	Liquids	1.01	1.01	1.01	1.01
	Truck (2.7-4.5t)	BEV	Same as liquids			
	Truck (4.5-12t)	Liquids	3.60	3.60	3.60	3.60
	Truck (4.5-12t)	BEV	Same as liquids			
	Truck (>12t)	Liquids	4.16	4.16	4.16	4.16
	Truck (>12t)	BEV	Same as liquids			

Table A.10: Selected transportation sector costs, Reference and Advanced Technology Scenarios

			Reference Technology					**Advanced Technology**			
Parameter	**Class**	**Tech**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
CAPEX and non-fuel OPEX (2010$/ vkt)	Truck (0-2.7t)	Liquids	1.14	1.14	1.14	1.14		1.14	1.26	1.33	1.33
	Truck (2.7-4.5t)	Liquids	1.25	1.25	1.25	1.25		1.25	1.35	1.47	1.46
	Truck (4.5-12t)	Liquids	1.35	1.35	1.35	1.35		1.35	1.46	1.59	1.59
	Truck (>12t)	Liquids	1.37	1.37	1.37	1.37		1.37	1.48	1.61	1.60
Capital costs (purchase) (2010$/ vehicle)	Compact Car	Liquids	17746.8	17746.8	17746.8	17746.8		17746.8	18985.5	18381.6	18320.8
		Hybrid Liquids	20996.0	19696.3	18884.0	18802.8		20996.0	21071.0	19559.5	19410.9
		BEV	48825.8	28817.2	19324.3	19158.3		48825.8	28817.2	19324.3	19158.3
	Midsize Car	Liquids	25634.3	25634.3	25634.3	25634.3		25634.3	30220.4	29282.5	29089.2
		Hybrid Liquids	29605.5	28017.0	27024.2	26924.9		29605.5	33029.5	30870.2	30553.8
		BEV	64950.7	37950.4	36092.8	34235.2		64950.7	45870.3	30784.2	30418.9
	Large Car	Liquids	33521.7	33521.7	33521.7	33521.7		33521.7	36031.9	37042.6	36925.7
		Hybrid Liquids	38816.7	35904.5	34911.7	34712.4		38816.7	38593.0	38578.5	38347.4
		BEV	88211.6	50856.0	48286.0	45715.9		88211.6	56943.2	38894.7	38674.2
	Light Truck and SUV	Liquids	34507.7	34507.7	34507.7	34507.7		34507.7	37963.6	37914.2	37898.5
		Hybrid Liquids	39923.0	37756.8	36403.0	36267.6		39923.0	41538.1	39996.6	39831.5
		BEV	91686.7	52682.0	49998.5	47315.0		91686.7	64840.4	42775.0	42325.4

Table A.11: Vehicle Intensities, Selected Technologies, Reference and Advanced Technology Scenarios

			Reference Technology					**Advanced Technology**			
Class	**Tech**	**Units**	**2005**	**2020**	**2035**	**2050**		**2005**	**2020**	**2035**	**2050**
Compact Car	Liquids	MJ/vkm	2.914	2.176	1.672	1.655		2.914	1.861	1.245	1.179
	Hybrid Liquids	MJ/vkm	2.186	1.690	1.311	1.298		2.186	1.446	0.976	0.924
Midsize Car	Liquids	MJ/vkm	3.728	2.784	2.139	2.118		3.728	2.381	1.593	1.509
	Hybrid Liquids	MJ/vkm	2.797	2.162	1.677	1.660		2.797	1.850	1.249	1.183
Large Car	Liquids	MJ/vkm	3.868	2.888	2.220	2.197		3.868	2.471	1.653	1.566

	Hybrid Liquids	MJ/vkm	2.902	2.244	1.740	1.722		2.902	1.920	1.296	1.227
Light Truck and SUV	Liquids	MJ/vkm	4.039	3.016	2.318	2.294		4.039	2.580	1.726	1.635
	Hybrid Liquids	MJ/vkm	3.030	2.343	1.817	1.798		3.030	2.004	1.352	1.281
Truck (0-2.7t)	Liquids	MJ/vkm	4.740	3.451	2.930	2.809		4.740	3.146	2.520	2.409
Truck (2.7-4.5t)	Liquids	MJ/vkm	5.358	4.510	4.182	4.019		5.358	4.266	3.553	3.430
Truck (4.5-12t)	Liquids	MJ/vkm	10.792	9.343	8.475	8.145		10.792	8.646	7.199	6.952
Truck (>12t)	Liquids	MJ/vkm	13.317	11.530	10.458	10.052		13.317	10.670	8.884	8.579

Appendix B: U.S. Department of Energy (DOE) Energy Assumption Documentation

The assumptions below are DOE information that was provided to the PNNL modeling team for their consideration and translation into model inputs, together with their other assumptions and policy frameworks. Hence, the assumptions in the Mid-Century Strategy were informed by U.S. Department of Energy data, but changes were made as the data were translated into GCAM model inputs.

The Advanced Technology assumptions reflect achievement of DOE program goals through success of continued RDD&D at current levels, while the Stretch Technology assumptions reflect more aggressive RDD&D goals, such as would be enabled by Mission Innovation.

Table B.1: Descriptions of Analysis Cases

EPSA Base Case: A variation of the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2015 High Oil and Gas Resource Case,[5] which includes one potential implementation of the Clean Power Plan, wind and solar tax credit extensions[6], updated carbon capture utilization and storage cost and performance estimates,[7] and updated solar and wind technology cost and performance estimates that are consistent with AEO 2016.
Advanced Technology Assumptions: Current DOE energy program goals overlaid on top of the EPSA Base Case. Major changes from the Base Case to the Advanced Technology assumptions include: changes to cost and performance of new and retrofitted coal and new natural gas combined cycle units with carbon capture, utilization, and storage (CCUS), a representative advanced nuclear plant, central and distributed solar, onshore and offshore wind, geothermal, and hydropower, and enhanced transmission capacity and load shifting to reflect modernization of the electric grid. Significant changes to costs in industrial, buildings, and transportation technologies are also included and reduce demand for electricity generation. Assumes all current goals are met, though this outcome is uncertain.
Stretch Technology Assumptions: Stretch DOE energy program estimates (including more ambitious cost and performance) enabled by additional RDD&D support such as through Mission Innovation and overlaid on top of the Advanced Technology assumptions. Major changes from the Advanced Technology assumptions include: changes to costs for a representative advanced nuclear plant, new and retrofitted coal and new natural gas combined cycle CCUS plants, onshore and offshore wind, central and distributed solar, hydropower plants and geothermal sites; increased hydropower and geothermal resource availability; reduced costs for biofuel processing; improved light-duty vehicle battery, light-weighting, and electric drive systems; increased efficiency for heavy duty vehicles; reduced cost of hydrogen; improved manufacturing and industrial motor system efficiency; increased efficiency for building appliances; increased maximum percentage of variable generation allowed on the electric grid, enabled by advances in grid modernization.

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[5] Documentation found at: "Table 1: Summary of AEO2015 Cases" in the AEO 2015 Report, available at http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf.

[6] The federal renewable tax credits were extended in the *Consolidated Appropriations Act, 2016*, which is available at https://www.congress.gov/114/bills/hr2029/BILLS-114hr2029enr.xml. Summaries of the current federal production and investment tax credits can be found at http://programs.dsireusa.org/system/program/detail/734 and http://programs.dsireusa.org/system/program/detail/658, respectively.

[7] Cost and performance characteristics are based on the National Energy Technology Laboratory (NETL) Baseline Studies (new units with CCS): https://www.netl.doe.gov/research/energy-analysis/baseline-studies, and the NETL Quality Guidelines for Energy System Studies (retrofit of existing units with CCS): http://www.netl.doe.gov/energy-analyses/temp/QGESSRetrofitDifficultyFactors_083013.pdf, and http://www.netl.doe.gov/energy-analyses/temp/QGESSCapitalCostScalingMethodology_013113.pdf.

Further details on these and other aspects of DOE analysis aree forthcoming on the DOE website.

Advanced Technology Assumptions

Bioenergy: Reductions in biofuel costs for cellulosic ethanol and biofuel liquids processed using Fischer-Tropsch or pyrolysis pathways to achieve goals of $2.65 and $3.00 per gallon with biomass feedstock cost of $84 per ton (EERE BETO biomass cost assumption) ready for commercialization in 2020 and 2025; additional capital cost reductions from learning as more capacity is built after near-term goals are reached. Biomass-to-liquids processing conversion efficiency improved and planned new capacity of 50 million gallons/year of advanced biofuels by 2020 included (EERE BETO goals and sponsored demonstration).

Vehicles: Changes in vehicle costs and improved fuel economy for all vehicle types, and increase in availability of hybrid, electric vehicles (EVs), and fuel cell electric vehicles (FCEVs), leading to a 38% increase in average light-duty vehicle fuel economy sold in 2040 and a 21% increase in the on-road fleet average (vehicle attributes by type from Argonne National Laboratory Autonomie study[i]) in 2040 relative to the EPSA Base Case.

Vehicles: Modification of heavy duty-vehicle (HDV) types to better represent EERE VTO HDV classifications and changes in HDV costs and projected fuel economy by vehicle class (following BaSCe analysis of VTO program[ii]) leading to an average 20% improvement in new HDV fuel economy by 2040 and a 15% improvement in average HDV fuel economy by 2040 relative to the EPSA Base Case.

Fuel Cells: Short and long term cost reductions for the retail price of hydrogen, \$7/kg-H_2 ramping down to \$4/kg-H_2 by 2020 and held constant thereafter. For the fuel cell electric vehicles, costs and fuel economies from Argonne National Laboratory Autonomie outputs.

Buildings: For residential and commercial buildings, increased stringency of appliance standards and building codes, improved new building shell technology performance, introduced new cost effective energy efficient technologies, increased the rate of building shell upgrades, and increased consumer acceptance of high efficiency products (represented by lowering hurdle rates to 7 percent by 2025 and removal of non-economic decision-making factors) leading to achievement of the EERE BTO goal of reducing energy use per square foot in all U.S. buildings by 30% in 2030 from 2010 levels, with a longer term goal of achieving a 50% reduction.

Advanced Manufacturing: EIA AEO industrial high tech assumptions (earlier availability, lower costs, and higher efficiency industrial equipment and a more rapid rate of improvement in the recovery of biomass byproducts from industrial processes) combined with technology improvements, which yields more efficient energy use for pulp & paper, iron & steel, petroleum refining, chemicals, and cement (2007 and 2015 AMO Bandwidth studies[iii]), and updated data on the use of recycled aluminum (2006 – 2014 USGS Minerals Yearbook[iv]).

Fossil Energy: Improvements to capital cost trajectories, heat rates, and fixed and variable operating and maintenance costs for new full capture coal and NGCC CCUS plants, partial capture coal CCUS plants, and existing coal units that are retrofitted with CCUS.

Nuclear: 9% reduction in projected overnight capital costs for state-of-the art nuclear technology in 2025 and 32% by 2040 relative to the EPSA Base Case. O&M costs reduced by about 9% and new nuclear plant build times reduced from 6 to 5 years. Assumes existing nuclear plants will receive license extensions to operate for 80 years, with no early retirements. Note that recently announced retirements of nuclear generating units were not included in this analysis.

Electricity Delivery and Grid Modernization: Share of new transmission capacity applied to reserves increased from 75% to 85% reflecting improved sensors & controls and enhanced regional coordination. Available capacity on existing transmission lines was increased from 75% to 85%. Spinning reserve requirements for variable renewables decreased from 50% to 30% of generation, reflecting more use of energy storage and other demand side capabilities. Maximum use of load shifting technologies for reducing peak demand tripled from a national average of 3.5% to 11% by 2040, reflecting greater use of distributed energy resources and storage technologies. Improvement in utility grid interconnection limitation factors for new distributed generation in buildings was accelerated by 10 years.

Solar: Cost reductions for utility-scale, commercial, and residential PV following the Draft 2016 NREL Annual Technology Baseline (ATB) Low Case. Solar thermal/concentrated solar power (CSP) was modified to reflect a technology with 6-hours of electricity storage, leading to improved capacity factors and capital costs that are higher in the near term than the EPSA Base Case assumptions. By 2040, capital costs are 22% below the EPSA Base Case and O&M costs are 41% below the EPSA Base Case.

Wind:[8] For onshore and offshore wind power, capital costs were reduced from the EPSA Base Case by 20% and 32% respectively by 2020, and reduced by 19% and 44%, respectively, by 2040 for the best wind classes, with more modest reductions for lower wind classes based on the draft 2016 ATB Low Case.[v] Capacity factors were also improved, ranging from roughly a 13% to 28% increase for onshore wind by 2020 and a 24% to 44% increase by 2040, and a 15% to 19% increase for offshore wind by 2020 and a 28% to 34% increase by 2040 compared to the EPSA Base Case. Also lengthened the onshore wind PTC eligibility schedule by 1 year and increased the construction time from 3 to 4 years based on new IRS guidance.

Hydropower: Improved the site-specific costs, performance and resource availability for some hydropower sites, including adding upgrade options for existing sites.

Geothermal: Reduced site-specific costs for geothermal flash, binary and enhanced geothermal sites by 12.5% by 2040 compared to current costs, following the Draft 2016 NREL ATB.[vi]

Stretch Technology Assumptions

Bioenergy: Decreased cost of biofuels (biomass-to-liquids and pyrolysis) from $3/gallon in the Advanced Technology assumptions to $2.50/gallon by 2040 (at $84/ton biomass). Increased number of initial biofuel plants from 3 to 30 before NEMS growth limits start to apply. Same new planned capacity as for Advanced Technology assumptions included for Stretch Technology assumptions.

Vehicles: LDVs: Modified vehicle choice model to allow all types of LDVs to compete on vehicle attributes only. Advanced Technology cost assumptions plus an additional 4% weight reduction due to vehicle light-weighting by reducing fuel consumption by 6% (conventional/hybrid) or 4% (EVs) for every 10% decrease in vehicle weight. Reduced the cost of energy storage for plug-in hybrid EVs (PHEVs) and

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[8] The ATB Low Case does not capture all of the projected cost reductions anticipated in the current Wind Program Goals.

battery EVs (BEVs) to $100/kWh by 2030, compared to $120/kWh in the Advanced Technology assumptions.

Vehicles: HDVs: Advanced Technology cost assumptions plus increased maximum market penetration rate for hybrids and advanced conventional vehicles (following Super Truck definition); accelerated adoption of advanced conventional and hybrid vehicles by modifying S-shape diffusion curve 50% parameter from 14 to 10 years.

Fuel Cells: Reduced the modeled commercial scale cost of automotive fuel cells to $35/kW by 2030, and $30/kW by 2040. Reduced the cost of hydrogen (dispensed and untaxed) to $4.00/gge[9] in 2020, to $3.00 in 2030 and to $2.50 in 2040 (on the path towards $2.00 in 2050). Assumed all hydrogen was produced from renewable sources and had no GHG emissions associated with production.

Buildings: Residential Buildings: Advanced technology assumptions with the following changes: Reduced energy consumption by 40% from 2009 by 2030 for miscellaneous electric loads (MELs); removed the option for building shell packages that achieve less than 50% energy reduction from IECC 2009 levels from 2030 onwards.

Buildings: Commercial Buildings: Advanced technology assumptions with the following changes: for Miscellaneous Electronic Loads other than office equipment), flat energy use intensity after 2010. Modified new building shells to represent 100% adoption of a 50% reduction relative to the ASHRAE 90.1-2007 standards which is equivalent to a 29% improvement from the EPSA Base Case.

Geothermal: Increased efficiency for the least efficient geothermal heat pumps for use in residential and commercial buildings.

Advanced Manufacturing: For all of the non-refining manufacturing processes except cement & lime, aluminum, and glass, improved process efficiency by 50% beyond the EPSA Base Case by 2040. Improved industrial motor-driven system efficiency for pumps, fans and air compressors following Annual Energy Outlook 2014 Low Electricity Demand[vii] case. Net result is an approximately 20% reduction in non-refining industrial energy consumption by 2040 relative to the EPSA Base Case.

Fossil Energy: Improvements in capital costs, O&M costs, and heat rates for CCUS technologies are accelerated in the Stretch Technology assumptions, reaching the same long-term goals as the Advanced Technology assumptions 8 years earlier (by 2030).

Nuclear: 14% reduction in projected overnight capital costs for state-of-the art nuclear technology in 2025 and 30% by 2040 relative to the Advanced Technology assumptions (22% in 2025 and 53% from the EPSA Base Case). O&M costs reduced by 28% from Advanced Tech assumptions and new nuclear plant build times reduced from 5 years to 4 years.

Electricity Delivery and Grid Modernization: Advanced Technology assumptions plus increased maximum percentage of regional variable generation from 40% to 50%, enabled by grid advances.

Solar:[10] Similar overnight capital cost trajectories for utility solar PV as for Advanced Technology assumptions with no change in 2020 and 2025, but ramping down to a 13% reduction from the Advanced Technology assumptions and 52% improvement in O&M costs by 2040. For CSP, approximately a 35%

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[9] Gallon Gasoline Equivalent

[10] The Solar Energy Technologies Office has updated its technology cost and performance goals since this analysis was performed. The newly updated goal – to cut the levelized cost of electricity (LCOE) from utility-scale solar by an additional 50% between 2020 and 2030 to $0.03 per kilowatt hour, while also addressing grid integration.

reduction in overnight capital costs from the Advanced Technology assumptions in 2020 and then approximately a 6% cost reduction compared to the Advanced Technology assumptions out to 2040. 14% reduction in O&M costs for CSP from Advanced Technology assumptions. Reduced capital and O&M costs for rooftop solar PV in residential and commercial buildings by ~40% for capital and ~60% for O&M by 2040 compared to the Advanced Technology assumptions, and reduced degradation in PV panels.

Wind: Same capacity factors, construction time and similar fixed O&M costs as for the Advanced Technology assumptions. 25% lower overnight capital costs in 2025, and 55% lower overnight capital costs from 2030 onwards for onshore wind as compared to Advanced Technology assumptions. For offshore wind, 14% lower overnight capital costs in 2025 and ~50% lower overnight capital costs from 2030 onwards as compared to Advanced Technology assumptions.

Hydropower: Advanced Technology assumptions plus further reduced overnight capital costs for new stream reach development and non-powered dams by an additional 42% and 51%, respectively, beyond the Advanced Technology costs by 2040.

Geothermal: Added undiscovered hydrothermal and deep Enhanced Geothermal System sites and reduced initial costs for existing sites by 40% relative to the EPSA Base Case; by 2040, overnight capital costs are further reduced by 35%.

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[v] National Renewable Energy Laboratory, "Annual Technology baseline and Standard Scenarios." Available at http://www.nrel.gov/analysis/data_tech_baseline.html.

[vi] National Renewable Energy Laboratory, "Annual Technology baseline and Standard Scenarios." Available at http://www.nrel.gov/analysis/data_tech_baseline.html.

[vii] U.S. Energy Information Administration, "Annual Energy Outlook 2014", http://www.eia.gov/forecasts/archive/aeo14/.

Appendix C – GCAM-USA Model Output

Table C.1: GHG Emissions

		2005	2050	Units
Benchmark	Non-CO2	1.187	1.026	GtCO2e
Benchmark	CO2-Fossil Fuel and Industry	5.917	1.527	GtCO2e
Benchmark	CO2-LUC	-0.401	-0.645	GtCO2e
Benchmark	CO2 Removal	0.000	-0.574	GtCO2e
		2005	**2050**	**Units**
No CO2 Removal Technology	Non-CO2	1.187	0.970	GtCO2e
No CO2 Removal Technology	CO2-Fossil Fuel and Industry	5.917	1.276	GtCO2e
No CO2 Removal Technology	CO2-LUC	-0.401	-0.912	GtCO2e
No CO2 Removal Technology	CO2 Removal	0.000	0.000	GtCO2e
		2005	**2050**	**Units**
Limited Sink	Non-CO2	1.187	1.056	GtCO2e
Limited Sink	CO2-Fossil Fuel and Industry	5.917	0.833	GtCO2e
Limited Sink	CO2-LUC	-0.401	-0.409	GtCO2e
Limited Sink	CO2 Removal	0.000	-0.145	GtCO2e
		2005	**2050**	**Units**
Smart Growth	Non-CO2	1.187	0.997	GtCO2e
Smart Growth	CO2-Fossil Fuel and Industry	5.917	1.295	GtCO2e
Smart Growth	CO2-LUC	-0.401	-0.736	GtCO2e
Smart Growth	CO2 Removal	0.000	-0.221	GtCO2e
		2005	**2050**	**Units**
No CCUS	Non-CO2	1.187	0.930	GtCO2e
No CCUS	CO2-Fossil Fuel and Industry	5.917	1.327	GtCO2e
No CCUS	CO2-LUC	-0.401	-0.922	GtCO2e
No CCUS	CO2 Removal	0.000	0.000	GtCO2e
		2005	**2050**	**Units**
Limited Biomass	Non-CO2	1.187	0.960	GtCO2e
Limited Biomass	CO2-Fossil Fuel and Industry	5.917	1.360	GtCO2e
Limited Biomass	CO2-LUC	-0.401	-0.985	GtCO2e
Limited Biomass	CO2 Removal	0.000	0.000	GtCO2e
		2005	**2050**	**Units**
Beyond 80	Non-CO2	1.187	0.981	GtCO2e
Beyond 80	CO2-Fossil Fuel and Industry	5.917	1.068	GtCO2e
Beyond 80	CO2-LUC	-0.401	-0.889	GtCO2e
Beyond 80	CO2 Removal	0.000	-0.493	GtCO2e

Table C.2: Primary Energy

		2005	2050	Units
Benchmark	Oil	40.613	14.371	EJ
Benchmark	Oil w/ CCS	0.000	0.000	EJ
Benchmark	Gas	21.389	15.065	EJ
Benchmark	Gas w/ CCS	0.000	4.566	EJ
Benchmark	Coal	22.693	0.547	EJ
Benchmark	Coal w/ CCS	0.000	5.712	EJ
Benchmark	Biomass	3.227	5.321	EJ
Benchmark	Biomass w/ CCS	0.000	10.479	EJ
Benchmark	Nuclear	2.919	4.511	EJ
Benchmark	Hydro	0.982	0.945	EJ
Benchmark	Wind	0.064	7.896	EJ
Benchmark	Solar	0.004	4.201	EJ
Benchmark	Geothermal	0.060	0.334	EJ
		2005	**2050**	**Units**
No CO2 Removal Technology	Oil	40.613	13.242	EJ
No CO2 Removal Technology	Oil w/ CCS	0.000	0.000	EJ
No CO2 Removal Technology	Gas	21.389	12.033	EJ
No CO2 Removal Technology	Gas w/ CCS	0.000	6.060	EJ
No CO2 Removal Technology	Coal	22.693	0.294	EJ
No CO2 Removal Technology	Coal w/ CCS	0.000	5.982	EJ
No CO2 Removal Technology	Biomass	3.227	13.921	EJ
No CO2 Removal Technology	Biomass w/ CCS	0.000	0.000	EJ
No CO2 Removal Technology	Nuclear	2.919	4.841	EJ
No CO2 Removal Technology	Hydro	0.982	0.945	EJ
No CO2 Removal Technology	Wind	0.064	8.617	EJ
No CO2 Removal Technology	Solar	0.004	4.699	EJ
No CO2 Removal Technology	Geothermal	0.060	0.362	EJ
		2005	**2050**	**Units**
Limited Sink	Oil	40.613	10.727	EJ
Limited Sink	Oil w/ CCS	0.000	0.000	EJ
Limited Sink	Gas	21.389	7.284	EJ
Limited Sink	Gas w/ CCS	0.000	5.118	EJ
Limited Sink	Coal	22.693	0.155	EJ
Limited Sink	Coal w/ CCS	0.000	5.998	EJ
Limited Sink	Biomass	3.227	13.883	EJ
Limited Sink	Biomass w/ CCS	0.000	1.917	EJ
Limited Sink	Nuclear	2.919	5.779	EJ
Limited Sink	Hydro	0.982	0.945	EJ
Limited Sink	Wind	0.064	10.667	EJ

Limited Sink	Solar	0.004	4.848	EJ
Limited Sink	Geothermal	0.060	0.410	EJ
		2005	**2050**	**Units**
Smart Growth	Oil	40.613	16.005	EJ
Smart Growth	Oil w/ CCS	0.000	0.000	EJ
Smart Growth	Gas	21.389	14.768	EJ
Smart Growth	Gas w/ CCS	0.000	3.669	EJ
Smart Growth	Coal	22.693	0.352	EJ
Smart Growth	Coal w/ CCS	0.000	4.374	EJ
Smart Growth	Biomass	3.227	4.387	EJ
Smart Growth	Biomass w/ CCS	0.000	9.613	EJ
Smart Growth	Nuclear	2.919	3.801	EJ
Smart Growth	Hydro	0.982	0.945	EJ
Smart Growth	Wind	0.064	6.050	EJ
Smart Growth	Solar	0.004	3.288	EJ
Smart Growth	Geothermal	0.060	0.239	EJ
		2005	**2050**	**Units**
No CCUS	Oil	40.613	13.297	EJ
No CCUS	Oil w/ CCS	0.000	0.000	EJ
No CCUS	Gas	21.389	14.068	EJ
No CCUS	Gas w/ CCS	0.000	0.000	EJ
No CCUS	Coal	22.693	0.195	EJ
No CCUS	Coal w/ CCS	0.000	0.000	EJ
No CCUS	Biomass	3.227	12.570	EJ
No CCUS	Biomass w/ CCS	0.000	0.000	EJ
No CCUS	Nuclear	2.919	7.283	EJ
No CCUS	Hydro	0.982	0.945	EJ
No CCUS	Wind	0.064	10.463	EJ
No CCUS	Solar	0.004	5.741	EJ
No CCUS	Geothermal	0.060	0.407	EJ
		2005	**2050**	**Units**
Limited Biomass	Oil	40.613	14.426	EJ
Limited Biomass	Oil w/ CCS	0.000	0.000	EJ
Limited Biomass	Gas	21.389	11.868	EJ
Limited Biomass	Gas w/ CCS	0.000	6.742	EJ
Limited Biomass	Coal	22.693	0.238	EJ
Limited Biomass	Coal w/ CCS	0.000	6.090	EJ
Limited Biomass	Biomass	3.227	8.500	EJ
Limited Biomass	Biomass w/ CCS	0.000	0.000	EJ
Limited Biomass	Nuclear	2.919	5.021	EJ
Limited Biomass	Hydro	0.982	0.945	EJ

Limited Biomass	Wind	0.064	9.010	EJ
Limited Biomass	Solar	0.004	4.862	EJ
Limited Biomass	Geothermal	0.060	0.372	EJ
		2005	**2050**	**Units**
Beyond 80	Coal	22.693	0.310	EJ
Beyond 80	Oil	40.613	12.269	EJ
Beyond 80	Gas	21.389	10.745	EJ
Beyond 80	CCS	0.000	5.020	EJ
Beyond 80	Carbon Free	7.256	36.649	EJ

Table C.3: Electricity Generation

		2005	2050	Units
Benchmark	Oil w/o CCS	0.509	0.016	EJ
Benchmark	Oil w/ CCS	0.000	0.000	EJ
Benchmark	Gas w/o CCS	2.842	2.072	EJ
Benchmark	Gas w/ CCS	0.000	2.749	EJ
Benchmark	Coal w/o CCS	7.754	0.078	EJ
Benchmark	Coal w/ CCS	0.000	2.536	EJ
Benchmark	Biomass w/o CCS	0.233	0.127	EJ
Benchmark	Biomass w/ CCS	0.000	1.228	EJ
Benchmark	Nuclear	2.919	4.511	EJ
Benchmark	Hydro	0.982	0.945	EJ
Benchmark	Wind	0.064	7.896	EJ
Benchmark	Solar	0.004	4.201	EJ
Benchmark	Geothermal	0.060	0.334	EJ
		2005	**2050**	**Units**
No CO2 Removal Technology	Oil w/o CCS	0.509	0.011	EJ
No CO2 Removal Technology	Oil w/ CCS	0.000	0.000	EJ
No CO2 Removal Technology	Gas w/o CCS	2.842	1.215	EJ
No CO2 Removal Technology	Gas w/ CCS	0.000	3.674	EJ
No CO2 Removal Technology	Coal w/o CCS	7.754	0.016	EJ
No CO2 Removal Technology	Coal w/ CCS	0.000	2.698	EJ
No CO2 Removal Technology	Biomass w/o CCS	0.233	0.366	EJ
No CO2 Removal Technology	Biomass w/ CCS	0.000	0.000	EJ
No CO2 Removal Technology	Nuclear	2.919	4.841	EJ
No CO2 Removal Technology	Hydro	0.982	0.945	EJ
No CO2 Removal Technology	Wind	0.064	8.617	EJ
No CO2 Removal Technology	Solar	0.004	4.699	EJ
No CO2 Removal Technology	Geothermal	0.060	0.362	EJ
		2005	**2050**	**Units**
Limited Sink	Oil w/o CCS	0.509	0.004	EJ
Limited Sink	Oil w/ CCS	0.000	0.000	EJ
Limited Sink	Gas w/o CCS	2.842	0.110	EJ
Limited Sink	Gas w/ CCS	0.000	3.081	EJ
Limited Sink	Coal w/o CCS	7.754	0.001	EJ
Limited Sink	Coal w/ CCS	0.000	2.705	EJ
Limited Sink	Biomass w/o CCS	0.233	0.088	EJ
Limited Sink	Biomass w/ CCS	0.000	0.589	EJ
Limited Sink	Nuclear	2.919	5.779	EJ
Limited Sink	Hydro	0.982	0.945	EJ
Limited Sink	Wind	0.064	10.667	EJ

Limited Sink	Solar	0.004	4.848	EJ
Limited Sink	Geothermal	0.060	0.410	EJ
		2005	**2050**	**Units**
Smart Growth	Oil w/o CCS	0.509	0.011	EJ
Smart Growth	Oil w/ CCS	0.000	0.000	EJ
Smart Growth	Gas w/o CCS	2.842	1.037	EJ
Smart Growth	Gas w/ CCS	0.000	2.223	EJ
Smart Growth	Coal w/o CCS	7.754	0.020	EJ
Smart Growth	Coal w/ CCS	0.000	1.904	EJ
Smart Growth	Biomass w/o CCS	0.233	0.041	EJ
Smart Growth	Biomass w/ CCS	0.000	0.937	EJ
Smart Growth	Nuclear	2.919	3.801	EJ
Smart Growth	Hydro	0.982	0.945	EJ
Smart Growth	Wind	0.064	6.050	EJ
Smart Growth	Solar	0.004	3.288	EJ
Smart Growth	Geothermal	0.060	0.239	EJ
		2005	**2050**	**Units**
No CCUS	Oil w/o CCS	0.509	0.010	EJ
No CCUS	Oil w/ CCS	0.000	0.000	EJ
No CCUS	Gas w/o CCS	2.842	2.290	EJ
No CCUS	Gas w/ CCS	0.000	0.000	EJ
No CCUS	Coal w/o CCS	7.754	0.009	EJ
No CCUS	Coal w/ CCS	0.000	0.000	EJ
No CCUS	Biomass w/o CCS	0.233	0.386	EJ
No CCUS	Biomass w/ CCS	0.000	0.000	EJ
No CCUS	Nuclear	2.919	7.283	EJ
No CCUS	Hydro	0.982	0.945	EJ
No CCUS	Wind	0.064	10.463	EJ
No CCUS	Solar	0.004	5.741	EJ
No CCUS	Geothermal	0.060	0.407	EJ
		2005	**2050**	**Units**
Limited Biomass	Oil w/o CCS	0.509	0.008	EJ
Limited Biomass	Oil w/ CCS	0.000	0.000	EJ
Limited Biomass	Gas w/o CCS	2.842	0.792	EJ
Limited Biomass	Gas w/ CCS	0.000	4.093	EJ
Limited Biomass	Coal w/o CCS	7.754	0.006	EJ
Limited Biomass	Coal w/ CCS	0.000	2.736	EJ
Limited Biomass	Biomass w/o CCS	0.233	0.218	EJ
Limited Biomass	Biomass w/ CCS	0.000	0.000	EJ
Limited Biomass	Nuclear	2.919	5.021	EJ
Limited Biomass	Hydro	0.982	0.945	EJ

Limited Biomass	Wind	0.064	9.010	EJ
Limited Biomass	Solar	0.004	4.862	EJ
Limited Biomass	Geothermal	0.060	0.372	EJ
		2005	**2050**	**Units**
Beyond 80	Coal	7.754	0.004	EJ
Beyond 80	Oil	0.509	0.015	EJ
Beyond 80	Gas	2.842	0.409	EJ
Beyond 80	CCS	0.000	2.487	EJ
Beyond 80	Carbon Free	4.262	23.187	EJ

Table C.4: Industry Final Energy

		2005	**2050**	**Units**
Benchmark	Coal	1.650	0.235	EJ
Benchmark	Oil	2.307	1.332	EJ
Benchmark	Gas	6.380	3.056	EJ
Benchmark	Bioenergy	1.669	1.680	EJ
Benchmark	Elec (High CO2)	2.506	0.573	EJ
Benchmark	Elec (Low CO2)	0.962	6.850	EJ
		2005	**2050**	**Units**
No CO2 Removal Technology	Coal	1.650	0.151	EJ
No CO2 Removal Technology	Oil	2.307	1.113	EJ
No CO2 Removal Technology	Gas	6.380	2.290	EJ
No CO2 Removal Technology	Bioenergy	1.669	1.771	EJ
No CO2 Removal Technology	Elec (High CO2)	2.506	0.342	EJ
No CO2 Removal Technology	Elec (Low CO2)	0.962	7.570	EJ
		2005	**2050**	**Units**
Limited Sink	Coal	1.650	0.057	EJ
Limited Sink	Oil	2.307	0.671	EJ
Limited Sink	Gas	6.380	1.330	EJ
Limited Sink	Bioenergy	1.669	1.430	EJ
Limited Sink	Elec (High CO2)	2.506	0.034	EJ
Limited Sink	Elec (Low CO2)	0.962	8.876	EJ
		2005	**2050**	**Units**
Smart Growth	Coal	1.650	0.182	EJ
Smart Growth	Oil	2.307	1.288	EJ
Smart Growth	Gas	6.380	3.013	EJ
Smart Growth	Bioenergy	1.669	1.203	EJ
Smart Growth	Elec (High CO2)	2.506	0.372	EJ
Smart Growth	Elec (Low CO2)	0.962	7.185	EJ
		2005	**2050**	**Units**
No CCUS	Coal	1.650	0.119	EJ
No CCUS	Oil	2.307	1.088	EJ
No CCUS	Gas	6.380	2.168	EJ
No CCUS	Bioenergy	1.669	1.602	EJ
No CCUS	Elec (High CO2)	2.506	0.637	EJ
No CCUS	Elec (Low CO2)	0.962	7.244	EJ
		2005	**2050**	**Units**
Limited Biomass	Coal	1.650	0.119	EJ
Limited Biomass	Oil	2.307	1.085	EJ
Limited Biomass	Gas	6.380	2.144	EJ
Limited Biomass	Bioenergy	1.669	1.123	EJ

Limited Biomass	Elec (High CO2)	2.506	0.229	EJ
Limited Biomass	Elec (Low CO2)	0.962	8.085	EJ
		2005	**2050**	**Units**
Beyond 80	Coal	1.650	0.137	EJ
Beyond 80	Oil	2.307	0.898	EJ
Beyond 80	Gas	6.380	1.961	EJ
Beyond 80	Bioenergy	1.669	1.000	EJ
Beyond 80	Elec (High CO2)	2.506	0.135	EJ
Beyond 80	Elec (Low CO2)	0.962	8.315	EJ

Table C.5: Buildings Final Energy

		2005	**2050**	**Units**
Benchmark	Coal	0.088	0.000	EJ
Benchmark	Oil	1.887	0.067	EJ
Benchmark	Gas	7.541	3.919	EJ
Benchmark	Bioenergy	0.649	0.371	EJ
Benchmark	Elec (High CO2)	7.192	1.014	EJ
Benchmark	Elec (Low CO2)	2.760	11.488	EJ
		2005	**2050**	**Units**
No CO2 Removal Technology	Coal	0.088	0.000	EJ
No CO2 Removal Technology	Oil	1.887	0.063	EJ
No CO2 Removal Technology	Gas	7.541	3.590	EJ
No CO2 Removal Technology	Bioenergy	0.649	0.537	EJ
No CO2 Removal Technology	Elec (High CO2)	7.192	0.568	EJ
No CO2 Removal Technology	Elec (Low CO2)	2.760	11.993	EJ
		2005	**2050**	**Units**
Limited Sink	Coal	0.088	0.000	EJ
Limited Sink	Oil	1.887	0.055	EJ
Limited Sink	Gas	7.541	2.552	EJ
Limited Sink	Bioenergy	0.649	0.701	EJ
Limited Sink	Elec (High CO2)	7.192	0.051	EJ
Limited Sink	Elec (Low CO2)	2.760	12.765	EJ
		2005	**2050**	**Units**
Smart Growth	Coal	0.088	0.000	EJ
Smart Growth	Oil	1.887	0.305	EJ
Smart Growth	Gas	7.541	4.376	EJ
Smart Growth	Bioenergy	0.649	0.527	EJ
Smart Growth	Elec (High CO2)	7.192	0.507	EJ
Smart Growth	Elec (Low CO2)	2.760	9.216	EJ
		2005	**2050**	**Units**
No CCUS	Coal	0.088	0.000	EJ
No CCUS	Oil	1.887	0.062	EJ
No CCUS	Gas	7.541	3.498	EJ
No CCUS	Bioenergy	0.649	0.490	EJ
No CCUS	Elec (High CO2)	7.192	1.053	EJ
No CCUS	Elec (Low CO2)	2.760	11.510	EJ
		2005	**2050**	**Units**
Limited Biomass	Coal	0.088	0.000	EJ
Limited Biomass	Oil	1.887	0.070	EJ
Limited Biomass	Gas	7.541	3.659	EJ
Limited Biomass	Bioenergy	0.649	0.323	EJ

Limited Biomass	Elec (High CO2)	7.192	0.362	EJ
Limited Biomass	Elec (Low CO2)	2.760	12.251	EJ
		2005	**2050**	**Units**
Beyond 80	Coal	0.088	0.000	EJ
Beyond 80	Oil	1.887	0.273	EJ
Beyond 80	Gas	7.541	4.242	EJ
Beyond 80	Bioenergy	0.649	0.583	EJ
Beyond 80	Elec (High CO2)	7.192	0.180	EJ
Beyond 80	Elec (Low CO2)	2.760	10.785	EJ

Table C.6: Transportation Final Energy

		2005	**2050**	**Units**
Benchmark	Coal	0.000	0.000	EJ
Benchmark	Oil	27.529	8.292	EJ
Benchmark	Gas	0.022	1.877	EJ
Benchmark	Bioenergy	0.239	3.221	EJ
Benchmark	Elec (High CO2)	0.019	0.328	EJ
Benchmark	Elec (Low CO2)	0.007	3.834	EJ
		2005	**2050**	**Units**
No CO2 Removal Technology	Coal	0.000	0.000	EJ
No CO2 Removal Technology	Oil	27.529	7.664	EJ
No CO2 Removal Technology	Gas	0.022	1.772	EJ
No CO2 Removal Technology	Bioenergy	0.239	3.602	EJ
No CO2 Removal Technology	Elec (High CO2)	0.019	0.187	EJ
No CO2 Removal Technology	Elec (Low CO2)	0.007	4.057	EJ
		2005	**2050**	**Units**
Limited Sink	Coal	0.000	0.000	EJ
Limited Sink	Oil	27.529	6.229	EJ
Limited Sink	Gas	0.022	1.331	EJ
Limited Sink	Bioenergy	0.239	3.975	EJ
Limited Sink	Elec (High CO2)	0.019	0.018	EJ
Limited Sink	Elec (Low CO2)	0.007	4.622	EJ
		2005	**2050**	**Units**
Smart Growth	Coal	0.000	0.000	EJ
Smart Growth	Oil	27.529	9.701	EJ
Smart Growth	Gas	0.022	2.717	EJ
Smart Growth	Bioenergy	0.239	3.364	EJ
Smart Growth	Elec (High CO2)	0.019	0.066	EJ
Smart Growth	Elec (Low CO2)	0.007	1.383	EJ
		2005	**2050**	**Units**
No CCUS	Coal	0.000	0.000	EJ
No CCUS	Oil	27.529	7.660	EJ
No CCUS	Gas	0.022	1.755	EJ
No CCUS	Bioenergy	0.239	3.381	EJ
No CCUS	Elec (High CO2)	0.019	0.351	EJ
No CCUS	Elec (Low CO2)	0.007	3.951	EJ
		2005	**2050**	**Units**
Limited Biomass	Coal	0.000	0.000	EJ
Limited Biomass	Oil	27.529	8.417	EJ
Limited Biomass	Gas	0.022	1.846	EJ
Limited Biomass	Bioenergy	0.239	2.425	EJ

Limited Biomass	Elec (High CO2)	0.019	0.121	EJ
Limited Biomass	Elec (Low CO2)	0.007	4.213	EJ
		2005	**2050**	**Units**
Beyond 80	Coal	0.000	0.000	EJ
Beyond 80	Oil	27.529	6.860	EJ
Beyond 80	Gas	0.022	0.869	EJ
Beyond 80	Bioenergy	0.239	3.466	EJ
Beyond 80	Elec (High CO2)	0.019	0.064	EJ
Beyond 80	Elec (Low CO2)	0.007	4.595	EJ

Table C.7: Vehicle Miles Traveled – Light-Duty Vehicles

		2005	**2050**	**Units**
Benchmark	Gasoline/Diesel Vehicle	6.642	1.389	Trillion Passenger-Km
Benchmark	Hybrid Vehicle	0.007	1.252	Trillion Passenger-Km
Benchmark	Natural Gas Vehicle	0.000	0.467	Trillion Passenger-Km
Benchmark	Biofuel Vehicle	0.000	0.996	Trillion Passenger-Km
Benchmark	Electric Vehicle	0.000	5.534	Trillion Passenger-Km
Benchmark	Fuel Cell Vehicle	0.000	0.148	Trillion Passenger-Km
		2005	**2050**	**Units**
No CO2 Removal Technology	Gasoline/Diesel Vehicle	6.642	1.289	Trillion Passenger-Km
No CO2 Removal Technology	Hybrid Vehicle	0.007	1.169	Trillion Passenger-Km
No CO2 Removal Technology	Natural Gas Vehicle	0.000	0.460	Trillion Passenger-Km
No CO2 Removal Technology	Biofuel Vehicle	0.000	1.094	Trillion Passenger-Km
No CO2 Removal Technology	Electric Vehicle	0.000	5.611	Trillion Passenger-Km
No CO2 Removal Technology	Fuel Cell Vehicle	0.000	0.148	Trillion Passenger-Km
		2005	**2050**	**Units**
Limited Sink	Gasoline/Diesel Vehicle	6.642	1.050	Trillion Passenger-Km
Limited Sink	Hybrid Vehicle	0.007	0.985	Trillion Passenger-Km
Limited Sink	Natural Gas Vehicle	0.000	0.352	Trillion Passenger-Km
Limited Sink	Biofuel Vehicle	0.000	1.210	Trillion Passenger-Km
Limited Sink	Electric Vehicle	0.000	5.970	Trillion Passenger-Km
Limited Sink	Fuel Cell Vehicle	0.000	0.154	Trillion Passenger-Km
		2005	**2050**	**Units**
Smart Growth	Gasoline/Diesel Vehicle	6.642	2.016	Trillion Passenger-Km
Smart Growth	Hybrid Vehicle	0.007	1.836	Trillion Passenger-Km
Smart Growth	Natural Gas Vehicle	0.000	0.668	Trillion Passenger-Km
Smart Growth	Biofuel Vehicle	0.000	1.305	Trillion Passenger-Km
Smart Growth	Electric Vehicle	0.000	1.697	Trillion Passenger-Km
Smart Growth	Fuel Cell Vehicle	0.000	0.218	Trillion Passenger-Km
		2005	**2050**	**Units**
No CCUS	Gasoline/Diesel Vehicle	6.642	1.288	Trillion Passenger-Km
No CCUS	Hybrid Vehicle	0.007	1.175	Trillion Passenger-Km
No CCUS	Natural Gas Vehicle	0.000	0.449	Trillion Passenger-Km
No CCUS	Biofuel Vehicle	0.000	1.030	Trillion Passenger-Km
No CCUS	Electric Vehicle	0.000	5.670	Trillion Passenger-Km
No CCUS	Fuel Cell Vehicle	0.000	0.144	Trillion Passenger-Km
		2005	**2050**	**Units**
Limited Biomass	Gasoline/Diesel Vehicle	6.642	1.419	Trillion Passenger-Km
Limited Biomass	Hybrid Vehicle	0.007	1.297	Trillion Passenger-Km
Limited Biomass	Natural Gas Vehicle	0.000	0.451	Trillion Passenger-Km
Limited Biomass	Biofuel Vehicle	0.000	0.750	Trillion Passenger-Km

Limited Biomass	Electric Vehicle	0.000	5.695	Trillion Passenger-Km
Limited Biomass	Fuel Cell Vehicle	0.000	0.149	Trillion Passenger-Km
		2005	**2050**	**Units**
Beyond 80	Gasoline/Diesel Vehicle	6.642	1.274	Trillion Passenger-Km
Beyond 80	Hybrid Vehicle	0.007	1.095	Trillion Passenger-Km
Beyond 80	Natural Gas Vehicle	0.000	0.190	Trillion Passenger-Km
Beyond 80	Biofuel Vehicle	0.000	1.187	Trillion Passenger-Km
Beyond 80	Electric Vehicle	0.000	5.195	Trillion Passenger-Km
Beyond 80	Fuel Cell Vehicle	0.000	0.938	Trillion Passenger-Km

Table C.8: Vehicle Miles Traveled – Heavy-Duty Vehicles

		2005	**2050**	**Units**
Benchmark	Gasoline/Diesel Vehicle	2.064	1.023	Trillion Ton-Km
Benchmark	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
Benchmark	Natural Gas Vehicle	0.000	0.299	Trillion Ton-Km
Benchmark	Biofuel Vehicle	0.000	0.386	Trillion Ton-Km
Benchmark	Electric Vehicle	0.000	0.916	Trillion Ton-Km
Benchmark	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
No CO2 Removal Technology	Gasoline/Diesel Vehicle	2.064	0.960	Trillion Ton-Km
No CO2 Removal Technology	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
No CO2 Removal Technology	Natural Gas Vehicle	0.000	0.300	Trillion Ton-Km
No CO2 Removal Technology	Biofuel Vehicle	0.000	0.427	Trillion Ton-Km
No CO2 Removal Technology	Electric Vehicle	0.000	0.957	Trillion Ton-Km
No CO2 Removal Technology	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
Limited Sink	Gasoline/Diesel Vehicle	2.064	0.821	Trillion Ton-Km
Limited Sink	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
Limited Sink	Natural Gas Vehicle	0.000	0.246	Trillion Ton-Km
Limited Sink	Biofuel Vehicle	0.000	0.488	Trillion Ton-Km
Limited Sink	Electric Vehicle	0.000	1.155	Trillion Ton-Km
Limited Sink	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
Smart Growth	Gasoline/Diesel Vehicle	2.064	1.449	Trillion Ton-Km
Smart Growth	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
Smart Growth	Natural Gas Vehicle	0.000	0.446	Trillion Ton-Km
Smart Growth	Biofuel Vehicle	0.000	0.491	Trillion Ton-Km
Smart Growth	Electric Vehicle	0.000	0.298	Trillion Ton-Km
Smart Growth	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
No CCUS	Gasoline/Diesel Vehicle	2.064	0.968	Trillion Ton-Km
No CCUS	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
No CCUS	Natural Gas Vehicle	0.000	0.296	Trillion Ton-Km
No CCUS	Biofuel Vehicle	0.000	0.404	Trillion Ton-Km
No CCUS	Electric Vehicle	0.000	0.986	Trillion Ton-Km
No CCUS	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
Limited Biomass	Gasoline/Diesel Vehicle	2.064	1.069	Trillion Ton-Km
Limited Biomass	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
Limited Biomass	Natural Gas Vehicle	0.000	0.299	Trillion Ton-Km
Limited Biomass	Biofuel Vehicle	0.000	0.295	Trillion Ton-Km

Limited Biomass	Electric Vehicle	0.000	1.002	Trillion Ton-Km
Limited Biomass	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km
		2005	**2050**	**Units**
Beyond 80	Gasoline/Diesel Vehicle	2.064	1.049	Trillion Ton-Km
Beyond 80	Hybrid Vehicle	0.000	0.000	Trillion Ton-Km
Beyond 80	Natural Gas Vehicle	0.000	0.141	Trillion Ton-Km
Beyond 80	Biofuel Vehicle	0.000	0.526	Trillion Ton-Km
Beyond 80	Electric Vehicle	0.000	0.972	Trillion Ton-Km
Beyond 80	Fuel Cell Vehicle	0.000	0.000	Trillion Ton-Km

Appendix D: Model Documentation for the Global Timber Model as Applied for the U.S. Mid-Century Strategy for Deep Decarbonization

1.1 Introduction

The U.S. Mid-Century Strategy (MCS) for Deep Decarbonization report provides a road map for energy, transportation, industrial and land use sector mitigation policy action and technology development for achieving long-term climate stabilization targets prioritized under the Paris Agreement. The land use chapter relies on information from multiple models that represent components of the U.S. land use sectors, including detailed depictions of forested lands. Each modelling framework is different in how it depicts future forest land use and management decisions, but each can be used to inform the potential implications of policies targeting increased carbon sequestration or biomass energy expansion. One of the forest sector models used to inform the U.S. MCS analysis is the Global Timber Model (GTM) - an intertemporal economic optimization model of the global forestry sector developed and used in this analysis via collaboration between staff of The Ohio State University, U.S. Environmental Protection Agency and RTI International. The primary goal of this document is to provide a brief model description of GTM and an overview of key data and parameters within the model. Supplemental appendices provide additional detail on the model, its algebraic structure, and scenario assumptions for the MCS analysis.

1.2 Model Background

GTM provides a long-term view of forest resource use and product supply under assumed future market, policy, and environmental conditions. Specifically, it determines optimal levels of timber harvests, timber investments, and land use over time (by evaluating forest management profile including rotation lengths, species mix, and management intensity) and has detailed carbon accounting. GTM is a well-known global forest sector model that has been applied to a variety of different applications in numerous peer-reviewed publications. Initially it was used as a policy tool to assess climate change impacts in the forest sector (see Sohngen et al., 1999, 2001). It has subsequently been expanded for use in analysis of carbon sequestration potential in the forest sector under climate change mitigation incentives (Sohngen and Mendelsohn, 2003, 2007; Kindermann et al., 2008; Baker et al., 2016). Most recently, it has been used to assess the implications of bioenergy policies on carbon fluxes (Daigneault et al., 2012, Favero and Mendelsohn, 2014; Kim, 2015). Details on the market response functions in the model are described in Sohngen et al. (1999), the development of price paths for carbon sequestration are described in Sohngen and Sedjo (2006), and the response to these price paths by land supply, timber demand, and technical change in the forest sector is shown in Sohngen and Mendelsohn (2007).

1.3 Model Description

GTM generates projections using detailed biophysical and economic forestry data for different countries and regions globally, including the U.S. Specifically, GTM is generally used to project potential future timber resource and market conditions, and related carbon implications. To do so, the model maximizes the net present value of consumers' and producers' surplus (net welfare) in the forestry sector. Consumers' surplus for timber markets is derived from inverse timber demand functions calculated from timber prices and consumption quantities that are endogenous to the model solution. Producers' surplus is composed of the gross returns to timber harvests minus the costs of managing and holding timberland. The costs of managing timberland include the costs of replanting timber and the costs of harvesting, accessing, and transporting timber. There is an opportunity cost of maintaining land in forests rather than switching to agriculture for crop cultivation and livestock grazing.

GTM has the flexibility to be run over varying, long term time horizons (200+ years). The model has more than 150 disaggregated U.S. forest types and over 200 forests and management types globally, explicit representation of pulpwood and sawtimber demand, and endogenous global trade flows. The model solution determines how much to harvest in each age class and time period, how many hectares to regenerate in each type in each time period, how intensively to regenerate the hectares when they are planted, and how many new hectares of high-value plantations to establish. As a dynamic intertemporal economic optimization model, GTM relies on forward-looking behavior and solves all time periods at the same time. This dynamic optimization approach means that land owners incorporate future market expectations into land use and forest management decisions today to reflect future expectations (i.e., decisions anticipate future potential net returns).

Intertemporal optimization is an important model attribute, as in practice, forestry investments are made today with expected returns often decades into the future. For example, when forests are planted, the amount of money spent planting/managing forests is determined consistent with future expectations about timber prices. Forestland owners attempt to neither over-invest nor under-invest in forest resources, based on the current period's expectations of the future. In addition, when forests are harvested, forestland managers have the option to allow land to regenerate naturally or convert to a more intensively managed/planted system. This decision is based on anticipated future market conditions. The dynamic optimization modeling approach is based on Sedjo and Lyon (1990). The volume edited by M. Kallio et al. (1987) provides a detailed description of the differences among the various types of forestry models, while Sohngen and Sedjo (1998) illustrate the mathematical differences and the implications of the various forestry modeling approaches on policy outcomes.

The model determines forest product prices endogenously, demand is not fixed over time, and market prices are decision variables from optimal resource allocation. Emissions trajectories can fluctuate as demand is not fixed, and land use decisions are made so all markets clear simultaneously over the simulation, which can cause changes in decisions variables between periods. Also, as this type of modeling approach reflects investment behavior, it often reflects higher levels of forest carbon sequestration rates in the near or medium-term than other modeling techniques. For example, statistical forecasting and recursive dynamic models adjust to market conditions on a period to period basis, and therefore do not account for expected future returns. They adjust land use/management in each period based on previous period conditions and supply-side constraints (e.g., urban development assumptions).

1.4 Data and Key Parameters

GTM forest product demand growth globally is based on projections of population and gross domestic product growth, which can come from a number of sources. For instance, previous GTM analyses have calibrated GTM to macroeconomic projections from the U.S. Energy Information Administration's Annual Energy Outlook (AEO) and other global projections (e.g., Baker et al., 2016). For the U.S. MCS analysis, macroeconomic inputs, including population, GDP, and bioenergy demand, in GTM are derived from MCS Benchmark scenario (see Addendum A for more information on MCS scenario inputs).

1.4.1 *Forest Inventory Data*

Data on initial forest area and inventories in the model were obtained from multiple sources (see Table 1). For most developed countries and temperate forests, inventories were obtained from original sources within the countries or regions because those sources often also contain detailed information (such as age classes). For most developing countries in tropical regions, information on forest areas was obtained from the UN FAO (2005, 2010, and 2015).

Table 1: Sources of Forest Area and Inventory Data

Region	Data Source
United States	US Department of Agriculture, Forest Service. Various years. Forest Inventory and Analysis (www.fia.fs.fed). Data retrieved from 2014 FIA report
Europe	Kuusela (1993)
Russia	Russia: Forest Account (2004)—See Sohngen et al. (2005) for a discussion of this data.
Canada	Lowe et al. (1994); Updated with Canada's National Forest Inventory in 2010. See: https://nfi.nfis.org/hom.php
Australia	Australian Dept. of Agriculture and Water Resources, Bureau of Rural Sciences (2003); Australian Bureau of Agricultural and Resource Economics (1999)
New Zealand	New Zealand Ministry of Agriculture and Forestry (1987).
China	China (Ministry of Forestry, Center for Forest Inventory, 1994)
All other countries	UN FAO (2005, 2010, 2015)

1.4.2 *Forest Yield Growth*

As mentioned above, GTM model has more than 150 disaggregated U.S. forest types and over 200 forests and management types globally, explicit representation of pulpwood and sawtimber demand, and endogenous global trade flows. In this model, sawtimber and pulpwood are drawn from the same forest resource base, which is allocated to either product group after harvest. To account for differences in ecological productivity for different tree species, the model reflects different forest land classes for various regions of the world. These land classes have different yield functions for timber. For example, in the U.S., forest land classes can be based on species (e.g., Douglas Fir) and land quality (based on the FIA designation of site class productivity). Furthermore, forests are broken into different types of management classes. The management classes are moderately valued forests, inaccessible forests, low-value forests, low-value timberland in inaccessible areas, low-value timberland in semi-accessible areas, and lastly high-valued timber plantation.

GTM accounts for historical natural disturbances in yield functions in future projections, but does not typically account for climate change impacts on natural disturbance patterns in the future unless a specific future climate change scenario is applied. The model also accounts for historical carbon fertilization in yield functions into the future but it does not account for future increased carbon fertilization unless a specific future climate change scenario is applied. With increased future carbon fertilization included, future estimates are expected to be larger (depending on global productivity gains and prices).

1.4.3 Forest Product Demand

Price elasticities of demand in the demand functions for sawtimber and pulpwood were determined by examining the literature. Estimates for small regions or nations tend to suggest that forest demand is fairly inelastic, but these do not represent the entire global market for industrial wood. These estimates range from −0.14 to −0.17 in the Pacific Northwest (Haynes et al. 1981, for wood products), to −0.43 for pulpwood to −0.57 for sawtimber in the US South (Newman 1987). Estimates of demand elasticity using global datasets and looking across countries seem to suggest that demand is more elastic: (Simangunsong and Buongiorno (2001) reported end product elasticity estimates from −0.62 for sawnwood to −1.33 for plywood, with long-run estimates being more elastic than short-run estimates; Uusivuori and Kuuluvainen (2001) found own-price elasticity estimates for industrial roundwood imports from −0.69 for nontropical hardwoods to −0.92 for softwood and −0.95 for wood chips, and; Turner and Buongiorno (2004) found more inelastic demand for roundwood imports of −0.74.

For most applications, the model assumes that price elasticity of demand for both sawtimber and pulpwood is 1.0 (see Table 2 in Addendum A: GTM Scenario **Parameters, Assumptions and Key Results for Mid-Century Strategy for Deep Decarbonization Report**

For the MCS analysis, GTM scenarios were developed to present alternative futures for timberland management, investment, and carbon stocks as influenced by macroeconomic drivers and key policy variables. GTM presents a unique perspective on future forest management and associated forest carbon stock trends for several reasons. First, the intertemporal optimization framework uses forward-looking expectations of future market and policy conditions to invest in the forest resource base at the intensive and extensive margins. This modeling construct allows for the evaluation of how changes in policy assumptions (e.g., incentives to expand forest biomass utilization for energy) could lead to changes in forest sector investment and management. Second, GTM is a global model and thus recognizes that projected changes in the U.S. forest resource base (including harvest levels) will be driven in part by forest resource management and markets in the rest of the world. Thus, GTM scenarios developed for the MCS allow for a direct analysis of how climate/land use policy actions (such as bioenergy expansion and carbon sequestration programs) affect forest management trends and markets, both domestically and internationally.

For the MCS analysis, scenarios implemented with GTM were designed to reflect alternative futures for U.S. and global forestland management under different policy drivers aligned to the MCS Benchmark and other scenarios developed with the Global Change Analysis Model (GCAM). This approach allows for consistent alignment between GTM and other models employed for the MCS, drawing specific policy and macroeconomic variables from the MCS Benchmark GCAM scenario presented in the MCS Deep Decarbonization Report.

To align with the GCAM MCS scenarios, three separate scenarios were developed for GTM to represent alternative policy and market futures, thus yielding Low, Medium and High forest carbon sink scenarios that reflect different forest-derived biomass and carbon sequestration incentives as discussed below.

- **GTM Low Sink:** This scenario was created by taking GCAM regional GDP and population projections from the GCAM baseline and calculating aggregate income and population growth rates for the world. Based on these baseline projections, GTM per capita GDP is expected to grow globally at a rate of 1.8% per year on average over the next 50 years, tapering off to 1.6% per year for the next 50 years, and 1.0% per year for the ensuring century. It is assumed that demand growth falls to 0.0% per year in the final two decades of the scenarios to assist in imposing our terminal condition. These growth rates are used to shift the future demand for pulpwood and sawtimber products over time, with assumed income elasticities of 0.9 for both sawtimber and pulpwood. This scenario does not include additional demand growth in forest biomass to contribute to MCS renewable energy or negative emissions technology growth. Furthermore, this scenario does not incentivize carbon sequestration from the forest sector.

- **GTM Medium Sink:** The GTM Medium Sink scenario uses the same GDP and population growth rates as the Low Sink, but includes increased demand for woody biomass to meet bioenergy demands. The consumption levels are converted from Gigajoules to million m3 of forest biomass. The demand growth for pulpwood and sawtimber is then adjusted to account for this new source of demand. Demand is adjusted by assuming 70%-30% split between pulpwood and sawtimber to meet the biomass for energy requirement. This increase in demand incentivizes near term increased forest management and afforestation in anticipation of higher market returns and increased forest biomass demand in the future. Thus, the projected forest net flux increases in the near term in forest management beyond the Low Sink scenario levels.

- **GTM High Sink:** The GTM high sink scenario similarly adjusts pulpwood and sawtimber demand consistent with the Medium Sink scenario but also adds global carbon mitigation incentives that increase forest carbon sequestration. This approach combines the effect of increased investment in the forest sector driven by increased demand for biomass for energy with mitigation incentives for enhancing forest carbon sequestration, and the net result is a higher net emissions flux relative to the Low and Medium sink scenarios (this approach is discussed in Baker et al., 2016).

For the MCS analysis, GTM was run for 200 years at 10-year time steps, and relied on the global forest data, forest yield growth information and carbon modeling approach described in the main body of this report.

Addendum B. Algebraic Structure for list of indexes, variables, functions, and parameters). This estimate was chosen due to several reasons. First, this model employs a global demand function (not a regional or local demand function) so one would expect demand to be more inelastic for individual countries, where substitution possibilities may be more limited in the short term than globally. Second, the GTM demand function is for a general basket of industrial sawtimber or pulpwood which are used to produce a range of outputs and are fairly undifferentiated, with high substitution potential. Demand for industrial sawtimber or pulpwood, as undifferentiated commodities, is assumed to be more elastic than demand for specialized end products. Third, this model is a long-run optimization model and none of the estimates above use time periods as long as GTM (200 years, depending on the study at hand). Over longer time periods, one would expect more substitution possibilities and thus more elastic demand.

Income elasticity also plays a major role in the inverse demand function in GTM. Nearly all of the studies above estimate income elasticity to be fairly elastic, suggesting a small amount of increased income could lead to large increases in wood product demand. For example, Simangunsong and Buongiorno (2001) reported median estimates of income elasticity from the literature of around 1.0, and Turner and Buongiorno (2004) found that income elasticity for industrial roundwood is 2.21. The model therefore generally uses a slightly lower value, 0.9, than the estimates above to account for the potential influence of new products on the future market that will perform the same service as wood but do so more efficiently. Such substitution would lower demand for industrial wood, which is modeled here, even though demand for the output (wood services) could continue to rise with rising income.

The rate of aggregate forestland change is determined by land supply functions, as well as land rental functions that are applied to each region. These rental functions are generally shifting inward and upward (representing increasing demand for land use in agriculture in most regions of the world). Total timber area in each age class and forest type is a stock variable and adjusts over time dependent on initial forest area, afforestation, and harvested area. Bringing new forestland into the system requires an investment cost, represented by land supply and rental functions. As forest rents increase, the model increases the amount of land in forestry, paying increased costs for the extensive margin expansion. This is an important model attribute—policy mechanisms that increase demand for pulpwood or sawtimber, or that generally increase forestry rents, will drive extensive margin expansion on the land supply frontier.

There is a key difference between the conversions of land in the temperate/boreal zones and the tropics; the lands in the temperate/boreal regions are assumed to have no opportunity costs so they remain in forestry. In contrast, opportunity costs may be greater than 0 in the tropics (shown in equations 1.3i through 1.3n in Addendum B). Each inaccessible type in temperate and boreal zones is linked to a semi-accessible type (see equation 1.7). The semi-accessible types start with no forest area. When inaccessible forests are accessed, the hectares are converted to a similar semi-accessible type. Thus, the total area of inaccessible and semi-accessible forest area in moderately valued forests remain constant over the scenario time horizon. So, an implicit assumption is made in temperate and boreal regions that the opportunity costs of converting land in inaccessible/semi-accessible regions is 0 and thus that the rental costs are 0. However, in tropical zones semi-accessible and inaccessible low-value timberland are assumed to rental functions that are greater than 0. In tropical zones if the value of accessing the land exceeds the marginal access costs then the forest will be harvested. After harvest, the land can be converted to agriculture or returned to forest depending on the opportunity costs of land and the value of future timber harvests. There are two reasons why forests may be accessed in tropical regions, either due to timber demand or demand for land conversion. The demand for land conversion is driven by the rental functions, which generally are shifting inward and upward in tropical regions (representing increasing demand for land use in agriculture).

Some additional items that are considered within the model are the cost of transporting timber to timber to mills, and the decision to collect forest residues to be used for bioenergy. GTM has spatially explicit forest stands with the distance to harvest and distance to mills used to calculate the cost of accessing and transporting timber (equations 1.17 and 1.18 in Addendum B). Second, in scenario applications with policy incentives targeting forest bioenergy demand, the model can use pulpwood, sawtimber or forest residues from accessible timberlands for pulpwood. Furthermore, some residue material can be collected and used for pulpwood, where the costs of this collection is determined implicitly in the model (shown in equation 1.21 and 1.22 in Addendum B).

Forest biomass for energy production is captured by exogenous demand shifters in which the total demand for pulpwood and sawtimber is increased by the assumed amount of forest biomass demanded from the forest sector for energy generation purposes. This approach allows one to create custom scenarios in which forest biomass demand is calibrated directly to energy sector projections. That is, given expectations of renewable energy demand to be met from biomass sources, GTM demand projections are adjusted to account for the requisite biomass needed for the energy system. This approach requires separate recalibration of the demand functions for pulpwood and/or sawtimber to account for the exogenous demand increase driven by bioenergy expansion.

1.5 Carbon Modeling

Carbon modeling in GTM includes representation of the following forest carbon pools aboveground carbon, slash, marketed products, and soils. The model does not include data or results for urban forests, agricultural soils or landfilled yard trimmings and food scraps. The methods for calculating carbon follow the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance (Penman et al., 2003).

Aboveground carbon is estimated by using the density of wood, the root-to-shoot ratio, and the proportion of biomass that is carbon. This is determined for each timber type, age class, and time period. The calculation of aboveground carbon is show in equations 1.25 and 1.26 in Addendum C, with descriptions of the variables describes in table 3.

Carbon in the slash pool represents the dead timber material left in forests after harvests or land use conversion, material that is not used for marketed wood products and is too costly to remove from the forest. If forest residues are harvested, they are harvested from this pool. In some cases, slash is burned by landowners, and in other cases, slash is simply left behind to decompose. To calculate the amount of slash left in the forest at the time of timber harvest or land use conversion, the model starts with the amount of carbon in forests and deducts the amount removed for timber or other products (equation 1.27). Because the slash pool is built up over many years, at the start of the simulations GTM uses the initial-year harvests to calculate an initial slash pool for each timber type *i* based on the initial harvest. This calculation will affect the baseline rate of slash accumulation, but it will not alter the change in slash accumulation in the policy scenarios.

Carbon in harvested wood products is calculated similarly, although the difference in sawtimber and pulpwood products are accounted for. Methodologically, however, annual contributions to the sawtimber and pulpwood pools are calculated similarly (equations 1.29 and 1.30). It is assumed that some of the carbon in the marketed product pools turns over, or decomposes, and is released to the atmosphere each year (equations 1.31 and 1.32). Usually 25 to 35% of the amount harvested is emitted relatively quickly in the production process. This emission often occurs in the form of harvesting residues that are burned for energy or discarded immediately. Wood products then enter useful products and eventually are discarded and are assumed to decompose over time.

Soil carbon is maintained in three separate stocks: forest soil carbon in forests maintained as forests, agricultural soils on lands converted to forest, and forest soil converted to agricultural use. For forests maintained as forests (no land use change), the soil stocks remain constant. When land use changes, such as from forest to non-forest or vice versa, the model calculates the net gain or loss in carbon to or from the atmosphere. This is accomplished by tracking the total pool of soil carbon in forests but only deducting the net losses when forests are converted to agriculture (or vice versa for lands converted to forest). Soils that have converted from agriculture to forests begin with an average amount of carbon in soils for the given region and then accumulate carbon in soils over time. The pool of soil carbon accumulates over time according to a logistic growth function (Addendum C, equations 1.33 and 1.34). For soil carbon associated with land conversion of forests into agriculture, the present value of carbon lost over time is calculated and these losses are assigned to the hectares removed from forestry in the year removed. This approach simplifies the need to account for the carbon in these hectares after they have exited the model, and it results in a relatively conservative net estimate of the carbon losses when land is converted out of forest.

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Addendum A: GTM Scenario Parameters, Assumptions and Key Results for Mid-Century Strategy for Deep Decarbonization Report

For the MCS analysis, GTM scenarios were developed to present alternative futures for timberland management, investment, and carbon stocks as influenced by macroeconomic drivers and key policy variables. GTM presents a unique perspective on future forest management and associated forest carbon stock trends for several reasons. First, the intertemporal optimization framework uses forward-looking expectations of future market and policy conditions to invest in the forest resource base at the intensive and extensive margins. This modeling construct allows for the evaluation of how changes in policy assumptions (e.g., incentives to expand forest biomass utilization for energy) could lead to changes in forest sector investment and management. Second, GTM is a global model and thus recognizes that projected changes in the U.S. forest resource base (including harvest levels) will be driven in part by forest resource management and markets in the rest of the world. Thus, GTM scenarios developed for the MCS allow for a direct analysis of how climate/land use policy actions (such as bioenergy expansion and carbon sequestration programs) affect forest management trends and markets, both domestically and internationally.

For the MCS analysis, scenarios implemented with GTM were designed to reflect alternative futures for U.S. and global forestland management under different policy drivers aligned to the MCS Benchmark and other scenarios developed with the Global Change Analysis Model (GCAM). This approach allows for consistent alignment between GTM and other models employed for the MCS, drawing specific policy and macroeconomic variables from the MCS Benchmark GCAM scenario presented in the MCS Deep Decarbonization Report.

To align with the GCAM MCS scenarios, three separate scenarios were developed for GTM to represent alternative policy and market futures, thus yielding Low, Medium and High forest carbon sink scenarios that reflect different forest-derived biomass and carbon sequestration incentives as discussed below.

- **GTM Low Sink:** This scenario was created by taking GCAM regional GDP and population projections from the GCAM baseline and calculating aggregate income and population growth rates for the world. Based on these baseline projections, GTM per capita GDP is expected to grow globally at a rate of 1.8% per year on average over the next 50 years, tapering off to 1.6% per year for the next 50 years, and 1.0% per year for the ensuring century. It is assumed that demand growth falls to 0.0% per year in the final two decades of the scenarios to assist in imposing our terminal condition. These growth rates are used to shift the future demand for pulpwood and sawtimber products over time, with assumed income elasticities of 0.9 for both sawtimber and pulpwood. This scenario does not include additional demand growth in forest biomass to contribute to MCS renewable energy or negative emissions technology growth. Furthermore, this scenario does not incentivize carbon sequestration from the forest sector.

- **GTM Medium Sink:** The GTM Medium Sink scenario uses the same GDP and population growth rates as the Low Sink, but includes increased demand for woody biomass to meet bioenergy demands. The consumption levels are converted from Gigajoules to million m3 of forest biomass. The demand growth for pulpwood and sawtimber is then adjusted to account for this new source of demand. Demand is adjusted by assuming 70%-30% split between pulpwood and sawtimber to meet the biomass for energy requirement. This increase in demand incentivizes near term increased forest management and afforestation in anticipation of higher market returns and increased forest biomass demand in the future. Thus, the projected forest net flux increases in the near term in forest management beyond the Low Sink scenario levels.

- **GTM High Sink:** The GTM high sink scenario similarly adjusts pulpwood and sawtimber demand consistent with the Medium Sink scenario but also adds global carbon mitigation incentives that increase forest carbon sequestration. This approach combines the effect of increased investment in the forest sector driven by increased demand for biomass for energy with mitigation incentives for enhancing forest carbon sequestration, and the net result is a higher net emissions flux relative to the Low and Medium sink scenarios (this approach is discussed in Baker et al., 2016).

For the MCS analysis, GTM was run for 200 years at 10-year time steps, and relied on the global forest data, forest yield growth information and carbon modeling approach described in the main body of this report.

Addendum B. Algebraic Structure of the Harvest Decision Making

This section provides a general algebraic form of the Global Timber Model. GTM maximizes the present value of net welfare in the forestry sector. Net welfare is defined as the sum of consumers' and producers' surplus for timber markets that are derived from inverse timber demand functions and costs of managing and holding timberland. The costs of managing timberland include the costs of replanting timber and the costs of harvesting, accessing, and transporting timber. There is an opportunity cost of maintaining land in forests rather than switching to agriculture for crop cultivation and livestock grazing.

We begin with the demand for wood. There are two demand functions in this model, one for sawtimber and one for pulpwood. The inverse demand functions are formally written as,

$$P_t^P = D_p\left(Q_t^p; B_t, Y_t\right) \tag{1.1a}$$

$$P_t^S = D_s(Q_t^s; B_t, Y_t) \tag{1.1b}$$

Where P_t^P is the price of pulpwood and P_t^S is the price of sawtimber. The demand for either type of wood shifts is a function of the quantity of wood harvested, income, Y_t (or a composite for all other goods) and the demand for biomass energy, B_t. In our model, the demand for biomass will be 0 in the reference scenario, but positive in policy scenarios. The objective function of the optimization model can be written formally as:

$$\max_{\substack{H_{a,t}^{i,j,k,l,m,n}\ Z_{a,t}^{i,j,k,l,m,n}\ G_t^{i,k,m,n} \\ \forall i,j,k,l,m,n,a,t}} \sum_{t=0}^{\infty} \rho^t \{ \int_0^{Q_t^{p*}} D_p\left(Q_t^p; B_t, Y_t\right) dQ_t^p + \int_0^{Q_t^{S*}} D_s(Q_t^s; B_t, Y_t) dQ_t^s - \mathrm{C}_s\left(q_t^{i,k,m,n}, X_{a,t}^{j,l}\right)$$
$$-\mathrm{C}_p\left(q_t^{i,k,m,n}, X_{a,t}^{j,l}\right) - RESCOST(\,Q_t^{res}) - PLANTC_t(G_t^{i,k,m,n}, N_t^n, Z_{a=1,t}^{i,k,m,n})$$
$$-RENT_t(\mathrm{X}_{a,t}{}^{i,l,m,n})\} \tag{1.2}$$

Table describes indexes, variables, functions, and parameters in the social planner's problem (1.2). The maximization problem (1.2) is constrained such that each age class and forest type is a stock variable which is allowed to adjust over time due to harvesting, replanting, and land conversion. All choice variables are constrained to be nonnegative, while area of timber harvested is not allowed to exceed the total timber area (See: Sohngen et al. [2016] for formal description of underlying algebraic model).

$$X_{a,t}^i = X_{a-1,t-1}^i - H_{a-1,t-1}^i + G_{t-1}^i \ \forall\ a, t \tag{1.3i}$$

$$X_{a,t}^j = X_{a-1,t-1}^j - H_{a-1,t-1}^j \ \forall\ a, t \tag{1.3j}$$

$$X_{a,t}^k = X_{a-1,t-1}^k - H_{a-1,t-1}^k + G_{t-1}^k \ \forall\ a, t \tag{1.3k}$$

Table 2: Indexes, Variables, Functions, and Parameters in the Social Planner Problem

Category	Label	Description
Index	i	Moderate-value forest types in accessible regions
	j	Low-value forest types (inaccessible regions) in temperate and boreal zones
	k	Low-value forest types (semi-accessible type) in temperate and boreal zones
	l	Low-value forest types (inaccessible regions)in tropical zones
	m	Low-value forest types (semi-accessible regions) in tropical zones
	n	High-value forest type
	t	Time
	a	Age class
	p	Pulpwood
	s	Sawtimber
	res	Residues
Variable	H	The area of timber harvested (hectares)
	N	Brand new area planted (hectares)
	G	The area of timber regenerated (hectares)
	X	Total timber area
	$Z_{a,t}$	Stock of management intensity for age class a at time t
	$Z_{a=1,t}$	Management intensity determined at time of planting (a=1)
	q or Q	Timber harvested (cubic meter)
	Y	The quantity of other good consumed (measured by gross domestic product (GDP) per capita)
	B	The quantity of biomass energy demanded from the forestry sector

Category	Label	Description
	λ	The proportion of timbers for each wood product
Function	V(.)	Yield function
	D(.)	Inverse demand function
	C(.)	Cost of harvesting, accessing, and transporting timberland
	MC(.)	Marginal cost function of harvesting, accessing, and transporting timberland
	PLANTC(.)	Total cost function of regenerating forests including new plantation

(continued)

Table 2: Indexes, Variables, Functions, and Parameters in the Social Planner Problem (Continued)

Category	Label	Description
	RENT(.)	The opportunity cost of holding timberland by maintaining forests rather than agricultural land use
	Δ·	The hectares of area changed when converted from inaccessible into semi-accessible type
	RESCOST(.)	Cost of collecting residues on accessible lands
Parameter	φ, τ, δ, π	Parameter in yield function
	∅	Constant in inverse demand functions
	θ	Income elasticity of demand functions
	ω	Price elasticity of demand functions
	α, β	Constant in marginal cost functions for type i, k, m, n
	ξ	Constant in marginal cost functions for type n (associated with transportation cost for biomass)
	μ,ε	Constant in marginal cost for types j, l
	ca, cb, cc	Constant in cost of collecting residues function
	e	Establishment cost for new plantation in type n
	r	Constant price for a unit of management intensity (Sedjo and Lyon, 1990)
	A, η, z	Constant in rental function
	d	Decadal discount factor
	ρ	Discounting factor

$$X_{a,t}^{l} = X_{a-1,t-1}^{l} - H_{a-1,t-1}^{l} \;\forall\, a, t \tag{1.3l}$$

$$X_{a,t}^{m} = X_{a-1,t-1}^{m} - H_{a-1,t-1}^{m} + G_{t-1}^{m} \;\forall\, a, t \tag{1.3m}$$

$$X_{a,t}^{n} = X_{a-1,t-1}^{n} - H_{a-1,t-1}^{n} + G_{t-1}^{n} + N_{t-1}^{n} \;\forall\, a, t \tag{1.3n}$$

$$X_{a,t=0}^{i,j,k,l,m,n} \text{ is given } \forall\, i, j, k, l, m, n, a, \tag{1.4}$$

$$H_{a,t}^{i,j,k,l,m,n}\ \mathrm{Z}_{t}^{i,j,k,l,m,n}\ G_{t}^{i,j,k,l,m,n}\ N_{t}^{n}\ \geq 0\ \forall\ i,j,k,l,m,n\ a\ t, \tag{1.5}$$

$$H_{a,t}^{i,j,k,l,m,n}\ \leq\ X_{a,t}^{i,j,k,l,m,n}\ \forall\ i,j,k,l,m,n,a,t, \tag{1.6}$$

$$\Delta X_{a,t}^{j} + \Delta X_{a,t}^{k} = 0;\ \Delta H_{a,t}^{j} + \Delta H_{a,t}^{k} = \Delta G_{t}^{k}\ \forall\ t,a, \tag{1.7}$$

$$\Delta X_{a,t}^{l} + \Delta X_{a,t}^{m} \gtreqless 0;\ \Delta H_{a,t}^{l} + \Delta H_{a,t}^{m} \gtreqless \Delta G_{a,t}^{m}\ \forall\ t,a, \tag{1.8}$$

$$Z_{a,t}^{i} = Z_{a-1,t-1}^{i} + Z_{a=1,t-1}^{i}\ \forall\ t,a \tag{1.9}$$

$$Z_{a,t}^{n} = Z_{a-1,t-1}^{n} + Z_{a=1,t-1}^{n}\ \forall\ t,a \tag{1.10}$$

The model solution determines how much to harvest in each age class (a) and time period (t), $H_{a,t}^{i,j,k,l,m,n}$; how many hectares to regenerate in each type in time period t, $G_{t}^{i,k,m,n}$; how intensively to regenerate the hectares when they are planted, $\mathrm{Z}_{a=1,t}^{i,j,k,l,m,n}$; and how many new hectares of high-value plantations to establish, N_{t}^{n}.

Total timber area in each age class a and type, $X_{a,t}^{i,j,k,l,m,n}$, is a stock variable and adjusts over time according to equations (1.3i) through (1.3n). Initial stocks must be given (equation 1.4), and all choice variables are constrained to be greater than or equal to zero (equation 1.5). The area of timber harvesting does not exceed the total timber area (equation 1.6).

Equation (1.7) shows that each inaccessible type in temperate and boreal zones is linked to a semi-accessible type. The semi-accessible types start with no forest area. When inaccessible forests are accessed, the hectares are converted to a similar semi-accessible type. Thus, the total area of inaccessible and semi-accessible forest area in each i remains constant over the scenario time horizon. Thus, an implicit assumption in temperate and boreal regions is that the opportunity costs of converting land in inaccessible/semi-accessible regions is 0 and thus that the rental costs are 0.

In addition, equation (1.8) implies that each inaccessible type in the tropics also has a similar semi-accessible type associated with it; however as noted above, forestland is allowed to exit forestry in this region. Therefore, the area regenerated in these regions may be less than or more than the area harvested or removed in any period. There are two reasons why forests may be accessed in tropical regions, either due to timber demand or demand for land conversion. The demand for land conversion is driven by the rental functions, which generally are shifting inward and upward in tropical regions (representing increasing demand for land use in agriculture). Equations (1.9) and (1.10) are the equations of motion for management in forest type "i" and "n" in which forests are moderately and intensively managed, respectively.

Forest yields (volume per hectare) are given as $V_{a,t}^{i}$. The yield function measures the volume in each age class a and type i at time t all dependent on the management intensity for type i at time t. The functional form for the yield function is:

$$V_{a,t}^{i}\left(\mathrm{Z}_{a,t}^{i}\right) = h * \left[\exp\left(\delta^{i} - \frac{\pi^{i}}{a}\right)\right]. \tag{1.11}$$

The functional forms for other types (*j*, *k*, *l*, *m*, *n*) are the same, although the parameters will differ. Yield is calculated by the stocking density, h, where $h = \varphi^i\left(1 + \mathrm{Z}_{a,t}^i\right)^{\tau^i}$, which can be adjusted depending on the intensity of management, $Z_{a=1,t}^i$. Stocking elasticity, τ, is restricted to be positive and less than 1and affects the elasticity of management inputs in forestry to account for technology change. Initial stocking is denoted by φ^i. The model chooses management intensity by optimally choosing management intensity

The total quantity of timber harvested in each type *i* is the sum of the area harvested, $H_{a,t}^i$, times the yield per hectare, $V_{a,t}^i$, over age class:

$$q_t^i = \sum_a H_{a,t}^i\, V_{a,t}^i \;\forall\; t, i. \tag{1.12}$$

The model will endogenously shift wood into either pulpwood or sawtimber uses, depending on prices, harvesting costs, and marginal user costs. Total harvested trees are valued for either pulpwood or sawtimber in markets. Biomass energy can be derived either from sawtimber harvests or pulpwood harvests. We assume that the biomass demand shifts both demand functions out. We do not formally track the quantity of biomass energy demanded in this model

The form of equation (1.12) is applicable for types j, k, l, m, n. The term $\lambda_s^{i,j,k,l,m}$ is the proportion of timber harvested for sawnwood, and $\lambda_p^{i,j,k,l,m}$ is the proportion of wood harvested for sawnwood ($\lambda_p^{i,j,k,l,m} + \lambda_s^{i,j,k,l,m} = 1$). The quantities of timber harvested for sawtimber, Q_t^s, for pulpwood, Q_t^p, and for total timber, Q_t, are as follows:

$$Q_t^s = \sum_i \lambda_s^i q_t^i + \sum_j \lambda_s^j q_t^j + \sum_k \lambda_s^k q_t^k + \sum_l \lambda_s^l q_t^l + \sum_m \lambda_s^m q_t^m \tag{1.13}$$

$$Q_t^p = \sum_i \lambda_p^i q_t^i + \sum_j \lambda_p^j q_t^j + \sum_k \lambda_p^k q_t^k + \sum_l \lambda_p^l q_t^l + \sum_m \lambda_p^m q_t^m \tag{1.14}$$

$$Q_t = Q_t^s + Q_t^p = \sum_i q_t^i + \sum_j q_t^j + \sum_k q_t^k + \sum_l q_t^l + \sum_m q_t^m + \sum_n q_t^n \tag{1.15}$$

As noted above, the model has two types of market-valued wood: sawtimber and pulpwood, each with its own downward-sloping demand function. The functional forms of the inverse demand functions are shown in equation (1.16), where Y_t is the quantity of other goods consumed (e.g., GDP), B_t is the quantity of biomass demanded by markets, f^p is a function that converts the component of biomass demand drawn from pulpwood into a demand shift, f^s is a function that converts the component of biomass demand drawn from sawnwood into a demand shift, $\emptyset_t^{p,s}$ are constants, θ is income elasticity, and ω is price elasticity:

$$P_p = D_p\left(Q_t^p, Y_t\right) = \left(\frac{Q_t^p}{\mathrm{f}^p(\mathrm{B}_t)\emptyset_t^p(Y_t)^\theta}\right)^\omega \quad P_s = D_s(Q_t^s, Y_t) = \left(\frac{Q_t^s}{\mathrm{f}^s(\mathrm{B}_t)\emptyset_t^s(Y_t)^\theta}\right)^\omega. \tag{1.16}$$

Other costs included in the model for forests and land use are: the costs of harvesting, accessing, and transporting timbers to mills, the costs of collecting residues to be used for biofuels, the costs of regenerating forests including new plantations, and the opportunity costs of holding timberland. This is formally derived and explained in Sohngen et al. (2016).

The model includes many costs of forests and land use, including a) costs of harvesting, accessing, and transporting timbers to mills; b) costs of collecting residues to be used for biofuels; c) costs of regenerating forests including new plantation; and d) (opportunity) costs of holding timberland. First, equations (1.17) through (1.19) show that costs of harvesting, accessing, and transporting for sawtimber, pulpwood, and biomass are the following functional forms, respectively, where $MC_{s,p}(.)$ are the marginal cost functions in equations (1.19) and (1.20). The forms of equations (1.19) and (1.20) are also applicable for types *k* and *m*:

$$\begin{aligned} \mathrm{C}_s\left(q_t^{i,k,m}, X_{a,t}^{j,l}\right) &= \textstyle\sum_i \lambda_s^i \left[\int_0^{q_t^{i*}} MC_s\left(q_t^i\right) dq_t^i\right] + \sum_k \lambda_s^k \left[\int_0^{q_t^{k*}} MC_s\left(q_t^k\right) dq_t^k\right] \\ &+ \textstyle\sum_m \lambda_s^m \left[\int_0^{q_t^{m*}} MC_s(q_t^m) dq_t^m\right] + \sum_j \lambda_s^j \left[\varepsilon^j \left(\sum_a X_{a,t}^j\right)^{\frac{1}{\mu^j}}\right] + \sum_l \lambda_s^l \left[\varepsilon^l \left(\sum_a X_{a,t}^l\right)^{\frac{1}{\mu^l}}\right] \end{aligned} \tag{1.17}$$

$$\begin{aligned} \mathrm{C}_p\left(q_t^{i,k,m}, X_{a,t}^{j,l}\right) &= \textstyle\sum_i \lambda_p^i \left[\int_0^{q_t^{i*}} MC_p\left(q_t^i\right) dq_t^i\right] + \sum_k \lambda_p^k \left[\int_0^{q_t^{k*}} MC_p\left(q_t^k\right) dq_t^k\right] \\ &+ \textstyle\sum_m \lambda_p^m \left[\int_0^{q_t^{m*}} MC_p(q_t^m) dq_t^m\right] + \sum_j \lambda_p^j \left[\varepsilon^j \left(\sum_a X_{a,t}^j\right)^{\frac{1}{\mu^j}}\right] + \sum_l \lambda_p^l \left[\varepsilon^l \left(\sum_a X_{a,t}^l\right)^{\frac{1}{\mu^l}}\right] \end{aligned} \tag{1.18}$$

$$MC_s\left(q_t^i\right) = \alpha_s^i + \beta_s^i (q_t^i)^{\beta_s^i - 1} \tag{1.19}$$

$$MC_p\left(q_t^i\right) = \alpha_p^i + \beta_p^i (q_t^i)^{\beta_p^i - 1} \tag{1.20}$$

Second, in addition to using pulpwood and sawtimber for biofuels, the model allows the use of forest residues for pulpwood. These residues are set to be collected from accessible timberlands. They are material that is left on the forest floor after timber is harvested. Typically this material is called slash and it is left on site. Sometimes it is collected into piles and burned. At other times, it is just left to decompose. It is assumed that some of this material can be collected and used for pulpwood, where the costs of collecting this material are modeled as:

$$RESCOST(Q_t^{res}) = ca + cbQ_t^{res} + cc(Q_t^{res})^2, \text{ where} \tag{1.21}$$

$$Q_t^{res} \leq 0.3 * 0.5\, Q_t. \tag{1.22}$$

In equation (1.22), 0.3 is the proportion of total forest yield that is forest residues, and 0.5 is the proportion of forest residues that can be removed from the stand.

Third, the costs of regenerating forests (including new plantation) are given as:

$$\begin{aligned} PLANTC_t(G_t^{i,k,m,n}, N_t^n, Z_{a=1,t}^{i,k,m,n}) &= \textstyle\sum_i Z_{a=1,t}^i G_t^i + \sum_n Z_{a=1,t}^n (G_t^n + N_t^n) + e^n N_t^n \\ &+ \textstyle\sum_k Z_{a=1,t}^k G_t^k + \sum_m (Z_{a=1,t}^m + 2000) G_t^m, \end{aligned} \tag{1.23}$$

where $Z_{a=1,t}^{i,k,m,n}$ is the value of initial management intensity at age class one only, which is calculated by a unit of management intensity at only age class one times constant price r (Sedjo and Lyon, 1990); e^n is the marginal cost of establishing new hectares of plantation. The costs of establishing new plantations in fast-growing types are assumed to be fairly high because these forests are highly valuable, and they require substantial site preparation efforts to obtain such high growth rates.

For the accessible/semi-accessible type of forests (types *i*, *k*, and *m*), they are assumed to have only regenerating trees, $G_t^{i,k,m}$, and new plantation area N_t^n is assumed to be only in type *n*. For inaccessible types *j* and *l*, which are low-value trees, both $G_t^{j,l}$ *and* $N_t^{j,l}$ are assumed to be zero.

Fourth, the opportunity costs of holding timberland rather than using it as agricultural land to grow crops or livestock are represented by a rental cost function, $RENT_t(\mathrm{X}_{a,t}{}^{i,l,m,n})$. Inaccessible and semi-accessible lands in the temperate and boreal regions are assumed to have zero rental costs. This assumption is consistent with the internally generated bare land value returns calculated by the model for forest types in these regions. Rental costs are given as functions that increase as more land is added to the forestry area:

$$RENT_t(\mathrm{X}_{a,t}{}^{i,l,m,n}) = \sum_i \left[\mathrm{A}^i\left\{\sum_a X_{a,t}^i\right\}^{\frac{1}{\eta^i}}\right] + \sum_n \left[\mathrm{A}^n\left\{\sum_a X_{a,t}^n\right\}^{\frac{1}{\eta^n}}\right] + \sum_{l,m}\left[-\mathrm{z}^{l,m}\left\{\sum_a X_{a,t}^{l,m}\right\} + \frac{1}{\frac{1}{\eta^{l,m}}+1} A^{l,m}\left\{\sum_a X_{a,t}^{l,m}\right\}^{\frac{1}{\frac{1}{\eta^{l,m}}+1}}\right], \tag{1.24}$$

where *d* is a decadal discount factor and the parameters η and A are calibrated parameters.

Addendum C: Algebraic Structure of the Carbon Modeling

This section describes how carbon is calculated in the Global Timber Model. As previously mentioned methods for calculating carbon follow the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance (Penman et al., 2003). Carbon is tracked in four basic pools: aboveground carbon, slash, marketed products, and soils. Aboveground carbon is calculated on any given hectare in the model as:

$$Carb_{a,t}^{i} = \left[V_{a,t}^{i}\left(\mathrm{Z}_{a,t}^{i}\right)\right] * \left[WD^{i}\right] * \left[BEF^{i}\right] * \left[R^{i}\right] * \left[CF^{i}\right]. \tag{1.25}$$

The variables shown in equation (1.25) are described in Table 3. The parameters are obtained from various sources, including Penman et al. (2003). To determine total carbon in a given timber type, the hectares in each age class are summed as follows:

$$TCarb_{t}^{i} = \sum\nolimits_{a}\left[Carb_{a,t}^{i}\right] * \left[H_{a,t}^{i}\right] \tag{1.26}$$

Total carbon for all timber types can be determined by further summing across timber types, i.

The slash pool contains dead timber left in the forest after harvests or land use conversion. It is material that is not removed due to high cost. If residues are harvested due to high demand, it is removed from this pool. However, in other cases slash is either burned by landowners or left to decompose. To calculate the amount of slash left in the forest at the time of harvest or land use conversion, the amount of carbon removed from harvesting of timber or other products is deducted from initial forest carbon amounts.

Carbon in the slash pool is the dead timber left in forests after harvests or land use conversion. Slash is the material that is not used for marketed wood products and is too costly to remove from the forest. If residue is harvested, it is harvested from this pool. In some cases, slash is burned by landowners, and in other cases, slash is simply left behind to decompose. To calculate the amount of slash left in the forest at the time of timber harvest or land use conversion, the initial amount of carbon in forests is calculated in (1.27) and the amount removed for timber or other products is deducted. This is:

$$AnnSlash_{t}^{i} = \left[TCarb_{t}^{i}\right] - \left[Mkt_{t}^{i}\right], \tag{1.27}$$

where Mkt_{t}^{i} is the amount of carbon stored in marketed products. The slash pool is composed of the annual contribution to slash minus decomposition from previous years:

$$SlashPool_{t+1}^{i} = SlashPool_{t}^{i} + AnnSlash_{t}^{i} - dr^{i}\left[SlashPool_{t}^{i}\right]. \tag{1.28}$$

Decomposition rates, dr^{i}, range from 3% per year in boreal regions to 7% per year in tropical regions. Because the slash pool is built up over many years, at the start of the simulations the initial-year harvests is used to calculate an initial slash pool for each timber type i. This calculation will affect the baseline rate of slash accumulation, but it will not alter the change in slash accumulation in the policy scenarios.

Market carbon is calculated similarly, although we account for differences in sawtimber and pulpwood. Methodologically, however, annual contributions to the sawtimber and pulpwood pools are calculated similarly:

Annual sawtimber market carbon: $SMkt_t^i = \left[carm^i\right] \sum_a \left\{\lambda_{a,t}^i \left[V_{a,t}^i\left(Z_{a,t}^i\right)\right] \left[H_{a,t}^i\right]\right\}$ (1.29)

Annual pulpwood market carbon: $PMkt_t^i = \left[carm^i\right] \sum_a \left\{\left[1 - \lambda_{a,t}^i\right] \left[V_{a,t}^i\left(Z_{a,t}^i\right)\right] \left[H_{a,t}^i\right]\right\}$ (1.30)

Some of the carbon in the marketed product pools is assumed to turn over, or decompose, and is released to the atmosphere each year. The equations for keeping track of this process is given as:

$$SawPool_{t+1}^i = SawPool_t^i + \left(1 - \gamma_s^i\right) SMkt_t^i - drw_s^i \left[SawPool_t^i\right] \tag{1.31}$$

$$PulpPool_{t+1}^i = PulpPool_t^i + \left(1 - \gamma_p^i\right) PMkt_t^i - drw_p^i \left[PulpPool_t^i\right] \tag{1.32}$$

In equations (1.31) and (1.32), some proportion, usually 25 to 35% of the amount harvested is emitted relatively quickly in the production process. This emission often occurs in the form of harvesting residues that are burned for energy or discarded immediately. Wood products then enter useful products and eventually are discarded. They are assumed to decompose over time at rate $drw_{s,p}^i$.

Soil carbon is maintained in three separate stocks. The first stock is for forests maintained as forests. If forests do not change land use, soil stocks are constant. When land use changes, such as from forest to nonforest or vice versa, the model calculates the net gain or loss in carbon to or from the atmosphere. This is accomplished by tracking the total pool of soil carbon in forests but only deducting the net losses when forests are converted to agriculture.

The second stock of soil carbon is for soils that have converted from agriculture to forests. These soils begin with an average amount of carbon in soils for the given region and then accumulate carbon in soils over time. The pool of soil carbon accumulates over time according to a logistic growth function, with growth rate rr^i. K^i is the steady-state soil carbon potential for each timber type:

$$SoilC_{t+1}^i = SoilC_t^i + f\left(SoilC_t^i\right) \tag{1.33}$$

where

$$f\left(SoilC_t^i\right) = \left(rr^i\right)\left(SoilC_t^i\right)\left[\frac{K^i - SoilC_t^i}{SoilC_t^i}\right]. \tag{1.34}$$

The third stock of soil carbon is the soil carbon associated with land use conversions out of forests and into agriculture. When these changes occur, the present value of carbon lost over time is calculated using equation 1.34, and these present value losses or gains are assigned to the hectares that are removed from forestry (or added to forestry) in the year the land use changes. This simplifies the need to account for the carbon in hectares after they have exited the model, and it results in a relatively conservative net estimate of the carbon losses when land is converted out of forest.

Table 3: Variables, Functions, and Parameters in the Carbon Calculations

Category	**Label**	**Description**
Variable	Carb	Carbon in age class *a* and time period *t* for timber type *i*
	$\lambda_{a,t}^{i}$	Proportion of total wood harvest allocated to sawtimber
Parameters	WD	Wood density
	BEF	Biomass expansion factor (tons biomass per m^3 wood material)
	R	Root-shoot ratio
	CF	Proportion of biomass that is carbon
	dr	Decomposition rate
	$carm$	Tons of carbon per m^3 wood used in markets
	$\gamma_{s,p}^{i}$	Initial emission from the sawtimber or pulpwood pool
	$drw_{s,p}^{i}$	Wood products pool turnover (or decomposition) rate
	rr^i	Growth rate
	K^i	The steady state soil carbon potential for each timber type.

Appendix E: Model Documentation for the U.S. Forest Assessment Model as Applied for the U.S. Mid-Century Strategy for Deep Decarbonization

John W. Coulston[11] & David N. Wear[12]

Introduction

Recent evaluations of forest carbon dynamics in the US (Woodall et al. 2015; EPA 2016) and projections of future greenhouse gas emissions (BR 2016, Wear and Coulston 2015) indicate that forest carbon sequestration continues to provide a strong net offset to emissions from other sectors but that the offset is expected to decline due to land use pressures, management, forest aging, and other biophysical dynamics. These projections generally anticipate future forest carbon sequestration without policy interventions that could increase sink strength. We evaluate the potential for policies in the forest sector to contribute additionally to reductions in U.S. emission futures. By examining an additive and plausible set of scenarios for expanding forest carbon sequestration between 2017 and 2050 we set out the potential upper bounds on future offsets.

Our scenarios address a set of policy targets measured in terms of forest area and harvested forest products consistent with land use/management options that could influence forest carbon dynamics and that have some historical precedent. While we do not model the market mechanisms for achieving these physical outputs—i.e., subsidies, carbon cap and trade or tax strategies—the broad context for these projections is a future with a high cost placed on carbon emissions that would encourage increased sequestration and decreased emission activities. Given the complexity of the biophysical dynamics that ultimately govern how these activities influence carbon sequestration, defining the potential range of responses defines a critical first step before pursuing a more nuanced design of policy mechanisms—i.e., through taxes, cap and trade programs, etc...

Carbon sequestration in the forest sector results from the net effects of carbon accumulations in and emissions from standing forests, land use changes, harvested wood products in use, and landfills, with the largest share (~85%) accruing to standing forests where carbon accumulation has long exceeded the emissions from harvesting and disturbances such as fire. Land use changes have resulted in concurrent gains and losses in forest area with net gains accruing in the US over the past twenty years. Projections of forest carbon developed for the 2016 US Biennial Report by USDA (USDA OCE 2015) included a reference scenario that anticipates the elimination of net gains in forestland in the next decade followed by a slight decline in forest area through 2050. The combined effects of projected land use changes, market-clearing production of various wood products, and forest growth dynamics and disturbances result in an overall slowing of carbon sequestration rates by the forest sector. This reference scenario defines the reference case for weighing a range of policy options.

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Future Scenarios

Three human interventions dominate changes in the forest sector: land use choices, forest management and harvesting, and fire/fuel management. Accordingly, we consider three possible mechanisms for enhancing forest C sequestration in the United States: 1) altering the area of forests by reducing land development or by encouraging afforestation on other rural land uses or by restoring persistently nonstocked forest areas (areas in a forest land use without tree cover), 2) forest management efforts to reduce the occurrence of wildfire, 3) expanding the use of solidwood products or bioenergy products from forests. We construct and evaluate the following additive set of scenarios to determine a plausible range of sequestration futures for the US:

1. **Reduced deforestation.** Current USDA projections anticipate land development in response to a growing US population and economy. This scenario—an alternative projection developed for the Biennial Report (USDA OCE 2015)—anticipates a shift toward lower development intensities that result in no net loss of forest area beginning in 2025.
2. **Afforestation/reforestation.** We evaluate expanded forest area for a high and a low policy case. In the eastern US we simulate the effects of an afforestation program of between 10 (low) and 30 (high) million acres. Conservation Reserve Program (CRP) already funds the "retirement" of private marginal cropland to support conservation efforts and the cap on the program has reached as high as 36.8 million acres and currently stands at about 24 million acres. This scenario anticipates a similar program (perhaps an extension of the current CRP) to compensate landowners for establishing forests in the eastern US on other rural lands. Additionally, the nation's forest inventory includes areas that remain persistently understocked in trees in western regions-- 13.0 million acres with 9.2 million located on federal forests. Forest regeneration could be focused through public agencies and this scenario simulates the influence of reforestation on 80 (high) percent or 50 (low) percent of these 9.2 million acres.
3. **Fire mitigation.** Wildfire causes carbon emissions and lateral transfer of carbon among pools followed by recapture of carbon by growing forests. This scenario simulates a 10 percent reduction in fire occurrence throughout the US by reducing the rate of stand-replacing fire events by 10% and then adjusting carbon among forest pools consistent with observed fire/no fire distributions in the inventory (e.g., shifts from live to dead tree pools)
4. **Expanded Wood Construction.** Solid wood products provide a means of storing carbon captured by growing forests for several decades. While the U.S. consumes more wood per capita than any other nation, the use of solidwood products could be expanded. This scenario evaluates increases in the wood product content of construction by 10 percent on carbon stored in forests and in the wood products.
5. **Bioenergy.** We simulate the effect of bioenergy futures (developed by the Department of Energy) on forest carbon futures. Current bioelectricity capacity is 414 MW. The biomass scenario targets a doubling of this capacity every 10-years from 2025 to 2055 such that in 2055 the total capacity is 3312 MW. Under this scenario we assume that forest energy crops will contribute 50% each to meeting increased demand. This suggest increases forest bioenergy crops from approximately 1 million acres currently to 6.7 million acres in 2050. We present the results of the bioenergy scenario separate from scenarios 1-4 described above.

Our core analysis focuses on constructing scenarios in additive fashion (table 1). We start with the reduced deforestation scenario, then add afforestation/restoration, then add fire mitigation, then add expanded wood construction options. To examine the influence of policy timing, we also examine a scenario that defers the implementation of the afforestation/restoration policy by five years.

The bioenergy scenario is held separate from our core analyses. Increased acreage of forest bioenergy plantations is assumed to come from under-utilized pasturelands and increases are staged to meet energy sector demands. Because the system is designed to meet these increased demands it is at a steady state (emissions=sequestration) after year 2055.

Subsequent to evaluating the incremental scenarios we construct a scenario that defines a more aggressive afforestation policy and spreads out afforestation and restoration across a longer time frame with the objective of defining some approximation of an upper bound for potential sequestration. We augment the high afforestation level of 30 million additional acres in the East with another 5 million acres in the East and 10 million acres in the West for a total of 45 million acres. We label this the **Target 2050 scenario** and it also includes the fire mitigation and expanded wood construction elements described above.

Table 1. Definition of reference and various policy scenarios evaluated for effects on carbon sinks. See notes for explanation of policy components.

	Scenario components			
Scenario label	Land use scenario	Afforestation + restoration policy	Fire mitigation policy	Expanded wood products use
Reference	USDA-BR Reference			
Reduced development	USDA-BR Low development			
High	USDA-BR Low development	High		
High/fire	USDA-BR Low development	High	yes	
High/fire/cut	USDA-BR Low development	High	yes	yes
Low	USDA-BR Low development	Low		
Low/fire	USDA-BR Low development	Low	yes	
Low/fire/cut	USDA-BR Low development	Low	yes	yes
Target2050(fire/cut)*	USDA-BR Low development	Highest	yes	yes
High/defer	USDA-BR Low development	High-deferred		
Low/defer	USDA-BR Low development	Low-deferred		
Bioenergy	none	no	no	no

Notes:

-Land use scenarios: developed from the USDA projections (USDA OCE 2015)
-Afforestation + restoration policy:
High option- 30 million acres afforested in the east + 14 million acres restored in the west.
Low option-10 million acres afforested in the east + 9 million acres restored in the west.
Deferred-indicates a five year delay in policy implementation
Highest option-35 million acres afforested in the east; 10 million in the west + 14 million acres restored in west

-Fire mitigation: reduce areal extent of wildfire by 10%
-Expanded wood products use: increase solid wood product by 10% in construction.
-Bioenergy: increase forest bioenergy crops to 6.7 million acres in 2050 to meet demand.
*-the Target2050 also defers implantation of policy options to steadily increase sequestration over the time period.

Results

Reduced Development:

Our results suggest that policy intervention can significantly influence both the trajectory of annual C sequestration rates and the cumulative amount of C sequestered by forests between 2017 and 2050 (Table 2). For example under the reference scenario the annual forest C sequestration rate was projected to be -323 Tg CO_2-eq yr^{-1} in 2050. A policy aimed at reducing deforestation (no net change in forest area) may increase the annual forest sequestration rate to -362 Tg CO_2-eq yr^{-1}. From a cumulative perspective our results show that, compared to the reference scenario (-14103 Tg CO_2-eq), the reduced deforestation scenario sequesters 1127 Tg CO_2-eq of additional carbon from 2017-2050.

Table 2. Carbon sequestered (Tg CO_2 eq / yr) by U.S. forests (forests remaining forests) by Scenario.

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	(Tg CO_2 eq/yr)							
Reference	-480.7	-451.2	-430.8	-401.4	-370.1	-343.4	-341.3	-322.6
Reduced development	-480.7	-453.5	-452.2	-439.2	-410.5	-398.7	-386.7	-362.2
low	-480.7	-497.5	-503.5	-455.9	-444.3	-430.5	-419.3	-412.2
low/fire	-480.7	-497.3	-516.5	-467.6	-445.7	-441.9	-427.8	-416.0
low/fire/HWP	-480.7	-480.3	-489.0	-442.1	-423.2	-422.6	-410.9	-400.8
high	-480.7	-527.9	-526.6	-482.2	-490.6	-503.6	-487.7	-469.3
high/fire	-480.7	-529.6	-543.0	-488.2	-493.3	-516.1	-500.4	-476.1
high/fire/HWP	-480.7	-512.6	-515.5	-462.6	-470.8	-496.8	-483.5	-460.9
target2050	-480.7	-453.0	-440.1	-464.5	-490.4	-546.2	-570.1	-578.1
Alternative timing:								
high(defer)	-480.7	-456.5	-513.1	-522.9	-459.4	-476.9	-478.4	-480.3
low(defer)	-480.7	-457.6	-483.4	-491.7	-433.3	-425.8	-423.8	-402.8

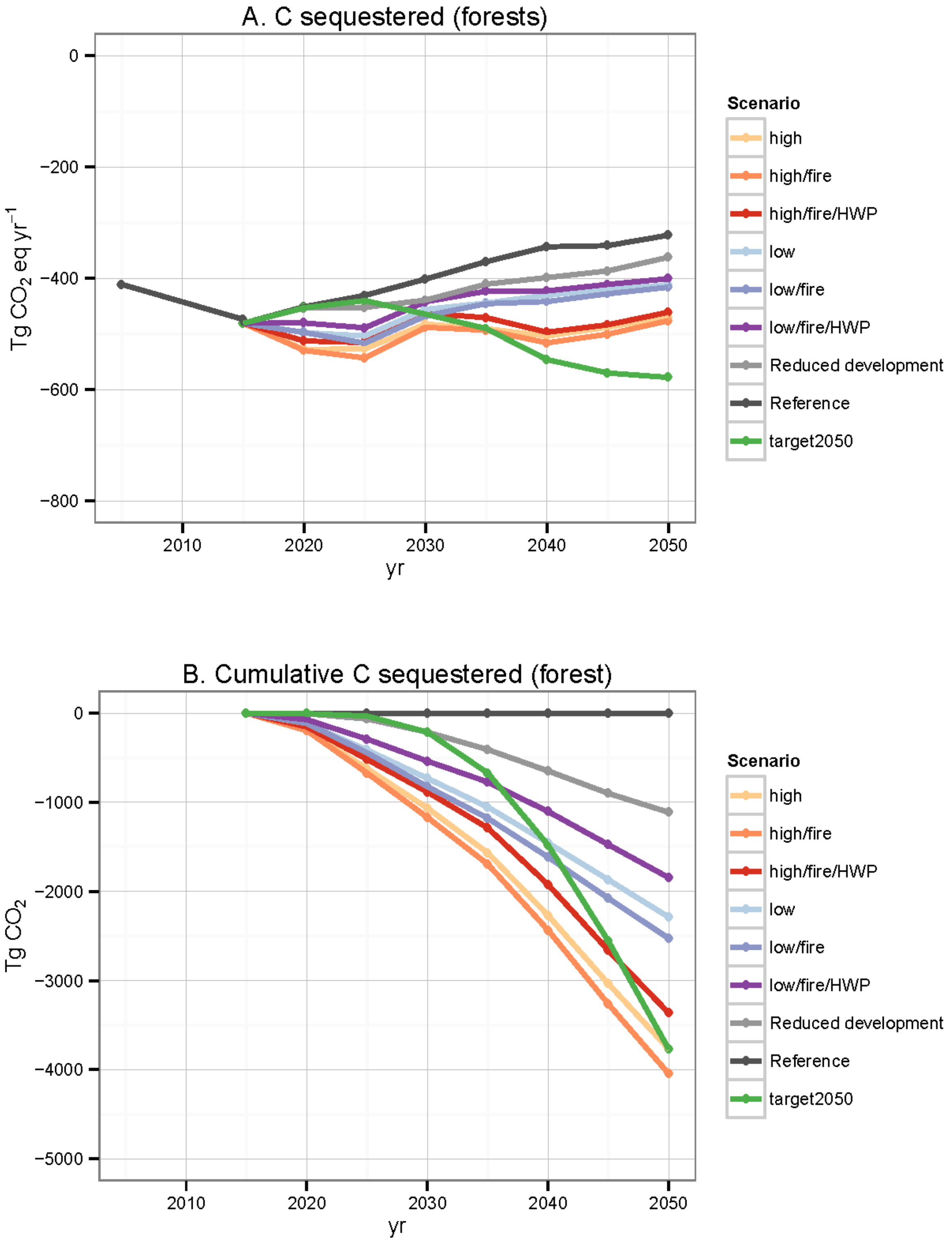

A. C sequestered (forests)
Tg CO$_2$ eq yr^{-1}
0
−200
−400
−600
−800
2010
2020
2030
2040
2050
yr
Scenario
high
high/fire
high/fire/HWP
low
low/fire
low/fire/HWP
Reduced development
Reference
target2050
B. Cumulative C sequestered (forest)
Tg CO$_2$
0
−1000
−2000
−3000
−4000
−5000
2010
2020
2030
2040
2050
yr
Scenario
high
high/fire
high/fire/HWP
low
low/fire
low/fire/HWP
Reduced development
Reference
target2050

Figure 1. (A) Annual forest carbon sequestration (Tg CO2 eq yr-1), and (B) cumulative sequestration (Tg CO2 eq) over the simulation period relative to the reference case. Note that these charts reflect carbon sequestered in the forest carbon pool alone and do not reflect associated changes in the harvested wood products carbon pool.

Afforestation and restoration:

The afforestation/restoration scenarios in combination with the reduced deforestation scenario showed further increases over the reference scenario with the ‘high’ option increasing annual sequestration to -469 to -480 Tg CO_2-eq yr^{-1} in 2050 depending whether the implementation was immediate or deferred (table 2). Deferred implementation yielded greater sequestration rates in 2050 but the cumulative sequestration between 2015-2050 was somewhat smaller for the deferred implementation (-3275 Tg CO_2-eq) than with immediate implementation (-3818 Tg CO2-eq) compared with the reference scenario. The reduced deforestation and the afforestation/restoration options also influences land use transfer of C. These transfers, while not interactions with the atmosphere, do move existing carbon stocks into forest from other land uses. There were significant land use transfers associated with the low and high afforestation scenarios under the immediate and deferred options. The restoration scenario did not cause an increase in land use transfer C because the perpetually non-stocked areas where restoration was targeted were classified as a forest land use.

Fire mitigation:

Because we were interested in the additive nature of the policy options the reduced fire scenario was added to the reduced deforestation, immediate implementation of the high and low afforestation/restoration scenarios. The effect of this scenario was minimal in the east. In the west however, the reduced fire scenario increased average annual sequestration rates by -7 to -11 Tg CO_2-eq yr^{-1} and from a cumulative perspective the fire scenario increases carbon storage by -251 and -304 Tg CO_2-eq over the low immediate and high immediate afforestation/restoration options respectively. There were significant lateral transfers associated with fires and while empirical evidence suggests a substantial decrease in the live tree carbon density (-7 Mg C ha^{-1}) this was partially offset by substantial increases in dead tree carbon density (4 Mg C ha^{-1}) (fig 3). Further, the avoidance of fire modified age transition probabilities such that the ‘aging process’ increased (see methods).

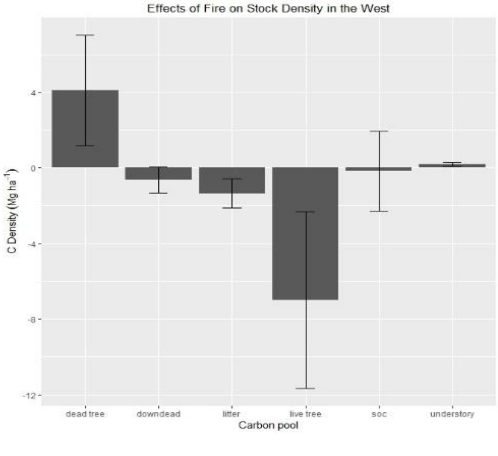


Figure 2. Example of lateral C pool transfers due to fire in the western United States. Error bars display the variability across western forest types.

Expanded solidwood products:

The expanded wood construction scenario was considered in addition to the reduced fire scenario. The increased forest harvesting to support expanded wood products construction decreased forest sequestration rates by 15.2 Tg CO_2-eq yr-1 in 2050 and 25.6 Tg CO_2-eq yr-1 in 2030 as compared to the reduced fire scenario (Table 2). However these decreases were offset by increases in the harvest wood products carbon pool.

The reference harvested wood products scenario, develop from the US Forest Products Model, was aligned with the assumptions of the forest reference scenario. Under the reference HWP scenario annual sequestration in harvested wood products increases from -112 Tg CO_2-eq yr^{-1} in 2015 to -148 Tg CO_2-eq yr^{-1} in 2050 (Table 3). Table 3 also depicts increases to the harvested wood products pool that were a result of the increased cutting to provide solidwood material. Under this scenario from 2015-2050 sequestration in the harvested wood products pool ranged from -23 to -30 Tg CO_2-eq yr^{-1} and the cumulative effect was 876 Tg CO_2-eq. Results suggest that the increased solid wood construction scenario increases the overall harvest wood products pool sequestration to -171 Tg CO_2-eq yr^{-1} in 2050. When considering the entire forest sector (persisting forest, and harvested wood products carbon) the expanded solidwood products scenario increases sequestration by 8 Tg CO_2-eq yr^{-1} over the reduced development plus afforestation/restoration plus fire mitigation suppression scenario (Table 4).

Table 3. Total carbon sequestered (Tg CO_2 eq / yr) in harvested wood products broken down by detailed pools for two scenarios (Reference and expanded wood products use [HWP]) (2015-2050).

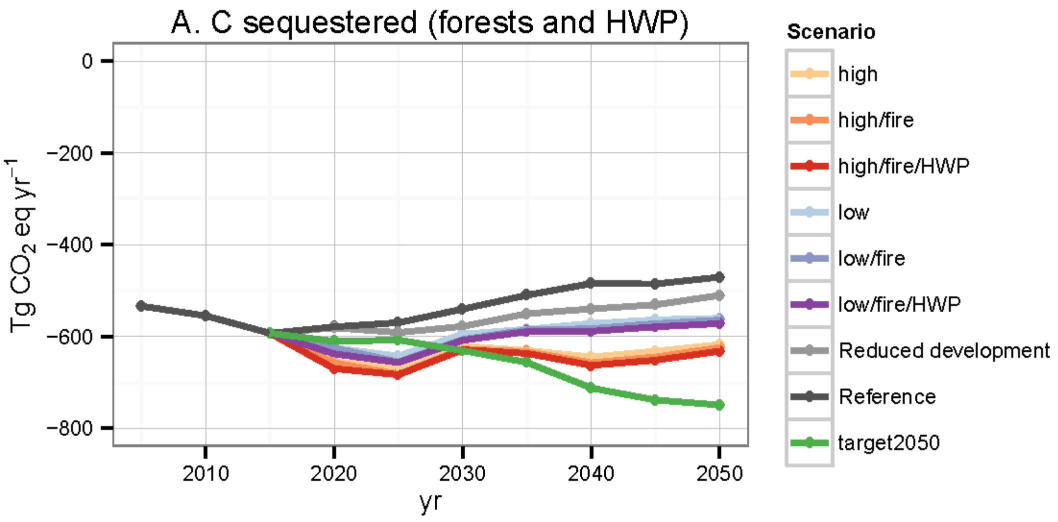
Scenario/component	2015	2020	2025	2030	2035	2040	2045	2050
				(Tg CO_2 eq/yr)				
Reference Scenario: Total	-112.3	-127.7	-139.2	-138.9	-140.0	-141.2	-144.3	-148.2
HWP Scenario: Total	-112.3	-157.6	-167.8	-166.3	-166.2	-166.2	-168.3	-171.1
A. Wood products in use	-42.7	-52.6	-59.4	-56.1	-54.7	-53.7	-54.2	-54.6
Solidwood products	-37.5	-48.8	-45.7	-55.7	-54.8	-53.4	-53.0	-52.4
Paper products	-5.2	-3.8	-2.6	-0.4	0.1	-0.3	-1.1	-2.2
B. Landfilled wood	-69.5	-75.1	-79.9	-82.9	-85.2	-87.5	-90.1	-93.6
Solidwood products	-46.2	-50.0	-53.8	-56.9	-59.8	-62.4	-64.9	-67.6
Paper products	-23.4	-25.1	-26.1	-26.0	-25.5	-25.1	-25.2	-26.1
C. HWP Scenario: Additional	0.0	-29.9	-28.6	-27.4	-26.2	-25.0	-24.0	-22.9

Notes: Reference scenario is defined by components A+B. HWP Scenario is defined by components A+B+C.

Table 4. Total carbon sequestered (Tg CO_2 eq / yr) by forests (forests remaining forests) and in harvested wood products by scenario (2015-2050).

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	(Tg CO2 eq/yr)							
Reference	-593.0	-578.9	-570.0	-540.3	-510.1	-484.6	-485.6	-470.8
Reduced development	-593.0	-581.2	-591.4	-578.1	-550.5	-539.9	-531.0	-510.4
low	-593.0	-625.2	-642.7	-594.8	-584.3	-571.7	-563.6	-560.4
low/fire	-593.0	-625.0	-655.7	-606.5	-585.7	-583.1	-572.1	-564.2
low/fire/HWP	-593.0	-637.9	-656.8	-608.4	-589.4	-588.8	-579.2	-571.9
high	-593.0	-655.6	-665.8	-621.1	-630.6	-644.8	-632.0	-617.5
high/fire	-593.0	-657.3	-682.2	-627.1	-633.3	-657.3	-644.7	-624.3
high/fire/HWP	-593.0	-670.2	-683.3	-628.9	-637.0	-663.0	-651.8	-632.0
target2050	-593.0	-610.6	-607.9	-630.8	-656.6	-712.4	-738.4	-749.2
Alternative timing:								
high(defer)	-593.0	-584.2	-652.3	-661.8	-599.4	-618.1	-622.7	-628.5
low(defer)	-593.0	-615.2	-651.2	-658.0	-599.5	-592.0	-592.1	-573.9

Notes: Reference case projections of C in harvested wood products are applied to all scenarios except those labelled HWP or target 2050, which use the wood products C estimates from the HWP scenario (see Table 3).



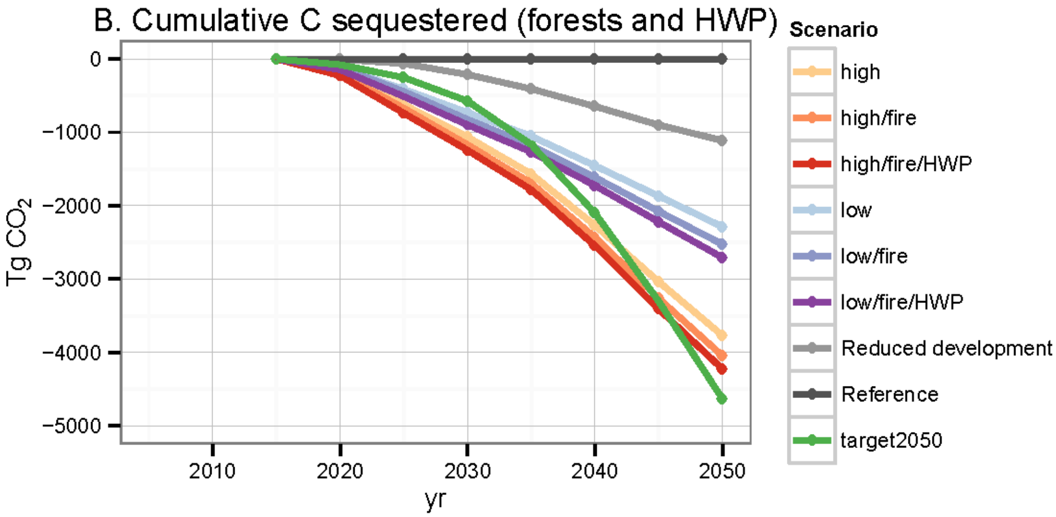


Figure 3. (A) Annual forest carbon sequestration (Tg CO2 eq yr-1), and (B) cumulative sequestration (Tg CO2 eq) over the simulation period relative to the reference case. Note that these charts reflect carbon sequestered in the forest carbon pool plus associated changes in the harvested wood products carbon pool.

Bioenergy:

Under the bioenergy scenario, to accommodate the increased capacity of the electricity sector additional acres are needed for bioenergy plantations. Assuming a 10-year rotation, the approximately one million ac in current bioenergy plantations would need to increase to about 6.7 million ac in 2050 and 8.2 million acres in 2055 to supply electricity sector (see methods). These additional acres would be staged based on decadal increases in demand (Figure 4a). Because the plantations are established 10 years before the supply is needed there is an increased sequestration from 2020-2055 (Figure 4b). However after 2055 the system reaches a steady state and sequestration is zero Tg CO_2-eq yr^{-1}. Results from this scenario are not included in the other scenarios (reduced development, afforestation and restoration, fire management, increased solid wood products, or target 2050).

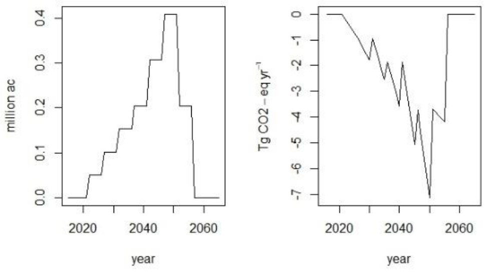


Figure 4. Annual acreage additions to bioenergy plantations (a), annual sequestration of bioenergy plantations (b).

Target 2050:

Under the reference scenario sequestration rates declined by 21% between 2015 and 2050 (Figure 3). Our most aggressive policy high/fire/HWP increased sequestration rates by 7% between 2015 and 2050. The target2050 was devised to contemplate the magnitude of actions needed to significantly increase the forest sector sink in 2050. We found that increasing the afforestation component by 15 million acres and adjusting the timing of afforestation/restoration increased forest sequestration rates by 26% (156.2 Tg CO_2-eq yr^{-1}) between 2015 and 2050 (fig 3). However because forest growth rates and hence sequestration are maximized at earlier stand ages, sequestration would decrease after 2050.

Discussion

Our reference scenario assumes no policy intervention over the projection period and suggests that forest sector carbon sequestration rates will decrease to -471 Tg CO_2 yr^{-1} by 2050 primarily due to the interaction of forest ageing, forest disturbance, and land use change. Based on our analysis policies that modify these interacting drivers can increase sequestration during the projection period. Retaining forest land addresses the expected loss of forest land through land use change but does not influence the forest aging process where older forests sequester less carbon. Adding new forestland through an afforestation policy influences carbon through land use change, partially influences the ageing component and therefore the disturbance component. However the afforestation policies, whether immediately implemented or deferred, cause a surge in sequestration as additional acreage moves through the most productive age classes but then subsides as the new forests mature. This was similar for the restoration activities. Regardless, adjusting the land use change component offered the largest incremental gains.

Fire mitigation is both the most intractable and the least influential of strategies for enhancing sink strength for several reasons. First, the implementation of this type of policy would be very difficult because it would require effective fire management/silvicultural treatments on an additional 0.7 million ac yr^{-1}. Second, fire is a natural part of many forest communities in the United States and particularly in the western United States fire often acts as a stand replacing event. The stand replacing event however does not necessarily mean a complete emission of all material. Rather lateral transfers between forest carbon pools result in retention of a significant portion of the carbon in the standing dead tree pool and these trees may decay quite slowly, particularly in arid and semi-arid climates, while the understory quickly responds and grows. Third, reducing fire through mitigation allows the ageing process to continue for those areas where forest fire management was carried out and fire avoided.

Under the most aggressive set of policies (avoided deforestation, high afforestation/restoration, fire mitigation, and expanded wood products) 30 million ac would be added to the forest land base of ~ 700 million ac. In combination the forest management scenarios (restoration, fire mitigation, and expanded wood products) would influence less than 50 million acres of the ~730 million ac forest land base (7 percent). The target2050 scenario provides a more aggressive alternative still influences less than 9% of the projected forest land base. It results in an increase in sequestration in 2050 but that increase subsides under observed forest dynamics.

There are important regional dynamics and the policy options implemented in the eastern United States had larger influences on both average sequestration rates (2017-2050) and cumulative sequestration rates than in the western United States. This was primarily driven predominately by the higher growth rates of forest in the eastern United States. Also, the fire mitigation strategy was relatively ineffective in the East where its implementation only increased sequestration rates by ~ 2 Tg CO_2-eq yr^{-1}.

In summary, we implement 11 different scenarios to examine their possible impact on forest carbon sequestration rates as compared to a reference scenario. Avoided deforestation in conjunction with a large area afforestation and restoration initiative provided the largest marginal gains. The fire mitigation scenario had a comparatively minor influence of overall C dynamics. The increased wood products scenario also had a comparatively minor increase in overall sequestration. Aggressive policies to maximize forest sector CO_2 sequestration in 2050 were examined however, these scenarios do no provide for sustained CO_2 sequestration rates. Examining cumulative sequestration over a prescribed period of time will provide a reasonable basis to judge the overall effectiveness of potential policies for increasing forest carbon sequestration.

Methods

Data

We used inventory data as provided by the USDA Forest Service Forest Inventory and Analysis program to quantify and project C stock and C stock change for the conterminous US. These data were consistent with the data used in BR 2016 and Woodall et al. (2015). Total carbon was used in this analysis and included the following pools: down dead wood, forest floor, live trees above ground, live trees below ground, standing dead wood, soil organic C, understory vegetation above ground, and understory vegetation below ground. Further details on C pool models are presented by Woodall et al. (2015).

Projection models

The forest component of the land use sector is one element of the national Greenhouse Gas Inventory and accumulation in forests involves transfers between forests and other land uses. Area that is transitioned from a non-forest use to a forest use is included as an increase in the forest C pool while transition from forest to non-forest use is included as a loss from the forest pool. Accordingly, net change in forest C includes both C exchange with the atmosphere and transfers to or from other terrestrial C pools. Additionally, some harvested forest C may be transferred to durable forest product C pools and this is accounted for as a separate component. We decompose the total change in the forest C pool into a land transfer component and a forest growth component. The latter provides an estimate of the net C exchange between forests and the atmosphere. The FIA database provides State-level estimates of net changes in forest area (ΔA), total change in forest C (ΔC), and carbon densities by pool, including the average density of soil C (C_{soil}) We approximate the C transfer associated with net forest area change as $\Delta A \bullet C_{soil}$, and the C sequestered as:

$$\boldsymbol{C_{seq} = \Delta C - \Delta A \cdot C_{soil}}$$

Western projection model. In the western regions of the United States (Pacific and Rocky Mountain Regions in Fig. 1), where forest sampling is less intense and transition measures are not yet available, we model changes in forest C using inventory aggregates and a stage-class forest population model [29]. Consider the following general description of forest C inventory change:

$$C_t = \boldsymbol{F}_t \cdot \boldsymbol{Den} \qquad (1)$$

where C_t is total forest C at time t within the analysis area, F is a 1 x n vector of forest area by age class (n is the number of age classes and the nth age class is a terminal age class, ideally defined where C reaches a stable maximum) and Den is an n x 1 vector of per unit area forest C densities arrayed by forest age class. Note that this can be generalized to account for multiple forest types or to distinguish among other relevant forest attributes (e.g., n=jk where j= the number of age classes and k=number of forest types). Inter-period forest C dynamics can be described by introduction of a transition matrix (T):

$$\boldsymbol{F}_{t+m} = \boldsymbol{F}_t \cdot \boldsymbol{T} \qquad (2)$$

where **T** is an n x n matrix and each element T_{ij} defines the proportion of forest area in class i transitioning to class j and m defines the time increment of the projection. The values of the elements of T depend on a number of factors, including forest disturbances such as harvests, fire, storms, and others, and the value of m, especially relative to the span of the age classes. For example, consider a case where we hold area fixed, allow for no mortality, define the time step m equivalent to the span of age classes, and define five age classes. T would be:

$$\boldsymbol{T} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \qquad (3)$$

where all forest area progresses to the next age class and forests within the terminal age class are retained forever. With this version of **T**, after five time steps all forests would be in the terminal age class. Relaxing these assumptions changes the structure of **T**. If we account for disturbances including harvesting and fire that result in stand regeneration and allow for stochastic elements in forest aging:

$$\boldsymbol{T} = \begin{pmatrix} 1 - t_1 - d_1 & d_2 & d_3 & d_4 & d_5 \\ t_1 & 1 - t_2 - d_2 & 0 & 0 & 0 \\ 0 & t_2 & 1 - t_3 - d_3 & 0 & 0 \\ 0 & 0 & t_3 & 1 - t_4 - d_4 & 0 \\ 0 & 0 & 0 & t_4 & 1 - d_5 \end{pmatrix} \qquad (4)$$

where t_i is the proportion of forest of age class i transitioning to age class i+1, d_i is the proportion of age class i that experiences a stand-replacing disturbance, and $(1 - t_i - d_i)$ is the proportion retained within age class i.

Once **T** is specified, forest C at the end of the next period is defined as:

$$C_{t+m} = \boldsymbol{F_t} \cdot \boldsymbol{T} \cdot \boldsymbol{Den} \qquad (5)$$

And change in C is defined as:

$$\Delta C_t = C_{t+m} - C_t = (\boldsymbol{F_t T} - \boldsymbol{F_t}) \cdot \boldsymbol{Den} \qquad 6$$

We can also incorporate land use change as a 1 x n vector L with positive entries indicating increased forest area and negative entries indicating loss of forest area.

$$\Delta \mathrm{C_t} = \mathrm{C_{t+m}} - \mathrm{C_t} = (\boldsymbol{F_t T} - \boldsymbol{F_t}) \cdot \boldsymbol{Den} + \boldsymbol{L_t} \cdot \boldsymbol{Den} \qquad 7$$

$$\boldsymbol{F_{t+m}} = \boldsymbol{F_t} + \boldsymbol{L_t}$$

We model change in the West at the State level except in California, Oregon, and Washington where we separate the states into areas on the western and eastern sides of the Cascade mountain divide due to vast differences in forest productivity. For each State/substate we query the FIA inventory for all plot records to construct the C density vector (***Den***) by 5-year age classes from age 1-5 to greater than age 200. We also include an age class with recorded age of 0, which is largely composed of forests classified as non-stocked (where a land use change is not indicated by reforestation has yet to occur). For each State/substate we also define the age class distribution for the current forest area (F_1). Non-stocked areas are treated separately in the simulations. For reference cases we assume that these forests persist in a non-stocked condition, but also explore scenarios where some of these areas would be restored to a productive condition. An average historical stand-replacing disturbance rate (d_i) is defined by dividing the area of forests currently in the 1-5 year age class by total forest area (excluding non-stocked area) multiplied by the average transition rate (t). We apply this as a constant disturbance rate across age classes---our assumption then is that the recent disturbance pattern leading to forest replacement carries into the future. Note that d includes all events that reset the stand age including fire, weather, insects, and harvesting. We define an age transition rate (t_i) of 0.85 for all age classes to complete the definition of the transition matrix ***T*** (equation 4).

Simulations proceed by applying equation 7, using ***Den, F***, and ***T*** matrices defined above and with areas of forest area change (***L***) defined by assumptions that vary by scenario. For net gains in forest area we assume that new forest is added to the 1-5 year age class; for losses we remove forests proportionately across all age classes. We calculate the C transfers associated with land use change assuming that the soil organic C component of the vector ***Den*** transfers to/from the outgoing/incoming land use. Scenarios regarding future land use changes (incorporated in ***L***), potential shifts in productivity (adjustments to the ***Den*** vector), and forest restoration activities (through the ***T*** matrix) drive a set of projections using these models. Separate simulations are constructed for each of the 18 State/subState units and results are summarized for Pacific and Rocky Mountain Regions. Model validation is conducted using the inverse of T ($\boldsymbol{F_{t-m}} = \boldsymbol{F_t T^{-1}}$) and historical land use change to backcast ***F***, C, and dC based on equations 5-7.

Eastern projection model. Projection models for the eastern regions of the US (South and North regions in Fig. 1) utilize remeasured inventory plots. The preceding formulation of C inventory change is based on simulated forest type/age transitions and average C densities for given ages. A higher degree of specificity can be defined if we decompose the forest in a way that accounts for the effects of specific forest disturbances and other dynamics recorded for remeasured inventory plots. Consider the following modification to equation [7]:

$$\Delta \mathrm{C_t} = \mathrm{F_t} \cdot \delta \mathrm{C} \qquad 9$$

Where ΔC is total forest C change within the analysis area, **F** is as previously defined; **δC** is an n x 1 vector of per unit area forest C stock change per year arrayed by forest age class. Inter-period forest C dynamics are described as in equation [2] but the age transition matrix (**T**) is estimated from the observed data directly. Forest C change at the end of the next period is defined as:

$$\Delta C_{t+m} = \boldsymbol{F_t} \cdot \boldsymbol{T} \cdot \boldsymbol{\delta C} \qquad 10$$

We incorporate land use change and cutting, fire, weather, and insects/diseases disturbances by generalizing equation [10] to account for the above change vectors and undisturbed forest remaining as undisturbed forest:

$$\Delta C_{t+m} = \sum_{d \in L} (\boldsymbol{A_{td}} \cdot \boldsymbol{T_d} \cdot \boldsymbol{\delta C_d}) \qquad 11$$

where **A** is the area by age class of each mutually exclusive land category in **L**. **L** is (FF, NFF, FNF, F_{cut}, F_{fire}, $F_{weather}$, F_{id}) where FF=undisturbed forest remaining as undisturbed forest, NFF=non-forest to forest conversion, FNF=forest to non-forest conversion, F_{cut}=cut forest remaining as forest, F_{fire}=forest remaining as forest disturbed by fire, $F_{weather}$=forest remaining as forest disturbed by weather, and F_{id}=forest remaining as forest disturbed by insects and diseases . When more than one disturbance occurs on a plot a dominant disturbance is assigned with cutting dominating when it occurs. Otherwise, the disturbance associated with the greatest tree mortality is assigned. In the case of land transfers (FNF and NFF), **T** is an n x n identity matrix and $\boldsymbol{\delta C}$ is a C stock transfer rate by age. Paired measurements for all plots in the inventory provide direct estimates of all elements of $\boldsymbol{\delta C}, \boldsymbol{T_d},$ and $\boldsymbol{A_{td}}$ matrices. Scenarios are implemented by adjusting $\boldsymbol{A_{td}}$ for the NFF and FNF categories. Productivity shifts are implemented as adjustments to C stock transfer rates in $\boldsymbol{\delta C_d}$**.**

Scenario implementation

Reduced deforestation

Current trends from the FIA data suggest that forest area has been increase xx and xx ha per year in the east and west respectively. To implement the reduced deforestation in the west $\mathbf{F_t}$ was modified for each *m* time step as to maintain the xx increase per year until 2025. Subsequently $\mathbf{F_t}$ remained constant. In the east, $\mathbf{A_{td}}$ was modified for the NFF and FNF categories was modified in a similar fashion. The $\boldsymbol{\delta C}$ was assumed to remain constant for NFF and FNF categories.

Afforestation/restoration

Forest restoration was implemented in the western United States. To implement this scenario, $\mathbf{F_t}$ was augmented by adding a portion of the persistently nonstocked component of the forest inventory in western states over a ten year period (portion and timing of the transfer was defined by the scenario). Because nonstocked areas are included in the forest land use, restoration does not affect any transfers of carbon associated with land use change.

The afforestation scenario was implemented in the eastern United States. To implement this scenario $\mathbf{A}_{\mathbf{td}}$ was modified for the NFF category such that the requisite area transition into forest and the requisite time period. The simulation future afforestation was assumed to follow the same dynamics as observed afforestation in terms of area by age class distribution and carbon density by age class.

Fire management

The fire management scenario was implemented by decreasing the amount of fire by 10%. This focused on reducing the extent of fire not classified as ‘ground fire’ in the FIA database. In the east this was implemented by modifying $\boldsymbol{A_{td}}$ for the F_{fire} category described above. To implement this scenario in the west we extended the methodologies suggested in Woodall et al. (2015). Based on an analysis of the FIA data the amount of C stored in areas that have recently burned is $\mathbf{C}_{\text{fire}}=F_{\text{fire}}\cdot\mathbf{Den}_{\text{fire}}$ where F is forest area and **Den** is carbon density by pool. Likewise in area without fire $\mathbf{C}_{\text{fire'}}=F_{\text{fire'}}\cdot\mathbf{Den}_{\text{fire'}}$. To implement a 10% reduction in fire $\mathbf{C}_{\text{fireR}}=0.9\cdot F_{\text{fire}}\cdot\mathbf{Den}_{\text{fire}}$. This causes and increase to $\mathbf{C}_{\text{fire'R}}=(((1\text{-}0.9)\cdot F_{\text{fire}})+F_{\text{fire'}})\cdot\mathbf{Den}_{\text{fire'}}$. The original C stock was $\mathbf{C}=\mathbf{C}_{\text{fire}}+\mathbf{C}_{\text{fire'}}$. C stocks under reduced fire were $\mathbf{C}_{\text{R}}=\mathbf{C}_{\text{fireR}}+\mathbf{C}_{\text{fire'R}}$. This model was implemented on a forest type basis and **Den** was recalculated as $\mathbf{Den_R}=\mathbf{Den}\circ\mathbf{C}_{\text{R}}\circ\mathbf{C}^{-1}$. **T** was also modified yielding $\mathbf{T_R}$ such that there was 10% less disturbance affecting age transitions.

Wood products carbon

The wood product carbon scenario required tracking increases to the wood products pools and increases in forest cutting required to meet the requisite increase in wood products carbon. The target increase was 8.3 Tg C yr^{-1} going into structural wood products used in construction. We developed a model to predict the area of forest cutting (A_{cut}) based on carbon ending up in wood products (P). This was required because only a portion of the carbon removed from the forest becomes a product (Skog 2008). When parametrizing this model we assumed that increased cutting would occur in the Southern region of the United States because of its strong forest industry infrastructure. The model was

$$A_{cut}=\frac{P-m}{b\cdot\overline{\delta C_{cut}}}+e$$

Where A_{cut} was the area of forest cutting in the Southern US, *P* was wood products carbon in products, *m* was an estimated parameter for wood products carbon produced outside of the Southern region, *b* was an estimated parameter for the ratio wood products carbon produced from Southern forests to forest carbon stock change from cutting in the Southern region, $\overline{\delta C_{cut}}$ was average carbon stock change per unit area from cutting, and *e* was error. Because the scenario suggests that the 10% increase in P will be in the structural lumber pools we targeted increased cutting in the 25-40 age classes. To solve for A_{cut} under a 10% increase in P and targeting the 25-40 year age classes we iteratively solved for A_{cut} by recalculating $\overline{\delta C_{cut}}$ to target the requisite age classes. This was necessary because forests of different age classes generally have differ stock densities and harvesting practices (e.g. clearcut vs. partial-cut). Increasing the area in specific age classes changes $\overline{\delta C_{cut}}$. Given the A_{cut} estimate for harvest in the 25-40 year classes we modified $\boldsymbol{A_{td}}$ for the F_{cut} category described above.

We used the decay model provided by IPCC 2006 to model the additional C entering the harvested wood products pool.

$H_i=e^{-k}*H_{i-1}+[(1-e^{-k})/k]*prod_{i-1}$

Where, K is based on the half-life of various products=ln(2)/halflife, Prod=production, H= harvested wood products carbon, i=year. Because the increase production was assumed to provide material for structural building we used the halflife for material in single family homes (78 yrs). Stock change in H was then H_i-H_{i-1}.

Bioenergy

Current bioelectricity capacity is 414 MW. The biomass scenario targets a doubling of this capacity every 10-years from 2025 to 2055 such that in 2055 the total capacity is 3312 MW. Assuming approximately 1.5 green tons of biomass per MWh this suggests that the current electricity sector demand for biomass from energy crops is approximately 5 million green tons per year. Under a decadal doubling of capacity this suggest that approximately 40 million green tons per year are needed in 2055 supplied half from agricultural land and half from forestland. We further assume that these additional acres of forestland will come from pastureland.

Forest bioenergy planation crops considered are *Populus Sp*., *Salix Sp*., and *Liriodendron tulipfera*. We examined the FIA database (http://www.fia.fs.fed.us/library/database-documentation/index.php) for young plantations (0-15 year) where these species were planted. Above ground carbon stocks (C_{ag}) by age are presented in table x. We assume that dry tons of biomass are half of green tons biomass and that carbon is half of dry tons of biomass. Based on a portion of the literature, the rotation ages for these plantations range from 5-13 years (Miller and Bender 2012, Zamora et al. 2013, Zalesney et al. 2011, Berguson et al. 2010).

Table x. Above ground stock density by age for poplar and willow plantations.

age	C above ground live (short tons C per ac)
0	0.05
5	5.42
10	6.3
15	6.57

To accommodate the increased capacity of the electricity sector in this scenario additional acres are needed for bioenergy plantations. Given the range of rotation ages for these plantation we assumed a 10 year rotation. We employed the Wear and Coulston (2015) modeling framework to project carbon dynamics associated with this scenario. We only consider dynamics in the above ground live pool. The additional acreages were assumed to enter the system at age zero and the model was run on a yearly time-step. We track net forest sequestration (total sequestration-harvest) and biomass harvest.

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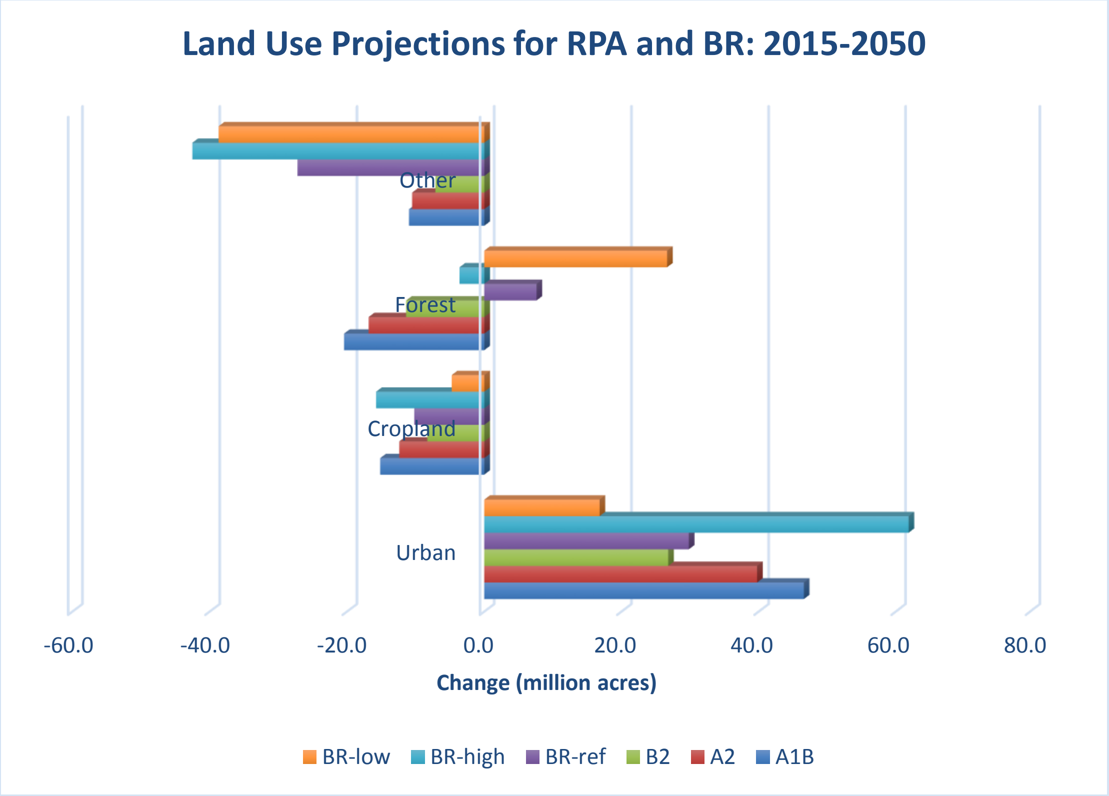
SECTION 2 APPENDIX. LAND USE FUTURES

The forest other land use projections used for this analysis are derived from previous work for two USDA Assessments which have examined change in resource conditions based in part on expected changes in land uses across the United States. One is the 2010 RPA Assessment, designed to provide 50-year projections for all regions of the CONUS. For this assessment, we modeled land use change driven by different scenarios regarding growth in and distributions of population and income across the US derived from the IPCC A1B, A2, and B2 storylines. In addition, the "USDA Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals" provides an integrated assessment of forest carbon futures based in part on land use projections using a methodology based on a national-level model that extrapolates rates of change for a reference case and alternatives with higher and lower rates of urbanization. The two assessments project changes in forest and cropland using different approaches. The USDA Assessment uses USDA Agricultural projections to predict future cropland and links change in forest area to recent (15-year) observed rates of change. The RPA Assessment uses economic information to project the future of rural land uses on a county-by-county basis.

Projections from the two Assessments for the period 2015-2050 are summarized in Figure 1.



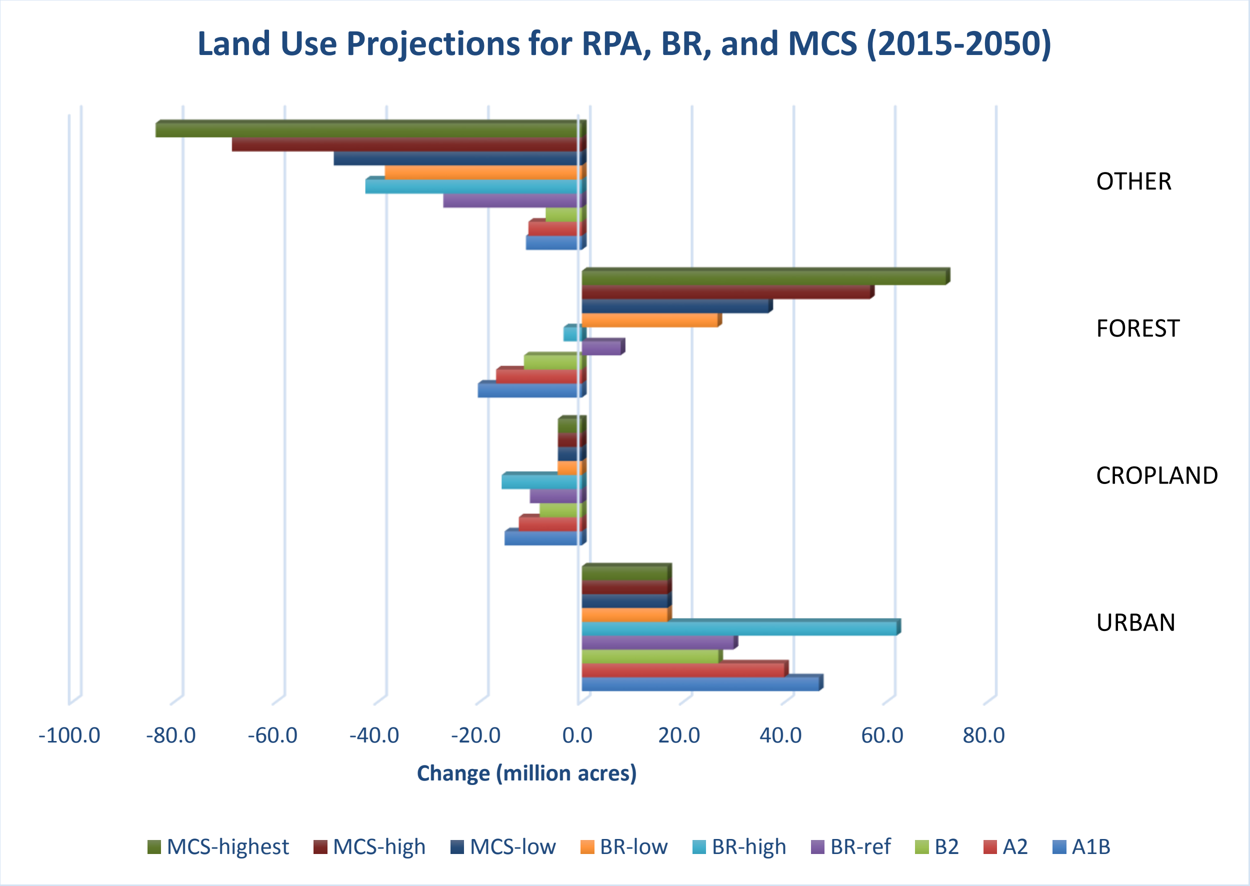
Urbanization: USDA-IP reference case projects that urban use grows by about 30 million acres (ma). The low development and high development cases indicate +17 and +62 ma respectively. The RPA projections range from +27 ma for the B2 scenario to +47 ma (A1B). Urbanization under the USDA-IP reference case and RPA B2 scenario are quite comparable.

Cropland projections: USDA-IP scenarios range from a loss of 5 ma (low development) to a loss of 16 ma (high development). RPA scenarios range from a loss of 8 million (B2) to a loss of 15 ma (A1B). Cropland loss is also comparable between USDA-IP reference and RPA B2 scenarios.

Forest projections: USDA-IP and RPA projections of forest differ substantially. USDA-IP reference scenario projects an increase of 8 million acres and range from a loss of 4 ma (high development) to a gain of 27 ma (low development). RPA projections range from a loss of 11 ma (B2) to a loss of 20 ma (A1B). However, the forestland base is very large relative to change so that the range of change is -2.5% to +3.5% across all scenarios examined.

2.1 Midcentury Strategy Scenarios

Policy scenarios to support the Midcentury Strategy for greenhouse gas emission reductions use the USDA-IP as a foundation. These scenarios address different levels of afforestation and forest restoration along with changes in wildfire and increased use of solid wood products with associated changes in net carbon accumulation in forest and product pools. All scenarios are built off of the USDA-IP low development scenario as a reference case. Figure 2 summarizes the land use change basis for these policy scenarios.



“MCS-low” defines scenarios with a low level of afforestation (+10 million acres) /restoration (+9 million acres) effort while MCS-high defines scenarios with a high level of afforestation (+30 million acres) /restoration (+14 million acres) effort. The MCS-highest (target2050) scenario increases the level of afforestation to 45 million acres. Scenarios examine alternative timing of these activities between 2015 and 2050.