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

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Supplementary Materials

Sections S1: Electricity trade in GCAM-USA

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

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

Sections S2: Variable energy integration – capacity factors

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

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

The resource curves for solar PV and onshore wind in each state are presented below as Figure S2.1. These curves are developed utilizing data from the Regional Energy Deployment System (ReEDS) model – specifically resource potential, grid connection costs, and hourly capacity factor for multiple "resource regions" and resource classes within each state. The hourly capacity factor data are aggregated to annual average capacity factors, mapped to resource potential, and sorted from highest capacity to lowest capacity factor, generating the resource curves depicted in Figure S2.1. (The same hourly capacity factor data are used to generate the segment capacity factors – i.e., the capacity factor specific to each monthly day/night dispatch segment – for each resource and state.) Grid connection costs are included in the model as a separate cost component (considered in investment decisions only). Concentrating solar power and offshore wind resources are represented in the same way (also using data from ReEDS), although not every state has these resources.

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

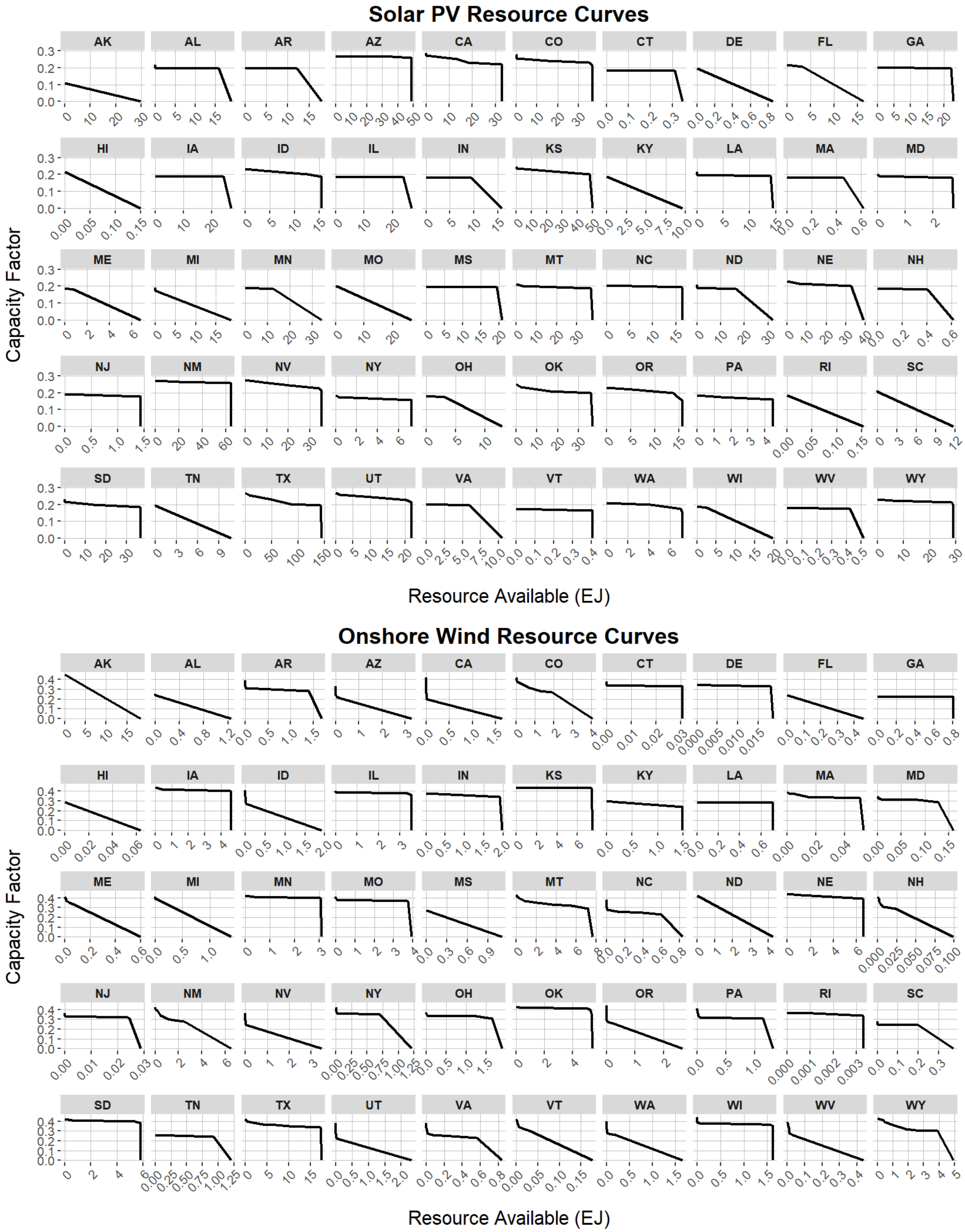

Figure S2.1. Solar PV (top) and onshore wind (bottom) resource curves. Annual capacity factor (y-axis) decreases as resource deployment (x-axis) increases.

Sections S3: End-use Sector Energy and Service Demands

The GCAM-USA Reference scenario entails steady population and economic growth throughout the 21st century at a national level, with population increasing 40% relative to 2015 and GDP nearly quadrupling. These macroeconomic drivers drive growth in demand for energy services (passenger kilometers traveled, building floorspace which drives space heating and cooling demands, etc.), which are translated into demands for final energy carriers to provide those services in each sector. Generally, GCAM-USA by default includes conservative assumptions about energy efficiency polices. For example, building sector technologies reflect a continuation, but not an expansion or strengthening, of current energy efficiency policies (e.g., building efficiency standards); vehicle efficiencies assume marginal future efficiency gains but not significant strengthening of Corporate Average Fuel Economy (CAFE) standards.

Economic growth in the GCAM-USA Reference scenario far outpaces energy service demands, which outpace final energy demands. On net, total final energy demands increase across sectors as efficiency improvements are slower than increases in demand for end-use energy services (industrial output, space heating and cooling driven by increased building floorspace, passenger and freight transportation, etc.), although the relative balance between population and income driven demand growth and energy efficiency vary by sector. Broadly, the GCAM-USA Reference scenario represents a plausible future evolution of the USA energy, water, and land systems absent significant changes in policy or energy efficiency (Binsted et al., 2020). Alternate scenarios with more stringent energy efficiency or policy assumptions can be compared against this counterfactual reference scenario; individual model users can also modify the refence scenario to reflect evolving technology, policy, or behavioral trends at the national or subnational level.

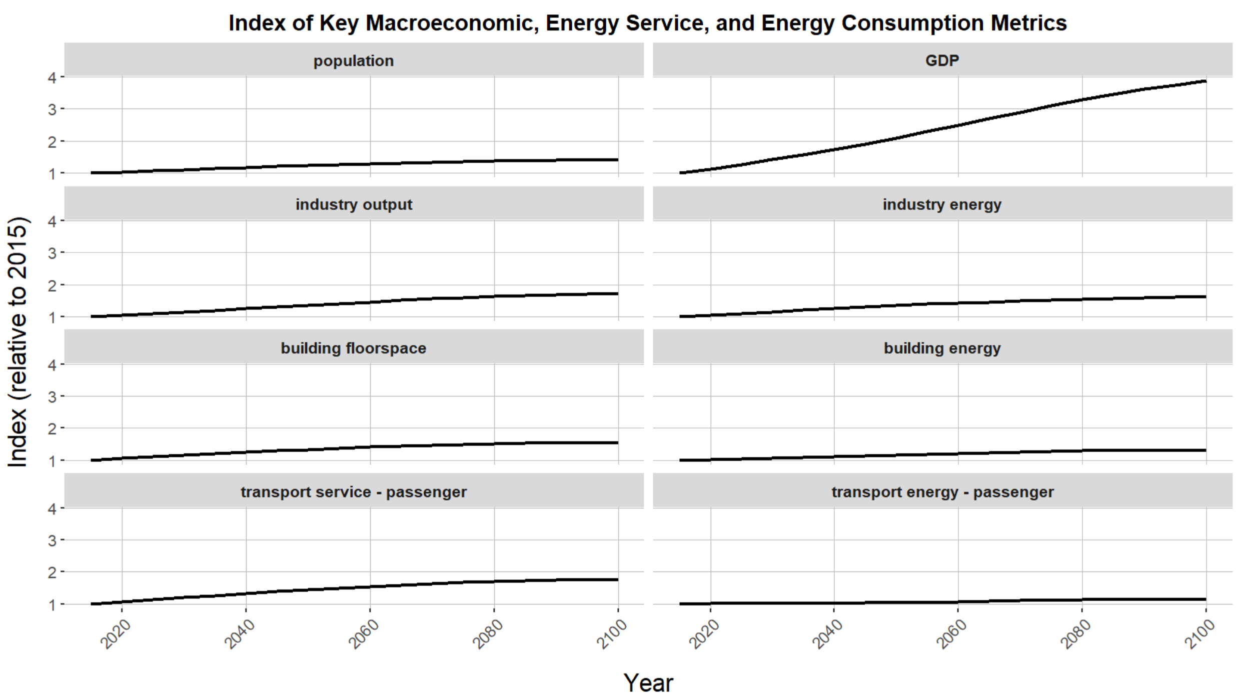

Figure S3.1. Key macroeconomic drivers (population, GDP), energy service indicators (industry output, building floorspace, vehicle km traveled), and energy consumption metrics indexed to 2015 values (2015 = 1).

Sections S4: Transportation Sector Assumptions and Alternate Scenarios

The GCAM-USA Reference scenario does not reflect subnational transportation policies (energy efficiency, emissions, etc.) or regionally differentiated consumer preferences for alternate drivetrains (electric vehicles (EVs), hydrogen fuel cell electric vehicles (FCEVs), etc.). Vehicle costs are the same in every state (non-energy technology costs are homogenous across states for all sectors in GCAM-USA). Electric vehicle penetration is virtually zero in the historical period (2015); thus, the model has little information about varying regional preferences for EVs around which to calibrate. Given the absence of historical regional consumer preferences for alternate drivetrains or state-level ZEV mandates in the model, the transportation energy mix in GCAM-USA tends to evolve more homogenously across states compared to other sectors. Nevertheless, GCAM-USA contains several levers for representing regional transportation dynamics/policies, including:

- Technology costs and efficiencies. Non-energy costs (predominantly purchase price but also reflecting registration and insurance, tolls, maintenance, and infrastructure costs) and fuel efficiencies can be adjusted by vehicle type (drivetrain), size class and state,
- Subsidies for low-carbon vehicles. Subsidies such as federal and state tax credits for electric vehicles can be implemented as additional (negative) non-energy costs by vehicle type (drivetrain), size class and state.
- Vehicle sales standards. Policies such as California's Zero-Emission Vehicle (ZEV) program, can be implemented by state (and vehicle size class, if desired). See http://jgcri.github.io/gcam-doc/policies.html#energy-production-policies for additional information on energy production policies in GCAM. In this case the model will calculate an implicit subsidy required to reach the specified sales share.
- Consumer preferences for alternate drivetrains. States may vary in terms of their preference for alternate drivetrains such as BEVs, which could be influenced by many factors (including, for example, regional differences in availability of charging infrastructure). The share-weights which reflect non-cost factors influencing technology deployment of transportation technologies can be adjusted by vehicle size class and state, (See Table S7 for default assumptions.)

Table S1: GCAM-USA Model Overview (Reference Card)

The following tables provide a high-level overview of GCAM-USA. The table format is based upon, and draws heavily from, the Integrated Assessment Modelling Consortium (IAMC) wiki (https://www.iamcdocumentation.eu/index.php/IAMC_wiki) Reference Card format. For readability, the table is split into six parts:

- Table S1A: Model scope and methods
- Table S1B: Socio-economic drivers and macro-economy
- Table S1C: Energy Supply and Transformation
- Table S1D: Energy end-use
- Table S1E: Land use
- Table S1F: Emissions, climate, and impacts

Table S1A: Model scope and methods

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Model type					global multisector model
Geographical scope					global
Objective					GCAM-USA is an integrated, multi-sector model that explores interactions between human and Earth systems. The model links representations of economic, energy, water, and land systems in a consistent global framework; it is computationally efficient enough to run on a personal computer or allow for broad scenario and uncertainty exploration. GCAM-USA is an economic model that operates in physical quantities (EJ of energy, cubic km of water, square km of land, etc.); individual modules are process-based and reflect the latest science on key system dynamics but operate at lower levels of detail than individual sectoral models.
Solution concept					Partial equilibrium (price elastic demand)
Solution horizon					Recursive dynamic (myopic)
Anticipation					GCAM-USA is a dynamic recursive model; decision-makers make choices based on present conditions (prices, policies, etc.) without knowledge of future circumstances. Decisions in one period impact conditions in the next through resource depletion, capital stock investments and retirements, land-use changes, etc.

Spatial Dimension					GCAM-USA divides the world into 32 geopolitical regions (the scale at which energy and economy are represented), 235 water basins, and 384 land-use regions. The USA energy and economic systems are further disaggregated into 50 states plus the District of Columbia (51 “state-level regions”). Twenty-three of the water basins and land-use regions fall at least partially within the United States. GCAM-USA also aggregates the states into 15 “grid regions” among which electricity is traded.
Policies	Emission tax	x			
	Emission pricing	x			
	Cap and trade	x			
	Fuel taxes	x			
	Fuel subsidies	x			
	Feed-in-tariff	x			
	Portfolio standard	x			
	Capacity targets	x			
	Emission standards	x			
	Energy efficiency standards	x			
	Agricultural producer subsidies	x			
	Agricultural consumer subsidies	x			
	Land protection	x			
	Pricing carbon stocks	x			

Table S1B: Socio-economic drivers and macro-economy

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Population			x		
Population age structure				x	
Education level				x	
Urbanization rate				x	
GDP			x		
Income distribution				x	Can be included; not included by default
Employment rate			x		
Labor productivity			x		
Total factor productivity			x		
Economic sectors					Energy, industry, transportation, residential, commercial, agriculture, forestry
Trade	Coal	x			Heckscher-Ohlin (H-O) / Armington hybrid
	Oil	x			Heckscher-Ohlin (H-O) / Armington hybrid
	Gas	x			Heckscher-Ohlin (H-O) / Armington hybrid
	Uranium	x			Heckscher-Ohlin (H-O)
	Electricity	x		x	Electricity is not traded between GCAM's 32 core energy-economic regions. However, electricity is freely traded between U.S. state-level regions in the same grid region (GCAM-USA contains 15 grid regions) and traded on a more limited basis between grid regions. For more information on electricity trade in GCAM-USA, see Sections S1: Electricity trade in GCAM-USA.
	Bioenergy crops	x			
	Food crops	x			
	Emissions	x			Emissions markets can be set up to permit or restrict trading.
Institutional and political factors	Early retirement of capital allowed	x			
	Interest rates differentiated by country/region		x		Homogenous by default but can be differentiated.

	Regional risk factors included		x		Homogenous by default but can be differentiated.
	Technology costs differentiated by country/region		x		Homogenous by default but can be differentiated.
	Technological change differentiated by country/region		x		Homogenous by default but can be differentiated.
	Behavioral change differentiated by country/region		x		Varies by sector. By default, technology preferences evolve homogenously across regions for some sectors/technologies and are differentiated for others (e.g., nuclear power). Technology preferences and behavioral change an be differentiated.
Resource use	Coal	x			
	Conventional oil	x			
	Unconventional oil	x			
	Conventional gas	x			
	Unconventional gas	x			
	Uranium	x			
	Bioenergy	x			
	Water	x			
	Raw materials	x			Limestone for cement production
	Land	x			
Technological change	Energy conversion technologies		x		
	Energy End-use		x		
	Material Use		x		
	Agriculture		x		

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Table S1C: Energy Supply and Transformation

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Energy technology substitution	Energy technology choice				Logit choice model
	Energy technology substitutability				Mixed high and low substitutability
Electricity technologies	Coal w/o CCS	x			conventional and integrated gasification combined cycle (IGCC)
	Coal w/ CCS	x			conventional and IGCC
	Gas w/o CCS	x			combined cycle (CC), steam turbine (ST), and combustion turbine (CT)
	Gas w/ CCS	x			CC
	Oil w/o CCS	x			combined cycle (CC) and steam/CT
	Oil w/ CCS	x			CC
	Bioenergy w/o CCS	x			conventional and IGCC
	Bioenergy w/ CCS	x			conventional and IGCC
	Geothermal power		x		geothermal is not available in all states; deployment is endogenous in regions outside the USA
	Nuclear power	x			generation II (historic) and III (next gen)
	Solar power	x			central PV, distributed PV, CSP
	Wind power	x			onshore, offshore (only states with coastline on Atlantic Ocean, Pacific Ocean, Gulf of Mexico, or Great Lakes)
	Hydroelectric power		x		
	Ocean power			x	
Hydrogen production	Coal to hydrogen w/o CCS	x			
	Coal to hydrogen w/ CCS	x			
	Natural gas to hydrogen w/o CCS	x			

	Natural gas to hydrogen w/ CCS	x			
	Oil to hydrogen w/o CCS			x	
	Oil to hydrogen w/ CCS			x	
	Biomass to hydrogen w/o CCS	x			
	Biomass to hydrogen w/ CCS	x			
	Nuclear thermochemical hydrogen	x			
	Solar thermochemical hydrogen			x	
	Electrolysis			x	included in global regions (but not GCAM-USA state-level regions)
Refined liquids	Coal to liquids w/o CCS	x			
	Coal to liquids w/ CCS	x			
	Gas to liquids w/o CCS	x			
	Gas to liquids w/ CCS			x	
	Bioliquids w/o CCS	x			
	Bioliquids w/ CCS	x			
	Oil refining	x			
Refined gasses	Coal to gas w/o CCS	x			
	Coal to gas w/ CCS			x	
	Oil to gas w/o CCS	x			
	Oil to gas w/ CCS			x	
	Biomass to gas w/o CCS	x			
	Biomass to gas w/ CCS			x	
Heat generation	Coal heat			x	district heat is represented for some global regions (but not GCAM-USA state-level regions)
	Natural gas heat			x	
	Oil heat			x	

	Biomass heat			x	
	Geothermal heat			x	
	Solar thermal heat			x	
	CHP (coupled heat and power)	x			represented in state-level industry sectors
Grid Infra Structure	Electricity		x		Electricity is freely traded between U.S. state-level regions in the same grid region (GCAM-USA contains 15 grid regions) and traded on a more limited basis between grid regions. For more information on electricity trade in GCAM-USA, see Sections S1: Electricity trade in GCAM-USA.
	Gas			x	
	Heat			x	
	CO2		x		Geologic carbon storage potentials and costs are represented at the grid-region level.
	Hydrogen			x	

Table S1D: Energy end-use

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Passenger transportation	Passenger trains	x			liquid fuels (standard and advanced), electric (standard and advanced), high speed rail (electric)
	Buses	x			
	CNG Buses	x			
	Electric Buses			x	
	Light Duty Vehicles (LDVs)	x			2 size classes (Car, Large Car and Truck)
	Gasoline LDVs	x			no distinction between gasoline and diesel internal combustion engine (ICE) vehicles
	Diesel LDVs			x	
	Hybrid LDVs	x			
	Electric LDVs	x			
	Hydrogen LDVs	x			
	Passenger aircrafts	x			
	Diesel Three-wheelers	x			
	CNG Three-wheelers			x	
	Electric Three-wheelers	x			
	LPG/CNG LDVs	x			
Freight transportation	Freight trains	x			coal, liquid fuels (standard and advanced), electric (standard and advanced)
	Heavy duty vehicles	x			3 size classes (light truck, medium truck, heavy truck); liquid fuels and LPG/CNG for each
	Freight aircrafts			x	
	Freight ships	x			
Industry	Steel production			x	
	Aluminum production			x	
	Cement production	x			
	Petrochemical production			x	not explicitly represented, but feedstock use of energy carriers in the industrial sector is represented
	Plastics production			x	

	Paper production			x	
	Pulp production			x	
Residential buildings	Space heating				Electric (furnace, heat pump), gas (furnace, high-efficiency), liquid fuel (furnace, high-efficiency), biomass (wood furnace)
	Space cooling	x			Electric (standard, high-efficiency)
	Water heating	x			Gas (standard, high-efficiency), electric (resistance, resistance high-efficiency, heat pump), liquid fuel (standard, high-efficiency)
	Lighting	x			Electric (incandescent, fluorescent, solid state)
	Refrigerators				Electric (standard, high-efficiency)
	Freezers	x			Electric (standard, high-efficiency)
	Dishwashers	x			Electric (standard, high-efficiency)
	Cooking				Electric, gas (standard, high-efficiency), LPG (standard, high-efficiency)
	Clothes washers	x			Electric (standard, high-efficiency)
	Clothes dryers	x			Electric (standard, high-efficiency), gas
	Televisions	x			Electric
	Computers	x			Electric
	Furnace fans	x			Electric
	Other	x			Electric, gas, liquid fuels
Commercial buildings	Space heating	x			Electric (furnace, heat pump), gas (furnace, high-efficiency), liquid fuel (fuel furnace), biomass (wood furnace)
	Space cooling				Electric (standard, high-efficiency), gas
	Water heating	x			Gas (standard, high-efficiency), electric (resistance, heat pump), liquid fuel
	Ventilation	x			Electric (standard, high-efficiency)
	Cooking				Electric (standard, high-efficiency), gas (standard, high-efficiency)
	Lighting	x			Electric (incandescent, fluorescent, solid state)
	Refrigeration	x			Electric (standard, high-efficiency)
	Office	x			Electric
	Other	x			Electric, gas, liquid fuels

Table S1E: Land use

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Land cover	Cropland	x			
	Cropland irrigated	x			
	Cropland food crops	x			
	Cropland feed crops	x			
	Cropland energy crops	x			
	Forest	x			
	Managed forest	x			
	Natural forest	x			
	Pasture	x			
	Shrubland	x			
	Built-up area	x			
Agriculture and forestry demands	Agriculture food	x			
	Agriculture food crops	x			
	Agriculture food livestock	x			
	Agriculture feed	x			
	Agriculture feed crops	x			
	Agriculture feed livestock	x			
	Agriculture non-food	x			
	Agriculture non-food crops	x			
	Agriculture non-food livestock	x			
	Agriculture bioenergy	x			
	Agriculture residues	x			
	Forest industrial roundwood	x			
	Forest fuelwood	x			

	Forest residues	x			
Agricultural commodities	Wheat	x			
	Rice	x			
	Other coarse grains	x			
	Oilseeds	x			
	Sugar crops	x			
	Ruminant meat	x			
	Non-ruminant meat and eggs	x			
	Dairy products	x			

Table S1F: Emissions, climate, and impacts

Dimension	Sub-Dimension	Endogenous	Exogenous	Not Included	Details
Greenhouse gases	CO2 fossil fuels	x			
	CO2 cement	x			
	CO2 land use	x			
	CH4 energy			x	Included in GCAM but not currently included in GCAM-USA
	CH4 land use			x	Included in GCAM but not currently included in GCAM-USA
	CH4 other			x	Included in GCAM but not currently included in GCAM-USA
	N2O energy			x	Included in GCAM but not currently included in GCAM-USA
	N2O land use			x	Included in GCAM but not currently included in GCAM-USA
	N2O other			x	Included in GCAM but not currently included in GCAM-USA
	CFCs			x	Included in GCAM but not currently included in GCAM-USA
	HFCs			x	Included in GCAM but not currently included in GCAM-USA
	SF6			x	Included in GCAM but not currently included in GCAM-USA
	PFCs			x	Included in GCAM but not currently included in GCAM-USA
Pollutants	CO energy			x	Included in GCAM but not currently included in GCAM-USA
	CO land use			x	Included in GCAM but not currently included in GCAM-USA
	CO other			x	Included in GCAM but not currently included in GCAM-USA
	NOx energy			x	Included in GCAM but not currently included in GCAM-USA
	NOx land use			x	Included in GCAM but not currently included in GCAM-USA
	NOx other			x	Included in GCAM but not currently included in GCAM-USA
	VOC energy			x	Included in GCAM but not currently included in GCAM-USA
	VOC land use			x	Included in GCAM but not currently included in GCAM-USA
	VOC other			x	Included in GCAM but not currently included in GCAM-USA
	SO2 energy			x	Included in GCAM but not currently included in GCAM-USA
	SO2 land use			x	Included in GCAM but not currently included in GCAM-USA
	SO2 other			x	Included in GCAM but not currently included in GCAM-USA
	BC energy			x	Included in GCAM but not currently included in GCAM-USA
	BC land use			x	Included in GCAM but not currently included in GCAM-USA
	BC other			x	Included in GCAM but not currently included in GCAM-USA
	OC energy			x	Included in GCAM but not currently included in GCAM-USA

	OC land use			x	Included in GCAM but not currently included in GCAM-USA
	OC other			x	Included in GCAM but not currently included in GCAM-USA
	NH3 energy			x	Included in GCAM but not currently included in GCAM-USA
	NH3 land use			x	Included in GCAM but not currently included in GCAM-USA
	NH3 other			x	Included in GCAM but not currently included in GCAM-USA
Climate indicators	Concentration: CO2			x	Included in GCAM but not currently included in GCAM-USA
	Concentration: CH4			x	Included in GCAM but not currently included in GCAM-USA
	Concentration: N2O			x	Included in GCAM but not currently included in GCAM-USA
	Concentration: Kyoto gases			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: CO2			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: CH4			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: N2O			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: F-gases			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: Kyoto gases			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: aerosols			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: land albedo			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: AN3A			x	Included in GCAM but not currently included in GCAM-USA
	Radiative forcing: total			x	Included in GCAM but not currently included in GCAM-USA
	Temperature change			x	Included in GCAM but not currently included in GCAM-USA
Carbon dioxide removal	Bioenergy with CCS	x			
	Reforestation	x			
	Afforestation	x			
	Soil carbon enhancement			x	
	Direct air capture			x	
	Enhanced weathering			x	
Climate change impacts	Agriculture		x		Not included by default but possible to implement
	Energy supply			x	

	Energy demand	x			Not included by default but possible to implement
	Economic output			x	
	Built capital			x	
Co-Linkages	Energy security: Fossil fuel imports & exports (region)	x			
	Energy access: Household energy consumption	x			
	Air pollution & health: Source-based aerosol emissions			x	Included in GCAM but not currently included in GCAM-USA
	Air pollution & health: Health impacts of air Pollution			x	
	Food access	x			
	Water availability	x			
	Biodiversity			x	

Table S2: GCAM-USA Reference scenario Socioeconomic Assumptions

GCAM-USA Reference scenario Population (million persons)

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

GCAM-USA Reference scenario GDP (billion 2015 USD)

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

Table S3: GCAM-USA High Growth scenario Socioeconomic Assumptions

GCAM-USA High Growth scenario Population (million persons)

Region	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
AK	0.74	0.73	0.74	0.76	0.8	0.84	0.88	0.92	0.96	1.01	1.05	1.09	1.14	1.18	1.21	1.24	1.27	1.29
AL	4.85	4.92	5.07	5.31	5.59	5.88	6.18	6.48	6.82	7.15	7.5	7.84	8.16	8.49	8.77	9.04	9.26	9.48
AR	2.98	3.04	3.14	3.28	3.45	3.62	3.8	3.98	4.18	4.38	4.58	4.78	4.97	5.17	5.33	5.49	5.62	5.74
AZ	6.83	7.41	7.98	8.49	8.99	9.5	10.04	10.58	11.18	11.78	12.4	13.02	13.62	14.21	14.74	15.27	15.69	16.11
CA	38.95	39.95	41.4	43.57	46.2	48.83	51.65	54.48	57.6	60.73	63.95	67.17	70.29	73.41	76.17	78.93	81.18	83.43
CO	5.45	5.86	6.24	6.62	7	7.38	7.79	8.2	8.66	9.11	9.58	10.04	10.5	10.95	11.34	11.74	12.06	12.38
CT	3.59	3.58	3.66	3.84	4.07	4.29	4.53	4.78	5.04	5.31	5.59	5.86	6.13	6.4	6.63	6.86	7.05	7.24
DC	0.68	0.72	0.75	0.8	0.84	0.9	0.95	1	1.06	1.12	1.18	1.25	1.3	1.36	1.42	1.47	1.52	1.56
DE	0.94	0.99	1.04	1.1	1.17	1.23	1.3	1.37	1.45	1.52	1.6	1.68	1.76	1.83	1.9	1.96	2.02	2.07
FL	20.22	21.93	23.46	24.88	26.31	27.74	29.27	30.8	32.5	34.19	35.93	37.67	39.35	41.03	42.51	43.98	45.18	46.38
GA	10.18	10.74	11.31	11.93	12.61	13.28	14	14.71	15.51	16.31	17.13	17.94	18.73	19.51	20.19	20.87	21.4	21.94
HI	1.42	1.42	1.44	1.5	1.57	1.65	1.74	1.82	1.92	2.01	2.1	2.2	2.29	2.38	2.46	2.54	2.61	2.67
IA	3.12	3.19	3.29	3.45	3.63	3.82	4.01	4.21	4.43	4.65	4.87	5.09	5.3	5.51	5.69	5.88	6.02	6.16
ID	1.65	1.82	1.98	2.1	2.21	2.33	2.45	2.57	2.71	2.85	2.98	3.12	3.25	3.39	3.5	3.61	3.7	3.79
IL	12.86	12.7	12.87	13.44	14.22	15	15.84	16.68	17.61	18.54	19.5	20.45	21.37	22.3	23.11	23.92	24.57	25.23
IN	6.61	6.77	7.02	7.38	7.79	8.21	8.66	9.1	9.6	10.09	10.6	11.11	11.59	12.08	12.5	12.92	13.26	13.59
KS	2.91	2.92	2.99	3.13	3.31	3.48	3.67	3.86	4.07	4.28	4.49	4.7	4.91	5.11	5.29	5.47	5.61	5.74
KY	4.43	4.5	4.65	4.86	5.12	5.38	5.65	5.93	6.23	6.54	6.85	7.16	7.45	7.75	8	8.25	8.45	8.64
LA	4.66	4.65	4.72	4.92	5.19	5.46	5.74	6.03	6.34	6.66	6.98	7.3	7.6	7.91	8.18	8.44	8.65	8.86
MA	6.8	6.99	7.28	7.67	8.12	8.58	9.07	9.56	10.1	10.64	11.2	11.76	12.29	12.83	13.31	13.78	14.17	14.56
MD	5.99	6.09	6.29	6.62	7.01	7.41	7.83	8.26	8.73	9.2	9.68	10.17	10.63	11.1	11.52	11.93	12.26	12.6
ME	1.33	1.35	1.38	1.44	1.52	1.59	1.66	1.74	1.82	1.9	1.99	2.08	2.15	2.23	2.3	2.37	2.42	2.47
MI	9.93	10.06	10.35	10.85	11.46	12.06	12.72	13.37	14.1	14.82	15.56	16.3	17.01	17.72	18.34	18.95	19.44	19.93
MN	5.48	5.7	5.96	6.27	6.6	6.94	7.3	7.66	8.06	8.46	8.87	9.28	9.67	10.06	10.39	10.73	11	11.26
MO	6.07	6.17	6.37	6.68	7.05	7.43	7.83	8.23	8.68	9.12	9.58	10.04	10.47	10.91	11.29	11.67	11.96	12.26
MS	2.99	2.99	3.04	3.17	3.33	3.49	3.67	3.84	4.03	4.22	4.41	4.61	4.79	4.97	5.13	5.28	5.4	5.52
MT	1.03	1.08	1.13	1.18	1.24	1.3	1.37	1.43	1.5	1.57	1.64	1.71	1.78	1.84	1.9	1.96	2	2.04
NC	10.03	10.61	11.2	11.81	12.46	13.11	13.8	14.49	15.25	16.02	16.8	17.58	18.33	19.07	19.72	20.36	20.87	21.37
ND	0.75	0.77	0.8	0.84	0.88	0.93	0.97	1.02	1.07	1.12	1.18	1.23	1.28	1.33	1.37	1.41	1.44	1.48
NE	1.89	1.95	2.03	2.14	2.26	2.38	2.5	2.63	2.77	2.92	3.06	3.21	3.35	3.49	3.61	3.73	3.82	3.92
NH	1.34	1.37	1.42	1.49	1.56	1.64	1.73	1.81	1.9	1.99	2.09	2.18	2.27	2.36	2.43	2.51	2.57	2.63
NJ	8.87	8.97	9.24	9.7	10.27	10.84	11.44	12.05	12.73	13.4	14.09	14.78	15.45	16.12	16.71	17.3	17.78	18.26
NM	2.09	2.1	2.16	2.26	2.38	2.5	2.64	2.77	2.92	3.06	3.21	3.36	3.5	3.65	3.77	3.9	4	4.09
NV	2.87	3.16	3.43	3.66	3.88	4.09	4.33	4.56	4.82	5.08	5.34	5.61	5.87	6.12	6.35	6.58	6.76	6.94
NY	19.66	19.51	19.82	20.72	21.92	23.12	24.41	25.7	27.13	28.55	30.02	31.48	32.89	34.3	35.54	36.78	37.78	38.78
OH	11.62	11.77	12.12	12.71	13.44	14.17	14.95	15.73	16.6	17.47	18.36	19.25	20.11	20.96	21.71	22.46	23.06	23.66
OK	3.91	3.97	4.09	4.28	4.52	4.75	5	5.25	5.53	5.81	6.09	6.37	6.64	6.91	7.15	7.38	7.56	7.74
OR	4.02	4.28	4.52	4.77	5.04	5.31	5.6	5.89	6.21	6.53	6.86	7.18	7.5	7.82	8.09	8.37	8.59	8.8
PA	12.79	12.87	13.22	13.85	14.64	15.43	16.28	17.12	18.06	18.99	19.95	20.91	21.83	22.75	23.55	24.35	24.99	25.63
RI	1.06	1.06	1.09	1.14	1.21	1.28	1.35	1.43	1.51	1.59	1.67	1.76	1.84	1.92	1.99	2.06	2.12	2.17
SC	4.89	5.21	5.52	5.83	6.15	6.47	6.82	7.16	7.54	7.92	8.3	8.69	9.06	9.43	9.75	10.07	10.32	10.57
SD	0.85	0.9	0.95	1	1.05	1.1	1.15	1.21	1.27	1.33	1.39	1.45	1.51	1.57	1.62	1.66	1.7	1.74
TN	6.59	6.9	7.24	7.62	8.04	8.46	8.91	9.35	9.85	10.34	10.85	11.36	11.84	12.32	12.74	13.16	13.49	13.81
TX	27.49	29.46	31.35	33.22	35.16	37.11	39.2	41.29	43.6	45.91	48.28	50.65	52.94	55.23	57.23	59.24	60.85	62.46
UT	2.98	3.27	3.53	3.75	3.97	4.18	4.41	4.63	4.89	5.14	5.4	5.65	5.9	6.15	6.37	6.59	6.76	6.94
VA	8.36	8.63	9	9.46	10	10.54	11.11	11.68	12.32	12.96	13.61	14.26	14.88	15.51	16.05	16.6	17.03	17.46
VT	0.62	0.63	0.64	0.67	0.7	0.73	0.77	0.8	0.84	0.87	0.91	0.95	0.98	1.01	1.04	1.07	1.09	1.11
WA	7.16	7.75	8.28	8.78	9.28	9.78	10.31	10.84	11.44	12.03	12.63	13.24	13.82	14.41	14.92	15.43	15.84	16.25
WI	5.76	5.87	6.06	6.34	6.67	7.01	7.36	7.72	8.11	8.5	8.9	9.3	9.68	10.06	10.39	10.72	10.98	11.24
WV	1.84	1.79	1.8	1.86	1.95	2.05	2.14	2.24	2.35	2.46	2.57	2.68	2.78	2.88	2.97	3.06	3.12	3.19
WY	0.59	0.58	0.59	0.61	0.64	0.68	0.71	0.75	0.79	0.83	0.87	0.91	0.94	0.98	1.02	1.05	1.07	1.1

GCAM-USA High Growth scenario GDP (billion 2015 USD)

Region	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
AK	56	55	57	64	74	84	94	105	117	130	145	161	179	200	220	242	267	295
AL	197	215	241	276	319	363	411	459	514	574	643	718	801	894	992	1100	1214	1342
AR	118	124	135	153	177	201	227	253	283	316	353	394	438	488	541	600	661	730
AZ	292	349	415	486	564	646	733	824	927	1040	1169	1312	1468	1645	1832	2041	2260	2506
CA	2536	2995	3522	4102	4773	5466	6213	6986	7859	8821	9921	11141	12479	13986	15592	17377	19254	21368
CO	322	376	441	513	595	680	771	866	972	1090	1223	1372	1534	1717	1912	2127	2354	2609
CT	253	259	284	323	376	430	488	548	615	690	775	870	973	1090	1214	1351	1496	1659
DC	122	136	153	177	206	237	270	304	342	385	434	488	547	614	686	765	849	943
DE	69	68	73	82	96	109	124	139	157	176	197	221	247	277	308	343	380	421
FL	874	1026	1205	1401	1626	1857	2106	2363	2653	2971	3335	3738	4180	4676	5205	5793	6411	7106
GA	501	575	657	758	878	1002	1136	1273	1428	1598	1792	2008	2242	2507	2787	3098	3424	3790
HI	81	87	95	107	124	141	160	178	200	223	249	278	311	347	385	427	472	522
IA	176	184	204	233	269	306	346	387	433	484	541	605	674	752	835	927	1022	1130
ID	66	79	94	110	127	145	164	183	205	229	257	287	321	358	398	442	488	540
IL	775	835	945	1087	1262	1443	1637	1838	2064	2314	2599	2915	3261	3650	4064	4524	5008	5552
IN	324	355	398	457	530	605	685	768	862	965	1082	1212	1354	1514	1684	1872	2069	2290
KS	152	166	186	213	247	282	320	358	402	449	504	565	630	705	783	871	962	1065
KY	189	201	222	253	292	333	376	420	470	525	587	656	732	816	905	1004	1107	1223
LA	242	248	272	309	358	407	460	515	577	644	722	807	900	1005	1116	1239	1368	1513
MA	491	553	635	734	853	977	1109	1247	1401	1572	1767	1983	2220	2486	2771	3086	3418	3791
MD	360	399	444	510	593	678	771	866	974	1093	1229	1380	1545	1731	1929	2149	2379	2640
ME	56	62	69	79	91	103	116	129	144	161	179	200	222	247	274	303	333	367
MI	460	517	594	685	795	907	1027	1151	1291	1445	1621	1815	2028	2267	2520	2801	3096	3428
MN	325	362	410	470	544	620	701	784	877	980	1098	1227	1369	1528	1697	1884	2080	2300
MO	288	309	352	405	469	535	606	679	762	853	957	1071	1197	1338	1487	1653	1827	2022
MS	104	109	119	135	156	177	200	223	249	277	310	346	385	429	475	526	580	639
MT	47	48	52	59	68	77	87	97	108	121	135	150	167	186	206	228	251	277
NC	489	549	635	733	848	967	1094	1224	1371	1534	1718	1922	2145	2395	2660	2954	3261	3607
ND	57	56	64	74	85	96	109	122	136	152	170	189	211	235	260	289	318	352
NE	115	121	134	154	178	203	230	258	289	324	363	406	454	508	564	627	693	766
NH	74	83	94	107	124	141	159	178	199	222	248	277	309	345	382	424	467	516
NJ	558	604	680	781	907	1038	1178	1322	1485	1665	1870	2097	2347	2627	2926	3258	3608	4001
NM	95	101	112	129	149	170	192	215	241	269	301	337	377	421	467	519	573	634
NV	141	163	190	220	256	293	333	374	420	471	530	595	666	746	831	925	1025	1136
NY	1431	1570	1774	2040	2368	2707	3070	3446	3870	4337	4869	5459	6106	6833	7607	8467	9370	10387
OH	604	654	732	839	974	1112	1261	1415	1588	1779	1997	2239	2503	2800	3116	3467	3835	4249
OK	203	210	235	269	311	355	401	449	503	562	630	705	786	878	975	1083	1196	1322
OR	200	239	279	324	376	429	486	545	612	685	768	861	962	1076	1196	1330	1471	1629
PA	709	778	880	1011	1173	1339	1518	1702	1910	2139	2400	2689	3004	3360	3737	4156	4595	5089
RI	55	57	62	71	82	94	107	120	135	151	170	191	213	239	266	297	329	364
SC	198	220	245	280	324	369	418	467	524	586	656	734	819	915	1016	1129	1246	1379
SD	47	49	55	62	72	81	92	102	114	128	143	159	177	197	219	242	267	294
TN	314	358	414	478	554	631	714	799	896	1002	1122	1256	1401	1565	1738	1931	2132	2359
TX	1662	1865	2173	2522	2930	3351	3803	4270	4797	5378	6041	6776	7581	8487	9449	10519	11640	12903
UT	148	178	214	250	290	331	375	420	471	528	592	663	741	828	922	1025	1134	1256
VA	475	526	606	700	812	927	1051	1178	1321	1480	1660	1859	2078	2323	2584	2873	3176	3517
VT	30	32	35	40	46	52	59	65	73	81	90	100	111	123	136	150	165	181
WA	463	588	736	871	1010	1153	1307	1466	1645	1841	2066	2315	2587	2893	3219	3581	3961	4389
WI	298	330	376	432	499	568	641	716	801	894	1000	1117	1245	1388	1540	1709	1886	2084
WV	73	78	89	102	117	133	150	167	187	208	232	258	287	320	354	392	431	475
WY	41	41	43	49	57	65	73	82	92	102	115	128	143	159	177	196	217	239

Table S4: GCAM-USA Grid Regions

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

Table S5: Thermal power plant cooling systems

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

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

Table S6: Key Input Data Sources for GCAM-USA Calibration

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

Table S7: Share Weight Assumptions for Key Sectors

During GCAM-USA's calibration routine, GCAM uses the cost of each subsector or technology to estimate the (unobserved) logit share weight parameters, ensuring that historically observed outcomes are reproduced (Calvin et al., 2019). Technology shares are derived from the historical (calibration) data, leaving share weights as the unknown parameter in the logit equation that is solved for. These share weight parameters capture unobserved factors, including preferences, which impact economic choice but aren't explicitly represented in the model's choice indicator (cost). The dominant technology (technology with the highest share historically) receives a calibrated share weight of 1.

In future model periods, exogenous assumptions are made about whether to maintain or phase out these calibrated share weights. Most commonly, share weights are held constant at their final (2015) calibration values. Share weights are also often converged to a common value, usually 1, in some future model period. In a case where all subsectors or technologies within a node have the same share weight (such as the case where all share weights are converged to 1), the subsector (often-fuel level) or technology competition is based solely on cost, with no non-modeled factors influencing the competition, Because share weights are mostly maintained at their calibration values or slowly phased out, the preferences and other non-modeled factors captured by GCAM's calibration routine continue to influence model decisions in future model periods (most strongly in initial model years). Table S7, below, presents future share weight assumptions for key sectors in GCAM-USA. Note that often sectors contain only one subsector, or subsectors contain only one technology, in which case there is no competition in that nest and share weight assumptions do not impact solution (unless the assumption is a zero share weight, which precludes production from that subsector/technology).

Sector	Regional Scale	Subsector	Subsector Share Weight	Technology	Technology Share Weight
Refining - Oil	State			Oil Refining	Fixed at calibrated values through 2100. This implies that states with no oil refineries historically will not refine oil in the future.
Refining - Biomass Liquids				Corn Ethanol Cellulosic Ethanol Cellulosic Ethanol CCS level 1 Cellulosic Ethanol CCSS level 2 Biodiesel FT Biofuels FT Biofuels CCS level 1 FT Biofuels CCS level 2	Interpolate from calibrated values to 1 in 2100 except for cellulosic ethanol (1 in 2025) and FT biofuels (1 in 2020)
Refining - Coal to Liquids				Coal to Liquids Coal to Liquids CCS level 1 Coal to Liquids CCS level 2	Coal to Liquids without CCS assumed unavailable; Coal to Liquids CCS technologies interpolate to 1 in 2050
Gas Processing	USA	Natural Gas Biomass Gasification Coal Gasification	Interpolate from calibrated values to 1 in 2100		

Sector	Regional Scale	Subsector	Subsector Share Weight	Technology	Technology Share Weight
Electricity (investment)	State	Coal	Fixed at calibrated values through 2100		
		Gas	Interpolate from calibrated values to 1 in 2030, then fixed at 1 from through 2100; Exception is HI which is fixed at 0 from 2015 through 2100		
		Refined Liquids	Fixed at 0 from 2015 through 2100 Exception is HI, which is fixed at calibration values from 2015 through 2100		
		Solar Wind	Interpolate from calibrated values to 1 in 2030, then fixed at 1 through 2100		
		Nuclear	Zero share-weights throughout the century for states with no nuclear in base year. For states with nuclear in the base year, zero shareweights from 2015 to 2030; from 2035 onward, fixed at 1 through 2100.		
		Biomass	Interpolate from calibrated values to 1 in 2100.		
		Geothermal	Unavailable for new investment after 2015		
Building - Heating	State	Biomass Electricity Gas Refined Liquids	Fixed at calibrated values through 2100, except for refined liquids which is phased to near-zero (0.1) availability by 2050	Electric Furnace vs. Electric Heat Pump; Gas Furnace vs. Gas Furnace Hi-Eff; Fuel Furnace vs. Fuel Furnace Hi-Eff;	Set to 1 in all future model periods
Building - Cooling	State	Electricity Gas	Fixed at calibrated values through 2100	air conditioning air conditioning hi-eff	Set to 1 in all future model periods
Industry - Energy	State	Biomass Coal Electricity Gas Hydrogen Refined Liquids	Fixed at calibrated values through 2100, except for hydrogen which is interpolated to 1 in 2050, then fixed at 1 through 2100	Biomass (no cogen vs. cogen) Coal (no cogen vs. cogen) Gas (no cogen vs. cogen) Refined Liquids (no cogen vs. cogen)	Fixed at calibrated values through 2100
Industry - Feedstocks	State	Coal Gas Refined Liquids	Fixed at calibrated values through 2100		
Industry - Cement (Process Heat)	State	Biomass Coal Gas Refined Liquids	Fixed at calibrated values through 2100		

Sector	**Regional Scale**	**Subsector**	**Subsector Share Weight**	**Technology**	**Technology Share Weight**
Transport - Freight	State	Road Rail Shipping	Fixed at calibrated values through 2100		
Transport - Road Freight	State	Light truck Medium truck Heavy truck	Fixed at calibrated values through 2100	Liquids NG (natural gas)	Liquids - fixed at calibrated values through 2100; NG - interpolate to 1 in 2050, then fixed at 1 through 2100
Transport - Passenger	State	Walk Cycle Light Duty Vehicle Bus Rail High-Speed Rail Aviation	Fixed at calibrated values through 2100		
Transport - Passenger Vehicles	State	Car Large Car and Truck	Fixed at calibrated values through 2100	Liquids Hybrid Liquids BEV FCEV NG (natural gas)	Liquids - fixed at calibrated values through 2100s; Hybrid Liquids - set to 1 from 2020 through 2100; BEV - interpolate to 1 in 2050, then fixed at 1 through 2100; FCEV and NG - interpolate to 1 in 2100
Animal Agriculture (Beef, Dairy, Pork, Poultry, Sheep/Goat)	USA			(feed types) FodderHerb_Residue Pasture_FodderGrass FeedCrops Scavenging_Other	Fixed at calibrated values through 2100
Feed Crops	USA			Corn FiberCrop MiscCrop OilCrop OtherGrain PalmFruit Rice RootTuber SugarCrop Wheat DDGS and feedcakes	Fixed at calibrated values through 2100, except for DDGS and feedcakes which is not available until 2020

Figure S1: Energy System CO2 Emissions by Scenario

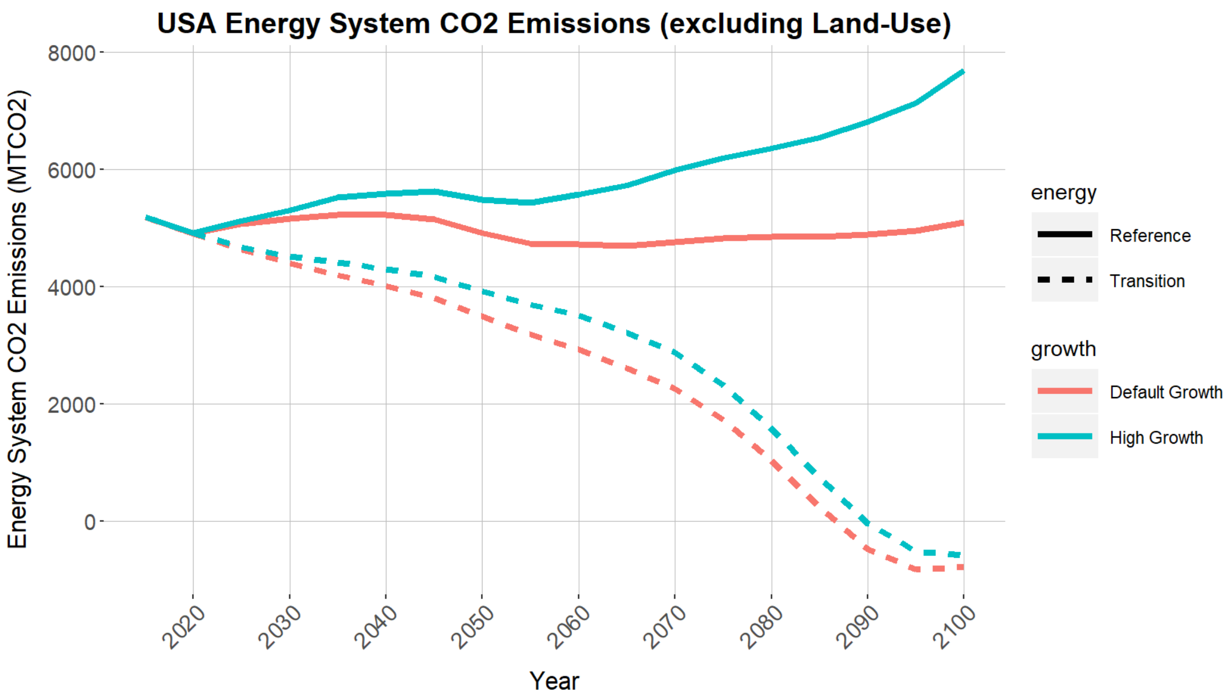

Figure S1. Energy system CO2 emissions by scenario.

Figure S2: Passenger Transportation Electrification Rate (Percent of Passenger Miles Traveled)

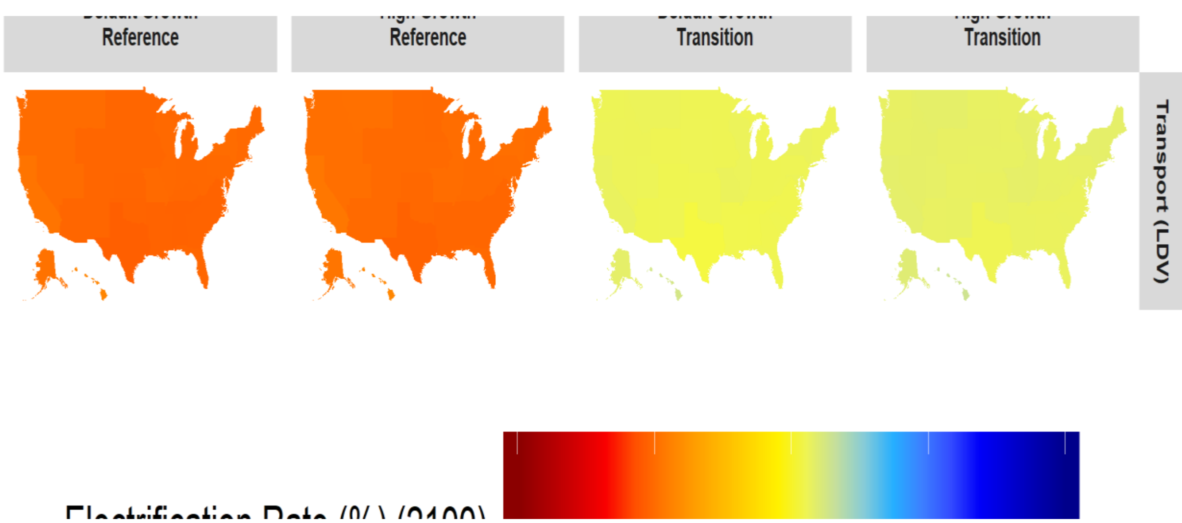

Figure S2. Battery electric vehicle (BEV) share of passenger vehicle transportation service (passenger miles traveled) by scenario in 2100.

Figure S3: National Average Electric Power Technology Capacity Factors

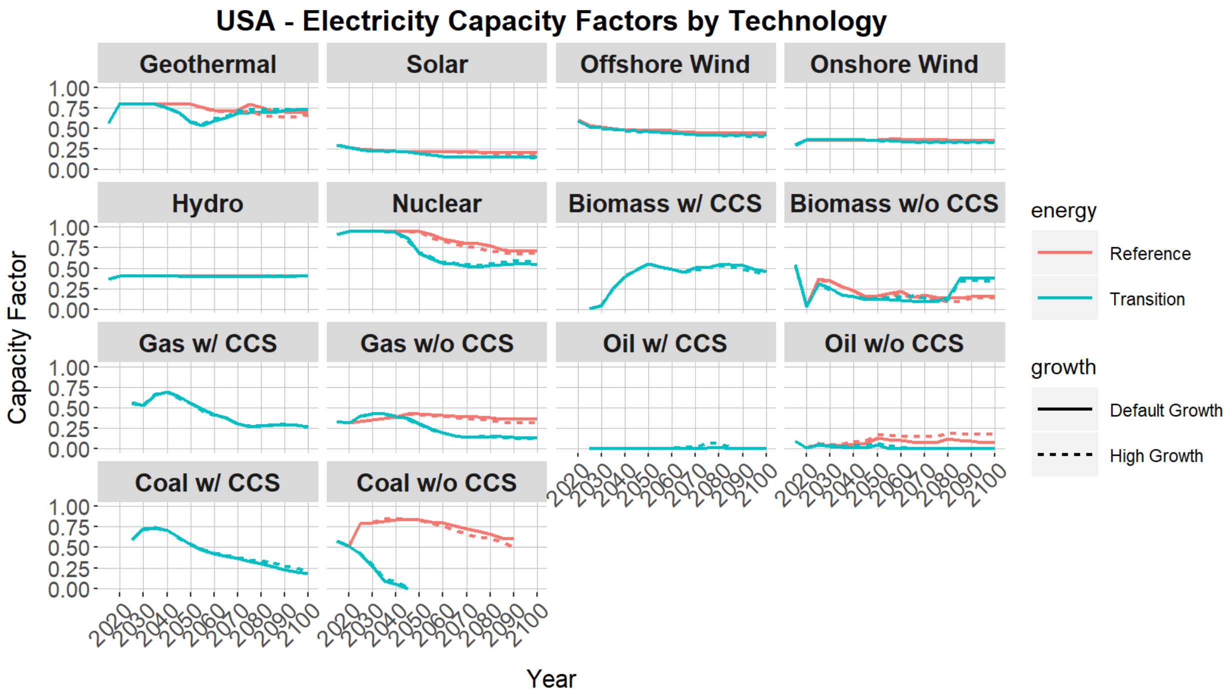

Figure S3. USA average electric power capacity factors by technology and scenario.

Figure S4: Water Resource Curves

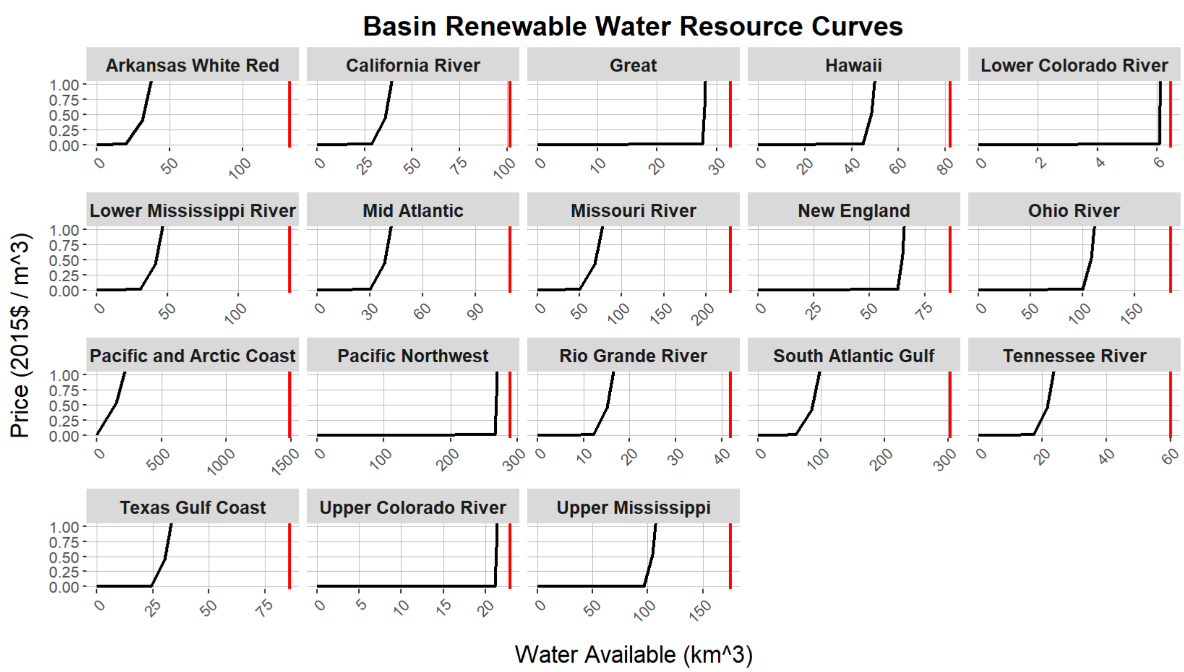

Figure S4a. Renewable water resource curves by river basin. The black line represents the resource curve at prices at or below $1/m^3$; the red line represents the maximum resource potential (some basins have significant potential available at higher prices). Note that these volumes represent annual renewable resource potential.

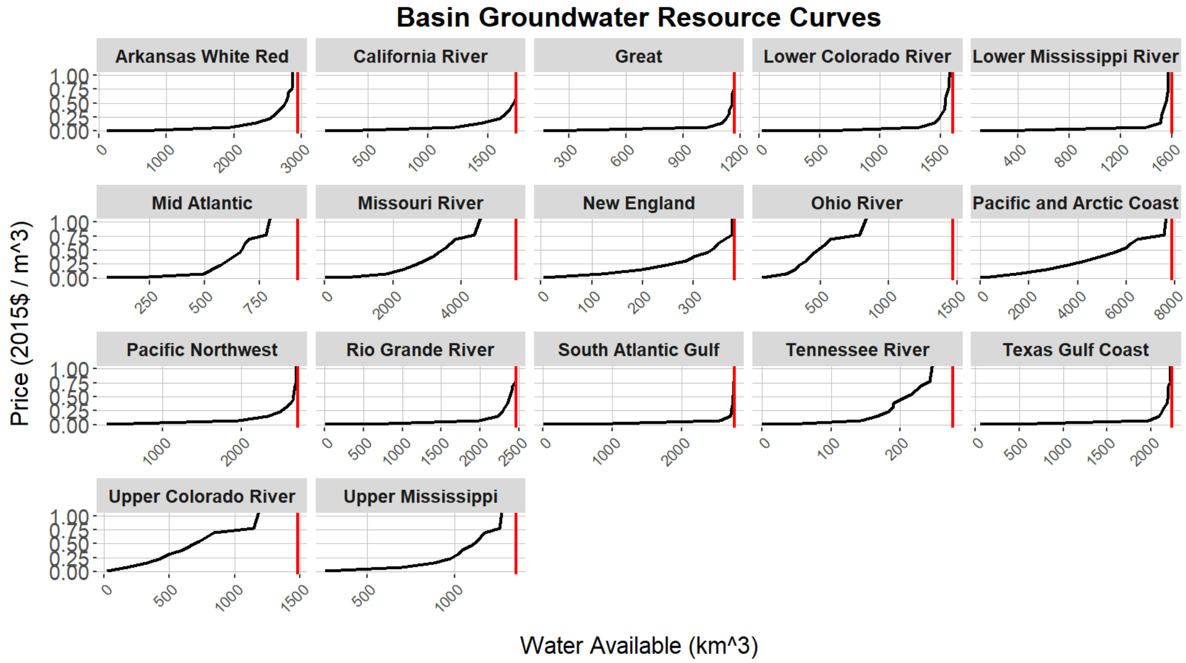

Figure S4b. Groundwater resource curves by river basin. The black line represents the resource curve at prices at or below $1/m^3$; the red line represents the maximum resource potential (some basins have significant potential available at higher prices). Note that these volumes represent depletable potential; once any volume is extracted, it is consumed and not available in the future.

Figure S5: Basin-Level Shadow Price of Water

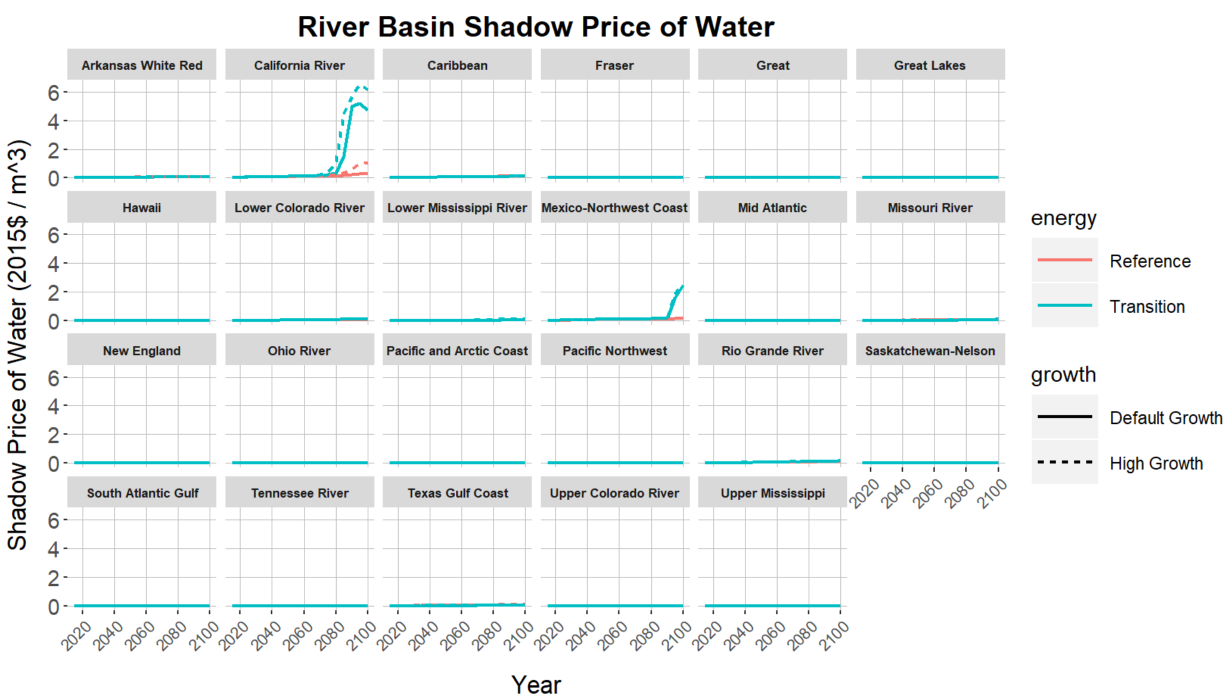

Figure S5. Shadow price of water by river basin and scenario. Note that GCAM-USA's water prices represent a shadow price on water – the intention is not to predict real-world consumer prices, but to reflect water scarcity and provide a

price signal to water consuming sectors when basins face water scarcity and the marginal water demand is provided by expensive ground water extraction or desalination (where available).

Figure S6: Change in Crop Land Allocation by Scenario and Basin (2100 relative to 2015

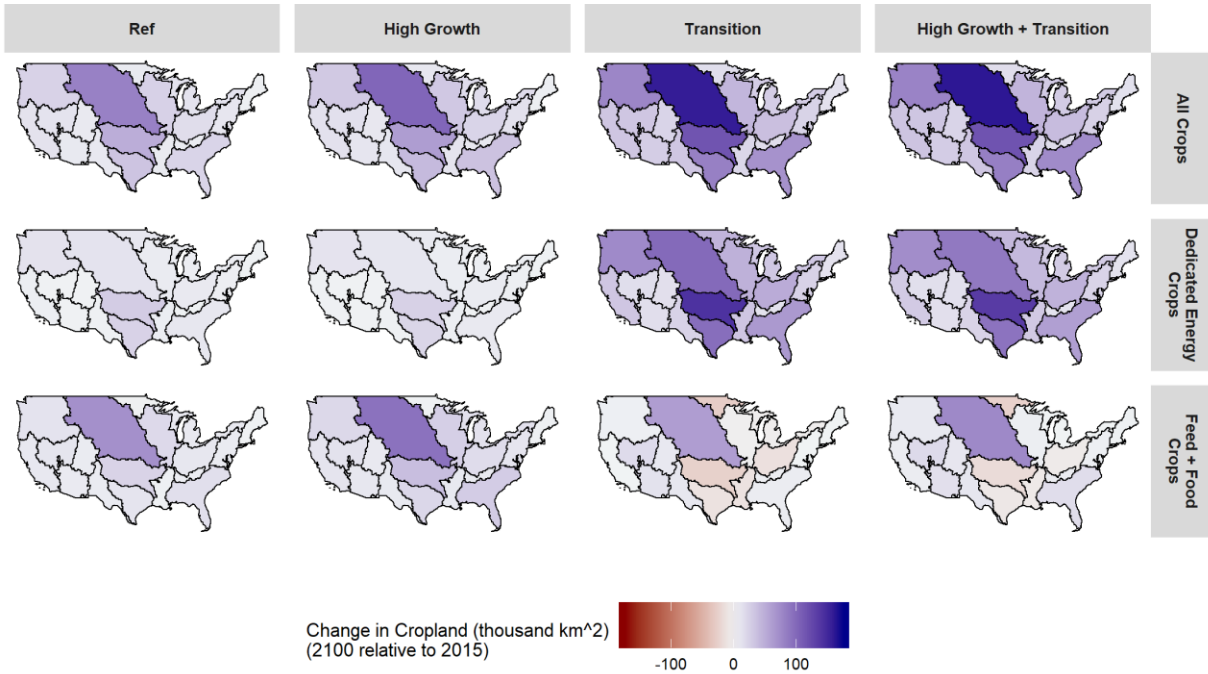

Figure S6a. Absolute change in cropland allocation in 2100, relative to 2015, by water basin, scenario, and crop type (distinguishing between traditional food + feed crops and dedicated bioenergy crops). Red shades indicate a reduction in cropland allocation, while blue shades indicate an increase in cropland.

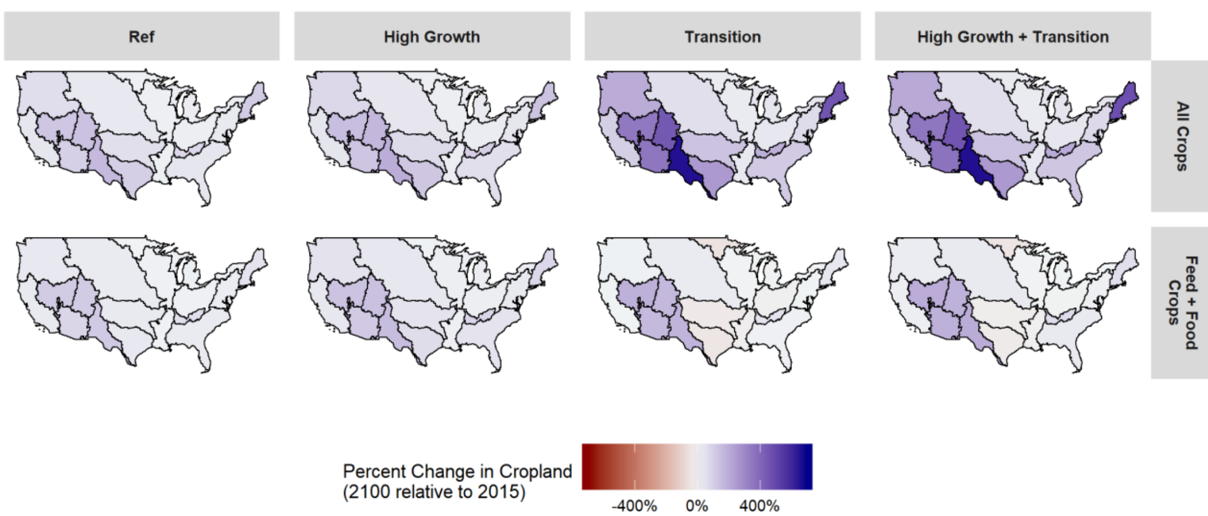

Figure S6b. Percentage change in cropland allocation in 2100, relative to 2015, by water basin, scenario, and crop type (distinguishing between traditional food + feed crops and dedicated bioenergy crops). Red shades indicate a reduction in cropland allocation, while blue shades indicate an increase in cropland. Dedicated Energy Crops are missing from this plot because there is no dedicated energy cropland in 2015 (percent change is INF).

Additional References

Binsted, M., Iyer, G., Cui, R., Zarrar Khan, Dorheim, K., and Clarke, L.: Evaluating long-term model-based scenarios of the energy system, Energy Strategy Reviews, 32, 2020.