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

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Abstract. This paper describes GCAM-USA v5.3_water_dispatch, an open source model that represents key interactions across economic, energy, water, and land systems in a consistent global framework, with subnational detail in the United States. GCAM-USA divides the world into 31 geopolitical regions outside the United States (U.S.) and represents the U.S. economic and energy systems in 51 state-level regions (50 states plus the District of Columbia). The model also includes 235 water basins and 384 land-use regions; 23 of each fall at least partially within the United States. GCAM-USA offers a level of process and temporal resolution rare for models of its class and scope, including detailed subnational representation of U.S. water demands and supplies and sub-annual operations (day/night for each month) in the U.S. electric power sector. GCAM-USA can be used to explore how changes in socioeconomic drivers, technological progress, or policy impact demands for, and production of, energy, water, and crops at a subnational level in the United States, while maintaining consistency with broader national and international conditions. This paper describes GCAM-USA's structure, inputs, and outputs, with emphasis on new model features. Four illustrative scenarios encompassing varying socioeconomic and energy system futures are used to explore subnational changes in energy, water, and land-use outcomes. We conclude with information about how public users can access the model.

1 Introduction

Modern societies depend on a complex set of interacting and co-evolving human and natural systems, including economic, energy, water, land, agriculture, and climate systems. Studying these systems in an integrated fashion is important because of the potential for changes in one system, region, or sector to impact others. However, representing these interactions in a comprehensive and robust manner is challenging because human and Earth systems are complex and nonlinear (Baker et al., 2018; Clarke et al., 2018), with processes and feedbacks that span a wide range of geographic (sub-national to global) and temporal (seconds to decades) scales. Because the behavior and co-evolution of these interconnected systems is important at global, national, and subnational spatial scales (Clarke et al., 2018; Moss et al., 2016; Oppenheimer et al., 2014; Wilbanks

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and Fernandez, 2013), modelers must account for complex regional and sub-national factors that affect these systems and their interactions, while maintaining consistency with broader national and global processes and conditions.

Traditionally, multisector models have been used to study human-Earth system interactions at coarse geographic and temporal scales, dividing the world into one to three dozen geopolitical regions and running in half-decade increments (Calvin and Bond-Lamberty, 2018). In response to the need for understanding human-Earth system interactions at finer spatial and temporal scales, previous modeling efforts have begun to incorporate more detail into such models (Iyer et al., 2017a; Iyer et al., 2017b; Khan et al., 2021) and in some cases, studies have employed model coupling and downscaling approaches (e.g. coupling multisector models with more detailed sector-specific models) (Cohen and Caron, 2018; Feijoo et al., 2018; Hejazi et al., 2015; Iyer et al., 2019; Kraucunas et al., 2014; O'Connell et al., 2019; Yuan et al., 2021).

This paper introduces the latest version of GCAM-USA, a version of the Global Change Analysis Model (GCAM) with subnational detail in the United States. The newest version of GCAM-USA consolidates past efforts to incorporate spatial and temporal detail in GCAM and includes subnational detail for economic, energy, water, and land systems in the United States (U.S.). Specifically, GCAM-USA represents the economic and energy systems in 50 states and the District of Columbia (D.C.). The model also includes subnational representations of water demands (at the state-level) and supplies (at the Hydrologic Unit Code 2 (HUC-2) river basin level); activity in the land system is represented in land-use regions (also corresponding to river basins), of which there are 23 in the U.S. Furthermore, while GCAM-USA runs in 5-year time intervals from 2015 (final calibration year) to 2100, the latest version includes a new electric power sector module which separates multi-decadal decisions about capacity investments from operational decisions about deploying capacity to meet electricity demands at sub-annual time scales (day/night for each month). Finally, GCAM-USA is housed within the global version of GCAM (Calvin et al., 2019) and includes the representations of economic-energy-water-land systems in 31 geopolitical regions outside of the U.S. Thus, subnational outcomes within the U.S. are consistent with international conditions.

This level of spatial and temporal detail in GCAM-USA v5.3_water_dispatch extends the boundary compared to other global multisector models. Specifically, the latest version of GCAM-USA can be used to answer a variety of science questions related to the impacts of short-term and long-term stressors on co-evolving human and natural systems at spatial scales ranging from states, basins, and multi-state regions to national, continental, and global scales. The improved temporal detail in the power sector of GCAM-USA also opens the door to a variety of questions related to the impacts of short-term stressors such as climate variability and fuel price shocks on the electric grid. Finally, the latest model lays the foundation for improved coupling with finer scale and sector-specific tools.

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Using GCAM-USA v5.3_water_dispatch, we explore four scenarios which encapsulate varying assumptions about future socioeconomic drivers and energy system pathways. While a large range of future scenarios can be explored using this new capability, these four scenarios are meant to be an illustrative sample of those explored in the literature to demonstrate the capabilities of the model. Detailed exploration of other scenarios is reserved for future work.

The remainder of the paper proceeds as follows. Section 2 provides a high-level overview of GCAM and GCAM-USA. (A detailed description of the GCAM framework, within which GCAM-USA is embedded, is available in Calvin et al. (2019).) Section 3 describes new model features in GCAM-USA v5.3_water_dispatch (relative to GCAM-USA v5.2). A qualitative description of key sectors in the GCAM-USA Reference scenario is provided in Sect. 4. Section 5 presents four scenario simulations to demonstrate the model's capabilities and new features; Sect. 6 presents the energy, water, and land outcomes at various scales from these simulations. Discussions and conclusions follow in Sect. 7; the final section provides information about how to access the model. More detailed documentation of the GCAM model is available online at http://jgcri.github.io/gcam-doc; the GCAM-USA documentation page can be accessed at http://jgcri.github.io/gcam-doc/gcam-usa.html.

2 Model overview

2.1 Overview of GCAM

The Global Change Analysis Model is an open-source model developed and maintained by the Pacific Northwest National Laboratory. GCAM is a partial equilibrium model which captures key interactions between global economic, energy, water, land, and climate systems. The world is divided into 32 geopolitical regions (the scale at which energy and economy are represented), 235 water basins, and 384 land-use regions; the model solves for the equilibrium prices and quantities for all energy, water, agricultural, and emissions markets in five-year intervals from 2015 to 2100. The climate system is represented by the open-source simple climate model Hector 2.5.0, which translates greenhouse gas (GHG) emissions from the energy and land systems into GHG concentrations, global mean radiative forcing, global mean temperature, and other key Earth system variables (Hartin et al., 2015) (https://github.com/JGCRI/hector). GCAM is an object-oriented program developed in C++ (Kim et al., 2006); an R data package, *gcamdata*, is used to prepare the model input data (Ben Bond-Lamberty et al., 2019) (https://github.com/JGCRI/gcamdata). Key model inputs include assumptions about socioeconomic drivers (population and economic growth), resource endowments (potentials and extraction costs), technologies (costs and efficiencies), and policies.

GCAM simultaneously solves for equilibrium in energy, water, agriculture, and emissions markets. After market equilibrium is reached, computations are performed to evaluate the state of the climate system. These systems are directly linked in the computer code; their interaction and coevolution are captured dynamically within the model. For instance, Calvin et al.

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(2019) provides a detailed description of bioenergy as an example of the coupled nature of complex systems in GCAM. Bioenergy is demanded, transformed, and consumed in the energy system, where it competes with other fuels for the provision of end-use energy services; demand for these services is influenced by the size of the population and economy. Bioenergy is supplied by the land system, where production depends on the price and cost of growing bioenergy crops compared to those of other land-uses; bioenergy production requires fertilizer (produced by the energy system) and water inputs, the prices of which are determined by supply costs and influenced by demand for alternative uses of these resources. The model solves for the market clearing price (where supply equals demand) of bioenergy and all other energy, water, land, and emissions markets simultaneously. This integrated, multisectoral framework allows users to analyze the interdependencies, feedbacks, and co-evolution of such coupled systems under alternate futures.

2.2 Overview of GCAM-USA

GCAM-USA is a version of GCAM with subnational detail in the USA (Binsted et al., 2020; Feijoo et al., 2018; Iyer et al., 2017a; Iyer et al., 2019). The model remains global in scope but contains 51 state-level regions (50 states plus the District of Columbia) which represent the U.S. economic and energy systems. These state-level regions contain detailed and heterogeneous representations of socioeconomic drivers, resource endowments, energy transformation sectors, and final energy services; agriculture / land use activity and water resources are represented at the HUC-2 river basin level, while fossil resource extraction and livestock are represented at the national level. State-level regions are connected to the rest of the world through global markets for primary energy carriers, and the USA is linked to the rest of the world via agricultural markets. Thus, sub-national outcomes in the U.S. are consistent with international conditions. GCAM-USA is included in the regular GCAM model release packages (https://github.com/JGCRI/gcam-core/releases); *gcamdata* includes all the additional input data and data processing routines needed for GCAM-USA. Below is a short description of the four broad systems – socioeconomics, energy, water, and land – in GCAM-USA.

2.2.1 Socioeconomics

GCAM-USA contains heterogeneous state-level assumptions about population and economic growth (labor productivity) which set the scale for activity in the energy system. The "sum-of-states" population and GDP from GCAM-USA differ from the default USA population and GDP in GCAM, although GCAM-USA's socioeconomic assumptions are still broadly consistent with the "middle-of-the-road" Shared Socioeconomic Pathway 2 (SSP2) assumptions (O'Neill et al., 2017) that are utilized for the other 31 regions in the GCAM-USA Reference scenario.

State-level populations are based on historical values from the U.S. Census Bureau through 2018. Beyond 2018, population growth is based on downscaled projections from the SSP2 (Shared Socioeconomic Pathways 2) scenario developed by Jiang et al. (2018). The data includes state-level population projections from 2010 to 2100 in 10-year intervals. To avoid inconsistencies between the more recent historical data and the SSP projections, population growth rates are linearly transitioned from historical trends (2010-2018) to those derived from Jiang et al. (2018) (for the period 2020-2030) in 2030. Beyond 2030, we apply growth rates directly from the Jiang et al. (2018) downscaled SSP2 projections.

Similarly, state-level GDP is based on historical data through 2018. Future labor productivity growth assumptions are developed in two stages. In the near-to-medium-term, to maintain heterogenous growth patterns, we harmonize with U.S. Census Division level per-capita GDP growth rates from the U.S. EIA's Annual Energy Outlook (AEO) 2019 (U.S. Energy Information Administration, 2019) by transitioning linearly from historical labor productivity growth rates to near-term census division growth rates in 2030, and then directly applying growth rates from AEO 2019 from 2030 to 2050 (assuming uniform growth rates for all states within a census-region). Beyond 2050, we linearly interpolate growth rates from state-level 2050 values to the USA's SSP2 labor productivity growth rate in 2100, such that all states converge to a common rate of economic growth by the end of the century. This reflects the fact that projecting state-level differences in economic growth becomes more difficult for more distant decades. GCAM-USA Reference scenario population and GDP assumptions are provided in Supplementary Table SM1.

2.2.2 Energy

GCAM-USA features a detailed energy system coordinating multi-scale energy supply, transformation, and demand. Primary energy supply of depletable resources (coal, oil, natural gas, uranium) is represented at the national level, with resource supply curves containing extraction prices and resource availability. Renewable energy resources (solar, wind, geothermal, and hydropower) are represented at the state-level, with resource supply curves for all but hydropower (for which production is exogenously prescribed). GCAM-USA also represents key energy transformation processes at the state-level (electricity generation, refining, fertilizer production) with a few sectors still modeled at the national level (gas processing, hydrogen production). The electricity sector in GCAM-USA is particularly detailed; long-term decisions about capacity expansion are separated from operational decisions about deploying capacity to meet electricity demands for 25 sub-annual time segments. (A more detailed discussion of the new GCAM-USA electric power sector is provided in Sect. 3.3).

These transformation sectors produce energy carriers which are consumed, and ultimately translated into energy services, in the building, transportation, and industry end-use sectors. Inter-state electricity trade (see Supplementary Note 1 for additional information) and regionally differentiated fuel prices for key energy carriers (electricity, refined liquids, natural gas, and coal) are captured in the model. Some end-use sectors are also more detailed in GCAM-USA. For instance, the GCAM-USA industry sector includes a vintage structure which reflects the long-lived nature of industrial capital. GCAM-USA also includes expanded technological and energy service detail in the buildings sector (relative to GCAM). In addition to space heating and cooling, both the residential and commercial building sectors include services such as lighting and water heating, and various appliances (refrigerator, dishwasher, oven / range, clothes washer, clothes dryer, etc.) (Zhou et al.,

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2014). Each of these services contains a set of technologies that compete with one another for market share; among these technologies are low and high-efficiency options that are powered by both secondary fuels (such as electricity) and primary fuels (such as gas and biomass). Technology costs and efficiencies are taken from the inputs to the EIA's National Energy Modeling System (NEMS) and are consistent with the 2016 Annual Energy Outlook (see Iyer et al. (2017a) for detailed technology assumptions).

2.2.3 Water

The water system is a key new development for GCAM-USA and is described in detail in Sect. 3.2. For more detail on water demands in GCAM, see Calvin et al. (2019). For a description of water supplies and water market mechanisms in GCAM, see Kim et al. (2016) and Turner et al. (2019). Both features are also thoroughly described in the GCAM documentation at http://jgcri.github.io/gcam-doc/water.html.

2.2.4 Land

The agriculture and land system in GCAM-USA is largely unchanged from its representation in the core (32-region) GCAM. The fundamental geographic unit for the land system in GCAM-USA is still the GCAM land-use regions (water basins intersected with 32 core GCAM regions), 23 of which lie in the United States. While the interconnections between agriculture and other systems in GCAM-USA often involve the state regions (for instance, fertilizer production is represented at the state-level; agricultural water demands are tracked at the state-level), agricultural activity is not tracked at the state-level nor directly impacted by policies, technologies, or other drivers at the state-level. A detailed description of the GCAM land system is available in Calvin et al. (2019).

3 Major changes from GCAM-USA v5.2

3.1 Model base year updated to 2015

As of GCAM v5.3 (June 2020), the final calibration year (model base year) for GCAM and GCAM-USA was updated from 2010 to 2015. This encapsulates updates to the data used to calibrate GCAM's socioeconomic, energy, agricultural, and water systems. This means that, relative to other recent GCAM-USA studies (Binsted et al., 2020; Feijoo et al., 2018; Iyer et al., 2019), GCAM-USA's 2015 results reflect historical outcomes rather than model simulations, and future results based on model calibration of more recent data. A comparison of GCAM-USA's Reference scenario to historical data and other future scenarios is included in Sect. 6.5.

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3.2 Introduction of water markets behavior (supply and demand)

3.2.1 Water supplies

GCAM-USA now includes endogenous representation of water supplies and demands at a subnational scale. GCAM represents water supplies from three distinct fresh water sources: renewable water (surface and ground), non-renewable (or fossil) groundwater, and desalinated saltwater. Additionally, saltwater is available for cooling of thermal power plants (and treated as an unlimited resource) in coastal states only. These water resources are represented at the HUC-2 river basin level and include extraction costs and availability limits for each resource type, such that water prices escalate as demand increases. The USA's water is supplied by 23 water basins, some of which are shared with neighboring regions (Canada, Mexico, and the Caribbean).

3.2.2 Water demands

In GCAM, water demands from all sectors – primary energy (mining), agriculture (irrigation), livestock, electric power, manufacturing, and municipal – are tracked endogenously in two forms. Water withdrawal represents the total volume of water extracted from the supply system, while water consumption represents the fraction of withdrawals not directly returned to the system for immediate re-use. Water resource availability and demands (i.e., withdrawals) are endogenously resolved through a water market pricing mechanism at the river basin level.

In GCAM-USA, the drivers of water demands are modeled at multiple scales. All water demands are endogenously mapped to the state-level and resolved with water supplies at the basin level. Several water demand sectors, including electricity generation, manufacturing, and municipal water use, are represented directly at the state level. U.S. Geological Survey (USGS) historical water withdrawal data (https://water.usgs.gov/watuse/data/) is used to calculate state-specific water demand coefficients for the municipal and manufacturing sectors. Municipal water demands are driven by heterogeneous state level socioeconomic trends (see Sect. 2.2.1). All states' municipal water withdrawal-to-consumption ratio is assumed to improve at a constant rate over time. Manufacturing water demands are calculated from state-level U.S. Energy Information Administration (EIA) data for industrial energy consumption for historical years (https://www.eia.gov/state/seds/seds-data-complete.php), which is then matched with USGS water demand data to obtain state-specific water demand coefficients. These coefficients are held constant through the end of the century; future industrial water demands are purely a function of industrial activity at the state-level, with a presumption of no structural changes that would cause the water intensity of industry to deviate from historical levels.

In the electric power sector, GCAM-USA includes an endogenous competition between cooling systems for each thermal electricity generation technology. Broadly, GCAM-USA represents once-through, seawater (once-through), recirculating, cooling pond, dry cooling, and dry-hybrid cooling systems. Not all systems are available for every fuel / cooling technology

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(Supplementary Table SM3 specifies which fuel / cooling system combinations are available in GCAM-USA). Wind power is assumed to have no water demands (withdrawals or consumption), while photovoltaic solar (PV) requires a small amount of water for plant operations / maintenance. Hydropower has no water withdrawals but some consumption, due to evaporation losses associated with impoundment reservoirs. All other generation technologies (including concentrated solar power, or CSP) require a cooling system. Cooling system capital costs, along with the cost of providing cooling water, influence decisions about which technologies are deployed in future model periods; water prices also impact power sector operation decisions (see Sect. 3.3 for more detail).

Three other demand sectors – primary energy (mining), agriculture (irrigation), and livestock – are not represented at the state-level in GCAM-USA. Water demands for these sectors are driven by activity at the national level (primary energy, livestock) or land-use regions (irrigation). Calvin et al. (2019) describes how water demands for these three sectors are calculated. These demands are then endogenously downscaled (mapped) to the states using sector-specific historical demand shares based on 0.5 x 0.5-degree gridded water demand data from Huang et al. (2018). Thus, although activities such as natural gas extraction are modeled at the national level, water demands associated with such activities are tracked at the state-level within the model via endogenous downscaling of demands based on historical shares.

Across all demand sectors, state-level water demands are mapped to the basin-level (where supplies and demands are balanced). State-to-basin mappings are also conducted on the basis of Huang et al. (2018). In short, state shares of historical water demands for a given basin and sector are calculated based on Huang et al. (2018). Note that it's possible for a given state / sector's water demands to be supplied by multiple basins, or for multiple states' water demands for a given sector to come from a single basin. State-basin shares are held constant for future periods at their 2010 values; thus, future competition between basins to supply water for a given sector / state is pre-determined by the historical share of water demands. There is also competition within coastal state-basin combinations between natural fresh water (renewable or non-renewable) and fresh water from desalination.

With this new water market structure in GCAM-USA, users can track comprehensive water demands (withdrawals and consumption) for each region and sector. The model also outputs water supplies by water type (renewable, non-renewable, desalinated) at the basin-level.

3.3 Increased operational resolution in the electric power sector

One of the most significant developments in GCAM-USA v5.3_water_dispatch is the new electric power sector (dispatch) model (Fig. 1). This model now separates long-term decisions about capacity expansion (Fig. 1, panel A) and short-term decisions about dispatching that capacity (Fig. 1, panel B) to meet electricity demands at sub-annual time scales (Fig. 1, panel C). This finer-scale operational detail provides more robust results about the ability and timing of variable, or

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intermittent, energy sources to contribute to power supply, and requires new approaches to capture the contribution of various technologies to reserve capacity. Each of these features is described in detail below.

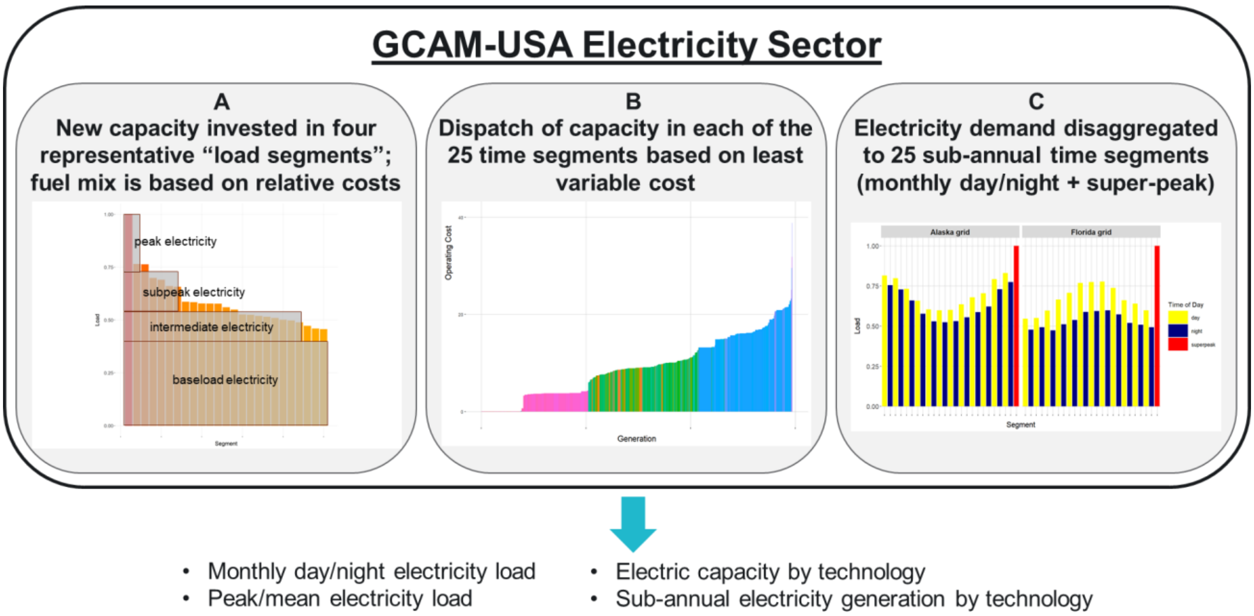

Figure 1. Conceptual diagram of new GCAM-USA electric power sector.

3.3.1 Electric power capacity investment and retirement

Economic decisions in the power sector occur on different time horizons. Capacity expansion – decisions about investing in new power plants – consider the profitability of these plants over the course of their expected lifetime, usually several decades. These decisions are in principle based on uncertain information – future fuel and electricity prices cannot be known at the time of investment. Thus, investment decisions in the GCAM-USA power sector are made using a probabilistic logit formulation which assumes a distribution of realized costs and preferences due to heterogeneous real-world conditions (Calvin et al., 2019; Clarke and Edmonds, 1993; McFadden, 1980).

Investment decisions are made in four representative "load segments" (baseload electricity, intermediate electricity, subpeak electricity, and peak electricity; Fig. 1, panel A) corresponding to how the plant is expected to operate: for example, nuclear technologies are available for investment in the baseload and intermediate segments, while gas combustion turbine technologies are invested only in the subpeak and peak segments. Within each investment sector, various fuels (subsectors) compete for share based on relative costs using the logit choice model described above. Within subsectors, different generation technologies (i.e. conventional coal vs. integrated gasification combined cycle (IGCC) coal) compete for share of

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generation within a given fuel type. Finally, within each generation technology, there is competition between alternate cooling systems (for thermal power plants). (See Sect. 3.2.2 for a description of which cooling systems are represented in GCAM-USA.)

Within the investment sectors (segments), each level of competition is based on relative levelized costs of electricity generation. These costs include power plant capital, cooling system capital, fixed operations and maintenance (O&M), variable O&M, resource inputs (fuel, water, etc.), policies (portfolio standards, emissions penalties) in place at the time of investment, and capacity credits (described in Sect. 3.3.3). Technology costs are the same across investment segments, but the capacity factors used to levelize technology costs vary by segment, corresponding to different a priori assumptions about how frequently plants in different investment segments are expected to operate. The baseload segment is assumed to have the highest capacity factors and peak load the lowest. These capacity factors will not necessarily match those which result from the capacity dispatch.

Investment decisions are made at the state-level and aggregated across the four investment segments. Power sector investments from each model period are vintaged and available to be dispatched until the end of their physical lifetimes (which vary by technology) unless the capacity is substantially underutilized and pre-maturely retired for economic reasons. Capacity investment requirements are calculated to ensure sufficient capacity is available to meet electricity demands across all dispatch segment in each model period, including a 15% reserve margin. New capacity requirements are allocated across the four investment segments by mapping each investment segment to the dispatch segment whose load most closely matches the average load of the investment segment and comparing the variable cost of the marginal existing generator to the full cost of investing in a new plant. The demand for new capacity is processed in order from low to high load (baseload first, peak last) so that the model knows how much capacity (including reserve margin) remains to be met by super-peak (the ten highest load hours of the year per grid region).

Existing capacity which becomes consistently too expensive to operate may be permanently retired before the end of its physical lifetime. These retirements could be driven by policies like an emissions price, sustained high fuel or cooling water input costs, or by a plant being displaced by lower-variable cost technologies in the dispatch curve. When making investment decisions, the model compares the variable cost of technologies not dispatched in each representative dispatch segment to the price of the corresponding investment sector (including both fixed and variable costs) using a simple smooth function. If a technology is more expensive to operate than the costs of building and operating an average new plant in the relevant investment segment, some of that technology's capacity will retire (a greater fraction will retire as that cost delta increases). These retirement decisions are lagged one model period; retirements each year are based on the previous period's dispatch.

3.3.2 Electric power dispatch

After new capacity investment decisions are made, all capacity (existing and newly invested) are gathered into a set of technologies available for dispatch at the grid-region level. At this point, there is no distinction among investment segments – a combined cycle gas plant is the same whether it was invested with the assumption of operating as baseload or in subpeak – although there is still a distinction among technology vintages (year of investment) because plant efficiencies and O&M costs evolve over time. Each grid region contains 25 load segments corresponding to daytime and nighttime loads for each month of the year, plus an annual super-peak containing the top 10 load hours of the year. Information on these sub-annual load profiles comes from Federal Energy Regulatory Commission Form No. 714.

For each of these 25 dispatch segments, the model sorts all available capacity by variable cost (including fuel and water costs, variable O&M costs, and policy costs tied to unit of energy or emissions production) and dispatches (operates) them based on least variable cost. Each generation technology is assigned a maximum production level for each segment which is a function of (1) the number of hours in the segment, (2) the amount of capacity available for that technology, and (3) a "segment capacity factor". For dispatchable technologies (nuclear, fossil fuels, biomass), the segment capacity factor is identical for each segment and reflects plant availability considering downtime for maintenance, refueling, etc. The exception to this rule is the super-peak segment, in which it's assumed that all dispatchable are available at their full capacity. For intermittent (or variable) technologies, the segment capacity factor varies by segment and reflects heterogeneous resource availability. For example, solar plants are only available during daytime segments and wind availability tends to be higher in nighttime segments. The model loops through each dispatch segment (S) and state-technology-vintage (T), assigning each T its maximum level of production to meet the demand in S until the full demand is met, creating a dispatch curve for each dispatch segment in the process.

The price of electricity is equal to an average of each segment's marginal generator's variable cost, plus the capacity price. By default, the load profiles in GCAM-USA are fixed over time – the distribution of annual load across the 25 sub-annual dispatch segments is calibrated to historical data for 2015 (by grid region) and fixed across future model periods. In contrast, Khan et al. (2021) utilized a version of GCAM-USA with "detailed demand segments" where the electricity load profile is distinguished by end-use sector (buildings, industry, transportation) for each grid region, and electricity from each load segment is explicitly consumed by each end-use sector. In this "demand segments" configuration, the annual load profile evolves endogenously within the model as the relative share of consumption across end-use sectors changes, and as demands for thermal building services (heating and cooling, represented at the same the monthly day/night temporal resolution) evolve over time. This model feature not included in the GCAM-USA v5.3_water_dispatch.

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3.3.3 Capacity markets and capacity credits

Historically, regulators and regional transmission operations have required that sufficient reserve capacity is available to minimize the probability that a shortage occurs by imposing a capacity reserve margin on electric utilities that prescribed a percentage of capacity (often 15%) to be maintained in excess of expected peak demand. The additional cost of this reserve capacity was incorporated into the electricity rates paid by consumers. Deregulated markets also have mechanisms in place to ensure capacity reserve margin, called capacity markets. In addition to the production and sale of electrical energy in real time, capacity markets generate revenues to maintain grid reliability by paying electricity generators a premium for capacity beyond what is earned from supplying electricity. Because all generators contribute to reliability, each generator can receive revenue in the capacity market. Revenues from capacity markets can be very important for the financial viability of power plants, particularly for peak-load plants which operate for a small percentage of hours per year.

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The GCAM-USA electricity dispatch model's investment segments represent demand and supply of capacity to meet peak demand plus a reserve margin. It also represents the economics of capacity markets. All generators are assumed to contribute to reserve margin and receive payments for their contributions. Dispatchable technologies can contribute their full rated capacity toward reserve margins and hence receive full payments – which is assumed to equal the levelized capital cost of a gas combustion turbine power plant (the least expensive dispatchable capacity to build), consistent with results from optimization models (for example, see Cole et al. (2017), Fig. 8). Due to their intermittency, renewables can contribute only a fraction of their rated capacity. In reality, this fraction – also known as the capacity credit or capacity value (CV) - is a function of the correlation between the temporal generation pattern of the resource and the peak load periods, as well as the fraction of intermittent generation compared to total regional output. As wind or solar constitute more of the system capacity, the variability of their peak-load operation will have a decreasingly beneficial effect on system reliability and hence, capacity value of a renewable technology decreases with its penetration. We model this decreasing capacity credit as a function of renewable energy (VRE) capacity shares by means of a simple sigmoid function. Wind power receives a 15% capacity value,

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but this credit is largely unaffected by the level of wind penetration; solar power receives 40% of the capacity credit at low levels of penetration, but this capacity value decreases to 5% by the time solar constitutes 20% of overall capacity (Cole et al., 2017).

In addition to decreasing capacity credits, VRE technologies may also face decreasing capacity factors as deployment increases, because locations with the strongest resources (solar insolation or wind speed) will tend to be utilized first and subsequent installations will be cited in locations with marginally poorer resources. Supplementary Note 2 describes how the GCAM-USA electricity dispatch model captures these dynamics.

The new GCAM-USA electric power sector provides a rich set of outputs for each scenario. Users can track electric capacity by technology (both existing capacity and new investments); monthly day/night electricity load and electricity generation by technology; variable costs and electricity dispatch order by monthly day/night electricity load segment; dynamically evolving technology capacity factors (as each technology-vintage's operation evolves over time). Most of these results are available at the state-level, although some of the decisions (e.g. electricity dispatch order) are represented at the grid-region level.

4 GCAM-USA Reference Scenario Storyline

Human-Earth system models simulate outcomes of dynamic systems whose future evolution is highly uncertain. For this reason, it is important to articulate a clear storyline, or "narrative description … highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution" (IPCC, 2014) (pg. 1773), about the evolution of the modeled system. This high-level description of drivers and trends provides the basis for clearly documenting assumptions, including choices about model structures and parameters, which may influence future model outcomes (Binsted et al., 2020). The following section outlines the storyline for the GCAM-USA Reference scenario. Additional description of the GCAM-USA Reference scenario storyline is available in the online GCAM-USA model documentation page (http://jgcri.github.io/gcam-doc/gcam-usa.html).

4.1 Socioeconomics and end-use energy demands

The GCAM-USA Reference scenario assumes a steadily growing U.S. economy and growing but gradually peaking population through the end of the century. (A detailed description of GCAM-USA's default socioeconomic assumptions is provided in Sect. 2.2.1) This population and economic growth translates to increasing service demands in all end-use sectors. The GCAM-USA Reference scenario assumes a continuation, but not an expansion or strengthening, of current energy efficiency policies (e.g. building efficiency standards); thus, final energy demands increase as efficiency improvements are slower than increases in demand for end-use energy services (space heating and cooling, passenger and freight

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transportation, industrial energy use, etc.). End-use sectors tend to become increasingly electrified over time, with the trend strongest in buildings (where many new energy demands come from electronic devices). Transportation remains reliant on liquid fossil fuels, although light-duty vehicles (LDVs) electrify more rapidly than the sector as a whole.

4.2 Electric power

In the GCAM-USA Reference scenario, electricity demand grows slowly but steadily over the next three decades, reaching approximately 5,600 TWh in 2050. Load grows slightly faster over the second half of the century, reaching 7,700 TWh in 2100. This demand is driven by increased electrification in buildings and industry, with modest growth in transportation after 2050. (The GCAM-USA Reference scenario does reflect existing policies to incentivize battery electric vehicle (BEV) deployment.) This future load growth departs from recent historical trends; USA electricity demand increased only 4% in the decade between 2009 and 2019 (EIA, 2020a).

In terms of electricity supply, rising electricity demand is met by increasing generation from natural gas and renewables in the GCAM-USA Reference scenario. Growth in gas generation dominates through 2050, with moderate increases in wind and solar; post-2050, gas generation flattens while wind and solar growth accelerate substantially. The GCAM-USA Reference scenario assumes no new deployment of coal-fired power plants without carbon capture and storage (CCS), based on the Clean Air Act Section 111 (b) New Source Performance Standards (Environmental Protection Agency, 2015). Coal generation remains roughly flat from 2020 to 2030 and remains a substantial portion of the generation mix through 2040, until much of the capacity reaches the end of its technical lifetime. New nuclear deployment does not occur in the GCAM-USA Reference scenario until 2030, considering the long lead time for permitting and construction and the dearth of nuclear plants currently under construction in the USA (with the exception of Vogtle Units 3 and 4 in Georgia). A more detailed description of the GCAM-USA Reference scenario storyline for the electricity sector is available in Binsted et al. (2020).

4.3 Water

At a national level, the GCAM-USA Reference scenario entails modest declines in water withdrawals through mid-century, with relatively flat water demands thereafter. The decline in demand is driven by a reduction in power sector cooling water. Despite growing electricity demand, the gradual retirement of plants with once-through cooling systems (which are assumed to be unavailable for installation in future model periods) coupled with a shift towards less water-intensive generation technologies (e.g. natural gas, renewables) result in diminishing power sector water demands in the GCAM-USA Reference scenario.

Declining power sector cooling water demands are partially offset by increased withdrawals from the agriculture, livestock, manufacturing, and municipal sectors; these demands are largely driven by economic growth. Per-unit water requirements for primary energy, livestock, and manufacturing are assumed to be constant through the end of the century, so the scale of those activities corresponds directly to water withdrawals. In the agricultural sector, there is a competition between irrigated and rainfed crop management systems; however, in the U.S., most agriculture is already irrigated, and the GCAM-USA Reference scenario assumes no improvement in crop-specific per-unit irrigation water requirements over time. Municipal water use does become somewhat more efficient over time, but these efficiency improvements are offset by population growth.

4.4 Land

Agricultural productivity increases gradually in the U.S. in the future, with annual productivity growth rates ranging from 0% to 0.67% per year between 2015 and 2100. Demand for agricultural commodities increases, driven by changes in population, income, and biofuels demand. Per capita food demand is relatively flat in the U.S. given its income level, with staple demand decreasing slightly over the century and non-staple demand increasing modestly (Edmonds et al., 2017). Demand for liquid biofuels increases by 160% between 2015 and 2050 in the reference scenario. The U.S. is a net exporter of crops, with ~21% of all crops produced exported in 2015 and ~25% exported in 2050 in a reference scenario.

5 Scenarios

The following section presents results for four illustrative scenarios constructed using GCAM-USA v5.3_water_dispatch. The scenarios vary across two dimensions: socioeconomic drivers and energy system evolution. These simple scenarios, outlined in Table 1, are designed to illustrate the behavior and capabilities of the model across a diverse range of potential futures.

Scenario	Socioeconomic drivers	Energy system evolution
Ref	Default (SSP2)	Default (no explicit policy)
High Growth	High growth (SSP5)	Default
Transition	Default	Long-term economy-wide transition toward low-carbon technologies
High Growth + Transition	High growth	Long-term economy-wide transition toward low-carbon technologies

Table 1: Scenario design

The Ref scenario is the default GCAM-USA Reference scenario based on the storyline described in Sect. 4. In this scenario, population and GDP growth assumptions are consistent with SSP2 (see Sect. 2.2.1 for more information on socioeconomic assumptions in GCAM). The High Growth scenario assumes faster population and economic growth consistent with SSP5. Note that, although the SSPs are global scenario narratives, our High Growth scenario assumes that only the U.S. population and economy grows at the accelerated SSP5 rates, in order to isolate the impact of economic growth in the U.S. on model outcomes.

The Transition scenario contains default (reference) socioeconomic assumptions but reflects a transition towards a lower-carbon energy system (reaching zero energy system carbon dioxide emissions by 2090; see Supplementary Figure SF1 for scenario emissions pathways). Finally, the High Growth + Transition scenario combines the higher growth (SSP5) scenario element with the transition towards a lower-carbon energy system.

In all scenarios, water availability is constrained to default levels of renewable and non-renewable groundwater as described in Kim et al. (2016) and Turner et al. (2019). Water prices will thus vary by basin; basins in which renewable water supplies exceed water demand will have negligible water prices, but as demands rise in the future across scenarios, some basins may need to utilize and non-renewable groundwater (and possibly desalinated water), raising the price of water and motivating a shift towards less water intensive technologies.

6 Results

This section presents results for the four GCAM-USA scenarios described above, focusing on model outputs for energy consumption (Sect. 6.1), electric power (Sect. 6.2), water (Sect. 6.3), and land use (Sect. 6.4). Each system will begin with a description of high-level national-aggregate trends but focus mainly on subnational detail within the model. The section concludes with a brief comparison to historical data and other future scenarios (Sect. 6.5).

6.1 Energy consumption

The four GCAM-USA scenarios presented in this paper entail vastly different future energy trends (Fig. 2). In the Ref scenario, total primary energy for the USA grows steadily throughout the century, with the energy mix dominated by fossil fuels. Oil consumption is relatively flat from 2015 to 2100; coal demand dwindles past 2050, while natural gas becomes the largest source of primary energy, with consumption nearly doubling in 2100 (relative to 2015 levels). The fuel trends are similar in the High Growth scenario, but total primary energy more than doubles in 2100 (relative to 2015), compared to only 38% growth in the Ref scenario over the same period.

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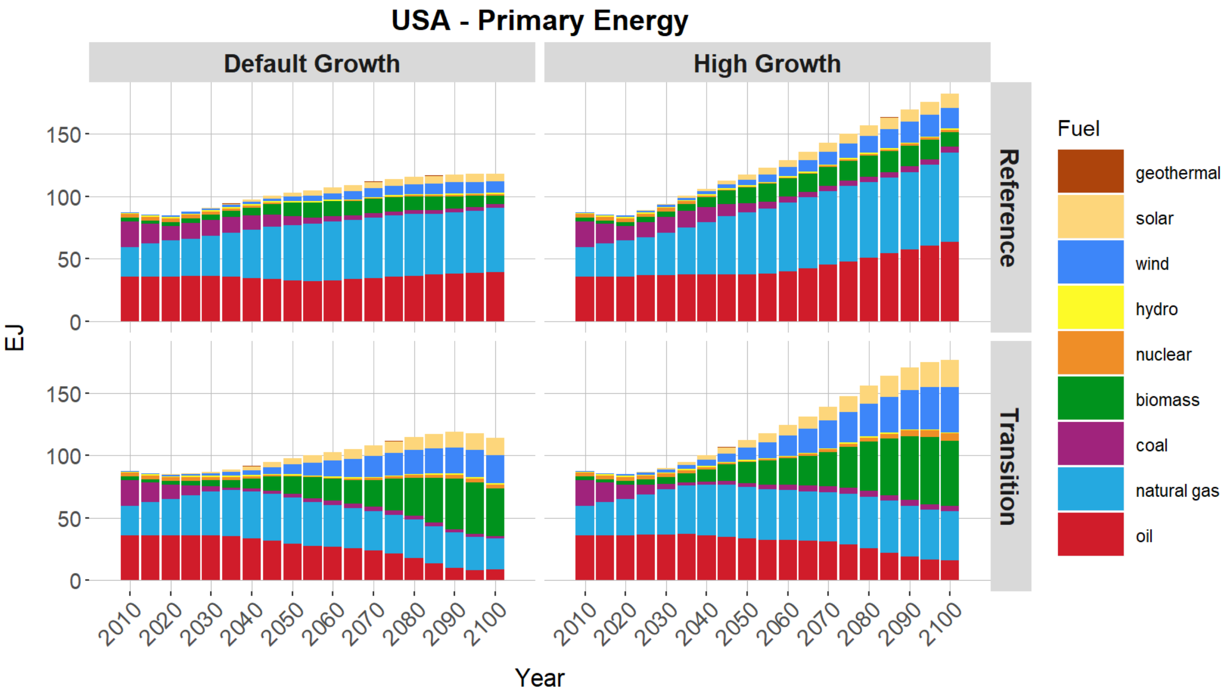

Figure 2. USA primary energy consumption (national total) by fuel and scenario. Columns reflect alternate assumptions about socioeconomic drivers; rows represent alternate assumptions about energy system evolution.

In the Transition scenario, the decline of coal happens sooner (mostly eliminated by 2035), while oil consumption is roughly flat through 2040 before declining in the second half of the century. Gas consumption grows over the next several decades but peaks by 2050. Bioenergy, wind, and solar consumption grow relatively slowly through 2050 and rapidly thereafter; by 2100, these three fuels constitute nearly two-thirds of total U.S. primary energy consumption. The Transition + High Growth scenario has similar trends, but primary energy demands are more than 50% greater in 2100.

Beneath these national-level results is significant heterogeneity in outcomes across states and sectors. Figure 3 shows the electrification rate (electricity share of final energy) by sector for each scenario in 2100. Across all scenarios, the building sector tends to be the most electrified, although there is significant regional variation. In the Ref scenario, building sector electrification ranges from 36% (Vermont) to 90% (Florida) in 2100; electrification rates are similar in the High Growth scenario, although they tend to be slightly higher. This range tightens substantially in the Transition scenario. Electrification of end-use sectors is a key emission reduction strategy; buildings, as the most electrified sector in the Ref scenario, tends towards the upper end of electrification, with electricity accounting for 79% of building energy consumption in New York and 97% in Florida.

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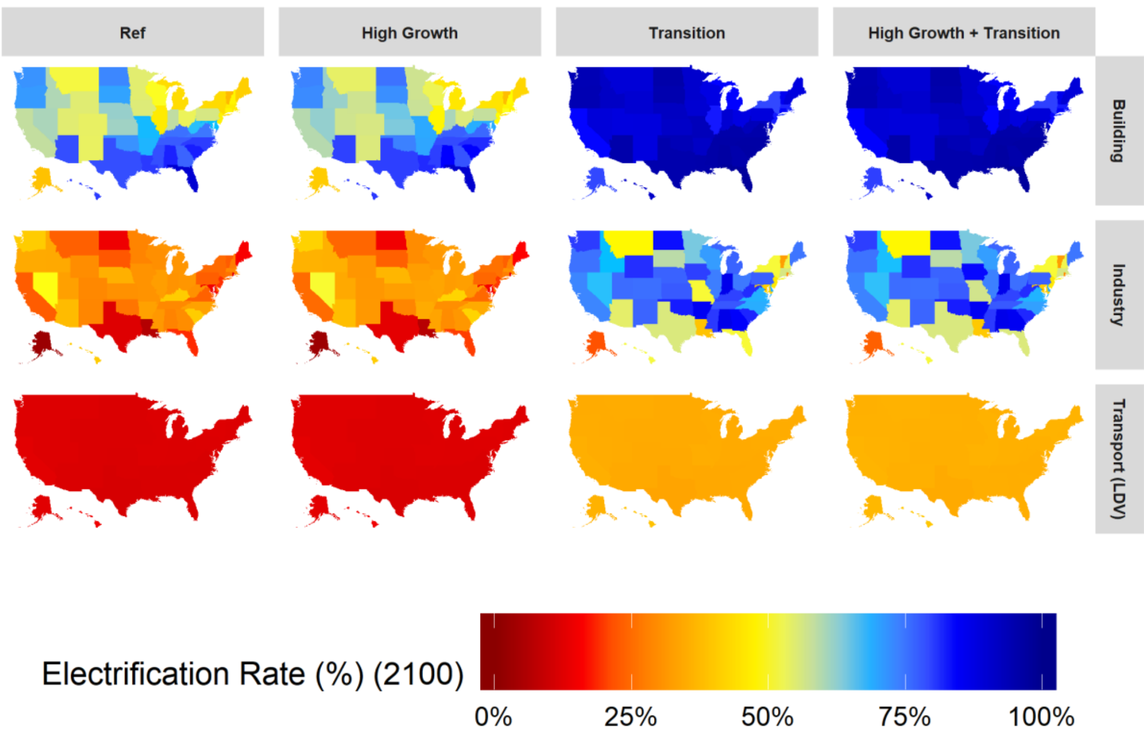

Figure 3. Electricity share of final energy by state, scenario, and end-use sector (building, industry, passenger vehicles) in 2100. Note that because electric drivetrains are more energy efficient than internal combustion engines, the share of passenger transportation service provided by electricity (BEVs) in the scenarios will exceed the energy consumption shares shown in this figure. A plot of passenger vehicle electrification by share of transportation service (passenger miles traveled) is provided as Supplementary Figure SF2.

Industry electrification rates are similarly diverse. In the Ref scenario, electricity accounts for between 2% (Alaska) and 50% (Nevada) of industrial energy use. Again, these rates are similar in the High Growth scenario, although the magnitudes of this electricity consumption are vastly different. For example, Ohio's industry sector has a 31% electricity share in Ref and a 32% share in High Growth, but the sector consumes 95.3 TWh in Ref compared to 158.3 TWh in High Growth. As with the building sector, industry electrifies quite substantially in the Transition scenario, although there is more heterogeneity in these outcomes. For example, Alaska has only a 22% industrial electrification rate in 2100, while Alabama has an 86% electrification rate (Transition scenario).

Electrification of passenger transportation is much more regionally homogenous than other sectors. In the Ref scenario, between 11% (Texas) and 14% (Hawaii) of states' passenger transport energy consumption comes from electricity. These rates are virtually identical in the High Growth scenario. In the Transition and Transition + High Growth scenarios, these electrification rates range from 33% to 40%. This represents a significant increase in electrification relative to the Ref and

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High Growth scenarios, although the range of outcomes is fairly small. There are several reasons for this. First, because electric vehicle (EV) penetration is very low in the historical period (2015), the model has little information about varying regional preferences for EVs around which to calibrate. Second, since these consumer preferences for EVs begin from a similar place (near zero deployment), these preferences tend to evolve homogenously over time in the model. Third, vehicle costs and emission costs are the same in every state in these scenarios; the scenarios do not represent existing state-level ZEV mandates. Finally, although GCAM-USA does capture regional differences in fuel prices (for both traditional liquid fuels and electricity), fuel prices tend to represent a small percentage of total vehicle ownership costs; thus these fuel price differences do not impact transportation results as much as they may in other sectors.

6.2 Electric power

GCAM-USA now explicitly tracks both electricity generation and generation capacity by technology and cooling system. Figure 4 presents both electricity generation and capacity for our four GCAM-USA scenarios. Electricity generation in the Ref scenario grows 85% over the course of the century (relative to 2015) to nearly 7,700 TWh, while capacity grows more than 250% to over 2,800 GW in 2100. The generation mix is dominated by fossil fuels in the near- to medium- term, with coal generation gradually declining and gas generation steadily growing. By 2060, fossil fuels account for just over 50% of total U.S. power generation, with wind and solar the next most significant generation sources (behind natural gas). Hydropower is exogenously specified in GCAM-USA and fixed at 2019 levels for all historical periods. Nuclear power represents a significant portion of the generation mix through about 2035, then dwindles for several decades (driven by an assumption of 60-year operational lifetimes) before growing again beginning around 2070. Capacity trends by fuel are similar, although wind and solar make up a larger share of capacity than generation due to their relatively low capacity factors (compared to other technologies like gas combined cycle and nuclear). The increasing penetration of wind and solar is one reason the national fleet's annual average capacity factor declines steadily from 45% in 2015 to 31% in 2100. Wind and solar constitute greater than 50% of power sector capacity by 2055, but don't account for 50% of electricity generation until 2080.

Fuel mix trends, in both generation and capacity, are similar for in the High Growth scenario. However, electricity demand in the High Growth scenario is 57% higher than in Ref, with electricity in generation in 2100 exceeding 12,000 TWh (290% higher than 2015 levels). Capacity growth, outpacing generation, approaches 4,800 GW, more than quadruple 2015 levels. The Transition scenario, with middle of the road population and economic growth but strong incentives to electrify end-use sectors to reduce their carbon intensity, sees even higher electricity growth, with generation reaching 12,900 TWh in 2100 and capacity reaching 6,140 GW. In this scenario, coal phases out even more quickly, while gas peaks in 2035 and declines steadily thereafter (although gas continues to provide nearly 10% of electricity generation in 2100, most of which is in combination with carbon capture in storage (CCS)). Wind and solar constitute 50% of total electricity generation by 2050 in the transition scenario and over 75% in 2100, while nuclear power also contributes about 5% of total generation in 2100).

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Again, the fuel mix in the High Growth + Transition scenario is similar to that of High Growth, but total electricity generation is 50% higher in the former (nearly 20,000 TWh in High Growth + Transition vs. 12,900 TWh in High Growth), with total power sector capacity exceeding 9,700 GW in 2100.

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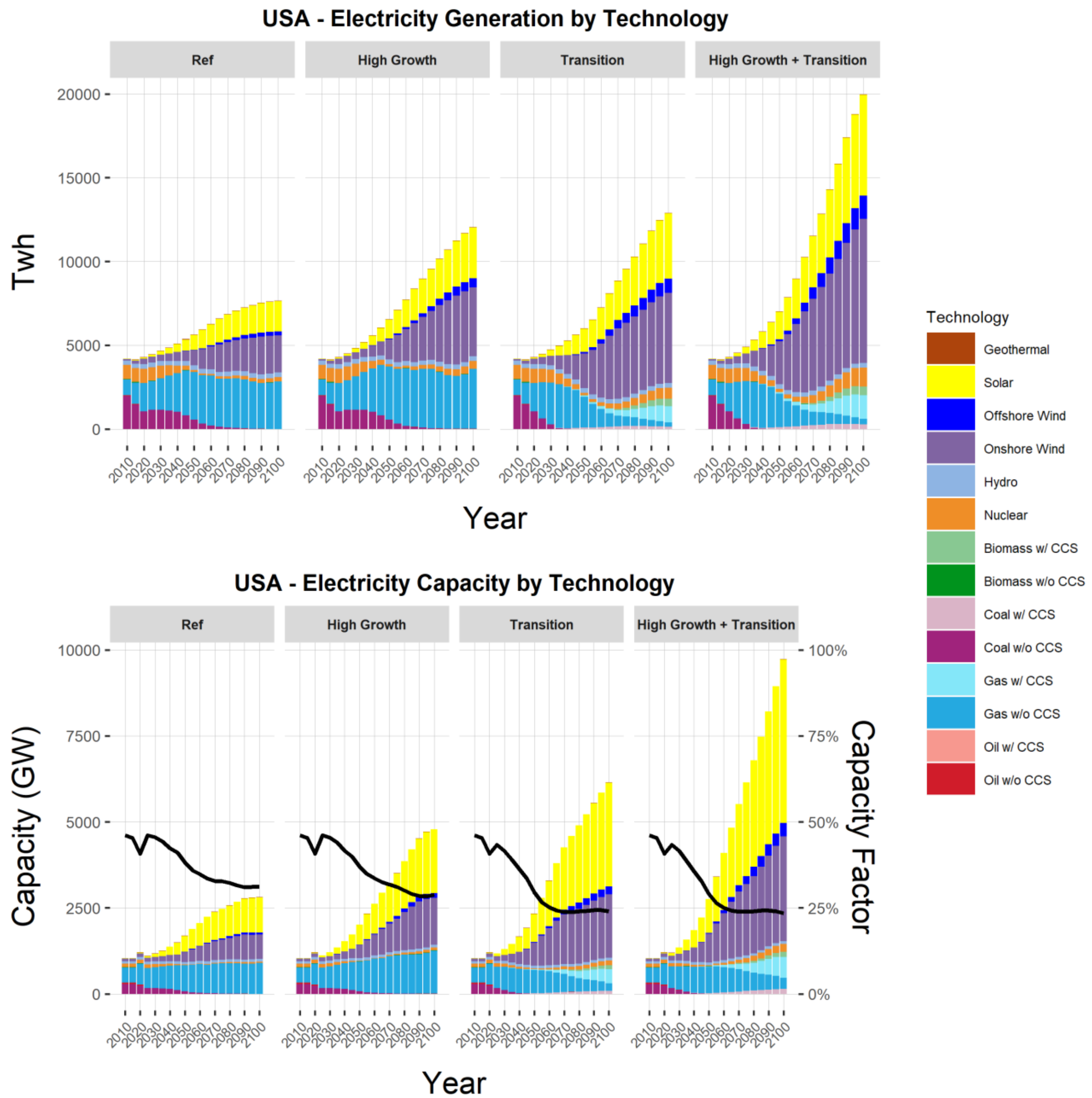

Figure 4. USA electricity generation (top) and capacity (bottom) by technology and scenario. Lines on capacity plots (bottom panel) represent national fleet average annual capacity factor and corresponds to the secondary (right) y-axis.

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The new electricity dispatch model in GCAM-USA also allows us to explore changes in the operation of power plants at the state-level. Figure 5 shows the endogenous capacity factors for four key technologies (coal without CCS, gas combined cycle (gas CC), photovoltaic solar (PV), and onshore wind) at the state level across all four scenarios in 2050. (Note that the color scales differ between technologies.) These results highlight the state-level heterogeneity in GCAM-USA – technology capacity factors (utilization rates) span a relatively wide range across states. In the Ref scenario, coal (without CCS) capacity factors range from 66% to 85%, although 23 state-level regions have no coal capacity in 2050. Gas CC capacity factors in the Ref scenario range from 21% (Missouri) to 66% (Washington) in 2050, with a national average of 49%. PV capacity factors range from just 5% (Alaska) to 31% (Arizona) (22% national average), while wind capacity factors range from 14% (Hawaii) to 44% (Kansas) (36% national average).

As observed with other rate variables, these endogenous technology capacity factors tend to be quite similar in the High Growth and Ref scenarios, particularly in 2050 when deployment of intermittent technologies is still more limited. Coal plant utilization is nearly identical in the High Growth and Ref scenarios, although a handful Midwest and Great Plains states have slightly diminished (1-10%) coal capacity factors as wind deployment increases. Gas CC plants are operated between 2% more frequently (Montana) and 5% less frequently (Washington) in the High Growth scenario (compared to Ref) in 2050. PV and onshore wind capacity factors are consistently lower in the High Growth scenario (compared to Ref) but the differences do not exceed 1.3% in 2050. By 2100, however, PV and onshore wind capacity factors in the High Growth scenario diverge more and are noticeably lower than in Ref. PV capacity factors are up to 7.6% lower (New Mexico, 10.4% vs 17%) in 2100, with the national average PV capacity factor about 1.4% lower. Similarly, onshore wind capacity factors are up to 5% lower in 2100 (New Jersey), with the national average 1.4% lower in High Growth (compared to Ref). The reason for these declines is the fact that the highest quality sites for variable energy (wind and PV) are utilized first. Deployment of these technologies is significantly higher in the High Growth scenario in 2100; these additional wind and PV installations are built in increasingly marginal areas with diminishing capacity factors.

A similar, and indeed exaggerated result is observed in the Transition and High Growth + Transition scenarios. PV capacity factors in the Transition scenario range from 4% (Alaska) to 27% (Utah) in 2050 – between 0% and 20% lower than those in the Ref scenario. The national average PV capacity factor is about 2.2% lower in Transition (19.6%) compared to Ref (21.8%) in 2050. Interestingly, PV capacity factors are not further degraded in the High Growth + Transition scenario, still ranging between 4% and 27%.

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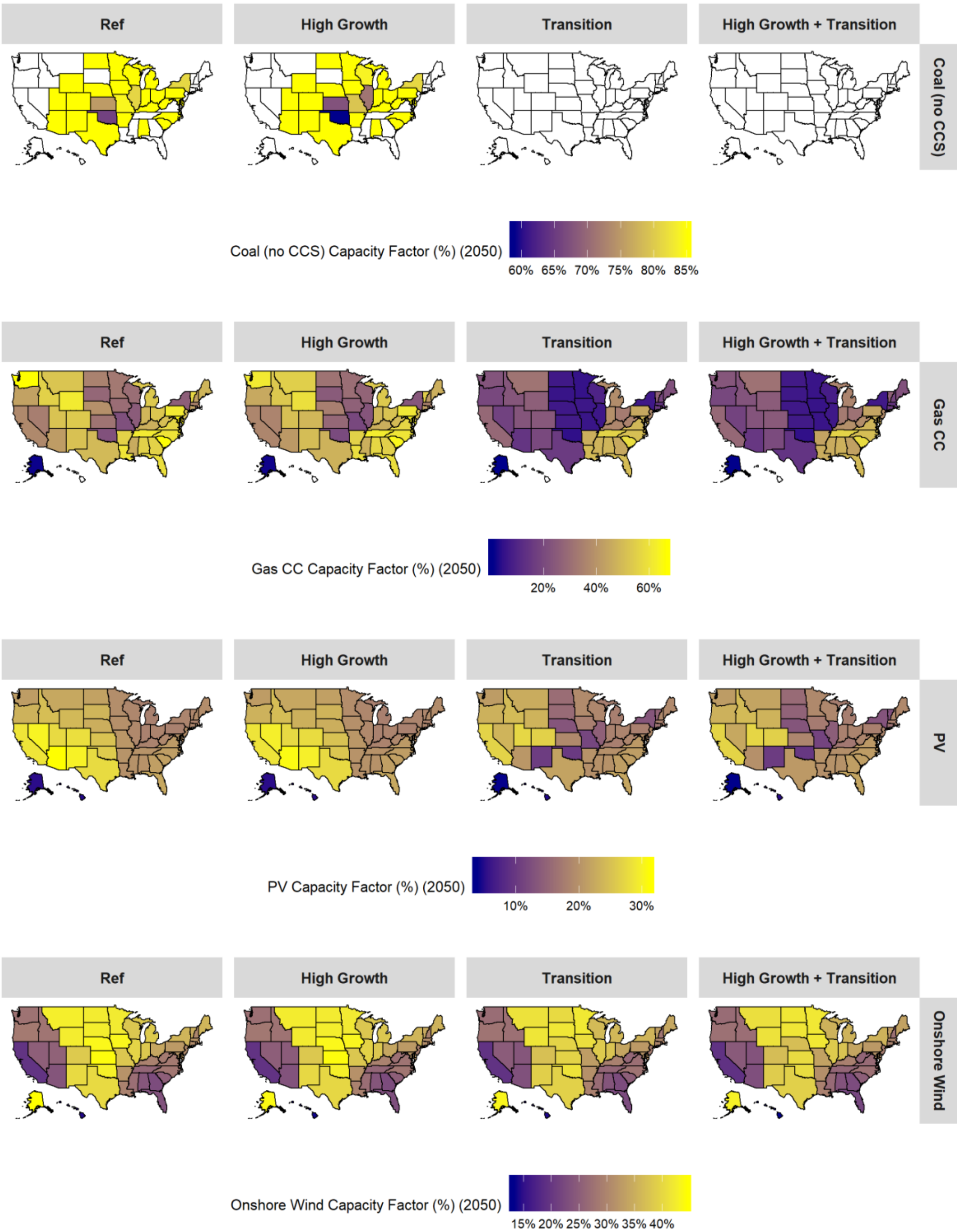

595 **Figure 5. USA power sector capacity factor, by scenario, for select technologies in 2050. Note that color scales differ between technologies. No shading (white) indicates zero capacity in that state / period / scenario.**

Onshore wind capacity factors in the Transition scenario (2050) range from 14% (Hawaii) to 43% (Alaska) with a national average of 36%. These capacity factors are again lower than those observed in the Ref scenario; greater deployment reduces the national average onshore wind capacity factor in the Transition by an additional 0.5% relative to the High Growth scenario. Contrary to PV, combining the high socioeconomic growth and energy system transition assumptions leads to further degradation of onshore wind capacity factors, which are between 0 and 2.6% lower in the High Growth + Transition scenario (relative to Transition).

Gas CC capacity factors drop in the Transition and High Growth + Transition scenarios (relative to Ref) because the emissions price used to incentivize a shift towards a lower carbon economy makes operating gas CC plants relatively more expensive. At the national level, gas CC (without CCS) capacity factors drop from roughly 49% in 2050 (Ref) to 32% (Transition); at the state level, these differences range from 2% higher in the Transition scenario (Mississippi) to 44% lower (Washington), relative to Ref. Coal power plant operations are even more strongly impacted because they are more carbon intensive; in the Transition scenario only 6 states have remaining coal capacity (without CCS) by 2040, and all coal capacity without CCS is retired by 2050.

One interesting regional pattern which emerges is that gas CC capacity factors tend to be higher in the southeastern states, especially in the Transition and High Growth + Transition scenarios. One reason for this is that the southeast has relatively poor wind resources, as indicated by the low capacity factors for onshore wind. For example, in 2050, wind accounts for just 2.1% of total capacity (1.1% of generation) in Georgia in the Ref scenario; in the Transition scenario, this increases to only 5.0% of capacity and 3.2% of generation. At night, with no solar generation and a dearth of wind generation (which tends to be stronger at night), the southeast must rely on other technologies – often gas CC – to support nighttime loads. This keeps gas CC capacity factors high in the southeast compared to other regions.

6.3 Water

GCAM-USA now provides a comprehensive accounting of water use (withdrawals and consumption) at the state level. Figure 6 presents a time series of water withdrawals by sector for each scenario. In 2015, cooling water for electricity generation is the largest source of water withdrawals at the national level, followed closely by agricultural irrigation. Together these sectors account for more than 290 cubic kilometers (km3) of water withdrawals, or more than three quarters of national withdrawals in 2015. However, while electricity sector withdrawals remain relatively flat through 2030 before declining rapidly to under 20 km3 by 2060 in all scenarios (and remaining low thereafter), irrigation water withdrawals grow steadily over the course of the century across all scenarios, reaching 210 km3 in 2100 in the Ref scenario (a 49% increase over 2015). Growth in agricultural water withdrawals in the Ref scenario is driven primarily by increasing population and GDP; in the High Growth scenario, withdrawals grow more rapidly to 240 km3 in 2100. In the Transition and High Growth

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+ Transition scenarios, agricultural withdrawals reach 271 and 295 km3 in 2100, respectively; this increase in demand for irrigation water is driven in large part by increased demand for bioenergy crops by the energy system, as described in Sect. 6.1.

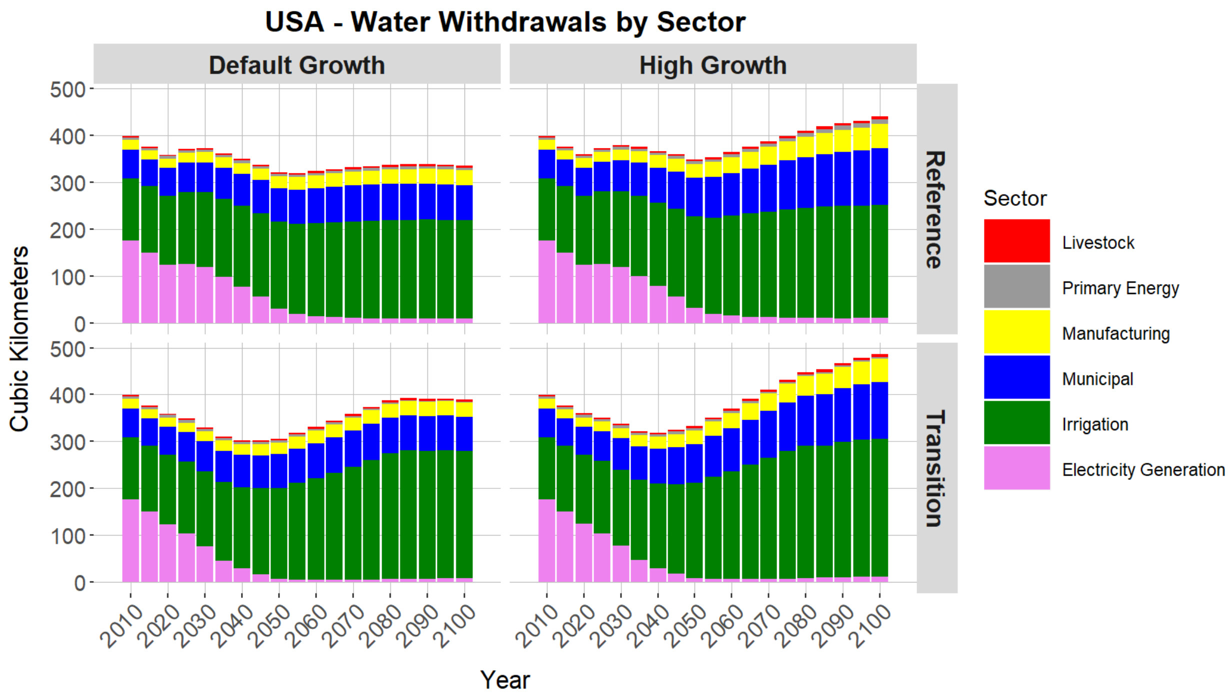

Figure 6. USA water withdrawals by sector and scenario. Columns reflect alternate assumptions about socioeconomic drivers; rows represent alternate assumptions about energy system evolution.

Municipalities are the third largest water user in terms of withdrawals, both historically and throughout the century across all four GCAM-USA scenarios. Municipal water demands grow steadily with socioeconomic growth, as do demands from manufacturing, the fourth largest source of water withdrawals nationally. Water demands for the mining (primary energy) and livestock sectors are relatively small from a national perspective across all scenarios. In total, national water withdrawals decline slightly to mid-century in the Ref scenario and are relatively flat thereafter, with end-of-century withdrawals about 10% lower than historical (2015) levels. In the High Growth scenario, the decline in electric power water withdrawals are more rapidly offset by increasing demands from agriculture and municipalities, with total USA withdrawals reaching 440 km3 in 2100 (nearly 20% higher than 2015 levels). Although irrigation water withdrawals grow even more rapidly in the Transition scenario (as highlighted above), municipal and manufacturing demands remain close to Ref levels; in turn, total water withdrawals are slightly lower by end-of-century in the Transition scenario (relative to High Growth) at just about 390 km3 in 2100. The High Growth + Transition scenario has by far the largest water withdrawals in 2100 (at 486 km3), although total withdrawals in 2050 are only 3% higher than the Ref scenario; in the near-to-medium term, growth in irrigation and municipal withdrawals (driven by increased demand for bioenergy crops and socioeconomic growth, receptively) is offset by faster declines in power sector water withdrawals due to less frequent operation of fossil fuel power plants (particularly coal, which requires substantial cooling water) and greater investment and generation from wind and PV (which have no cooling requirements).

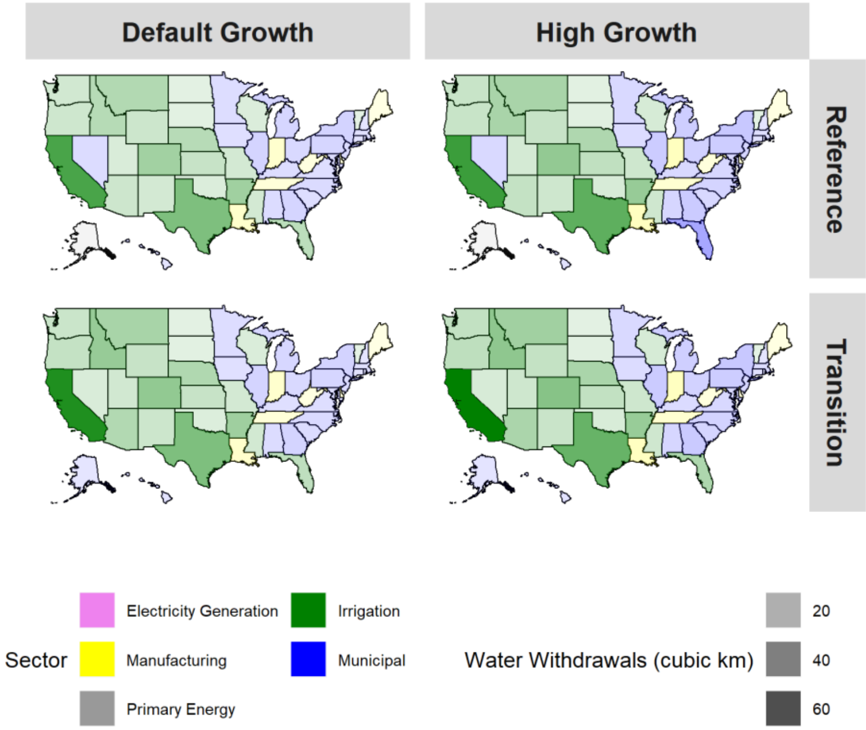

Figure 7. Water withdrawals by state and scenario in 2100. Fill color represents the sector with the largest water withdrawals in each state. Shading (transparency) corresponds the magnitude of total withdrawals (sum of all sectors) by state. Columns reflect alternate assumptions about socioeconomic drivers; rows represent alternate assumptions about energy system evolution.

However, as observed in the energy and electricity results, significant regional heterogeneity undergirds these national trends. Figure 7 presents water withdrawals by state and scenario in 2100; the map is color-coded according to which sector is the largest water user (in terms of withdrawals) in each respective state, while the shading of that color is scaled to total water demands (across all sectors) in the state; states with the highest water withdrawals appear most saturated. Irrigation accounts for the most water withdrawals nationally in 2100 and is also the largest water user in 22 states (mostly across the Great Plains and western US). Municipalities are the largest water users in 21 states (mainly along the eastern seaboard and Great Lakes), while manufacturing accounts for the most water withdrawals in six states. The regional distribution of water demands by sector is similar in the High Growth scenario, although municipal water use becomes larger than irrigation in Florida, and demands are generally higher across the board. Similar outcomes are observed in the Transition and High

Growth + Transition scenarios, with water withdrawals increasing in volume but the sectoral distribution by state (in terms of highest consuming sector) remaining relatively stable.

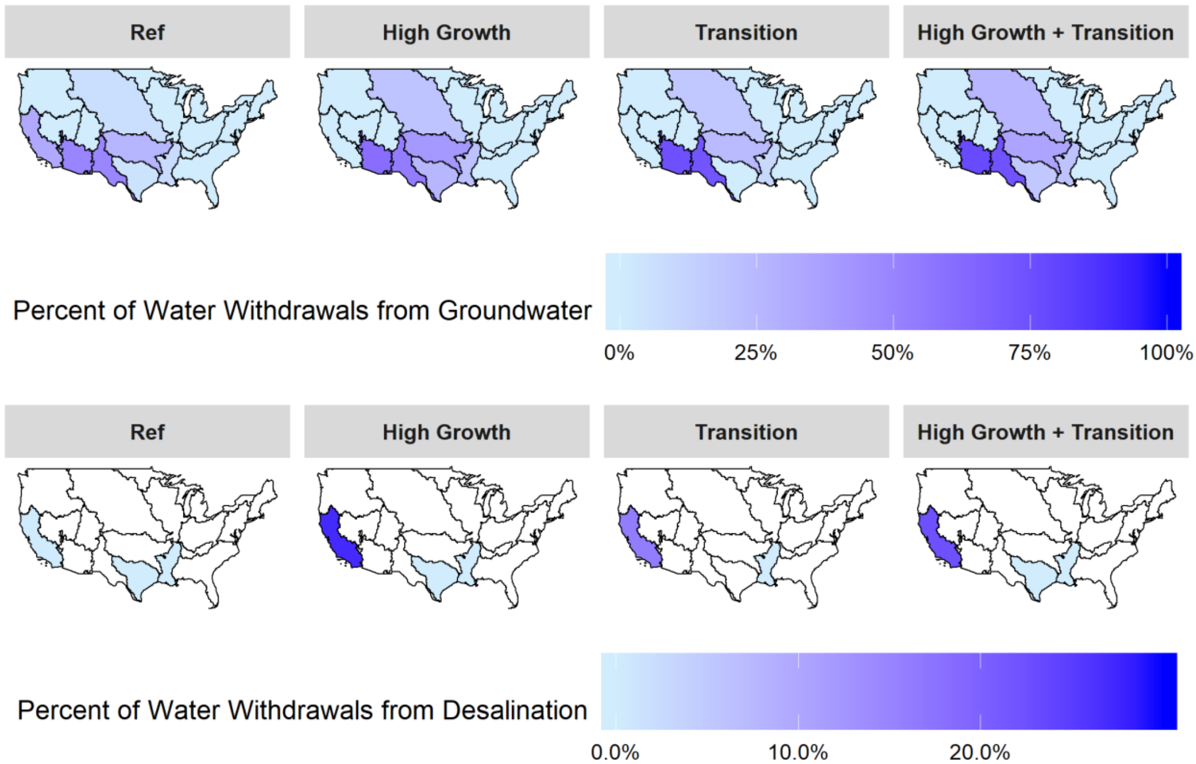

Figure 8. Percentage of total water withdrawals met by groundwater extraction (top panel) and desalination (bottom panel), by water basin and scenario in 2100.

In addition to water use (withdrawals and consumption), GCAM-USA also reports water supplies by source by water basin. Figure 8 presents the percentage of total water withdrawals supplied by groundwater (top panel) and desalinated water (bottom panel) in 2100 (the remaining withdrawals come from runoff, which is not included in the figure). In the Ref scenario, groundwater accounts for less than 10% of water withdrawals in most (15/20) water basins, although groundwater supplies between 25%-40% of water withdrawals for the Arkansas White Red, California River, and Mexico Northwest Coast basins, while the Rio Grande and Lower Colorado basins rely on groundwater for nearly 50% of their total withdrawals. Results are generally consistent in the High Growth scenario; the groundwater reliant regions from the Ref scenario become slightly more groundwater reliant, and the Lower Mississippi River, Missouri River and Texas Gulf Coast basins approach or exceed 20% of withdrawals from groundwater. The most notable change in this scenario, however, is the California River basin, which has virtually no groundwater extraction in 2100. This is a result of over-extraction in previous model periods; by 2100, remaining groundwater is limited and is expensive to access. The California River basin thus

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becomes more reliant on desalination in the High Growth scenario, with nearly 30% of water withdrawals provided by desalination (no other basin exceeds 1%, and most don't utilize desalinated water at all). The Transition and High Growth + Transition scenarios have similar spatial patterns of water stress; the southwestern U.S. becomes even more reliant on groundwater in these scenarios, with the Lower Colorado River and Rio Grande River basins both relying on groundwater for roughly three-quarters of their withdrawals in 2100 across both scenarios. This result is tied to an expansion of agriculture in the region, discussed further in the next section.

6.4 Land

GCAM-USA tracks land allocation in the USA across more than a dozen crop categories (corn, wheat, rice, other grains, fiber, root, sugar, and oil crops), two types of dedicated energy crops (trees and shrubs), managed and unmanaged forests, grasslands, shrublands, pasture lands, and several other land types. Figure 9 presents USA land allocation by aggregate land type for each scenario. In the Ref scenario, cropland expands gradually throughout the century, reaching 1.33 million square kilometers (km2) in 2100 (about 20% higher than 2015 levels). Cropland expands less rapidly than irrigation water withdrawals, implying a shift to more water intensive crops over time (the national share of irrigated agriculture is roughly constant throughout the scenario). A small amount of dedicated bioenergy cropland is also introduced throughout the century. This additional cropland comes mainly from pasture and other arable land; forest land expands marginally (2% higher in 2100) in the Ref scenario. Cropland expansion is more significant in the High Growth scenario, with cropland reaching 1.43 million square kilometers in 2100. This additional cropland results in less allocation to most other land types, including energy crops, although the biggest differences (in absolute magnitude) are in other arable land and forests.

The Transition and High Growth + Transition scenarios, by contrast, entail initial cropland expansion followed by contraction in the second half of the country, as traditional cropland is gradually replaced by energy cropland. Cropland in the Transition scenario is just 1.13 million km2 in 2100, just 1% higher than 2015 levels; in the High Growth + Transition scenario, traditional cropland accounts for 1.21 million km2 in 2100, as a larger population demands more food. Thus, the Transition scenario has the largest energy cropland allocation at 814 thousand km2 in 2100 (42% of total cropland), with the High Growth + Transition scenario next largest at 759 thousand square kilometers (39%). It should be noted that this large bioenergy cropland expansion is driven by the fact that bioenergy is considered to be carbon-neutral in the energy system; the Transition and High Growth + Transition scenarios entail a long-term transition towards a lower-carbon energy system but do not include efforts to value or incentivize the sequestration of carbon in the land system. Both the Transition and High Growth + Transition scenarios entail lower forest, grassland, shrubland, pasture, and other arable land than the Ref and High Growth scenarios.

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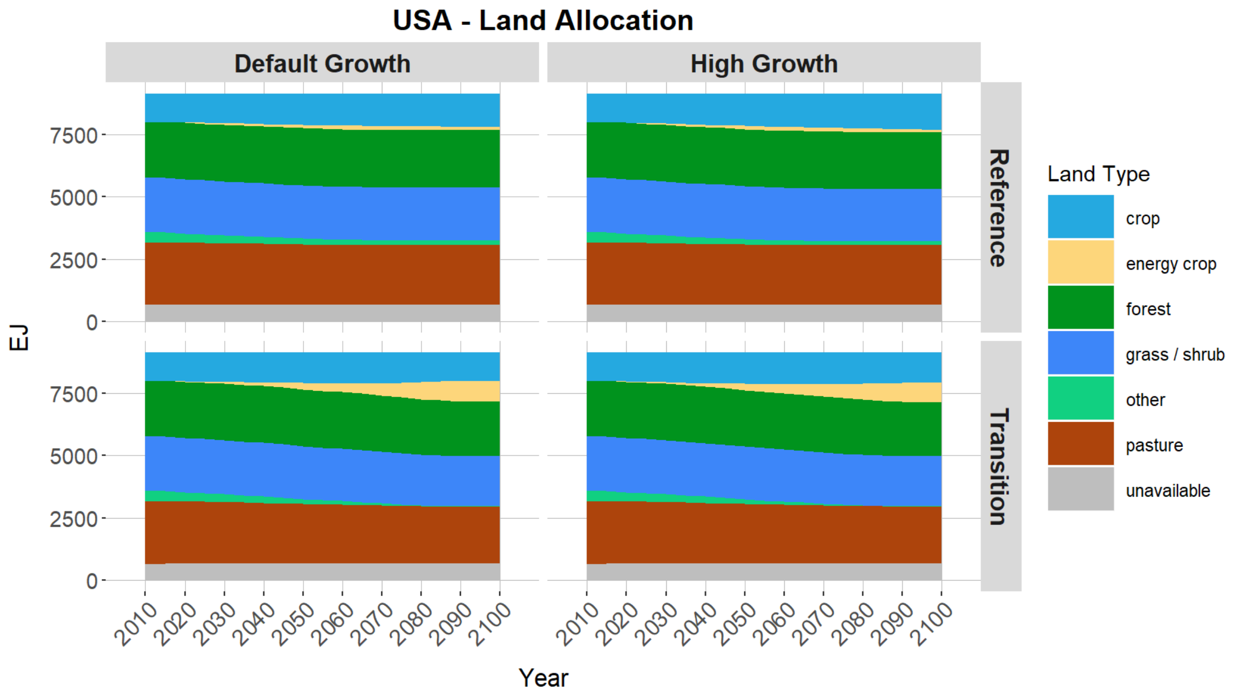
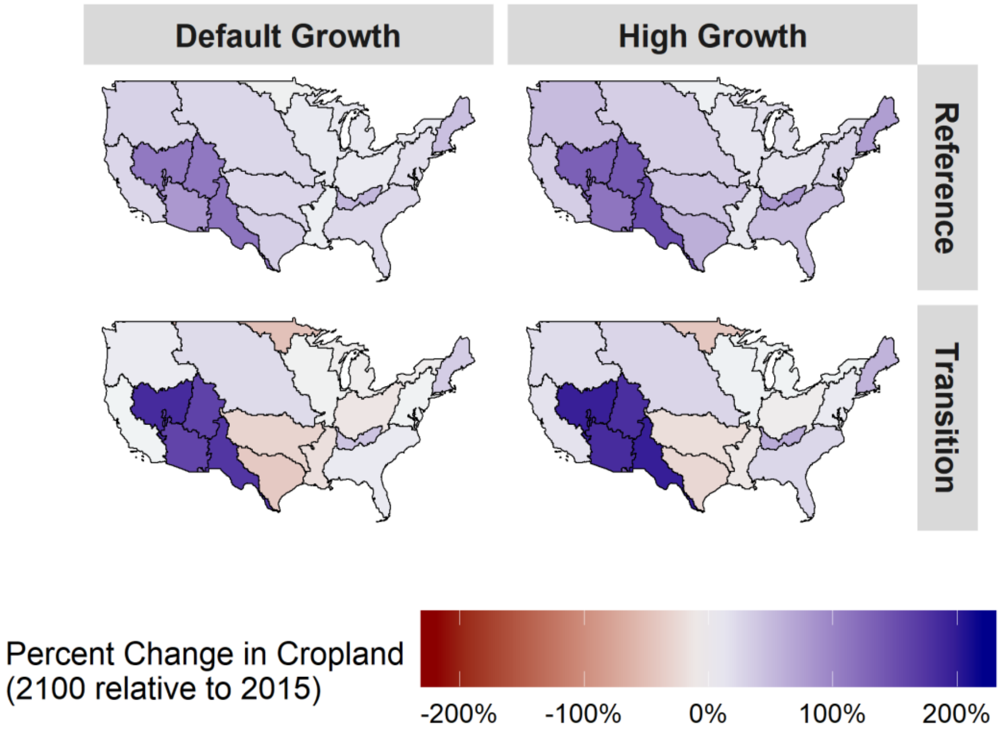


715 **Figure 9. USA land allocation by aggregate land type and scenario. Columns reflect alternate assumptions about socioeconomic drivers; rows represent alternate assumptions about energy system evolution.**

As with other systems, the way these national trends unfold varies by region. Figure 10 presents the percentage change in cropland (excluding dedicated energy crops) in 2100 relative to 2015, by land region for each scenario. In the Ref scenario, every region (besides the Nelson River basin) has more cropland in 2100 than it did in 2015, with cropland increases ranging between 3% to 113% (national average: 18%). The largest relative increases are in the southwestern U.S., with the Great Basin, Upper Colorado River, and Rio Grande River basins all more than doubling cropland in 2100 (relative to 2015), although these basins currently have a relatively small amount of cropland (about 18 thousand km2 combined in 2015). The largest absolute increase by far occurs in the Missouri River basin, which adds nearly 70 thousand square kilometers of cropland over the course of the century. These spatial trends are similar but larger in the High Growth scenario, with every basin increasing cropland and the Great Basin, Upper Colorado River, and Rio Grande River basins seeing 132%, 140%, and 150% increases in cropland in 2100 (relative to 2015), respectively.



730 **Figure 10. Percentage change in cropland allocation in 2100, relative to 2015, by water basin and scenario. Red shades indicate a reduction in cropland allocation, while blue shades indicate and increase in cropland.**

The Transition and High Growth + Transition scenarios entail both increasing and decreasing cropland across basins. In the Transition scenario, nine of twenty basins finish the century with less cropland than the final historical year; the biggest
735 decrease is 29 thousand km2 in the Nelson River basin. The Missouri River basin again sees the largest increase in total cropland with 60 thousand square kilometers of cropland added by 2100; the largest relative increases are again in the Great Basin, Colorado River (Upper and Lower), and Rio Grande River basins. Finally, as mentioned above, while the Transition and High Growth + Transition scenarios both have less cropland than their reference energy system counterparts (due to increased demand for bioenergy crops), the High Growth + Transition scenario has more cropland because of greater
740 population and corresponding total food demand. Thus, only five of twenty basins in this scenario experience net cropland contraction over the course of the century (and each is smaller than the corresponding reduction in the Transition scenario).

6.5 Comparison to historical data and other future scenarios

This section compares GCAM-USA v5.3_water_dispatch results to historical data and other future projections. Historical results for GCAM-USA are compared to inventory data for four metrics at the state level for the model's final historical year
745 (2015). The four historical metrics are total final energy consumption (across all fuels and end-use sectors), total electricity

generation (across all fuels), total water withdrawals (across all sectors), and energy system CO2 emissions (excluding emissions from the land system). State-level final energy consumption comes from the Energy Information Administration's (EIA) State Energy Data System (SEDS) "All consumption estimates" data set (https://www.eia.gov/state/seds/sep_use/total/csv/use_all_btu.csv). Historical data for electricity generation comes from the EIA's Electricity Data Browser (https://www.eia.gov/electricity/data/browser/). Data on state-level water withdrawals comes from the U.S. Geological Survey (USGS) (https://water.usgs.gov/watuse/data/), and data on historical CO2 emissions by state is taken from EIA's Energy-Related CO2 Emission Data Tables (https://www.eia.gov/environment/emissions/state/excel/table2.xlsx).

GCAM-USA is initialized over five historical periods (1975, 1990, 2005, 2010, 2015) and calibrated to match historical data. For energy flows, land allocation, and agricultural production, an exact match is enforced in the historical period. Water use and CO2 emissions are determined by coefficients calculated from historical data, but not forced to match observations. Historical observations are read into the model, which replicates these outcomes while maintaining GCAM's market equilibrium requirement that supplies and demands of all markets balance in each model period. Several data sets are used to provide historical calibration information for the model. At the global level, the IEA Energy Balances (IEA, 2019) is the primary data set used to calibrate historical energy flows, including energy production, transformation, and consumption. Fossil fuel production and consumption data are scaled globally to eliminate statistical differences and net stock changes and ensure supply-demand balance; electricity is similarly scaled for each GCAM region to remove inter-regional trade and statistical differences.

To ensure that global energy remains balanced, GCAM-USA downscales this processed IEA energy production, transformation, and consumption data for the USA to using state-level shares derived from the EIA's State Energy Data System. Some sectors are disaggregated beyond the level of detail in core GCAM; for instance, the building sector includes additional building services and technological detail and utilizes the EIA's Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS) to further disaggregate building energy. A full list of input data sets is included as Supplementary Table SM4; all model input data (except for the proprietary IEA Energy Balances data set) is available with the model or in the separate *gcamdata* package (https://github.com/JGCRI/gcamdata/).

Within GCAM, each sector contains at least one subsector, which in turn contains at least one technology. Subsectors (often corresponding to competing fuels) compete for share of the sector's total output; technologies within a given subsector compete for share of the subsector's output. This competition occurs on the basis of relative costs using a probabilistic logit choice function, which assumes a distribution of realized costs due to heterogeneous real-world conditions and allocates market share on the probability that a technology has the lowest cost compared to competing options. During the calibration routine, GCAM uses the cost of each subsector or technology (based on exogenous non-energy cost assumptions and endogenous energy prices) to estimate the (unobserved) logit share weight parameters, ensuring that historically observed outcomes are reproduced (Calvin et al., 2019). 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). Share weights are typically held constant at their final (2015) calibration values or gradually converged to a common value in some future model period. Thus, the preferences captured by GCAM's calibration routine influence on model decisions in future model periods (most strongly in initial model years).

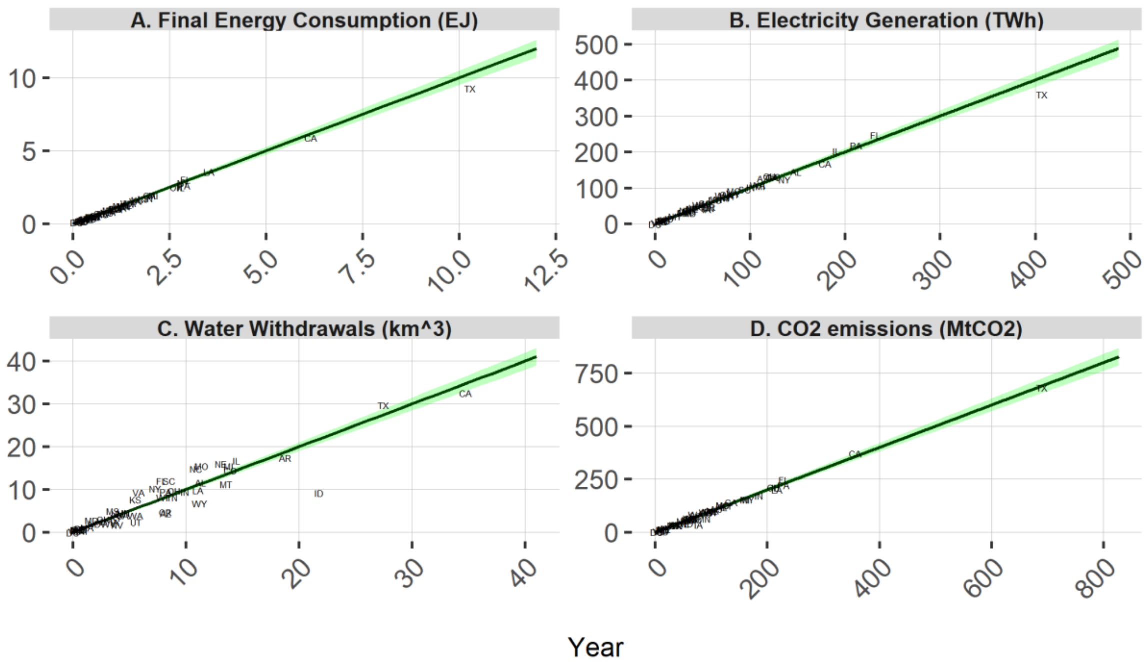


Figure 11. Comparison of state-level historical results (2015) from GCAM-USA to historical data for (a) final energy consumption, (b) electricity generation, (c) water withdrawals, and (d) energy system CO2 emissions. The line in each figure is a one-to-one line indicating an exact match between historical data and model outcomes; the green band around this line corresponds to a +/- 5% deviation from historical data. Individual state results are indicated by the position of the corresponding state abbreviation. Note that the units and axis scales vary by panel.

Figure 11 presents a comparison of historical (2015) state-level results from GCAM-USA and the historical inventory data (described above) as a scatterplot, with historical data on the horizontal axis and GCAM-USA results on the vertical axis. The line in each figure in is a one-to-one line indicating an exact match between historical data and model outcomes. As indicated by the tight grouping of data points along this one-to-one line, GCAM-USA results compare well to historical data for final energy consumption, electricity generation, and energy system CO2 emissions.

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Results for water withdrawals deviate more from the historical inventory data. This occurs for a couple of reasons. First, as discussed in Sect. 3.2.2, agriculture and land-use is modeled at the land region level, rather than the state-level; water consumption from this sector is mapped to state level based on a five-year running average share of withdrawals for each state-basin combination. The Huang et al. (2018) data used for this mapping runs only through 2010, so 2015 results are allocated to the states assuming 2010 shares. GCAM-USA also applies USA average irrigation efficiency values from Rohwer et al. (2007) to each land region; these values are likely to differ spatially, which would contribute to differences in state-level results compared to USGS data. A similar dynamic occurs with electric power sector withdrawals. Historical cooling system shares by state is based on data from 2012. While states are differentiated by the composition of cooling systems for each generation technology, water withdrawal (and consumption) demand coefficients for each power plant and cooling system combination are based on USA level national averages. Mining and livestock water withdrawals by state also tend to diverge from USGS data somewhat, while municipal and manufacturing demands match historical data exactly.

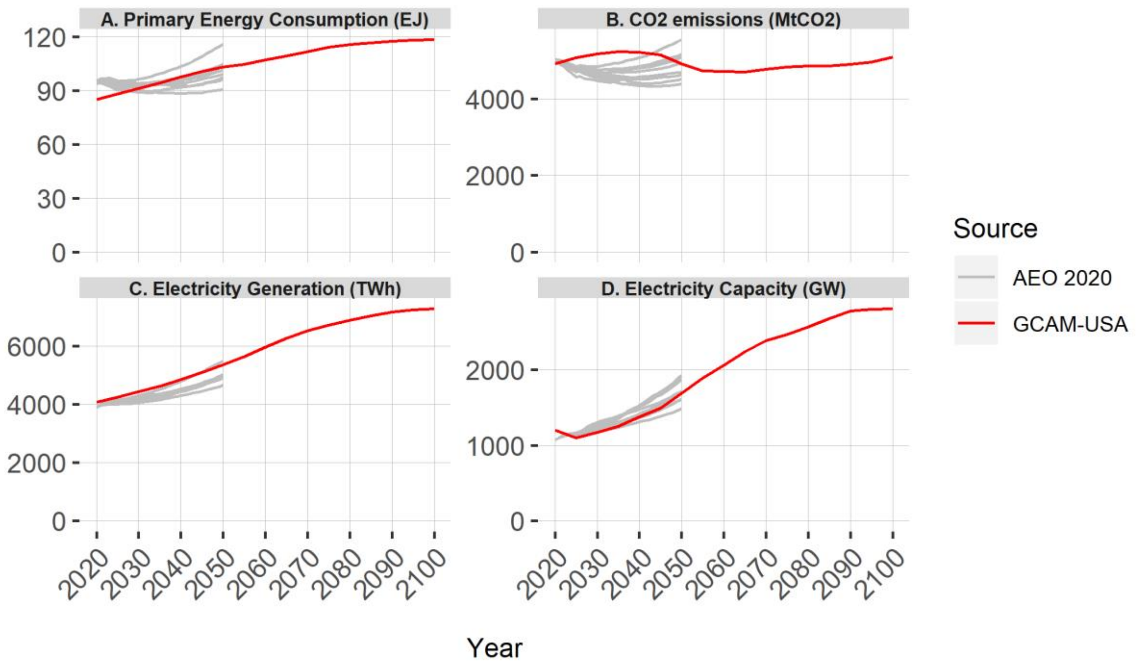

Figure 12. Comparison of national energy system projections from GCAM-USA (red line) and nine scenarios from the EIA's 2020 Annual Energy Outlook (grey lines). Results for (a) primary energy consumption, (b) energy system CO2 emissions, (c) electricity generation, and (d) electricity capacity.

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Figure 12 compares results for the GCAM-USA Ref scenario to nine scenarios from the EIA's 2020 Annual Energy Outlook (AEO)1. The AEO was chosen as the point of comparison for future results because it is one of the most cited projections of the future U.S. energy system. The National Energy Modeling System (NEMS) is used to create the AEO projections. NEMS' geographic scope is limited to the USA; AEO results are mostly reported at the national level. Thus, the comparison in Fig. 12 focuses on national aggregate results, rather than subnational ones. Additionally, NEMS has strong detail in the energy system but does not represent the land and water systems; thus, the metrics compared in Fig. 12 – total primary energy consumption (across fuels), total energy system CO2 emissions, total electricity generation, and total electricity capacity – focus on results from the energy system. Results are provided for the full future time horizon of each scenario (2020 through 2050 for the AEO and through 2100 for GCAM-USA).

Broadly, the GCAM-USA Ref scenario results fall within the range of AEO 2020 results for the scenarios shown through 2050. In terms of primary energy consumption, GCAM-USA's results for 2020 are about 10% lower than AEO's Reference case. This is in part because AEO is calibrated to 2019 outcomes, while GCAM-USA's final historical year is 2015. By 2030, GCAM-USA is well within the range of primary energy consumption for AEO scenarios and remains there through 2050.

In terms of CO2 emissions, GCAM-USA's simulated emissions in 2020 are 2% lower than the AEO 2020 Reference case. From there, the models diverge. The GCAM-USA Reference scenario projects increasing CO2 emissions through 2035, after which emissions decline for roughly three decades before rebounding to current (2020) levels in 2090. In contrast, AEO's scenarios generally project emissions decreasing to 2030 or 2040 before ticking up again thereafter. GCAM-USA's emissions growth is driven by increased emissions in the power sector, industry, and transport. Conversely, AEO projects decreasing emissions from electricity and transport, at least in part because the AEO "generally assumes that existing laws and regulations remain as enacted throughout the projection period" (EIA, 2020b), while the GCAM-USA Ref scenario does not explicitly include policies such as Corporate Average Fuel Economy (CAFE) standards or state-level renewable portfolio standards (RPS). By 2050, GCAM-USA Reference scenario CO2 emissions are within the spread of AEO scenarios and almost identical to the AEO 2020 Reference case.

For the electric power sector, GCAM-USA and AEO are generally in good agreement about the size of the sector, both in terms of capacity and total generation. GCAM-USA anticipates higher electricity generation than the AEO 2020 Reference case over the next four decades, although is always within the range of AEO 2020 cases. The GCAM-USA Ref scenario

[1] The specific AEO scenarios included are *Reference case*, *High economic growth*, *Low economic growth*, *High oil price*, *Low oil price*, High oil and gas supply, *Low oil and gas supply*, *High renewable cost*, and *Low renewable cost*.

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simulates slightly lower capacity than the AEO 2020 Reference case in the near-term, but falls right in the middle of the AEO 2020 range in the longer-term.

7 Discussion and conclusions

GCAM-USA has been used by public (The White House, 2016) and private (Lempert; et al., 2019) sector decision-makers as well as the research community (Feijoo et al., 2018; Iyer et al., 2019) to understand interconnections and trade-offs between U.S. economic, energy, agriculture, land, and water systems in a global context. The latest version of GCAM-USA, described here, includes several important new features which open the possibility for new avenues of research in subnational energy-water-land interactions, such as: the impact of water constraints on electricity capacity expansion (e.g. Liu et al. (2019)); the impacts of agriculture and electricity production on virtual water trade within the U.S. (e.g. Graham et al. (2020)); implications for electricity and end-use sectors of increasing deployment of variable renewable energy technologies; or energy-water-land implications of higher renewable fuel standard targets in the U.S. It also demonstrates how sub-national and sub-annual detail can be incorporated in a global multisector modeling framework, serving as blueprint for other regionally-detailed models like GCAM-China (see for example Cui et al. (2021)).

With models like GCAM-USA, there is a constant balancing act between global and sectoral coverage; regional, temporal, and process resolution; and computational tractability. While GCAM-USA has advanced significantly in recent years, there are still many areas ripe for model development, including:

1. State-level resource endowments and production, particularly for fossil resources (oil, gas, coal) but also hydropower.
2. Improved representation of electricity storage, electricity trade, and electrification potential of end-uses (particularly industry and transportation).
3. Improved representation of infrastructure, including electricity transmission lines, oil and gas pipelines, water conveyance networks, etc.
4. Increased detail in the industrial sector, representing different industrial subsectors and their corresponding technologies.
5. Improved representation of existing policies in the GCAM-USA Reference scenario, including federal policies (e.g. CAFÉ standards) and state-level policies (e.g. Hultman et al. (2020)).
6. Complete representation of non-CO2 emissions. GCAM-USA currently does not represent non-CO2 emissions for energy activities modeled at the state-level. Without emissions of these species in the USA, the picture of radiative forcing agents in the atmosphere is incomplete; thus, the Hector climate model is disabled when running GCAM-USA, and climate outcomes are not available for GCAM-USA scenarios. Complete accounting of non-CO2

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emissions (both non-CO2 greenhouse gases and traditional air pollutants) is an ongoing development priority for GCAM-USA; studies have been published with research versions of the model containing such capabilities (Feijoo et al., 2020; Ou et al., 2020; Shi et al., 2017).

7. State-level drivers for all activities. While decisions and outcomes in the land system are modeled at the sub-national level, these decisions are driven by national aggregate socioeconomic drivers which determine demands for food, fiber, and other agricultural products, rather than heterogenous state-level demands, preferences, and economic and policy contexts. Some energy transformation processes (e.g. gas processing, hydrogen production) also remain nationally resolved.

Ultimately, there are trade-offs between model detail on the one hand and computational tractability on the other. As presently configured, GCAM-USA requires balancing supplies and demands for nearly 1,700 markets simultaneously and produces databases in excess of 2 GB per scenario (run to 2100). The model can presently be run on a personal computer with 8 GB of RAM; additional developments inevitably increase memory requirements, solution complexity, and database size, although great effort is invested in making the GCAM framework as computationally efficient as possible to strike a balance between cutting-edge scientific capability and user functionality.

Code availability

GCAM-USA is an open-source model and is included in regular GCAM model release packages (https://github.com/JGCRI/gcam-core/releases). The version of GCAM-USA described in this paper, including all code and input data, is archived at https://zenodo.org/record/4898374. GitHub issues are monitored and addressed by the GCAM team and broader user community at https://github.com/JGCRI/gcam-core/issues. Model documentation is available at http://jgcri.github.io/gcam-doc/toc.html, including a user guide (http://jgcri.github.io/gcam-doc/user-guide.html) and documentation specific to GCAM-USA (http://jgcri.github.io/gcam-doc/gcam-usa.html).

Author contributions

MB led the writing of the paper with contributions from GI, PP, NG, YO, ZK, NK, KN, MH, SK, KC, and MW. Simulations in the paper were conducted and analyzed by MB. MB, GI, PP, NG, YO, ZK, NK, KN, MH, SK, KC, and MW all participated in the development of components included in GCAM-USA v5.3_water_dispatch as described in this paper.

Competing interests

Katherine Calvin is topical editor of GMD.

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References

Baker, J. S., Havlík, P., Beach, R., Leclère, D., Schmid, E., Valin, H., Cole, J., Creason, J., Ohrel, S., and McFarland, J.: Evaluating the effects of climate change on US agricultural systems: sensitivity to regional impact and trade expansion scenarios, Environ. Res. Lett., 13, 2018.

Ben Bond-Lamberty, Dorheim, K., Cui, R., Horowitz, R., Snyder, A., Calvin, K., Feng, L., Hoesly, R., Horing, J., Kyle, G. P., Link, R., Patel, P., Roney, C., Staniszewski, A., Turner, S., Chen, M., Feijoo, F., Hartin, C., Hejazi, M., Iyer, G., Kim, S., Liu, Y., Lynch, C., McJeon, H., Smith, S., Waldhoff, S., Wise, M., and Clarke, L.: *gcamdata*: An R Package for Preparation, Synthesis, and Tracking of Input Data for the GCAM Integrated Human-Earth Systems Model, Journal of Open Research Software, 7, 6, 2019.

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.

Calvin, K. and Bond-Lamberty, B.: Integrated human-earth system modeling—state of the science and future directions, Environmental Research Letters, 13, 063006, 2018.

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S. J., Snyder, A., Waldhoff, S., and Wise, M.: GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems, Geosci. Model Dev., 12, 677-698, 2019.

Clarke, J. F. and Edmonds, J.: Modelling energy technologies in a competitive market, Energy Economics, 15, 123-129, 1993.

Clarke, L., L. Nichols, R. Vallario, M. Hejazi, J. Horing, A.C. Janetos, K. Mach, M. Mastrandrea, M. Orr, B.L. Preston, P. Reed, R.D. Sands, and White, D. D.: Sector Interactions, Multiple Stressors, and Complex Systems., U.S. Global Change Research Program, Washington, DC, 638–668 pp., 2018.

Cohen, S. M. and Caron, J.: The economic impacts of high wind penetration scenarios in the United States, Energy Economics, 76, 558-573, 2018.

Cole, W., Frew, B., Mai, T., Sun, Y., Bistline, J., Blanford, G., Young, D., Marcy, C., Namovicz, C., Edelman, R., Meroney, B., Sims, R., Stenhouse, J., and Donohoo-Vallett, P.: Variable Renewable Energy in Long-Term Planning Models: A Multi-Model Perspective, "National Renewable Energy Laboratory", 2017.

Cui, R. Y., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M. R., Sen, A., Song, K., Bowman, C., Clarke, L., Kang, J., Lou, J., Yang, F., Yuan, J., Zhang, W., and Zhu, M.: A plant-by-plant strategy for high-ambition coal power phaseout in China, Nature Communications, 12, 1468, 2021.

Edmonds, J. A., Link, R., Waldhoff, S. T., and Cui, R.: A Global Food Demand Model For The Assessment Of Complex Human-Earth Systems, Climate Change Economics, 08, 2017.

EIA: Electricity Data Browser. U.S. Energy Information Administration, Washington, D.C., 2020a.

EIA, U. S.: Annual Energy Outlook 2020: Case Descriptions, U.S. Energy Information Administration, Washington, D.C., 2020b.

https://doi.org/10.5194/gmd-2021-197
Preprint. Discussion started: 6 July 2021

Environmental Protection Agency: Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units, 80 Federal Register 205 (23 October 2015) (40 CFR parts 60, 70, 71, and 98): 64513, 64546-64547, https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf (Accessed 16 December 2016). , 2015. 2015.

Feijoo, F., Iyer, G., Binsted, M., and Edmonds, J.: US energy system transitions under cumulative emissions budgets, Climatic Change, doi: https://doi.org/10.1007/s10584-020-02670-0, 2020. 2020.

Feijoo, F., Iyer, G. C., Avraam, C., Siddiqui, S. A., Clarke, L. E., Sankaranarayanan, S., Binsted, M. T., Patel, P. L., Prates, N. C., Torres-Alfaro, E., and Wise, M. A.: The future of natural gas infrastructure development in the United states, Applied Energy, 228, 149-166, 2018.

Graham, N. T., Hejazi, M. I., Kim, S. H., Davies, E. G. R., Edmonds, J. A., and Miralles-Wilhelm, F.: Future changes in the trading of virtual water, Nature Communications, 11, 3632, 2020.

Hartin, C. A., Patel, P., Schwarber, A., Link, R. P., and Bond-Lamberty, B. P.: A simple object-oriented and open-source model for scientific and policy analyses of the global climate system – Hector v1.0, Geoscientific Model Development, 8, 939-955, 2015.

Hejazi, M. I., Voisin, N., Liu, L., Bramer, L. M., Fortin, D. C., Hathaway, J. E., Huang, M., Kyle, P., Leung, L. R., Li, H. Y., Liu, Y., Patel, P. L., Pulsipher, T. C., Rice, J. S., Tesfa, T. K., Vernon, C. R., and Zhou, Y.: 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating, Proceedings of the National Academy of Sciences of the United States of America, 112, 10635-10640, 2015.

Huang, Z., Hejazi, M., Li, X., Tang, Q., Vernon, C., Leng, G., Liu, Y., Döll, P., Eisner, S., Gerten, D., Hanasaki, N., and Wada, Y.: Reconstruction of global gridded monthly sectoral water withdrawals for 1971–2010 and analysis of their spatiotemporal patterns, Hydrol. Earth Syst. Sci., 22, 2117-2133, 2018.

Hultman, N. E., Clarke, L., Frisch, C., Kennedy, K., McJeon, H., Cyrs, T., Hansel, P., Bodnar, P., Manion, M., Edwards, M. R., Cui, R., Bowman, C., Lund, J., Westphal, M. I., Clapper, A., Jaeger, J., Sen, A., Lou, J., Saha, D., Jaglom, W., Calhoun, K., Igusky, K., deWeese, J., Hammoud, K., Altimirano, J. C., Dennis, M., Henderson, C., Zwicker, G., and O'Neill, J.: Fusing subnational with national climate action is central to decarbonization: the case of the United States, Nature Communications, 11, 5255, 2020.

IEA: World Energy Balances. International Energy Agency (Ed.), Paris, France, 2019.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., 2014.

Iyer, G., Ledna, C., Clarke, L., McJeon, H., Edmonds, J., and Wise, M.: GCAM-USA Analysis of US Electric Power Sector Transitions. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26174.pdf, Pacific Northwest National Laboratory, 2017a.

Iyer, G., Ledna, C., Clarke, L. E., Edmonds, J., McJeon, H., Kyle, G. P., and Williams, J. A.: Measuring Progress from Nationally Determined Contributions to Mid-Century Strategies, Nature Climate Change, 7, 871–874, 2017b.

Iyer, G. C., M.Brown, S.M.Cohen, J.Macknick, P.Patel, M.Wise, M.Binsted, and N.Voisin: Improving consistency among models of overlapping scope in multi-sector studies: The case of electricity capacity expansion scenarios, Renewable and Sustainable Energy Reviews, 116, 2019.

Jiang, L., Zoraghein, H., and O'Neill, B. C.: Population projections for US states under the Shared Socioeconomic Pathways based on global gridded population projections, NCAR/UCAR, 2018.

Khan, Z., Iyer, G., Patel, P., Kim, S., Hejazi, M., Burleyson, C., and Wise, M.: Impacts of long-term temperature change and variability on electricity investments, Nature Communications, 12, 1643, 2021.

Kim, S., Edmonds, J., Lurz, J., Smith, S., and Wise, M.: The ObjECTS framework for integrated assessment: hybrid modeling of transporation. , Energy Journal 27, 63-91, 2006.

Kim, S. H., Hejazi, M., Liu, L., Calvin, K., Clarke, L., Edmonds, J., Kyle, P., Patel, P., Wise, M., and Davies, E.: Balancing global water availability and use at basin scale in an integrated assessment model, Climatic Change, 136, 217-231, 2016.

Kraucunas, I., Clarke, L., Dirks, J., Hathaway, J., Hejazi, M., Hibbard, K., Huang, M., Jin, C., Kintner-Meyer, M., van Dam, K. K., Leung, R., Li, H.-Y., Moss, R., Peterson, M., Rice, J., Scott, M., Thomson, A., Voisin, N., and West, T.: Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA), Climatic Change, 129, 573-588, 2014.

Lempert;, R., Preston;, B. L., Edmonds;, J., Clarke;, L., Wild;, T., Binsted;, M., Diringer;, E., and Townsend, B.: Pathways to 2050: Alternative Scenarios for Decarbonizing the U.S. Economy, Center for Climate and Energy Solutions (C2ES), 2019.

Liu, L., Hejazi, M., Iyer, G., and Forman, B. A.: Implications of water constraints on electricity capacity expansion in the United States, Nature Sustainability, 2, 206-213, 2019.

McFadden, D.: Econometric models for probabilistic choice among products, The Journal of Business, 53, S13-S29., 1980.

Moss, R., Fisher-Vanden, K., Delgado, A., Backhaus, S., Barrett, C., Bhaduri, B., Kraucunas, I. P., Reed, P. M., Rice, J. S., Sue Wing, I., and Tebaldi, C.: Understanding Dynamics and Resilience in Complex Interdependent Systems: Prospects for a Multi-Model Framework and Community of Practice 2016.

O'Connell, Voisin, N., Macknick, and Fu: Sensitivity of Western U.S. power system dynamics to droughts compounded with fuel price variability, Applied Energy, 247, 745-754, 2019.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W.: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, doi: 10.1016/j.gloenvcha.2015.01.004, 2017. 2017.

Oppenheimer, M., M. Campos, R.Warren, J. Birkmann, G. Luber, B. O'Neill, and Takahashi, K.: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099. pp., 2014.

Ou, Y., West, J. J., Smith, S. J., Nolte, C. G., and Loughlin, D. H.: Air pollution control strategies directly limiting national health damages in the US, Nature Communications, 11, 957, 2020.

Rohwer, J., Gerten, D., and Lucht, W.: Development of Functional Irrigation Types for Improved Global Crop Modelling, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany, 2007.

Shi, W., Ou, Y., Smith, S. J., Ledna, C. M., Nolte, C. G., and Loughlin, D. H.: Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA, Applied Energy, 208, 511-521, 2017.

The White House: United States Mid-Century Strategy for Deep Decarbonization (Washington, D.C., November 2016): 22, https://obamawhitehouse.archives.gov/sites/default/files/docs/mid_century_strategy_report-final.pdf (Accessed 1 February 2017). 2016. 2016.

Turner, S. W. D., Hejazi, M., Yonkofski, C., Kim, S. H., and Kyle, P.: Influence of Groundwater Extraction Costs and Resource Depletion Limits on Simulated Global Nonrenewable Water Withdrawals Over the Twenty-First Century, Earth's Future, 7, 123-135, 2019.

U.S. Energy Information Administration: Annual Energy Outlook 2019 with projections to 2050, U.S. Energy Information Administration, Washington, DC, 2019.

Wilbanks, T. J. and Fernandez, S.: Climate Change and Infrastructure, Urban Systems, and Vulnerabilities, 2013.

Yuan, M., Tapia-Ahumada, K., and Reilly, J.: The role of cross-border electricity trade in transition to a low-carbon economy in the Northeastern U.S, Energy Policy, 154, 112261, 2021.

https://doi.org/10.5194/gmd-2021-197
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Geoscientific Model Development Discussions

Zhou, Y., Clarke, L., Eom, J., Kyle, P., Patel, P., Kim, S. H., Dirks, J., Jensen, E., Liu, Y., Rice, J., Schmidt, L., and Seiple, T.: Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework, Applied Energy, 113, 1077-1088, 2014.