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

Matthew Binsted[1], Gokul Iyer[1], Pralit Patel[1], Neal Graham[1], Yang Ou[1], Zarrar Khan[1], Nazar Kholod[1], Kanishka Narayan[1], Mohamad Hejazi[1], Son Kim[1], Katherine Calvin[1], Marshall Wise[1]

[1]Joint Global Change Research Institute (Pacific Northwest National Laboratory and University of Maryland), 5825 University Research Court, Suite 3500, College Park, MD 20740, USA.

Correspondence to: Matthew Binsted. Email: matthew.binsted@pnnl.gov. Phone: +1 301-405-5353. Address: 5825 University Research Court, Suite 3500, College Park, MD 20740.

Response to Reviewer Comments

Reviewer 1

The authors thank the reviewer for their thorough and constructive feedback on our manuscript. We have responded to each comment individually below using GMD's suggested structure of (1) comments from referees/public (we italicized this text), (2) authors' response (plain text), and (3) authors' changes in manuscript (additions are bolded, existing content is plain text). To improve readability, we have inserted a series of dashes between each comment. A revised Supplementary Information document is attached to this response as a PDF.

----

(1) *The manuscript "GCAM-USA v5.3_water_dispatch: Integrated modeling of subnational U.S. energy, water, and land systems within a global framework" presents a new version of the GCAM model, with a focus on the energy, water and land representation of the United States. The model presented is a very welcome contribution of the "systems modelling", and more specifically to the IAM world, as it contains relevant detail on the regional scale. Furthermore, it expands the capabilities of IAMs to further investigate the "Climate-Land-Energy-Water" nexus. As such, both the manuscript – which largely functions as a qualitative description of the model - are a welcome addition to the literature.*

(2) The authors thank the reviewer for the compliment on our addition to the literature.

(3) There are no changes to manuscript corresponding to this comment.

----

(1) *While the manuscript is well written, structured, and clear, I think it could benefit by some improvements before publication. My main comments revolve around a better/clearer and more thorough explanation of some of the critical aspects of the model, as generally the current*

description is very ‘on the surface’, and doesn’t allow readers to fully understand how the model structure may affect its results. In this respect, the manuscript could also benefit from a broader discussion of the results. Many of my below comments can be addressed through an appendix with model details (ideally some sort of table with a description of many of the methodological details and assumptions of the model – Table 1 in Bauer et al. (2020) may offer some inspiration, though that focused specifically on bioenergy), as well as an expanded discussion section. More specifically:

(2) The authors thank the reviewer for the valuable feedback. We address each specific point below. The reference to the Bauer et al. (2020) Table 1 is helpful and appreciated. We have added large tabular overview of GCAM-USA as Table SM1 that draws heavily from the Integrated Assessment Modelling Consortium (IAMC) wiki’s (https://www.iamcdocumentation.eu/index.php/IAMC_wiki) reference card format and also informed by Bauer et al. (2020) Table 1.

(3) There are no changes to manuscript corresponding to this comment.

----

(1) *On line 81, GCAM is described as “...a partial equilibrium model which captures key interactions between global economic, energy, water, land, and climate systems.” Can some more details be given, for instance does it have perfect foresight? Does it optimize some function (I suspect not, given the logit formulation for market shares)?*

(2) The authors thank the reviewer for the helpful comment. We adjusted the existing sentence and added another to clarify the foresight and solution approach of GCAM and GCAM-USA. More information regarding GCAM’s market structure and solution approach is provided in the subsequent paragraph.

(3) Edits to manuscript
“GCAM is a **dynamic recursive**, partial equilibrium model which captures key interactions between global economic, energy, water, land, and climate systems **by simultaneously solving for equilibrium (price where demand equals supply) in energy, water, agriculture, and emissions markets. The model is myopic (not forward looking) and produces cost-effective solutions by clearing markets, although it does not optimize around any target function.**”

----

(1) *Concerning the projections for energy demand, on line 399 it states that “final energy demands increase as efficiency improvements are slower than increases in demand for end-use energy services”. Some explanation is needed for how the demand in energy services is dealt with. Specifically for buildings in developed regions there is largely a stagnation in energy demand so it is a bit surprising that final energy demand increases faster than efficiency over the entire 21st century.*

(2) The authors thank the reviewer for the helpful comment, which raises two important points. In response to the first point regarding the need for more explanation about how energy service demands are represented, a paragraph was added to section 2.2.2 Energy (within 2.2 Overview of GCAM-USA) describing how final energy demands are determined. In response to the second point about demand stagnation for building energy in developed regions, the reviewer's comment highlights that the sentence on line 399 needed further elaboration. The key drivers in the GCAM-USA Reference scenario are population growth and increasing per-capita service demands (such as per-capita floorspace or kilometers traveled) which, combined with conservative assumptions about future energy efficiency, result in slow but steady growth in total final energy demands over the century. These dynamics vary by end-use sector. We have added a clarifying clause in the manuscript as well as a Supplementary Note discussing these dynamics.

(3) Edits to manuscript (section 2.2.2)
Demands for final energy services are represented at the state-level in GCAM-USA utilizing the same demand functions as GCAM. Final demands include residential and commercial building floorspace and service outputs (space heating, space cooling, lighting, water heating, and various appliances), generic industrial energy service, use of energy carriers as feedstocks in industry, cement production (million tons), fertilizer production (million tons), passenger-kilometers traveled, (split between domestic travel and international aviation) and freight ton-kilometers shipped (split between domestic freight and international shipping). Within the building sector, service demands are a function of building floorspace and service demands per unit of floorspace. Building floorspace varies with population, income (per-capita GDP), and energy service prices, with exogenous satiation levels prescribing an upper-limit on per-capita floorspace. Building service demands per unit of floorspace depend on climate (for space heating and cooling), building envelope efficiency, service prices, and exogenous satiation (for a more detailed discussion, see Clarke et al. (2018)). Within industry, demand for nitrogen fertilizer is dictated by the agriculture sector, where technologies with low and high levels of fertilizer application compete for production shares of each crop. Demand for cement is driven by economic growth and modulated by price and income elasticities. Aggregate industry output is represented in generic terms as a function of income and the price of generic energy service and feedstock use. Fuels compete on costs for share of total energy with a low elasticity of substitution. Transportation service demands depends on income and services prices. Service prices among competing passenger transportation modes consider the value of time traveled, which is calculated from the wage rate (per-capita GDP divided by the number of working hours in a year), the mode's (exogenous) speed of travel, and an exogenous time value multiplier for each mode reflecting the valuation of people's time in transport and waiting times associated with in each mode.

Additional edits to manuscript (section 4.1)
The GCAM-USA Reference scenario assumes a continuation, but not an expansion or strengthening, of current energy efficiency policies (e.g., building efficiency standards). **In aggregate, total** 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 transportation, industrial energy use, etc.), **although the balance between population and income driven demand growth and service efficiency vary by sector. (Supplementary**

Note 3 provides information on service and energy growth by sector for the GCAM-USA Reference scenario.)

----

(1) *On line 442 it is stated that agricultural productivity in the US increases betweeen 0% to 0.67% per year between 2015 and 2100. An explanation of what drives this productivity is needed. Is it completely exogenous? Increased irrigation? Economic pressures? Closing of yield gaps? Is it crop or livestock-specific? What exactly is included in agriculture?*

(2) The authors thank the reviewer for the helpful question. Those agricultural productivity figures represent exogenously specified technical change which varies by crop, management practice (irrigated vs. rainfed, high vs. low fertilizer application), and year. This technological change represents factors like improved mechanization, crop breeding, etc. Changes in fertilizer use & irrigation practices are represented endogenously in the model and respond to changing economic forces; these management practice changes generate additional productivity changes beyond the numbers listed on line 442. We have added additional detail to clarify these questions in the manuscript (additions below in bold).

(3) Edits to manuscript
Agricultural productivity increases gradually in the U.S. in the future, with **crop-specific** annual productivity growth rates ranging from 0% to 0.67% per year between 2015 and 2100. **These productivity gains represent exogenously specified technical change which varies by crop, management practice (irrigated vs. rainfed, high vs. low fertilizer application), and year, reflecting factors like improved mechanization, crop breeding, etc. Alternate fertilizer use and irrigation practices are represented endogenously and respond dynamically to economic forces (commodity prices, land values, input costs, etc.) within the model; shifting management practices generate additional productivity changes beyond those listed above.**

----

(1) *Table 1 offers a brief overview of the scenario design, however the explanations are woefully vague, especially for the "Transition" scenario. An appendix with some details of what parameters were changed in the model would be useful when interpreting the results. Judging by fig 2, fossil fuels still play an important (though not dominant role), so it would be good to get a better understanding of what exactly drives this scenario. Is there a carbon price? Ad-hoc assumption? Cost reduction in renewables?*

(2) The authors thank the reviewer for the constructive comment. The scenarios in the paper are intentionally simple and intended to illustrate key model dynamics rather than develop detailed narratives of the future. A statement has been added to clarify this intention, as well as a sentence elaborating on how the Transition scenario was implemented.

(3) Edits to manuscript (section 5)
These scenarios, outlined in Table 1, are intentionally simple and designed to illustrate key

model behavior and capabilities across a range of potential futures; they are not intended to reflect “likely” outcomes or detailed narratives of future worlds.

Additional edits to manuscript (section 5)
The energy transition is implemented via a price on carbon dioxide emissions from the energy system of roughly \$22 / tCO2 (2015 USD), beginning in 2025 and escalating at 5% per year thereafter.

----

(1) *Along the same lines, I recognize that the manuscript presents a new model, and not necessarily a new scenario analysis, but since results are presented, some discussion is needed. Is the transition scenario based completely on improved supply options? If so, there needs to be a discussion as the "socioeconomic drivers" do not cover all "lifestyle aspects" which govern energy demand. Currently it is difficult to derive policy advice or compare the results with other scenario analyses since the projections seem to be little more than tinkering with the model (which is fine, but what was tinkered-with should be clear to the reader). An in-depth explanation and discussion of the scenario design would be helpful.*

(2) The authors thank the reviewer for the constructive comment. The reviewer is correct that more clarification of what is altered in the scenarios is needed. The Transition scenario includes on a price on carbon dioxide emissions from the energy system; no changes to technology options, technology characteristics, or consumer behavior/preferences are included in the scenario. Some of these dimensions have been explored in other papers. For example, Ou et al. (2021) examined the impact of renewable technology costs on US capacity expansion.

A sentence has been added to clarify the Transition scenario design (additions below in bold). As mentioned above, the scenarios in the paper are intentionally simple for the purposes of illustrating key model dynamics and thus not as rich as many other scenario analyses.

(3) Edits to manuscript
The Transition scenario does not include any new or improved technology options that are not available in the Ref scenario (only shifting technology deployment in response to the carbon price); it also does not explicitly reflect any “lifestyle” changes which could impact future energy demand (although end-use energy consumption responds endogenously to changes in energy prices).

----

(1) *On line 499 the projected ranges of electrification of building energy services across different states are presented. Can you please explain how the model methodology leads to this result? I guess it has to do with the heating/cooling dichotomy of different locations, but it would be good to point this (or any other relevant dynamic) to the reader. Similarly, for line 520 and the transport sector.*

(2) The authors thank the reviewer for the helpful suggestion. An explanation of the model methodology / dynamics that lead to these results have been added to the manuscript.

(3) Edits to manuscript (section 6.1)
The wide range of building electrification rates is driven by several factors. Differences in the energy service profile of the buildings sector vary by region; for example, southern states require more air conditioning (powered by electricity) and little heating, while northern states require little cooling but substantial space heating (often provided by gas, heating oil, or biomass, as well as some electricity). Historically estimated differences in fuel preferences for different services (e.g., electricity vs. gas (or other fuels) for space heating, water heating, cooking, etc.) by state are carried forward and influence future technology choices (GCAM-USA's calibration routine is discussed in Sect. 6.5.), as do regionally differentiated fuel prices (oil, gas, coal, and electricity prices all vary by grid region).

This range **in building electrification** tightens substantially in the Transition scenario. Electrification of end-use sectors is a key emission reduction strategy **in response to the carbon price in the Transition scenario**; 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. **With fossil fuel technologies facing a substantial price on the CO2 emissions they generate in the Transition scenario and electric options available for every building service, deep electrification of the buildings sector occurs across states by 2100, although some differences remain due to variations in regional preferences, fuel prices, and turnover rates of existing equipment stock.**

Additional edits to manuscript (section 6.1)
GCAM-USA's industry sector is represented at a more aggregate level than buildings, but the same basic factors – state-specific fuel preferences, capital stock accumulation, and regionally differentiated fuel prices – drive differences in industrial fuel mix across the states. Additionally, some states, such as those with large petrochemical sectors (e.g., Louisiana, Texas), use much of the energy in industry as feedstocks, which lowers the share of electricity in their industrial energy mix.

----

(1) *Lines 524 to 527 highlight a very interesting calibration problem the authors have faced. This is worth discussing at depth since it likely affects the results significantly. In fact, it would be great if a sensitivity analysis was conducted, where different "consumer preferences" are tested. Alternatively, different "consumer preference" parameterization could be used across the Reference-Transition scenarios, thus expanding the "transition scenario" design.*

(2) The authors thank the reviewer for the prescient comment and suggestion. Unfortunately, additional sensitivity scenarios or adjustments to the existing scenario design is beyond the scope of this model description paper. As mentioned previously, the scenarios in this paper are intentionally simple and intended to illustrate key model dynamics rather than develop detailed narratives of the future.

The reviewer is correct that this section highlights an interesting methodological issue that is worth exploring in more detail. To this end, we have added a supplementary note (Supplementary Note 4) where we elaborate on the default transportation assumptions in GCAM-USA v5.3_water_dispatch as well as how users can adjust these assumptions to create alternate scenarios for the transportation sector.

(3) Edits to manuscript
Additional information about the reference transportation assumptions in GCAM-USA v5.3_water_dispatch, as well as how alternate assumptions of state-level policy or consumer preferences could be implemented, is provided in Supplementary Note 4.

----

(1) *On lines 597 to 600, the reduction in capacity factors for all technologies is highlighted in the transition scenarios, a very interesting result. Is it appropriate to interpret this as "increased electrification leads to increased redundancy of generating capital", and thus a disproportionate increase in electricity prices? I think this is something worth discussing further especially in connection to the to the model formulation. How does the methodology lead to this result? Is this something directly related to the improved electricity module which, as shown in Figure 1, accounts for load variation at different temporal aggregations?*

(2) The authors thank the reviewer for the thoughtful comment. It is not necessarily correct to interpret this result as "increased electrification leads to increased redundancy of generating capital". As shown in Figure 4 of the original manuscript (note that figure numbers have changed in the revised manuscript as a new Figure 1 was added), national average electric capacity factors decrease across all scenarios, driven by greater penetration of intermittent renewable technologies (wind and solar), which have lower overall availability rates. The competition for investment in new generation capacity, based on levelized generation costs (inclusive of capital, operations and maintenance, fuel costs, and emissions penalties), tends to favor wind and solar in all scenarios; this is especially true in the Transition and High Growth + Transition scenarios where CO2 emissions face a carbon price. Rather than suggesting that increased electrification de-facto leads to increased redundancy of power sector capital, this suggests that intermittent renewables with lower capacity factors but also lower operating costs, no emissions (and associated costs), and rapidly improving capital costs, are most economical in this scenario.

Regarding the specific technologies show in Figure 5 (original manuscript) and discussed in lines 597 to 600 (original manuscript), capacity factors for fossil fuel (coal and gas) technologies without CCS capacity factors decrease in these scenarios because the price associated with their CO2 emissions makes them uneconomical to operate. In the new GCAM-USA electricity dispatch model structure, capacity is operated in order of least variable (operating) cost, which includes variable O&M, input (fuel and water) prices, and emissions penalties. Wind and solar capacity factors decline somewhat because resources are finite and heterogeneous – the resource representation in GCAM-USA assumes that the highest quality (highest capacity factor) resources are utilized first, so increased deployment entails exploiting lower quality resources and thus diminished capacity factors. The overall (national average) effect is small (2.2%/1.9%

reduction in PV/onshore wind capacity factors in 2050 for the Transition scenario, relative to Ref), although some states see larger reductions.

Not all technologies experience a reduction in capacity factor in the Transition scenario, although many do. A new Supplementary Figure SF3 presents national average electric technology capacity factors for all scenarios and model periods. Bioenergy with CCS capacity factors are stable in the Transition scenario; nuclear capacity factors decline through mid-century as intermittent renewables penetrate (nuclear has fuel costs and variable O&M costs which exceed those for solar and wind) but stabilizes from 2050 onward. Fossil technologies with CCS see steadily declining capacity factors over the course of the century as renewables continue to penetrate and carbon prices increase.

We have added a discussion of these dynamics to the manuscript (additions below in bold).

(3) Edits to manuscript

Broadly, national average electric capacity factors decrease across all scenarios (Figure 4; original manuscript), driven by greater penetration of intermittent renewable technologies (wind and solar), which have lower maximum availability rates. The competition for investment in new generation capacity is based on levelized generation costs (inclusive of capital, operations and maintenance, fuel costs, and emissions penalties). Despite their lower capacity factors, wind and solar account for a large share of new installations in all scenarios due to their low operating costs, lack of emissions (and associated costs), and rapidly improving capital cost. Wind and solar are especially economical in the Transition and High Growth + Transition scenarios where fossil fuel technologies face a carbon price on their CO2 emissions.

Wind and solar capacity factors themselves decline a bit over time across all scenarios (Supplementary Figure SF3 presents national average electric technology capacity factors for all scenarios and model periods); this reduction is a bit more pronounced in the Transition and High Growth + Transition scenarios (where wind and solar deployment is greatest). This is because wind and solar resource bases are finite and heterogeneously in quality; GCAM-USA assumes that the highest quality (highest capacity factor) resources are utilized first, so increased deployment over time entails exploiting lower quality resources and thus diminished capacity factors (Supplementary Note 2 explains this dynamic in greater detail). The overall (national average) reduction in capacity factor is small (2.2%/1.9% reduction in PV/onshore wind capacity factors in 2050 for the Transition scenario, relative to Ref), although some states see larger reductions.

Capacity factors for fossil fuel (coal and gas) technologies without CCS also decrease in in the Transition and High Growth + Transition scenarios because the price associated with their CO2 emissions makes them less economical to operate (as noted above). In the new GCAM-USA electricity dispatch model structure, capacity is operated in order of least variable (operating) cost, including variable O&M, input (fuel and water) prices, and emissions penalties. However, not all technologies experience a reduction in capacity factor in the Transition scenario. Supplementary Figure SF3 presents national average electric technology capacity factors for all scenarios and model periods. Bioenergy with CCS

capacity factors are stable in the Transition scenario; nuclear capacity factors decline through mid-century as intermittent renewable capacity increases (nuclear has fuel costs and variable O&M costs which exceed those for solar and wind) but stabilizes from 2050 onward. Fossil technologies with CCS see steadily declining capacity factors over the course of the century as renewable penetration grows and carbon prices steadily increase (making these as fossil plants with CCS more costly to operate, as these technologies still produce some residual CO2 emissions that escape capture).

----

(1) *Related to this, Supplementary Note 2 states that the dispatch of renewables depends on their supply curves, each containing a quantity of resource available at a specific capacity factor. This detail seems crucial so it would be good to get some insight on how these curves are constructed, and perhaps the curves should be presented as well.*

(2) The authors thank the reviewer for the helpful suggestion. Plots of the resource curves for onshore wind and PV in each state are now included in Supplementary Note 2 (as Figure SN2.1). A brief discussion of how GCAM-USA's renewable resource curves are generated is also included in Supplementary Note 2 (additions below in bold).

(3) Edits to Supplementary Info
The resource curves for solar PV and onshore wind in each state are presented below as Figure SN2.1. These curves are developed utilizing data from the Regional Energy Deployment System (ReEDS) model – specifically resource potential, grid connection costs, and hourly capacity factor for multiple "resource regions" and resource classes within each state. The hourly capacity factor data are aggregated to annual average capacity factors, mapped to resource potential, and sorted from highest capacity to lowest capacity factor, generating the resource curves depicted in Figure SN2.1. (The same hourly capacity factor data are used to generate the segment capacity factors – i.e., the capacity factor specific to each monthly day/night dispatch segment – for each resource and state.) Grid connection costs are included in the model as a separate cost component (considered in investment decisions only). Concentrating solar power and offshore wind resources are represented in the same way (also using data from ReEDS), although not every state has these resources.

----

(1) *Concerning the projections of agricultural water withdrawals mentioned on lines 267, is it correct to understand that irrigation rates are directly coupled to population and GDP growth (state or national?). Or are the intermediate drivers such as competition for land, food prices, etc.? These methodological choices should be crystal clear to allow the reader the fully appreciate the results.*

(2) The authors thank the reviewer for the question. (We assume the reviewer intended to refer to line 627, rather than line 267.) It is not the case that irrigation rates are directly coupled to population and GDP growth. Irrigation rates are a function of cost competition between irrigated and rainfed production for each crop and land region. Irrigated agriculture entails higher costs

(equipment + water costs) begetting greater yields. Agricultural water withdrawals are a function of total agricultural demand and these irrigation vs. rainfed choices across many crops. A discussion of these dynamics has been added to the manuscript (additions below in bold).

(3) Edits to manuscript
Growth in agricultural water withdrawals in the Ref scenario is driven primarily by **cropland expansion (see Figure 10) to meet increasing food demand caused by** growing population and GDP. **Nationally, cropland irrigation shares (the percentage of cropland that is irrigated as opposed to rainfed) for food and feed crops increase marginally over time across scenarios (16.4% in 2015, 17.4-19.6% in 2100), albeit with substantial variation across basins and crop types. Irrigation water demands are influenced by several factors, including agricultural land area (driven by food demand and modulated by competition between cropland and alternate land uses), competition between different crop types (which have different profit rates and water requirements), and competition among production strategies (irrigated vs. rainfed and high vs. low fertilizer application) based on their costs (including water and fertilizer prices), yields, and profitability (crop prices). Irrigated agriculture entails higher costs (equipment + water costs) but achieves higher yields.**

----

(1) *Similarly, on line 648 it is stated that increased demand for bioenergy crops in the Transition scenario drives the increased irrigation. Are all bioenergy plantations irrigated by default in the model?*

(2) The authors thank the reviewer for the helpful question. Bioenergy crops can be produced with the same four production strategies (combinations of irrigated vs. rainfed and high vs. low fertilizer application) as other crops. Bioenergy irrigation shares range between 8-11% across scenarios and model periods, but bioenergy cropland expands tremendously in the Transition scenario while traditional (food and feed) cropland only slightly exceeds historical levels in 2100. Some additional detail has been added to the manuscript (additions below in bold).

(3) Edits to manuscript
Bioenergy crops can be produced with the same four production strategies (combinations of irrigated vs. rainfed and high vs. low fertilizer application) as other crops. Irrigation shares are generally lower for bioenergy crops than they are for traditional (food and feed) crops (between 8-11% across scenarios and model periods), but bioenergy cropland expands tremendously in the Transition scenario while traditional cropland grows minimally, as described in Sect. 6.1. As a result, about 71% of the increase in irrigation water withdrawals in 2100 (relative to 2015) are attributable to bioenergy crops rather than food and feed crops.

----

(1) *Figure 10 excludes "dedicated energy crops" for the percentage change of cropland. Is there a justification for their exclusion? Does it skew the results? I think this would be an interesting result to show.*

(2) The authors thank the reviewer for the question. Bioenergy crops were excluded from Figure 10 (original manuscript) to emphasize the way food production shifts across basins within the scenarios. Additionally, there is no dedicated bioenergy cropland in the USA in 2015 (the model base year and base year for the percentage changes in Figure 10). Bioenergy cropland expansion in GCAM-USA tends to occur in marginal areas (bioenergy cropland expansion in the Transition scenario entails conversion of other arable land, pastureland, and to a lesser extent grassland and shrubland). The reviewer is correct that excluding dedicated energy crops from the figure paints an incomplete picture of total agricultural land. On the other hand, including dedicated energy crops in the figure can skew the picture of changes in cropland – areas with relatively little agriculture historically (e.g. areas with limited water availability or marginal land quality) may see large percentage increases in cropland for dedicated energy crops while traditional cropland expands only modestly.

The reviewer is correct that both dynamics are interesting – we have added a new supplementary figure (SF6) showing absolute and percentage changes in traditional cropland, energy cropland, and total (food + feed + energy cropland). The supplementary figure is highlighted in the text.

(3) Edits to manuscript

Bioenergy crops are excluded from Figure 11 to emphasize the way food production shifts across basins within the scenarios. There is no dedicated bioenergy cropland in 2015 (the model base year and base year for the percentage changes in Figure 11). Supplementary Figure SF6 presents absolute and percentage changes in traditional (food + feed) cropland, dedicated bioenergy cropland, and total cropland. In the discussion below, cropland is used to refer to traditional (food + feed) cropland, excluding dedicated energy crops.

----

(1) *Lines 755 onwards give a useful overview of the model calibration. Some more methodological details here would be interesting. Perhaps in an appendix. Are these calibration parameters the "share weights" mentioned on line 780, or are is the forcing simply a model "starting point"? How, is this forcing applied in the projections period? Is there a transition from forced-to-free? Or are the "forcing parameters" maintained?*

(2) The authors thank the reviewer for the pertinent question. The reference to GCAM-USA being "calibrated to match historical data" does indeed relate to logit share weights mentioned on line 780. A comment has been added to clarify this connection.

Additional detail on the calibration process has been added to the manuscript. We've also added a supplementary table outlining how the calibrated share weight parameters for key sectors are applied in future model periods. Additions are below in bold.

(3) Edits to manuscript (section 6.5)

GCAM-USA is initialized over five historical periods (1975, 1990, 2005, 2010, 2015) and calibrated **(by estimating estimate logit share weight parameter values)** to match historical data **(calibration is discussed in more detail below)**.

Additional edits to manuscript (section 6.5)
GCAM’s logit choice formulation is described in detail in Calvin et al. (2019). In short, technology shares within a nest are a function of the technology’s cost, its share weight, the logit exponent, and the costs and share weights of other competing technologies in the nest. The exogenous logit exponent regulates the extent to which cost (or profit) dictates share; larger absolute logit exponent values lead to greater shares for the lowest cost (most profitable) technology, all else equal. Technology costs in the logit equation include exogenous non-energy cost inputs and, endogenous energy and water prices (combined with exogenous conversion efficiencies), and emissions or other policy costs; non-energy cost and efficiency assumptions reflect exogenous technological improvement for most technologies/sectors.

During the calibration routine, GCAM uses the cost of each subsector or technology to estimate the (unobserved) logit share weight parameters, ensuring that historically observed outcomes are reproduced (Calvin et al., 2019). Technology shares are derived from the historical (calibration) data, leaving share weights as the unknown parameter in the logit equation that is solved for. These share weight parameters capture unobserved factors, including preferences, which impact economic choice but aren’t explicitly represented in the model’s choice indicator (cost). 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 model decisions in future model periods (most strongly in initial model years). **Table SM5 (supplementary materials) provides an overview of how the calibrated share weights parameters for key sectors are applied in future model periods.**

----

(1) *Concerning the technology costs which enter the logit formulation, is technological learning included. If so, is it endogenous or exogenous?*

(2) The authors thank the reviewer for the question. Technological improvement is included and exogenously specified. A sentence has been added to the manuscript to clarify this point (additions below in bold).

(3) Edits to manuscript
Technology costs in the logit equation include exogenous non-energy cost inputs and, endogenous energy and water prices (combined with exogenous conversion efficiencies), and emissions or other policy costs; non-energy cost and efficiency assumptions reflect exogenous technological improvement for most technologies/sectors.

----

(1) *Lines 864 to 885 list some future improvements for the model. For improvement (1) is this really a priority? While I’m not knowledgeable on the topic, I would expect that there is a lot of inter-state trade for resources and electricity (famously not for Texas though), so i would expect*

state-level resource endowments (except for land) to provide limited extra insights. I could very well be wrong, in which case a justification for this decision would be very welcome.

(2) The authors thank the reviewer for the question. The reviewer is correct that inter-state trade for resources and electricity limit the impact of these resources' regional distribution on energy consumption. However, representing state-level fossil resource endowments and production is valuable because it permits the accounting of associated energy consumption and emissions at the state level, and thus facilitates the exploration of changes in regional patterns of resource production under alternate future scenarios, such as those with heterogenous state-level policies.

Currently, hydropower capacity is exogenously prescribed for each state and model period (with hydropower capacity and capacity factors fixed at 2019 levels for all future model periods). However, hydropower capacity and generation could vary in the future under different socioeconomic, technology, policy, or water availability scenarios, which could play out differentially among the states and impact the generation and final energy mix for a given state and those with which it trades electricity.

These explanations have been added to item 1 in the list of potential model developments (additions below in bold).

(3) Edits to manuscript
State-level fossil resource endowments and production would permit the accounting of associated energy consumption and emissions at the state level and facilitates the exploration of changes in regional patterns of resource production under alternate scenarios. While hydropower production is exogenously prescribed for each state and model period (hydropower capacity and capacity factors are fixed at 2019 levels for all future periods), hydropower capacity and generation could vary in the future under different socioeconomic, technology, policy, or water availability scenarios, which could play out differentially among the states and impact the generation and final energy mix for a given state and its electricity trade partners.

----

(1) *Minor Comment:*

Figure 9: I suspect the unit is not suppled to say EJ. If so, that is a very odd unit to use for land use. I would suggest MHa or an other unit of area.

(2) The authors thank the reviewer for catching this error. The plot was erroneously labeled as EJ; it has been updated with the correct label (thousand square kilometers).

(3) This figure has been updated in the manuscript.

----

(1) *Minor Comment:*

Lines 749 to 754: question to the editor: Shouldn't websites be listed in the reference list with *date accesses?*

(2) The authors thank the reviewer for the question. The authors defer to the editor as to whether access dates should be included with the in-text website references.

(3) There are currently no changes to manuscript corresponding to this comment.

References

Clarke L, Eom J, Marten EH, Horowitz R, Kyle P, Link R, Mignone BK, Mundra A, Zhou Y (2018) Effects of long-term climate change on global building energy expenditures. Energy Economics 72:667-677. doi:https://doi.org/10.1016/j.eneco.2018.01.003

Ou Y, Binsted M, Iyer G, Patel P, Wise M (2021) US state-level capacity expansion pathways with improved modeling of the power sector dynamics within a multisector model. Energy Strategy Reviews 38:100739. doi:https://doi.org/10.1016/j.esr.2021.100739

Reviewer 2

The authors thank the reviewer for their constructive feedback on our manuscript. We have responded to each comment individually below using GMD's suggested structure of (1) comments from referees/public (we italicized this text), (2) authors' response (plain text), and (3) authors' changes in manuscript (additions are bolded, existing content is plain text). To improve readability, we have inserted a series of dashes between each comment. A zip file containing a conceptual figure explaining the water supply system in GCAM-USA (new Figure 1) and a revised Supplementary Information document is attached to this response.

----

(1) *The manuscript 'GCAM-USA v5.3_water_dispatch: Integrated modelling of subnational U.S. energy, water, and land systems within a global framework' presents an open-source Integrated Assessment Model version for GCAM with focus on Energy, Water Land representation of the United States. The manuscript is an important contribution to the community considering recent US climate commitments.*

(2) The authors thank the reviewer for the compliment on our contribution to the literature.

(3) There are no changes to manuscript corresponding to this comment.

----

(1) *The manuscript is structured in a very good manner but I felt that more of the information that should have been in the manuscript is referred to other papers which may not help the readers to fully understand the modelling framework.*

(2) The authors thank the reviewer for the valuable feedback. The reviewer is correct that some aspects of the model could be described more thoroughly in the manuscript. As with all papers, there is a balancing act between comprehensiveness and accessibility – including every detail in the main text (as opposed to supplementary information or citations to other literature) can clutter a paper's key messages and impede understanding. However, we appreciate that there are areas where more detail would be beneficial. We address each specific point below.

(3) There are no changes to manuscript directly corresponding to this comment.

----

(1) *The authors mentioned that the water sector is a 'key new development of GCAM-USA' while it's hard to fully grasp the water structure which is being used in the model. Line 190 explains the water supply system but it lacks an explanation of how the water supply data was obtained, processed. Additional Information on the water supply system and also data sources and spatial aggregation methods for the data could benefit the readers to know more. I highly recommend*

that the authors insert a figure explaining the water supply system and how it's linked to the demands within the framework.

(2) The authors thank the reviewer for the helpful suggestions. The reviewer is correct that the original description of the water supply system was insufficient. We've added two paragraphs of additional detail on the various water resources in GCAM and how they compete to supply water needs. The suggestion to add a conceptual figure was also a good one. A conceptual figure was added as Figure 1 at line 225.

(3) Edits to manuscript
GCAM's water supply system is described in detail in Kim et al. (2016) and Turner et al. (2019); a high-level overview is provided below.

Renewable water is the least expensive source of water in GCAM and includes direct extraction of surface water as well as pumping of recharged groundwater. A global hydrology model, Xanthos (Li et al. 2017; Vernon et al. 2019), is used to calculate long-term average annual streamflow for each water basin by routing gridded runoff at 0.5° spatial resolution. 10% of this average annual flow is allocated to environmental flow requirements and thus unavailable; the remaining portion represents the maximum renewable water supply. A fraction of this renewable water supply is considered currently accessible at low cost via existing infrastructure for capturing, storing, and delivering; this fraction is adjusted to reflect the amount available even in dry years (here forth referred to as "accessible volume") (Kim et al. 2016). For most basins, this accessible volume is derived from Xanthos simulations of base flows and storage reservoirs (utilizing the Global Reservoir and Dams inventory) (Kim et al. 2016); in some basins where estimates of groundwater depletion are available, the accessible portion of renewable water is derived as the historical difference between total water withdrawals and fossil groundwater pumping (Turner et al. 2019). In model simulations, basins can withdraw greater fractions of the total renewable water supply (beyond the accessible volume) at significantly higher costs which reflect the potential costs of interventions such as river rerouting, dam construction, or water transportation (Kim et al. 2016; Turner et al. 2019).

Each water basin in GCAM also contains a volume of potentially exploitable non-renewable groundwater, divided into several grades of increasing price based on estimated drilling and pumping costs. Total physically exploitable groundwater reserves (without considering economic and environmental constraints) are estimated at a 50-km grid scale for all major aquifers from data on aquifer areal extent, porosity, thickness, permeability, and groundwater depth as described in (Turner et al. 2019) (section 2.3). An extraction cost model is used to simulate groundwater pumping for each 50-km grid to estimate extraction costs including capital costs (a function of well depth and complexity), maintenance costs, and operating costs (reflecting well depth, yields, and country-specific electricity prices). Costs associated with water treatment and conveyance / storage are not included due to lack of available data. These water quantity and cost data points are then aggregated to the HUC-2 water basin level and organized into grades increasing cost. By default, only 25% of physically exploitable groundwater is assumed to be available for extraction to reflect environmental limits on groundwater depletion (in the absence of a

global data set facilitating basin-specific environmental factors in the model (Turner et al. 2019).

As the maximum renewable water supply is approached, non-renewable groundwater begins to become an economically competitive source of water withdrawals. However, groundwater supplies are depleted as they are exploited; non-renewable groundwater consumption leads to water price increases as each marginal unit of groundwater entails increased pumping costs. Desalinated seawater is also available in coastal basins and states (but not inland basins/states) to meet water demands excluding irrigation demands, although at a high price because due to the energy intensity of desalination. Water prices in GCAM are incurred directly by water consuming technologies and ultimately passed onto end users in the costs of goods (e.g., crops) and services (e.g., electricity). Thus, increasing water prices can motivate shifts to less water intensive production methods such as rain-fed agriculture or more water-efficient power plant cooling systems.

----

(1) *Line 470 explains the water availability is constrained to default levels of renewable and non-renewable groundwater. Please add more explanation on the constraints here instead of referring to existing papers. A figure or table on Supplementary information explanation on the water prices for USA could help the readers more.*

(2) The authors thank the reviewer for the helpful comments. A description of how resource supply curves for renewable water and groundwater (which constitute limits on their availability) is now included in Section 3.2.1 (Water supplies) based on the reviewer's previous comment. Thus, in this instance (Section 5, Scenarios), we refer the reviewer to Section 3.2.1 and briefly summarize the key limits to water availability in the scenarios. The two sentences added to Section 5 are included below in bold.

The authors agree that information on water resource cost curves and prices is also valuable for readers. These have been added as Supplementary Figures SF4 and SF5. The text has been updated to refer interested readers to these figures (additions below in bold).

(3) Edits to manuscript (section 5)
The methods for constructing GCAM's renewable water and groundwater resource curves are described in Section 3.2.1 (Water supplies). In short, this entails a 10% environmental flow restriction on renewable water, renewable water availability based on the stable volume of long-term average annual flow (i.e., not reflecting potential impacts of future climate change on water availability), and a 25% limit on physically exploitable groundwater extraction reflecting environmental limits on groundwater depletion. Renewable water and groundwater resource curves by river basin are included in Supplementary Figure SF4.

Additional edits to manuscript (section 6.3)
(The shadow prices of water for each river basin and scenario are included in Supplementary Figure SF5; broadly, we observe increasing water prices in

basins/scenarios with high reliance on groundwater extraction or desalination. Note that GCAM-USA's water prices represent a shadow price on water (Bierkens et al. 2019) – the intention is not to predict real-world consumer prices, but to reflect water scarcity and provide a price signal to water consuming sectors when basins face water scarcity and marginal water demand must be met by expensive ground water extraction or desalination (where available).)

----

(1) *I think energy system is explained in a well structured way whereas additional information on the water structure, prices and linkages in the framework can improve the manuscript overall.*

(2) The authors thank the reviewer for the compliment. We have added more detail on the water supply structure, water prices, and water market linkages as discussed above.

(3) There are no changes to manuscript directly corresponding to this comment.

References

Bierkens MFP, Reinhard S, de Bruijn JA, Veninga W, Wada Y (2019) The Shadow Price of Irrigation Water in Major Groundwater-Depleting Countries. Water Resources Research 55 (5):4266-4287. doi:https://doi.org/10.1029/2018WR023086

Kim SH, Hejazi M, Liu L, Calvin K, Clarke L, Edmonds J, Kyle P, Patel P, Wise M, Davies E (2016) Balancing global water availability and use at basin scale in an integrated assessment model. Climatic Change 136 (2):217-231. doi:10.1007/s10584-016-1604-6

Li X, Vernon CR, Hejazi MI, Link R, Feng L, Liu Y, Rauchenstein LT (2017) Xanthos A Global Hydrologic Model. Journal of open research software 5

Turner SWD, Hejazi M, Yonkofski C, Kim SH, Kyle P (2019) Influence of Groundwater Extraction Costs and Resource Depletion Limits on Simulated Global Nonrenewable Water Withdrawals Over the Twenty-First Century. Earth's Future 7 (2):123-135. doi:https://doi.org/10.1029/2018EF001105

Vernon CR, Hejazi MI, Turner SWD, Liu Y, Braun CJ, Li X, Link R (2019) A Global Hydrologic Framework to Accelerate Scientific Discovery. Journal of open research software 7