Core Model Proposal #394: Updated approach for intermittent electricity integration

Product: Global Change Analysis Model (GCAM)

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Related sector: energy

Type of development: code, data

Purpose: This Core Model Proposal (CMP) updates the cost adjustment applied to variable renewable electricity (VRE) generation (wind and solar, labeled "intermittent" technologies in GCAM) based on technology value parameterizations derived from the Regional Electricity Deployment System (ReEDS) model and the profitability-adjusted LCOE (PLCOE) metric. In addition, share-weights of wind and solar electricity are set to converge to one by 2030 (rather than 2100).

Overview

To analyze global, multi-sectoral impacts, multisector models like GCAM cannot represent individual sectors with as high resolution as sector-specific models, and instead make simplifying assumptions about economic competition. In the case of the electricity sector, multisector models typically do not represent with great detail the spatial and temporal (both diurnal and seasonal) variations in electricity demand in an electricity system, along with spatio-temporal constraints on supply-side technology availability and flexibility, which together result in real-world electricity value (i.e. price) that varies spatiotemporally. Instead, multisector models often rely on the simple levelized cost of electricity (LCOE) metric to compete technologies. Additional "integration" or "backup" costs are often added to VRE technologies to reflect the cost of other technologies deemed necessary to maintain system reliability in the presence of VRE generation. Current GCAM competes technologies via the LCOE metric and assumes that wind and solar investments must be coupled with investments in a specific backup technology (currently a natural gas combustion turbine or hydrogen combustion turbine), where the amount of backup required depends on each technology's market share in each region.

While LCOE-based competition is insufficient without adjustments like those in GCAM, there is no inherent link between wind/solar investments and any specific technology like combustion turbines in real-world power systems. There are a variety of resources on the grid that can provide reliability and flexibility needs, including storage, transmission, firm capacity resources, and even VRE curtailment (when economical). Instead of linking VRE investments with a specific backup technology, a more robust approach is to consider the economic value (i.e. avoided cost) that technologies provide toward the various spatio-temporal electricity system requirements, including energy, firm capacity, and operating reserves. Total value can then be combined with total direct cost for a complete competitiveness metric, for example benefit-cost ratio (BCR), or total value divided by total direct cost (Mowers and Mai, 2021a). Note that this approach still implicitly links technologies together, since lower contribution toward (and therefore value derived from) a system requirement means greater need for other resources to meet that requirement.

This CMP implements a recently developed comprehensive metric of electricity technology competitiveness - profitability-adjusted LCOE (PLCOE) (Mowers and Mai, 2021a) - to better reflect technology competition and the changing relative value of VRE generation at different levels of market share. PLCOE is equal to a technology's LCOE divided by its value factor (VF), where VF is defined as a technology's total value per unit of generated electricity divided by the average system electricity price. This means that PLCOE directly reflects the relative benefit-cost ratios of different technologies. From another perspective, a technology's PLCOE is equal to the hypothetical LCOE of an "average value" technology (with total value per unit electricity equal to the average system electricity price) that has equal BCR to the technology in question.

Description of Changes

PLCOE Change

In this CMP, value factors for wind and solar technologies (without on-site storage) are parameterized as a linear function of market share within each GCAM region, based on recently published work with the Regional Electricity Deployment System (ReEDS) model for the contiguous United States (Mowers et al., 2023). The value factor versus market share data, as well as the line fits for the VRE technologies are shown in **Fig. 1**. The VRE value factor intercepts and slopes are divided by the average of the non-VRE techs (0.903) to avoid any adjustments to non-VRE techs in GCAM while maintaining equivalent relative competitiveness between technologies. **Fig. 2** shows the onshore wind and utility-scale PV cost adjustments from the current and new approaches after translating the new value factor adjustments into additive cost terms, rather than multiplicative as implemented via the PLCOE metric in GCAM (Binsted et al., 2022). Similar cost adjustments derived from these ReEDS value factors have been implemented in the Emissions Prediction and Policy Analysis (EPPA) computable general equilibrium (CGE) model (Gurgel et al., 2023). Note that value factor versus market share relationships can be sensitive to certain assumptions used in the electricity model. For example, lower assumed costs for new electricity storage technologies can significantly reduce the steepness of the Utility PV value factor versus market share slope. For examples of different sensitivities on assumptions and their impact on the value factor relationships, see Mowers et al. (2023) "Supplementary data 1. Additional figures".

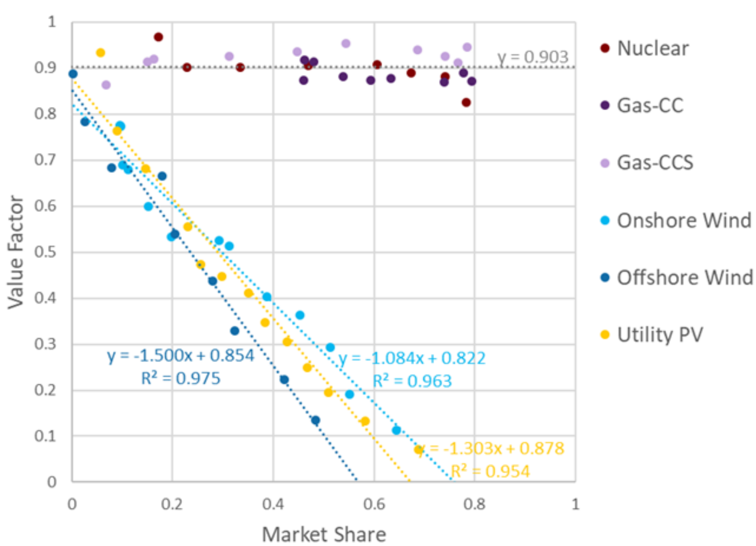

Fig. 1. Value factor versus market share and line fits for VRE technologies (Mowers et al., 2023). In GCAM, we leave non-VRE technology LCOEs unadjusted by value factor, and divide the VRE value factor intercepts and slopes by 0.903 to maintain equivalent relative competitiveness between technologies.

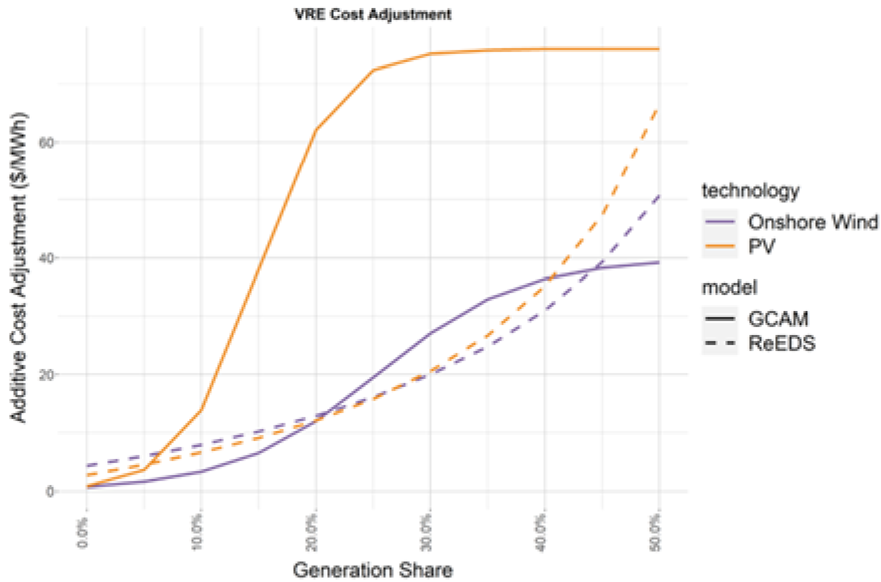

Fig. 2. A comparison of VRE additive cost adjustments from current GCAM (labeled "GCAM") and a translation of the new PLCOE approach (labeled "ReEDS"). This figure is taken from Binsted et al. (2022). The additive adjustment for the PLCOE approach is equal to (LCOE/VF - LCOE), which increases exponentially with market share because the VF relationship is assumed to be a linear function of market share (see **Fig. 1**).

Share Weight Change

In addition to the new value factor adjustments to LCOE, in this CMP we also linearly interpolate share weights of the wind and solar subsectors to one by 2030. In current GCAM, share weights of wind and solar are linearly interpolated to one by 2100. There are two reasons for this change. First, wind and solar technologies have deployed significantly globally in recent years (EIA 2024) and are expected to continue to do so in the near future; historical (2015) technology shares and observed preferences are not necessarily indicative of current trends for these more recently established technologies. Second, this CMP improves representation of VRE competitiveness in GCAM, obviating the need for additional adjustments to technology competition.

Code & Data Changes

This section provides a brief description of changes to GCAM's C++ code and gcamdata input data processing.

C++ Changes

This CMP entailed significant restructuring of the C++ code associated with VRE integration.

A new ValueFactorCalculator class was introduced; this class is similar in many ways to the existing CapacityLimitBackupCalculator class (used for the previous backup capacity approach to VRE integration) but is significantly simplified. The main function of this class is to look up the technology's market share, calculate the value factor adjustment based on that share and the linear function's slope and y-intercept parameters, and return this value factor adjustment to the IntermittentTechnology class.

The IntermittentTechnology class was re-implemented using the PLCOE approach to variable renewable technology integration; the class was significantly simplified since it no longer tracks backup capacity and backup electricity demands. The IntermittentTechnology class simply accesses the computed value factor adjustment from the ValueFactorCalculator class and applies it to technology costs within a much-simplified IntermittentTechnology::calcCost, dividing cost by value factor as shown in **Eq. 1**.

```
Eq. 1.     mCosts[aPeriod] = cost /  valueFactor;
```

Maintaining Backward Compatibility with the pre-Existing Intermittent Backup Approach

For some projects, it may be important to maintain compatibility with the existing backup calculator approach that has been used in GCAM for several years. To do this, we renamed the existing IntermittentTechnology class that contains that existing method to a new "BackupIntermittentTechnology" class, thus allowing for users who value the ability to quantify energy and emissions associated with backup electricity to use the previous variable renewable technology integration approach (NOTE: using the previous backup calculator approach requires foregoing the new PLCOE approach).

Users specify which method to use by using the appropriate intermittent technology class tag in their XML files. A bool (described below) has been added to gcamdata to allow users to specify which tag will be used for all relevant XMLs generated by gcamdata.

- XML tag for using new PLCOE approach to variable renewable technology integration: intermittent-technology
- XML tag for using existing backup calculator approach to variable renewable technology integration: backup-intermittent-technology

The model has been tested and confirmed to work as expected with either configuration.

gcamdata Changes

gcamdata changes associated with this CMP are relatively minor. A23.globalinttech.csv was modified to include information about the value factor markets and parameters (and remove information related to former backup markets and function parameters). The previous

A23.globalinttech.csv was renamed to A23.globalinttech_backup.csv to maintain the option for users to select the previous (backup capacity) VRE integration approach if desired. Table 1, below, shows the central value factor parameter (slope and intercept) assumptions used in this proposal, plus parameter values for lower barriers to integration and higher barriers to integration cases (which GCAM modelers could use to conduct sensitivity analyses related to VRE integration).

Table 1. Value factor relationship parameters for the central case (used in this proposal), a "low" barriers to integration case, a "high" barriers to integration case, and a "very high" barriers to integration case.

Sector	**Subsector**	**Tech**	**Trial Market**	**Case**	**VF intercept**	**VF slope**
electricity	wind	wind	wind	central assumptions (in A23.globalinttech.csv) ; used in this proposal	0.91	-1.2
electricity	solar	PV	solar		0.972	-1.443
electricity	solar	CSP	solar		0.972	-1.443
elect_td_bld	rooftop_pv	rooftop_pv	solar		0.972	-1.443
electricity	wind	wind_offshore	wind_offshore		0.946	-1.661
electricity	wind	wind	wind	low barriers to integration (based on Mowers et al. (2023) Advanced Battery case)	0.935	-1.163
electricity	solar	PV	solar		0.964	-1.054
electricity	solar	CSP	solar		0.964	-1.054
elect_td_bld	rooftop_pv	rooftop_pv	solar		0.964	-1.054
electricity	wind	wind_offshore	wind_offshore		0.981	-1.675
electricity	wind	wind	wind	high barriers to integration (based on Mowers et al. (2023) Conservative Battery case)	0.895	-1.239
electricity	solar	PV	solar		0.961	-1.684
electricity	solar	CSP	solar		0.961	-1.684
elect_td_bld	rooftop_pv	rooftop_pv	solar		0.961	-1.684
electricity	wind	wind_offshore	wind_offshore		0.913	-1.628
electricity	wind	wind	wind	very high barriers to integration (based on Mowers et al. (2023) No Storage case)	0.849	-1.205
electricity	solar	PV	solar		1.042	-2.393
electricity	solar	CSP	solar		1.042	-2.393
elect_td_bld	rooftop_pv	rooftop_pv	solar		1.042	-2.393
electricity	wind	wind_offshore	wind_offshore		0.856	-1.586

A new LEVEL2DATANAME and Model Interface header, GlobalIntTechValueFactor, was created to replace the previous GlobalIntTechBackup table type. TheGlobalIntTechBackup LEVEL2DATANAME and Model Interface header were adjusted to use the backup-intermittent-technology xml tag for users who elect to use the previous backup capacity approach to VRE integration. Minor changes were made to the electricity modules for GCAM and GCAM-USA to accommodate the new data (value factor intercept and slope) in A23.globalinttech.csv and use the new GlobalIntTechValueFactor table type. A switch, energy.ELEC_USE_BACKUP (default = FALSE), was added to constants.R and utilized in several xml R modules to permit users to use the previous backup approach to renewable integration if desired. The new subsector shareweight interpolation rules for wind and solar were specified in input data files. Finally, information related to the backup_electricity and csp_backup sectors, which have been deprecated, were removed from the associated energy/A26.* input files.

One important note: the energy.ELEC_USE_BACKUP switch does not revert the wind and solar subsector share weight changes included in this proposal. Users reverting to the previous backup capacity approach to VRE integration should carefully consider the share weight trajectories for these subsectors since the backup capacity approach entails asymptotic integration costs and thus may underestimate the reduced value of VRE at higher market shares (see Fig. 2).

Validation

Global GCAM

The PLCOE and share-weight changes result in two primary changes to model results. First, the share-weight change causes an increase in VRE generation relative to current GCAM in the near-term to mid-term, but by 2100 the VRE shares in this CMP in the reference case are very similar to current GCAM. Second, the shift from GCAM's existing backup capacity VRE integration approach to the new PLCOE approach results primarily in a shift from wind generation to solar generation, but also an increase in total VRE generation by 2100 in low carbon cases.

The combined impact of both changes in this CMP in a reference case ("ref") and low carbon case ("2p6"; emission reduction pathway consistent with 2.6W/m^2 radiative forcing in 2100) are shown in the figures below. **Fig. 3** shows that in the reference case, global VRE generation increases in the near- to medium-term with the new approach (labeled "plcoe", with all the changes described in this CMP), with the difference peaking at 21 EJ in 2050 as compared to the current GCAM ("core"). However, this difference dissipates to only 2 EJ in 2100. In the 2p6 case, global wind + solar generation (including rooftop PV) increases with the new approach resulting in a maximum difference of 36 EJ in 2075, . **Fig. 4** shows that most of the increase in VRE generation is solar, and by 2100 there is lower wind generation with the new approach as compared to current GCAM. **Fig. 5** shows that total global electricity generation remains largely unchanged between the new approach and current approach over the time horizon (within 2%), and **Fig. 6** shows that regional electricity prices (for Africa_Western, Brazil, China, India, and

USA) are within 5% of previous values. **Fig. 7** shows that global CO2 emissions decrease moderately by 2050 in the reference case with the new approach as compared to current GCAM, but this difference diminishes by 2100.

The new approach results in 2020 global wind + solar generation that is more aligned with historical EIA international energy data (EIA 2024), which is 8.7 EJ. This proposal results in 9.4 EJ (8% higher than historical values), while current GCAM has 7.6 EJ of wind + solar generation in 2020 (13% lower than historical data). In addition, assuming the historical growth rate of wind + solar generation from 2020 to 2022 continues through 2025, there would be a projected 17.2 EJ of wind + solar generation in 2025, based on the EIA data. This proposal results in 18.9 EJ in 2025 (10% higher than this simple projection), while current GCAM has 14.6 EJ (15% below this projection).

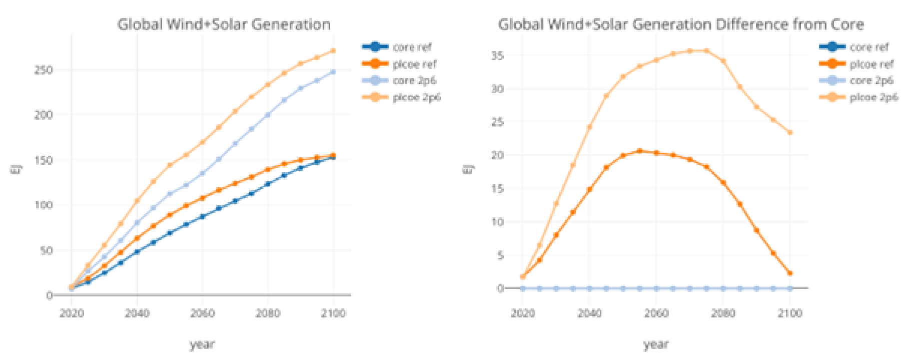

Fig. 3. Global wind + solar generation in current GCAM ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("2p6") scenario (left panel), and difference in generation from "core" (right panel)

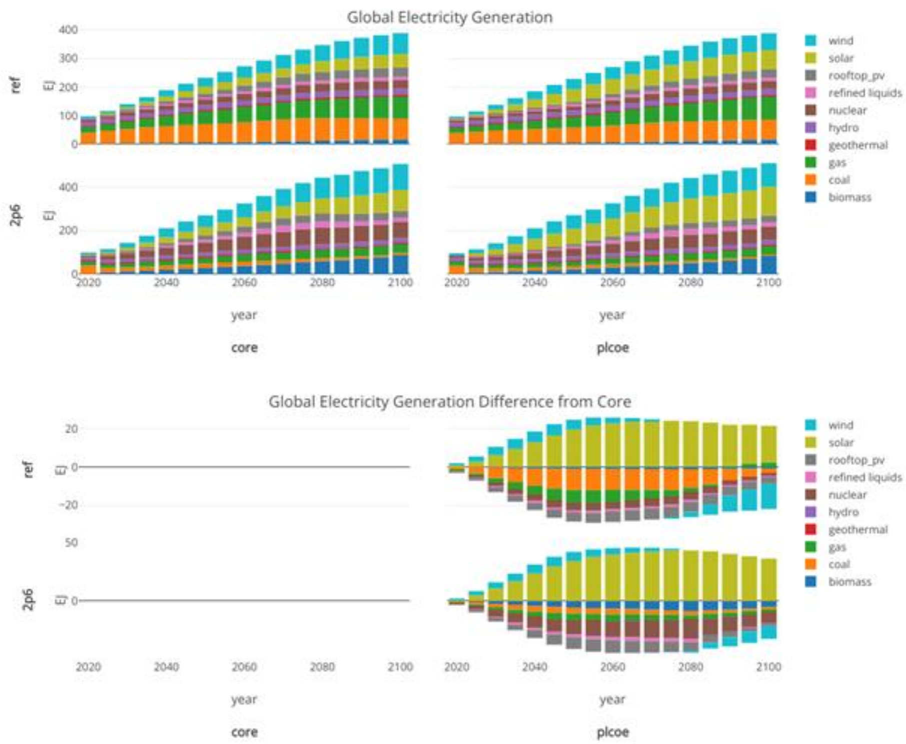

Fig. 4. Generation by technology in current GCAM ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("2p6") scenario (top panel), and difference in generation from "core" (bottom panel). **Supplementary Fig. 1** shows a more detailed breakdown of wind and solar technologies. **Supplementary Fig. 2** also shows these results for a version of GCAM with just the PLCOE change (without the share-weight change). **Supplementary Fig. 4** shows the gas consumption and electricity production provided by the "backup electricity" sector in core (GCAM v7.0), which is removed by this proposal.

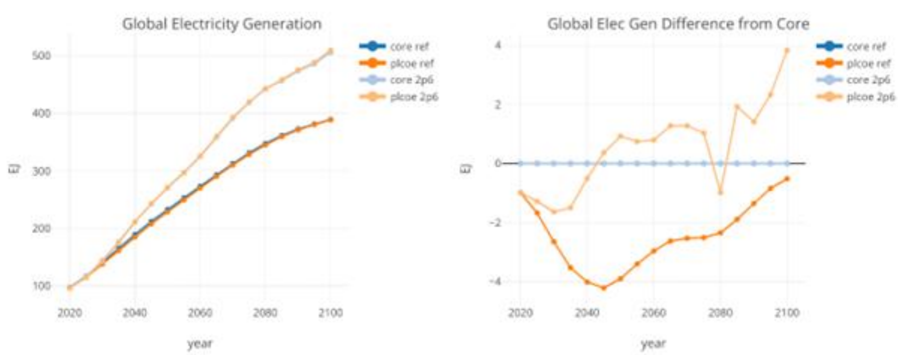

Fig. 5. Global total electricity generation in current GCAM ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("2p6") scenario (left panel), and difference in generation from "core" (right panel)

Fig. 6. Selected regional electricity prices in current GCAM ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("2p6") scenario (top panel), and difference in prices from "core" (bottom panel)

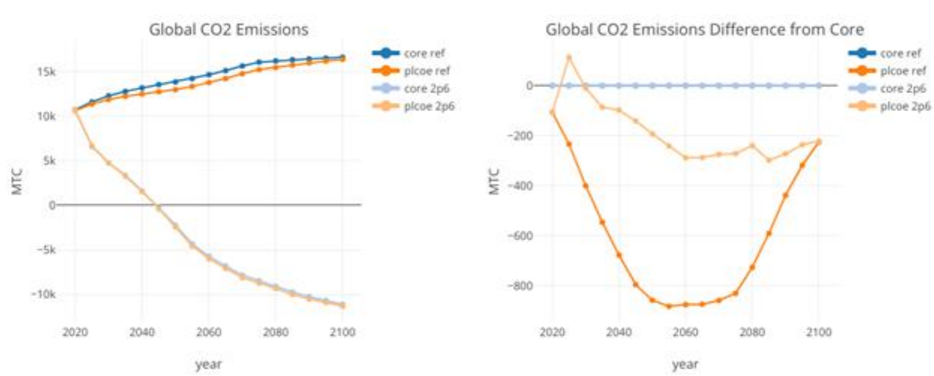

Fig. 7. Global CO2 emissions for a reference ("ref") and low carbon ("2p6") scenario (left panel), and difference in emissions from "core" (right panel)

GCAM-USA

A similar validation exercise was performed with GCAM-USA. Because GCAM-USA already interpolates wind and solar subsector share weights to 1 by 2030, we don't see the near-term increase in VRE that we see in Global GCAM. However, the PLCOE change still causes a shift from wind to solar generation, as well as an increase in total VRE generation by 2100 in a low carbon case.

The impact of the changes in this CMP in a reference case ("ref") and low carbon case ("tax25"; a carbon price of 25 1990$/tonC, which starts in 2025 and escalates at 3% per year) are shown in the figures below. **Fig. 8** shows that in the reference case, VRE generation in GCAM-USA is very similar in the reference case. In the tax25 case, wind + solar generation (including rooftop PV) in the new approach decreases in the near-term as compared to current GCAM-USA, but increases post-2060 to 2.6 EJ by 2100. **Fig. 9** shows that most of the increase in VRE generation is solar, and by 2100 there is lower wind generation with the new PLCOE approach as compared to current GCAM-USA. **Fig. 10** shows that total electricity generation in GCAM-USA remains largely unchanged between the new approach and current approach in the reference case, while there is a 5% increase in electricity generation in the tax25 case by 2100. **Fig. 11** shows that selected state-level electricity prices (CA, IA, NY, and TX) for the base load segment are slightly higher with the new approach as compared to current GCAM-USA. This is because wind's adjusted LCOE is slightly higher with the new approach, and solar (without dedicated storage) does not compete in the base load segment. On the other hand, electricity prices for the intermediate load segment (as well as sub-peak and peak load segments) are significantly lower with the new approach, as solar competes in these load segments, and solar's adjusted LCOE has reduced significantly with the new approach.

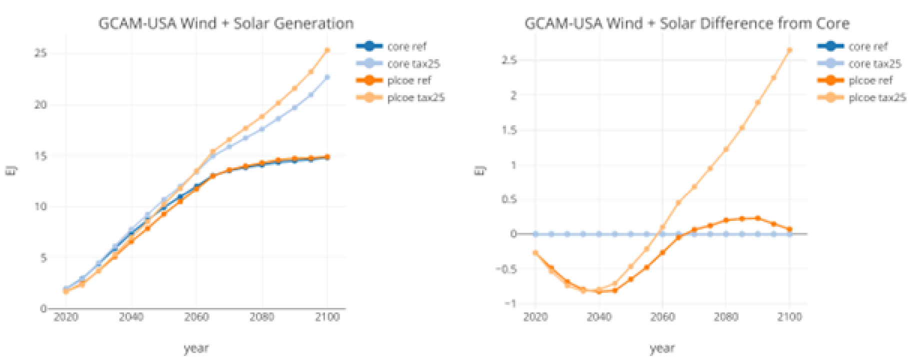

Fig. 8. Wind + solar generation in current GCAM-USA ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("tax25") scenario (left panel), and difference in generation from "core" (right panel)

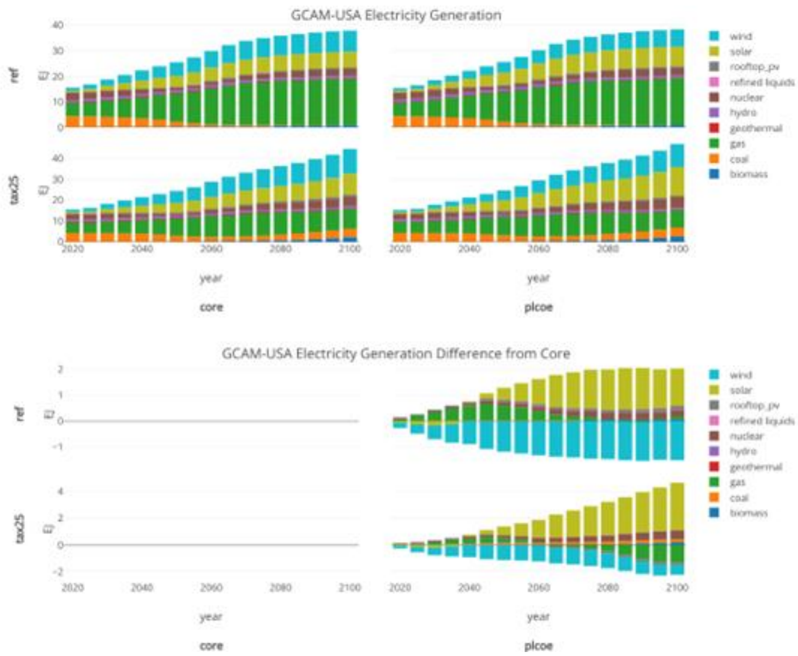

Fig. 9. Generation by technology in current GCAM-USA ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("tax25") scenario (top panel), and difference in generation from "core" (bottom panel)

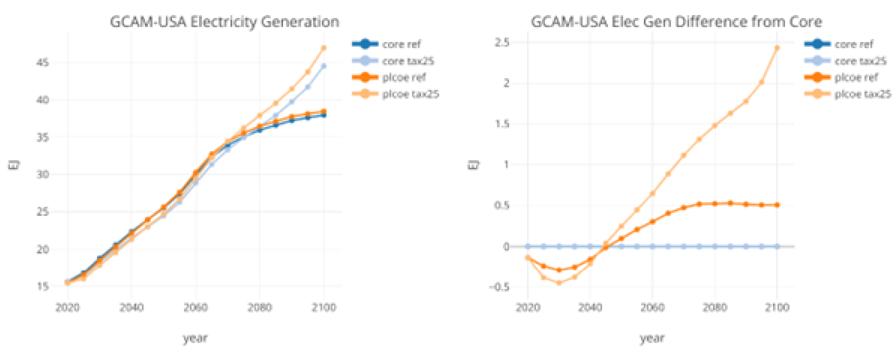

Fig. 10. Total electricity generation in current GCAM-USA ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("tax25") scenario (left panel), and difference in generation from "core" (right panel)

Fig. 11. Selected state electricity prices in current GCAM-USA ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("tax25") scenario for the base load segment (top panel), and intermediate load segment (bottom panel)

Limitations/Future Work

This CMP implements a more robust competitiveness metric (PLCOE) for electricity technology competition, which could allow for more price-sensitive competition in the electricity sector. Specifically, the current logit exponent used in the electricity sector is -3, which results in significant sharing of the market between technologies, but with the PLCOE approach in place, it may be more appropriate to implement tighter competition, for example a logit exponent of -6 or -10.

As the value factor relationships are derived from ReEDS, a model that is continually updating, future work could periodically regenerate the value factor relationships with the latest version of ReEDS and update GCAM accordingly. For example, the value factor relationships included in this CMP do not reflect recent changes to ReEDS which significantly increase its temporal resolution. In addition, since ReEDS currently only models the contiguous United States, future work could examine how much the value factor relationships vary by region, and whether this detail should be added in GCAM.

Recent unpublished work has indicated that non-VRE technologies (e.g. nuclear or non-dispatchable run-of-river hydropower) can have reductions in value factor as market share is increased, a result of spatial and/or operational inflexibility. Future work could examine other technologies in more detail, with potential application of value factors in GCAM as either linear or other functional relations to market share. Similarly, Mowers et al. (2023) showed that VRE technologies can interact, and at very high combined VRE market shares (above ~75%), the individual technology value factor relationships can break down. Future work could investigate functional forms of value factor relationships for technologies that depend not only on that technology's market share, but other technologies' market shares as well.

Finally, this CMP removes backup combustion turbine capacity (and any associated energy use and emissions) as an output of GCAM by default. (The ability to utilize the existing backup calculator approach to variable renewable technology integration is maintained for users who wish to continue utilizing this approach.) As described above, this is because VRE capacity is not inherently linked to combustion turbine capacity, and a variety of resources (e.g. storage, transmission, and firm capacity resources) can provide system flexibility. However, it is possible to calculate the total cost of these "backup" resources as the difference between PLCOE and LCOE multiplied by total electricity generated by the VRE technology. This cost could further be attributed to investments in storage, long-distance , and firm capacity resources like combustion turbines based on results from more detailed power sector models (e.g., ReEDS), although this division would be sensitive to the relative cost of these technologies. Future work could investigate the inclusion of these cost/capacity outputs in GCAM. Nevertheless, we believe that the improved representation of VRE competition in this proposal outweighs the loss of estimating combustion turbine capacity, energy consumption, or emissions.

References

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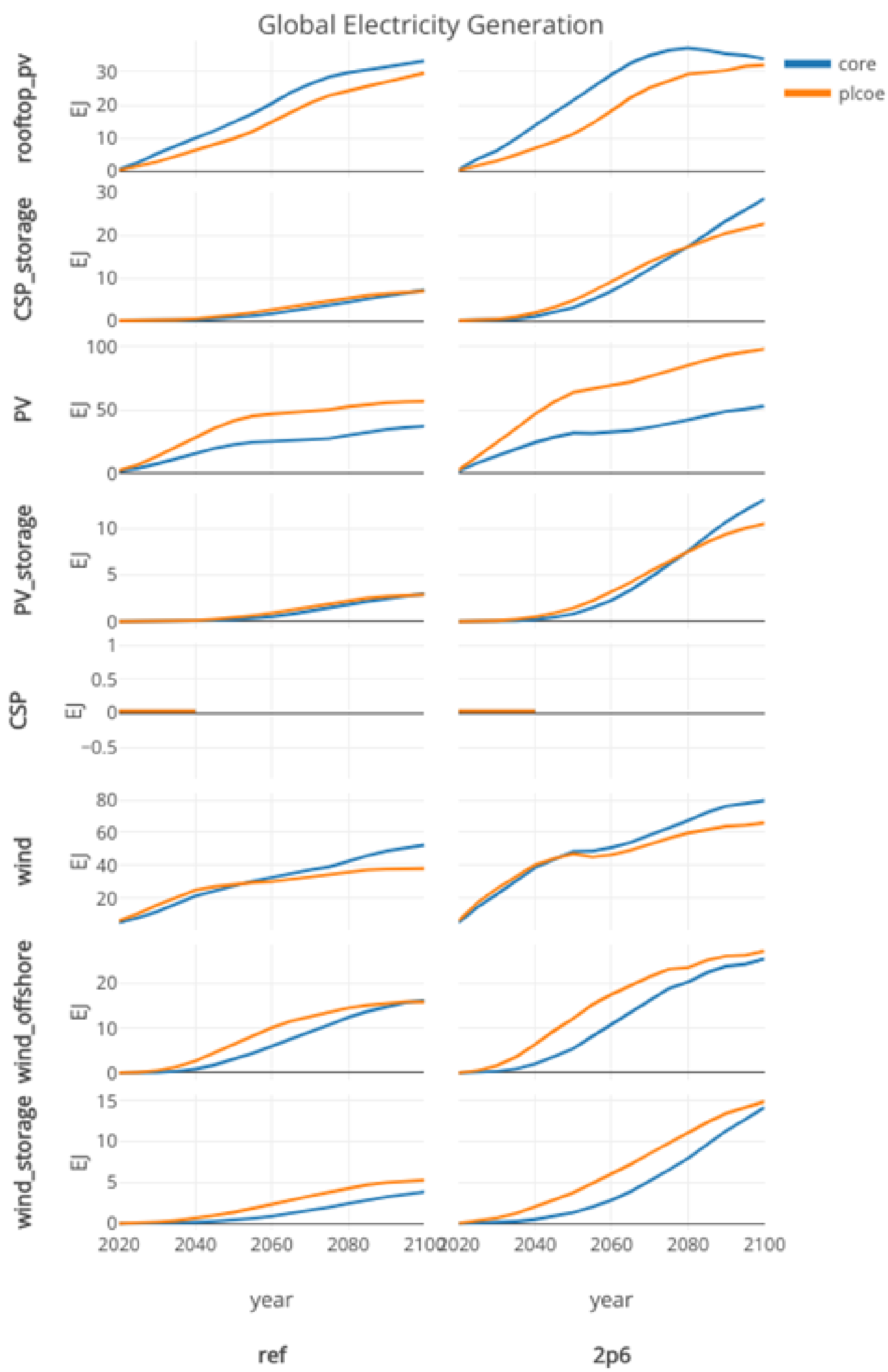
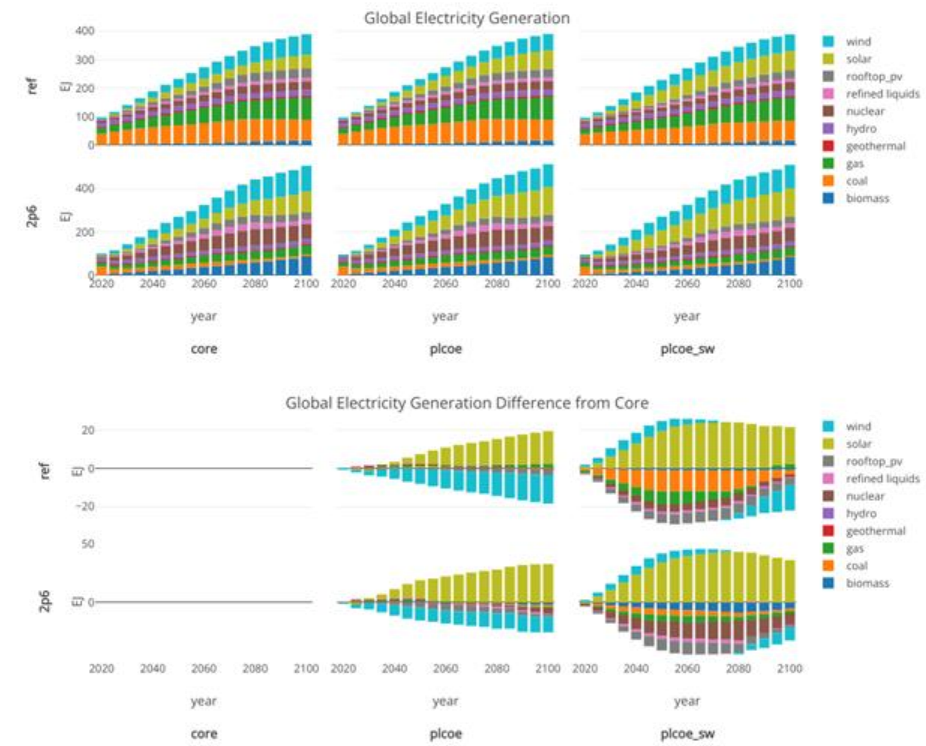
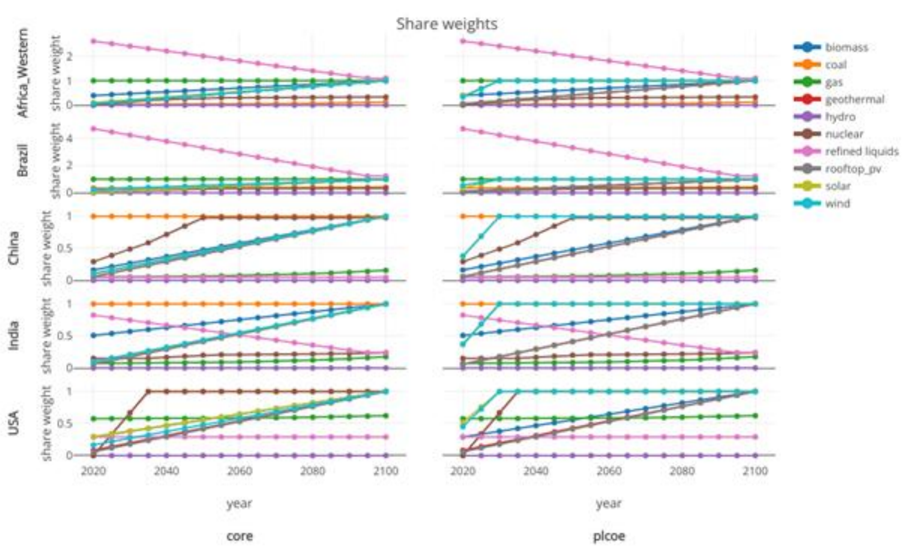
Supplementary Information



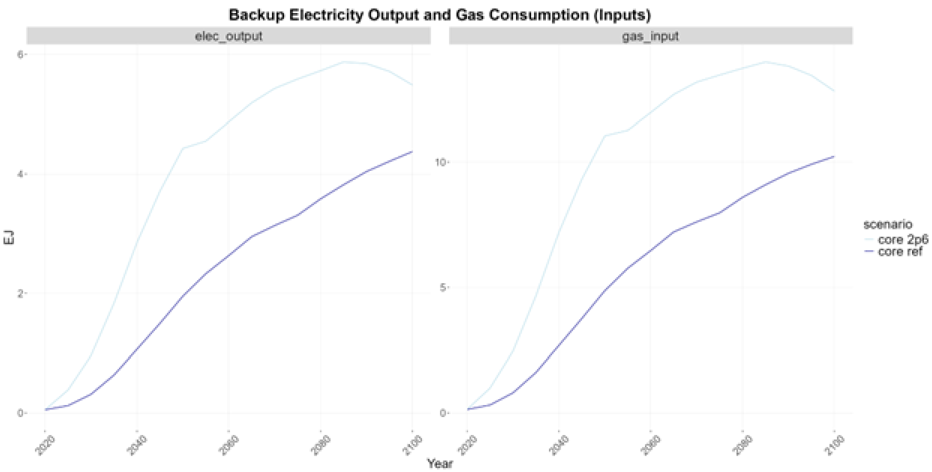
Supplementary Fig. 1. Generation by wind/solar technology in current GCAM ("core") and with the new approach ("plcoe") for a reference ("ref") and low carbon ("2p6") scenario.



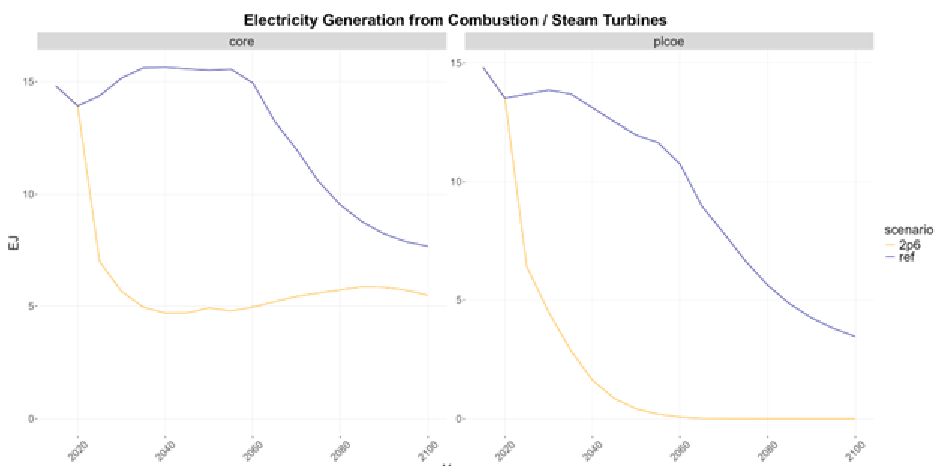
Supplementary Fig. 2. Generation by technology in current GCAM ("core"), using just the PLCOE change but not the share-weight change ("plcoe"), and the new approach with both the PLCOE change and the share-weight change ("plcoe_sw", note the name changes from the figures in the body of the proposal) for a reference ("ref") and low carbon ("2p6") scenario (top panel), and difference in generation from "core" (bottom panel).



Supplementary Fig. 3. Share-weights by technology for select regions in current GCAM ("core") and with the new approach ("plcoe")



Supplementary Fig. 4. Electricity production (left panel) and gas consumption (right panel) for GCAM's existing "backup electricity" sector in current GCAM ("core") for a reference ("ref") and low carbon ("2p6") scenario. The "backup electricity" approach is deprecated in this proposal, so no results are shown for the new intermittent electricity integration approach ("plcoe").



Supplementary Fig. 5. Electricity production from combustion / steam turbines (gas / refined liquid / H2 steam/CT technologies in electricity and backup electricity (core only for the latter) for core (left panel) and this proposal ("plcoe", right panel) for a reference ("ref") and low carbon ("2p6") scenario.