# Core Model Proposal #332: GCAM Macro-Economic Module (KLEM Version)

**Product:** Global Change Assessment Model (GCAM)

**Institution**: Joint Global Change Research Institute (JGCRI)

**Authors**: Pralit Patel, Jae Edmonds, Sonny Kim, Xin Zhao, Di Sheng, Stephanie Waldhoff, and Ellie Lochner

**Reviewers**: Gokul Iyer and Matthew Binsted

**Date committed**: 5/24/2023

**IR document number**: PNNL-34479

**Related sector**: Economy

**Type of development**: Data, Code, and Queries

**Purpose**: This Core Model Proposal introduces a GCAM macroeconomic module including a Material sector, labor markets, and saving-investment responses and incorporates two-way feedback between energy and macroeconomics.

# Contents

## 1. Introduction

The Global Change Analysis Model (GCAM) is a hierarchical, dynamic-recursive model of energy, the economy, agriculture, land use, and the physical Earth system (Calvin et al., 2019). GCAM includes highly detailed representations of the energy sector (including energy resources, supply, transformation, end-use, and potential reservoirs for geologic carbon storage), agriculture, land use, and land cover (including the production of bioenergy and carbon storage in the above and below ground stocks) and freshwater (including renewable and non-renewable sources of water, water withdrawals, and water consumption).

One of the most important determinants of energy, agriculture, and land use is the scale of economic activity, which we assume is proportional to the Gross Domestic Product (GDP). In previous versions of GCAM, dating back to the model's earliest formulations, the level of GDP was prescribed exogenously, though there has been an option to endogenously modify the initial GDP assumption to reflect changes in the cost of delivering energy services within a scenario (Edmonds and Reilly, 1983, 1985). However, that feedback elasticity was not determined structurally and was a simple scalar parameter. This model augmentation described here creates a two-way coupling between the scale of economic activity, measured as GDP, and the existing energy sector module. **Fig. 1** shows the new elements in relation to existing GCAM elements.

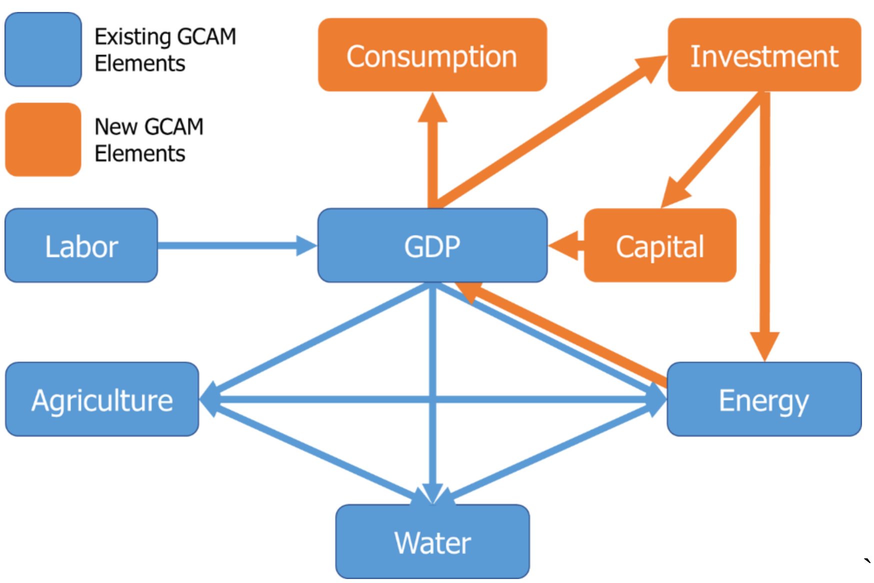


**Fig 1.** Schematic of the major components of the GCAM macroeconomic model (earlier version in blue; the version in this CMP in blue and orange)

Other integrated assessment models (IAMs), for example, MESSAGE (Messner and Schrattenholzer, 2000), IMAGE (Stehfest et al., 2014), and ReMIND (Luderer et al., 2011), also have hierarchical structures similar to GCAM's. These models employ a highly aggregated macroeconomic model to set the scale of economic activity. They build on the approach originally developed by Hogan and Manne (1977) and used by Manne and Richels (1990). The approach utilizes an aggregate production function that includes inputs of capital, labor, and energy.

The macroeconomic module in an IAM can perform a number of functions in addition to setting the scale of economic activity in the economy. It can provide the information needed to estimate economic welfare and a means for estimating feedback from the energy and other systems that can affect the productivity of capital and labor. And finally, the module can provide a constraint on the magnitude of capital and labor inputs deployed explicitly in IAM sectors such as energy.

In the simple macroeconomic model that we employ here, the two-way interaction is developed for each geo-political region in GCAM. The system is assumed to be open, with each of the regions interacting with others in the global economy via trade.

## 2. Methods

### 2.1. GCAM-Macro (KLEM) Description

The macroeconomic model is implemented by creating a Materials sector production function in each region. The Materials sector production function uses three inputs, capital, labor, and energy services, to produce the domestic output of NEW, FINAL goods and services. This would be the GDP except for the need to add net exports of energy to that value in order to get the full GDP. Net exports of energy are calculated in the GCAM energy module and used by the macroeconomic module.

We assume that all labor is employed in the Materials sector. The labor force is prescribed as a GCAM model input assumption. The Materials sector's capital stock is modeled as a simple capital accumulation equation with an annual decay rate. The capital stock used by the Materials sector and the capital stock employed in the energy sector are tracked separately.

In each time step, a fraction of the GDP is saved and/or allocated to energy-consuming consumer durables acquisition. The savings rate is one minus the ratio of non-durable consumption plus government spending to GDP. We prescribe the savings rate as a scenario input assumption. Savings plus net international capital transfers are allocated to Materials sector investments (gross additions to the Materials sector capital stock), energy sector investments, and purchases of energy-consuming durable goods. After the calibration year, net international capital transfers are prescribed as an exogenous input assumption. In the calibration year, they are observed values. In general, we assume that these values will be constant in future years.

The economy moves forward over time, driven by changes in labor force availability, capital accumulation, and technological change. We assume that over time the Materials sector's total factor productivity improves at an externally assumed rate. Total factor productivity is simply a scale multiplier appended to total output. Increasing total factor productivity means that for any set of inputs, the output will be larger by the rate at which the total factor productivity index increases.

### 2.2. GCAM-Macro (KLEM) theoretical derivations

In what follows, we provide the formal derivations of the GCAM-Macro (KLEM) module. At the heart of the production of GCAM's GDP in this CMP's macroeconomic model is the Materials sector, M. The Materials sector is the source of all net output not originating in the energy system, i.e., $X_M$ is sold as new final goods and services (In later versions of the model, Materials will also be sold to A (Agriculture) and E as intermediate inputs to those sectors). In addition, M consumes all net E output, here measured as efficiency-weighted end-use energy. $X_M$ is thus the retailer to the economy.

$$X_M = F_M\left(X_{K,M}, X_{L,M}, X_{E,M}\right) \tag{1}$$

- $X_{i,j}$ *=sale of product i to sector j, i=K, L, E, M and j=M*
- $F_M$ *is the production function for Materials, with the output of* $X_M$.

The production function $F_M$ is homogeneous of degree one and thus carries all of the properties of such functions. Note that the self-consumption of Materials is not included for simplicity.

We implement the Materials production function as a nested constant elasticity of substitution (CES) production function:

$$X_M = a\left(\left(bX_{L,M}{}^{\eta} + X_{K,M}{}^{\eta}\right)^{\rho/\eta} + cX_{E,M}{}^{\rho}\right)^{1/\rho} \tag{2}$$

- a, b, c, $\rho, \eta$ are constants.

We calculate GDP for a region using equation (3).

$$GDP = P_M F_M\left(X_{K,M}, X_{L,M}, X_{E,M}\right) + NX_E + X_{I,M} \tag{3}$$

- $X_{i,j} = \text{sale of product i to sector j, i} = \text{K, L, E, M and j} = \text{E, M, NX;}$
- $NX_E = net\ exports\ of\ E;$
- $P_M = Price\ of\ M$, *where* $P_M$=1;
- $X_{I,M} = net\ balance\ of\ trade.$

$X_{E,M}$ and $NX_E$ are taken directly from the GCAM energy module. The Materials sector is the sole consumer of final-energy production.

For simplicity, all labor is assumed to be employed by the Materials sector.

$$L = L_M \tag{4}$$

$$X_{L,M} = L_M h_L(t) \tag{5}$$

$h_L(t)$ is an exogenous labor productivity scalar

Similarly, effective energy is given by

$$X_{E,M} = E_M h_E(t) g_E(t) \tag{6}$$

- $h_E(t)$ is an exogenous energy productivity scalar, and
- $g_E(t)$ is an endogenous energy service efficiency scalar calculated as an energy service index within the GCAM energy module.

The capital investment market distributes savings and international capital flows between energy and investment:

$$S = X_{I,M} + X_{I,E} + NX_K \tag{7}$$

- $NX_K = net\ international\ capital\ flows$;

Savings in turn is assumed to be a function of GDP,

$$S = f(GDP) \tag{8}$$

Investment in capital stocks employed to produce energy services includes those deployed in industry as well as those deployed in the household sector, such as cars, air conditioners, furnaces, and hot water heaters. The concept of savings is similarly expanded to include resources devoted to expenditures on energy services providing durable goods.

The energy module in GCAM version 6.0 uses a putty-clay representation of capital. In other words, once an investment is made, that capital stock remains productive throughout its assigned lifetime as long as the vintage can cover its operating costs. If a vintage of capital cannot cover its operating costs, the model retires that vintage.

The Materials sector capital stock is determined by the following capital accumulation equation (lambda is depreciation rate):

$$X_{K,M}(t) = (1-\lambda) * X_{K,M}(t-1) + X_{I,M} \qquad (9)$$

Prices of inputs to the Materials sector are given by

$$P_i = P_M \frac{\partial F_M}{\partial X_{i,M}}, i = K, L, E \qquad (10)$$

Across regions, net exports must sum to zero:

$$0 = \sum_R NX_{i,R} \qquad (11)$$

where i=E, K, M and R=regions.

### 2.3. GCAM-macro (KLEM) Social Accounting Matrix

The two-way interactions between energy and the economy require the articulation of a set of simplifying assumptions about an economy. Those simplifying assumptions carry implications for the way national income and product accounts are tracked. To facilitate the appropriate accounting within the GCAM macro-economic system, we articulate an implied national Social Accounting Matrix (SAM). We use the SAM to help ensure macroeconomic consistency.

A SAM organizes an economy's transactions and resource transfers between production activities, factors of production and institutions into a consistent set of accounts. The process of drafting the GCAM SAM provides the occasion for explicitly confronting the simplifying assumptions that go into the model.

A SAM is a series of double-entry bookkeeping accounts for which each row has a corresponding column and the reverse. An important feature of a SAM is that row sums and the corresponding column sums MUST be equal. That system of equalities enables post-calculation cross-checks on GCAM macro-economy solutions. If a row and column are not equal, the model has failed to solve correctly. The GCAM-macro SAM follows the approach developed by Hogan and Manne (1977) and is given in **Fig. 2**.

| | | Outputs | | Final Demands | | | |
|---|---|---|---|---|---|---|---|
| | | E | M | HH+ GOV | Cap | ROW | $\sum$ |
| Factor Inputs | E | | $P_E X_{E,M}$ | | | $P_E X_{E,NX}$ | $P_E X_E$ |
| | M | | | CN + G | I+D | $X_{M,NX}$ | $X_M$ |
| | HH + GOV | | $P_L X_{L,M}$ | | | | $\Sigma j\ P_L X_{L,j}$ |
| | | $P_K X_{K,E}$ | $P_K X_{K,M}$ | | | | $\Sigma j\ P_K X_{K,j}$ |
| | Cap | | | S+D | | NX | S+D +NX |
| | ROW | | | | | | 0 |
| | $\sum$ | $P_E X_{E,M}$ | $\Sigma j\ P_j X_{j,M}$ | C+G+S | I+D | 0 | |

E=energy sector
M=materials sector
HH+GOV=household and government sectors
ROW=rest of world
CN=non-durable goods consumption
D=energy service providing durable goods
G=government spending
I=investment spending
NX=net exports
S=savings
Cap=Capital Account
Pi=price of one unit of i=energy, materials, labor,capital
$P_M$=1
C=D+CN
Xi,j=quantity of good i sold to user j
i=E, M, K, L, Cap
i=E, M, HH+GOV, Cap, ROW

**Fig. 2.** GCAM-macro (KLEM) Social Accounting Matrix. In the SAM accounting framework, light green cells report inter-industry transactions. While important for ensuring consistency in our representation of the macro economy, these transactions are not part of the GDP.

The GDP is the value of NEW, FINAL goods and services produced in a given year. Entries in the gold cells represent purchases of NEW, FINAL goods and services by three categories of economic agents. Our aggregate agents are households and government (HH+G), capital (Cap), and the rest of world (ROW). Our Materials sector (M) is the retailer to the economy, and thus, all sales of NEW, FINAL goods and services are sold by the Materials sector, with one important exception, the net export of energy products to the ROW. GDP is the sum of C+I+G+net exports or the sum of all the values in the gold cells.

Because each row and column must sum to exactly the same thing, we can also calculate our GDP as the sum of payments to factors of production, reported in the blue cells. That is, GDP also equals payments to the primary factors of production, which we aggregate into payments to capital (K) and labor (L). By definition, all primary factor rewards are paid to either household (HH) or government (G).

Another useful cross-checks that is enabled by the SAM is the savings-investment cross-check, where Savings (S) plus net international financial transfers (NX) equals Investment (I). Note that we have chosen to include energy-consuming consumer durable goods purchases, such as cars and household appliances, in our capital account (rather than lumped into consumption). They are not formally investment purchases but represent part of the underlying energy-using infrastructure of the economy. The net international financial transfers will be inherited from the historical national accounts data. In the data system, we provide a constant to allow users to phase it out by a certain year or hold it constant for all years. It is currently configured to phase out by 2035.

Another example of a useful cross-check is the equality between net exports of NEW, FINAL goods and services and offsetting international capital transfers. That is, both the "ROW" column and "ROW" row must sum to zero.

### 2.4. Calculating economic consequences of perturbations in GCAM

In previous versions of GCAM, the cost of emissions mitigation was calculated using a "deadweight loss" approach in which the area under a marginal abatement cost schedule (MAC) was calculated using multiple GCAM runs. A description of this approach is provided at https://jgcri.github.io/gcam-doc/policies.html. As stated there, "The cost of GHG emissions mitigation is a concept that is not uniquely defined. A wide range of measures are used in the literature. These include the price of carbon (or as appropriate given the policy) needed to achieve a desired emission mitigation goal, reduction in Gross Domestic Product (GDP), consumption loss, deadweight loss, and equivalent variation. Beyond that the concept of net cost, which includes the benefits of emissions mitigation as well as the resource cost of emissions reduction and the social cost of carbon are also encountered. GCAM makes no attempt to calculate the benefits."

The addition of the GCAM macro module adds to the set of options available for reporting the economic consequences of any model perturbation. The GCAM model can now report GDP changes, consumption changes and/or deadweight loss. Each measure provides its own insights. Deadweight loss is a more "bottom up" approach, essentially adding the cost of each technology switch. Consumption and GDP are macroeconomic measures. Consumption is the most directly mappable to welfare. GDP is a better measure of economic activity.

One important advantage of the macroeconomic module is that the GDP and/or consumption consequences of a much wider range of perturbations can be obtained as a direct model output and needs no post-processing. In contrast, the deadweight loss approach requires a case-by-case development of methods when the economy is perturbed by something other than emissions mitigation enforced using a carbon price. Changes in consumption and/or GDP can be observed, for example, in response to changes in regulatory interventions, changes in water availability, or weather/climate.

### 2.5. Connect the macro equations to GCAM

In this section, we describe, still at a high level, how these equations interact with existing GCAM behavior and the mechanics of how information is passed between the various places that need it.

#### 2.5.1. Macro connection to GCAM

All of the places in GCAM that use GDP to drive behavior still do, such as final demand, which may use an income elasticity or the food demand model. Previously they would look up the value of a GDP object. Given the GDP could change with every iteration of the solver, and the Macro equations are simultaneously dependent on the outcome of such calculations within GCAM, we utilize *TRIAL* markets to resolve the dependency. And therefore, the GCAM objects that need a GDP value can just look it up from this *TRIAL* market at any time. Note: for convenience and added error checking, we include a SectorUtil to look up the value.

#### 2.5.2. GCAM connection to Macro

There are three main accounts to gather from GCAM to feed into the Macro equations. In all cases, information again flows via *TRIAL* markets due to the simultaneous nature of these equations.
The main account is “final energy service,” which is an index measure of the energy service from Buildings (Commercial and Residential), Transport (Passenger, Freight, International Aviation and Shipping), and Industry (Aluminum, Agriculture, Cement, Chemicals, Construction, Mining, Iron & Steel, and Other Industry). To reiterate, we need to be careful to capture just the energy service and not the physical good, such as tons of cement, to avoid double accounting with the Materials sector. The energy services are indexed by using prices from the final calibration year. The C++ object responsible for doing this is the new AccountingOutput, as described below.

Another important consideration when calculating GDP is to adjust for trade balances. In particular, we want to explicitly track the trade of Oil, Gas, Coal, and Biomass in terms of dollar value. We take advantage of the “traded oil”, etc sectors to calculate export values and the "regional oil", etc / import technologies to calculate import values. The C++ object responsible for doing this is the new AccountingOutput and AccountingInut which are described in more detail below.

Finally, we are interested in tracking the annual capital investments which occur throughout the energy system in GCAM so that it can be deducted from total savings potentially reducing the availability to build up the capital stock within the Macro model. This includes tacking investments in primary energy (oil, gas, coal); secondary energy (electricity, refining, gas processing, H2); and final energy (buildings, transport, and industry). Note: at the moment we are not tracking investments in infrastructure, an important piece which can be addressed in future work. The C++ objects responsible for doing this is the existing InuptCapital and new TrackingNonEnergyInput, described in more detail below. One wrinkle here is that consumer purchases of durable goods lasting more than a year, such as Light Duty Vehicles, are not capital investments but rather "consumer durable" consumption. For our purposes we would like to treat it similar to capital investments. Therefore, we track LDVs and residential building equipment separately so that we can move them from the consumption account and add it to savings, in this way maintaining balance in our social accounting matrix yet still including them as part of our investment constraint.

### 2.6. Historical Data for Calibration

Historical calibration of national income accounts, such as GDP, capital stock, wages, and savings, and additional inputs and parameters, such as population, labor force, and savings and depreciation rates of the capital stock, were based on the Penn World Tables (Feenstra et al., 2015). Country-level data was aggregated to the 32-region representation in GCAM.

The final energy service expenditure for each GCAM region was calculated from calibrated energy quantities and endogenous service prices from GCAM to ensure consistency of historical and projected future energy expenditures at the 32-region representation. Calibration of energy quantities for all fuels and energy carriers for historical periods is based on the IEA Energy Balances (IEA, 2015). This, along with historical global fuel prices, ensures robust estimates of energy expenditures for GCAM regions. Calculations of future final energy service are determined endogenously in response to changes in the demand for energy and prices resulting from the interplay of resource supplies and demands. Investment demands by the energy sector are determined endogenously. Energy sector investments include all capital investments associated with the production, transformation, and delivery of energy services. All other investments are attributed to the Materials sector.

For any projected labor force and GDP pathway, total factor productivity values can be selected to reproduce that pathway. That is, the model can be calibrated to replicate reference scenario GDP values or to match any alternative future scenarios of GDP pathways, such as the Shared-

Socioeconomic Pathways (SSPs) (IIASA, 2018). Alternatively, estimates of future labor supply and assumptions of total factor / labor / capital / energy productivity improvements can be used directly for determining future GDP outcomes. In all cases, these projects can subsequently be run in open GDP mode, described further in the “GDP Operation Modes” section below.

Assumptions of savings and depreciation rates for future periods are exogenous inputs and can be readily changed. A simple regression model of the relationship between historical per capita GDP and savings rates was applied to adjust future savings rates from initial historical rates by region. Depreciation rates were held fixed to historical values, as they are more uniform across regions.

## 3. Description of changes

### 3.1. Code Changes

Several new code objects were added to enable the endogenous calculation of GDP. These are the NationalAccountContainer, InputAccouting, OutputAccounting, TrackingNonEnergyInput, and NestedCESProductionFuntionMacro and associated nested function inputs. The currently existing NationalAccounts object was revamped to include just the accounting information which is need specifically for the KLE version of the Macro model.

As the name implies, the NationalAccountContainer is a container of regional national accounts by period and also the container of the macroeconomic production function for calculating the GDP. The NationalAccountContainer triggers the calculation of the GDP, creates necessary trial markets, and gathers relevant national account information that are input to the GDP calculation. For this specific core model proposal for including energy feedback into the GDP calculation, final energy service measure, energy trade, capital investments, and consumer durable good measures are the relevant information that are input to the GDP calculation.

In order to collect and aggregate the wide range of necessary energy related information from GCAM sectors and industries, two additional objects were created to gather information at the technology level. These are the InputAccounting and OutputAccounting objects and are included as inputs to or outputs of technologies for financial accounting and information gathering purposes only. These newly created objects do not affect the characteristics or performance of the technology. Input and output objects provide the most detailed level of economic outputs in GCAM.

Additional changes are needed to track the dollar value needed for new investments in the energy system. We take advantage of the existing InputCapital object (used in the electricity sector), which contains detailed information about capital costs; here we just need to add the market name in which to add the dollar value and a flag to signal when a Technology is a “new” investment.  For sectors / technologies which are presently reading in a total levelized non-energy cost, a new object is derived from NonEnergyInput called TrackingNonEnergyInput, which in addition to the market name and new vintage flags, will need to know how to convert the total levelized non-energy cost to annual capital investment by applying a “capital coefficient”. This coefficient will need to account for 1) The fraction of the cost, which is capital (as opposed to O&M) 2) the fixed charged rate used to annualize the capital investment. In addition, the TrackingNonEnergyInput will need to handle cases where no explicit vintaging is implemented in some technology. For this, it will receive the “previous output” from the Technology during initCalc and will have an assumed depreciation rate read in. Then it can calculate “new” output for the purposes of investment by ($Output_i$ - $Output_{i-1}$) + $Output_{i-1}$ * depreciation_rate * timestep.

A “Push” strategy for gathering information was implemented to provide the greatest flexibility in gathering accurate and fine-grained accounting and quantity information. Technology inputs and outputs push their information to regional accounting markets where access to the collected information is readily available through the Marketplace object. Hence, the NationalAccountContainer and NestedCESProductionFunctionMacro retrieve up-to-date energy related accounting information through the Marketplace object for dynamically calculating the GDP.

The actual creation of these energy accounting markets is done through the existing TrialValueResource objects, which provide flexibility for gathering a range of accounting information and allow improved solution behavior by providing independent trial values of accounts responding to GDP changes.

We note that the previous GDP object has been eliminated, and access to the GDP and GDP/capita is available from anywhere within the GCAM hierarchy through the SectorUtils object. This approach greatly simplifies and provides greater access to the GDP information within the Region object.

### 3.2. GDP Operational Modes and Calibration Procedure

There are two operational modes to specify the future GDP pathway, “fixed” and “normal.” These settings are specified in the main GCAM configuration.xml file under the Boolean section. The “FixedGDP-Path” mode fixes the future GDP pathway to the exogenously specified values in the socioeconomic_<SSP scenario>.xml input file. This mode replicates current GCAM macroeconomic behavior. Note that while the GCAM equations are being fed the fixed GDP, the Macro GDP calculation is still active (provided the NestCESProductionFunction is parsed) so that during postCalc total factor productivity is back calculated, which would allow the endogenously calculated GDP to match the “fixed” GDP (under the same exact scenario configuration). It is stored in the NationalAccount object and is reported to the database.

In order to utilize the calibrated labor productivity, the GCAM Data-System must be re-run with the revised calibrated total factor productivity values updated in the gcamdata input (socioeconomics/gcam_macro_TFP_open.csv), which will then be passed through to an updated socioeconomic_<SSP scenario>.xml file. To help facilitate this process a new script is added to the gcamdata package: data-raw/update_macro_productivity.R . This script does the following:

1. Creates a mapping from gcamdata SSP names to scenario names and XMLDB from which to query updated TFP values.

2. Runs *git describe* to create a tag useful for users to understand when the last time a scenario TFP value was updated.

3. Loops over each of the databases and queries for new TFP values. Note: it is not necessary for all database/scenarios exist.

4. Loads the existing socioeconomics/gcam_macro_TFP_open and updates the values for the scenarios for which we had new databases (including the *git describe tag*).

5. Saves the updated TFP back to socioeconomics/gcam_macro_TFP_open.csv

At this point, a user should re-run the data system (hopefully with driver_drake) to actually re-produce the XMLs.

After completing the GDP calibration process, the “normal” mode for endogenous GDP responses is possible. Turning the “FixedGDP-Path” off by setting the Boolean to null values (0) in the configuration.xml file, sets the GDP to operate in “normal” mode. In the “normal” mode, GDP responds to changes in the energy system, including changes to technology characteristics, net trade of energy, energy investment demands, and policy implementations, as well as any indirect changes to the energy system. Global and regional emissions policy or sectoral and technology specific policies, such as renewable portfolio standards (RPS) and subsidies, will affect the GDP response.

The endogenous and dynamic changes to the GDP ensure a more accurate representation of the economic responses to energy and climate policies and secondary feedback of energy system changes to economic outputs. Changes to GDP from energy and climate policy impositions provide a direct measure of the GDP or consumption (GDP-savings) losses for comparing the economic impact of alternative policies. GDP responses to alternative technology pathways also occur. Improvements to economic productivity from improved technical change, such as more efficient energy and energy service technologies, also result in higher relative GDPs. This could highlight and identify the relative merits of improving technical change across energy and energy service sectors. Marginal Abatement Cost (MAC) curve calculations are no longer necessary for comparing policy cost differences but can be calculated for comparison purposes. However, the GDP operational mode should be "fixed" to ensure proper MAC cost calculations.

### 3.3. GCAM Data System Changes

Some new R processing chunks were added to process macroeconomic data by country and by GCAM region. This includes an L180.GDP_macro for initial harmonization at the country scale and the L280.GDP_macro to aggregate the macroeconomic data and include other assumptions such as the NestedCES substitution elasticities. In addition, an L281.macro_account_tracking chunk is added, which serves as a mapping to tag which sector/technologies are "final energy service" and which are related to energy trade.

Other R processing chunks for representing energy production and energy service demands were modified to produce CapitalTracking tables, as noted in the Code Changes section. These chunks will include sector-specific assumptions, listed in **Table 1**, to calculate the "capital coefficient" (i.e., capital: O&M ratio and fixed charge rate) as well as a depreciation rate (for some sectors/technologies).

**Table 1. Sector-specific assumption in energy production and energy service demand**

| Sector | Capital Ratio | FCR (rate/years) | Depreciation Rate |
|---|---|---|---|
| Primary Energy | 0.6 | 10% / Half the lifetime | NA[1] |
| Electricity | NA[2] | 15% / 30 | NA[1] |
| Refining | 0.6 | 10% / 30 | NA[1] |
| Gas Processing | 0.6 | 10% / 30 | NA[1] |
| H2 | 0.8 | 10% / 30 | NA[1] |
| Buildings | 1 | 10% / 1 | 15 |
| Industry | 0.9 | 10% / 30 | NA[1] |
| Industry / Off road | 0.9 | 10% / 10 | NA[1] |
| Transport / LDV | NA[2] | 10% / 10 | NA[1] |
| Transport | NA[2] | 10% / 10 | 15 |

[1] Explicit vintaging lifetime and shut down assumptions in GCAM makes this parameter unnecessary.
[2] Detailed cost data was available, so no further assumptions were needed.

The primary macroeconomic data comes from the Penn World Tables Version 9.1 (PWT) which includes economic data by country up to 2017. GDP, consumption, capital stock, capital stock depreciation, labor force, labor hours worked, labor wages, savings, savings rate, and investment data are required for the GCAM macroeconomic calculations. For determining rates and shares, the consistent dataset of the PWT is utilized. Both country and GCAM 32 region level data are generated.

However, GCAM's GDPs by SSP scenarios are calibrated to the SSP Database Version 9. The SSP database is also used for the total population and population by age cohort. The projection of the labor force for future years comes from the SSP database and aggregation of 15 – 64 age cohorts, excluding those in school and not available for work.

Future savings rate projections by GCAM regions are based on a linear regression model of GDP per capita growth rates and lagged savings rates from historical PWT data. The regression coefficients are then read into GCAM, thus no need to separate assumptions by SSP, for instance.

### 3.4. Model Interface Queries

The national account results, including the GDP and related macroeconomic components, are available from the socioeconomics folder. The single National Account query reports a full list of accounting information, including GDP, capital, savings, energy, and various productivity measures. We also provide a Social Accounting Matrix query (granted post-processing is required to reshape it into a Matrix), useful to ensure all accounts balance.

There are also queries to get detailed information about the GCAM energy financials including: Final Energy Service in $ by sector and tech, Gross energy trade in $ by sector and tech, and Capital investments by sector and tech.

### 3.5. Accounting for Carbon Market Values

Note that all behavior related to the imposition of a carbon policy continues to be handled in GCAM. The Macro model responds indirectly by observing changes in final energy service, the capital intensification of the energy system, and shifting energy trade patterns from GCAM. Given the structure of our Social Accounting Matrix any net revenues generated from the carbon market are financial transfers **within** the bounds of the Materials sector, thus, any further adjustments would be double accounting. However, a caveat is if a user wanted to model an **explicit** carbon permit regime with trade between regions, then the net trade value **does** need to be accounted for and show up in the "ROW" column of our Social Accounting Matrix. More model development is needed to fully support this feature thus the capability is **not** yet available in this version.

# 4. Reference and shared policy assumption (SPA) GCAM validation runs

## 4.1. Reference case reproduction

There is no GCAM results change as a result of simply adding the Macro model when run with Fixed GDP or in Reference scenarios using Open GDP with appropriately calibrated total factor productivity. In the following set of figures, we run the validation runs using Fixed GDP mode.

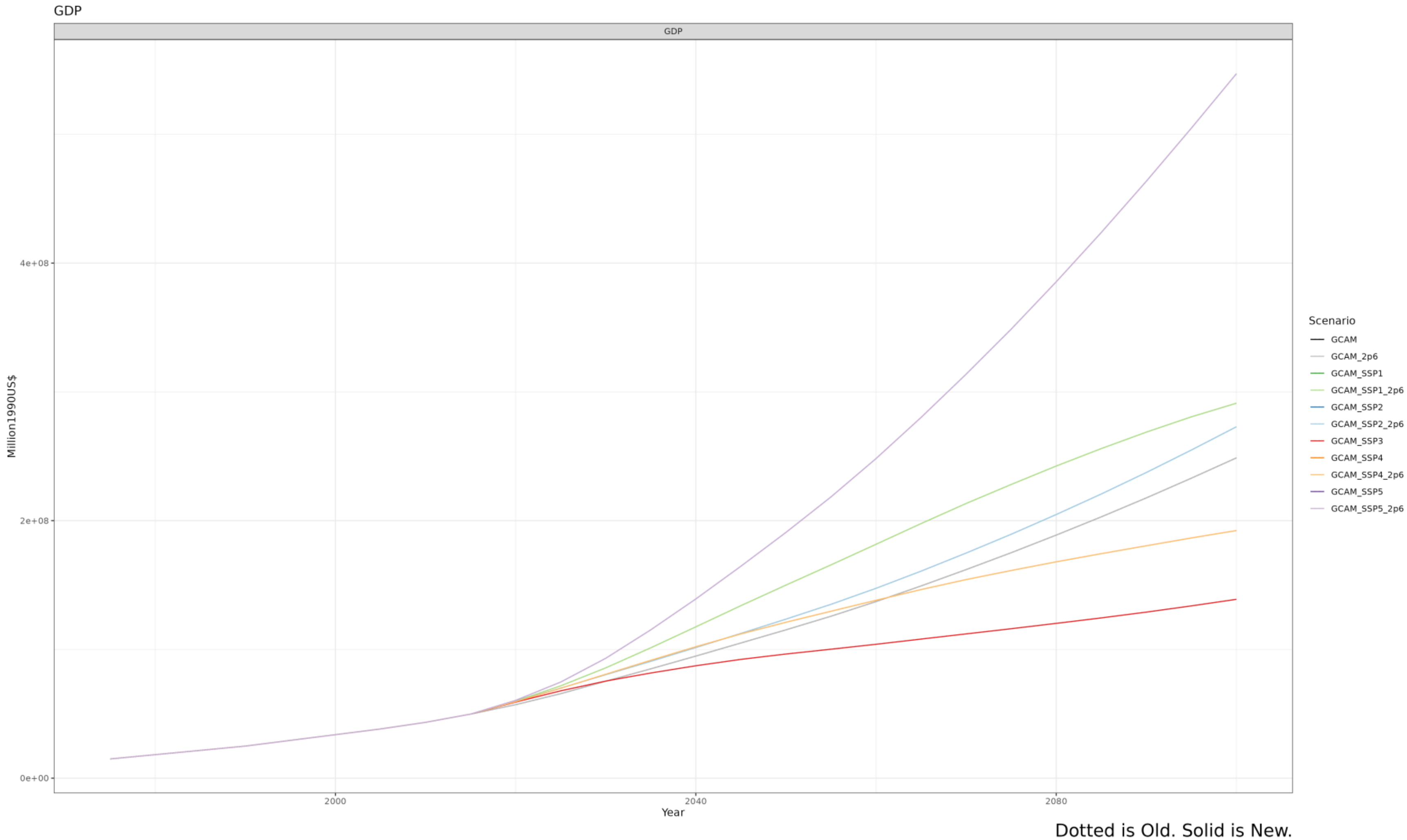


**Fig. 3** GDP projection in SPA runs using the "Fixed" mode

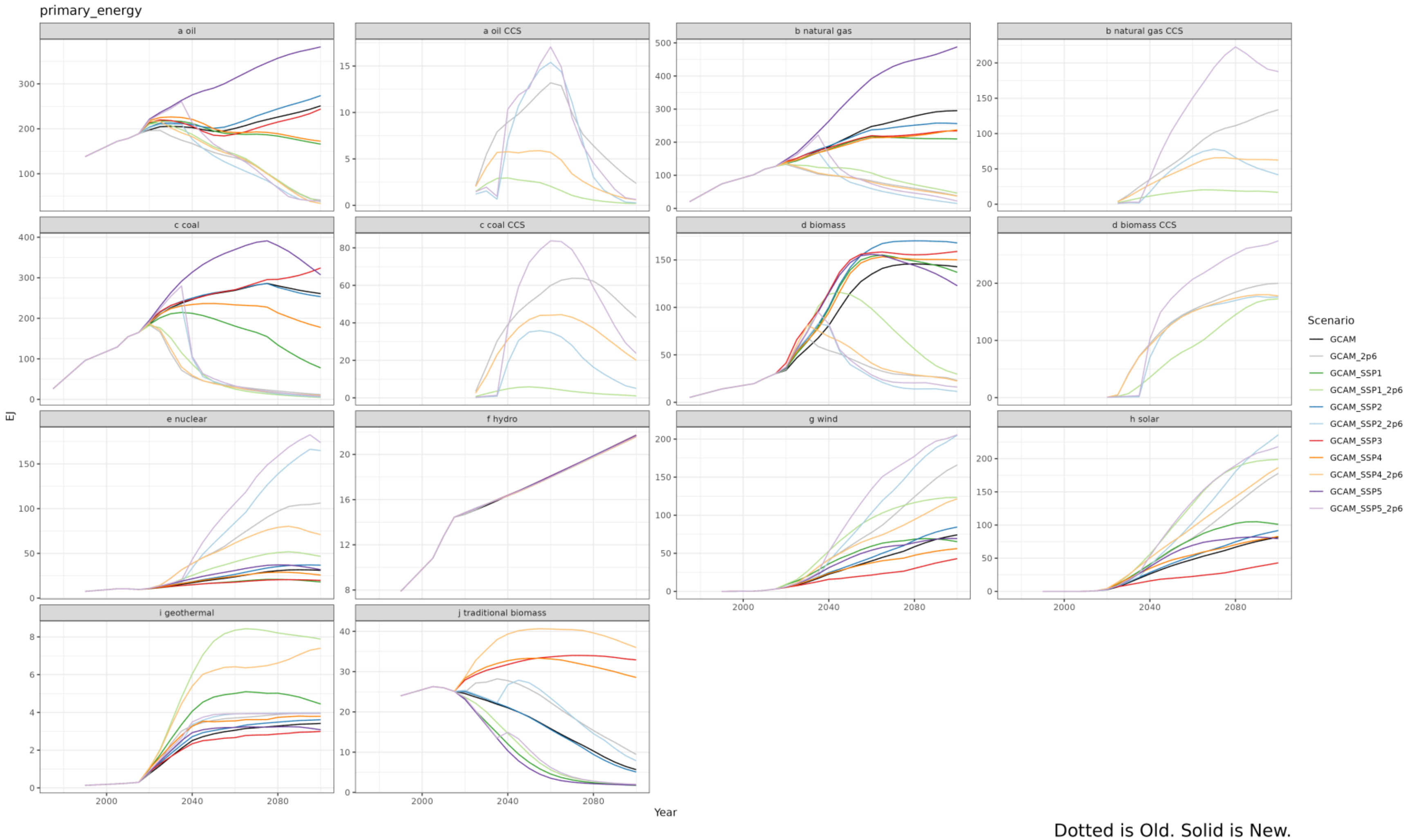


**Fig. 4** Primary energy projection in SPA runs using the "Fixed" mode

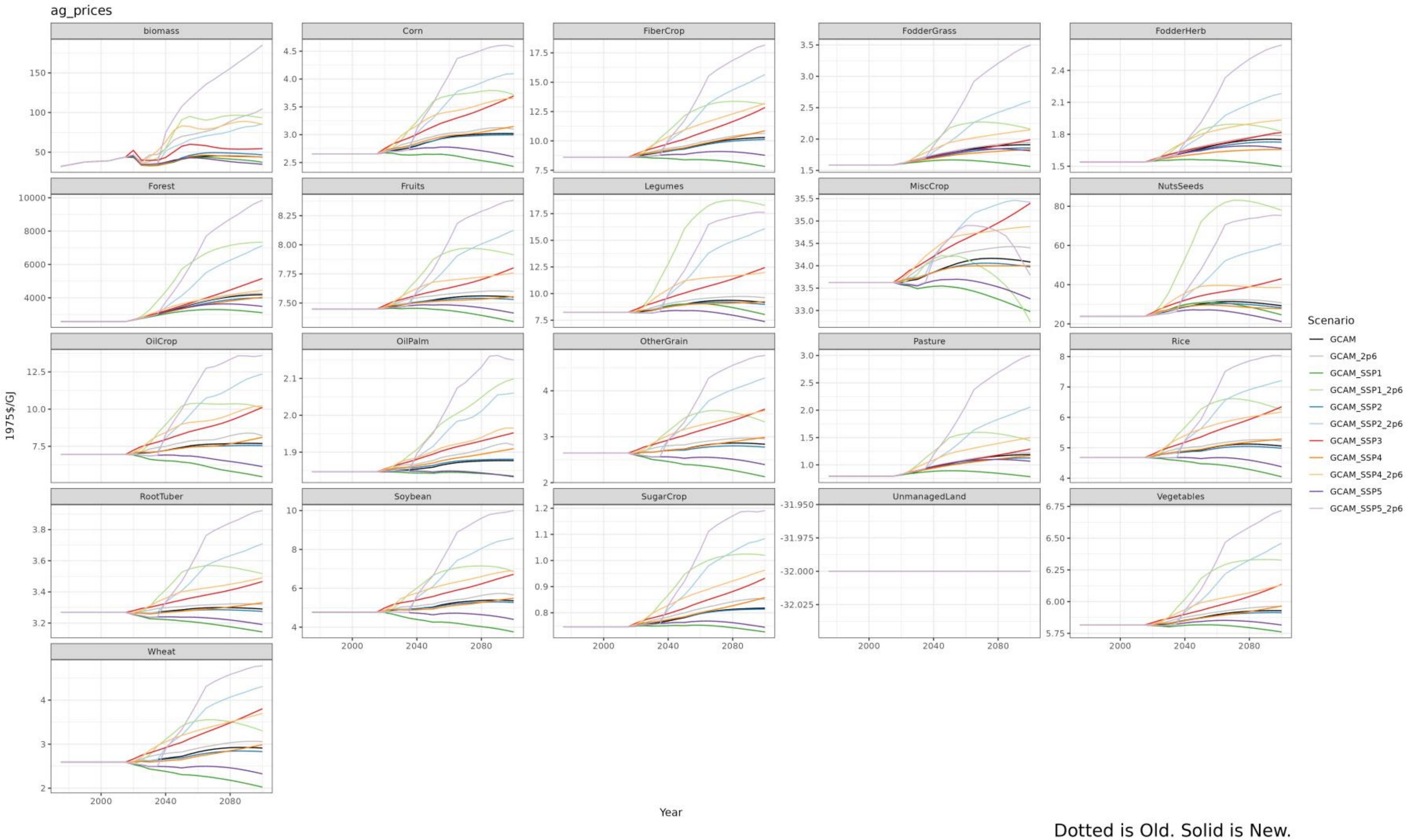


**Fig.5** Agricultural producer price projection in SPA runs using the “Fixed” mode

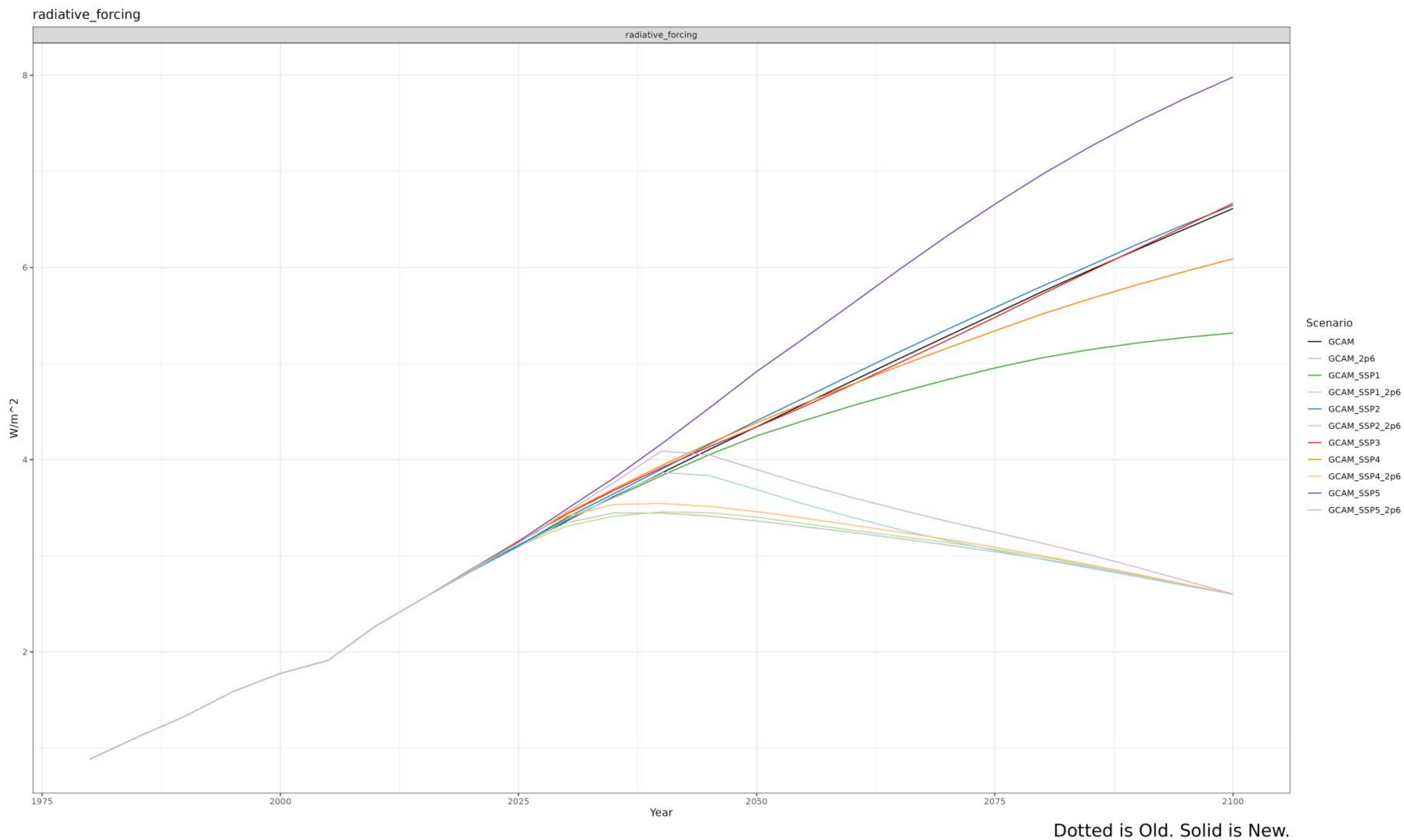


**Fig.6** Radiative forcing projection in SPA runs using the “Fixed” mode

When running a policy in Open GDP mode, we do expect to see a divergence in GDP and, subsequently, all other GCAM results. In the following set of figures, we ran the validation scenarios in Open GDP mode, feeding in the calibrated productivity from the above set of runs.

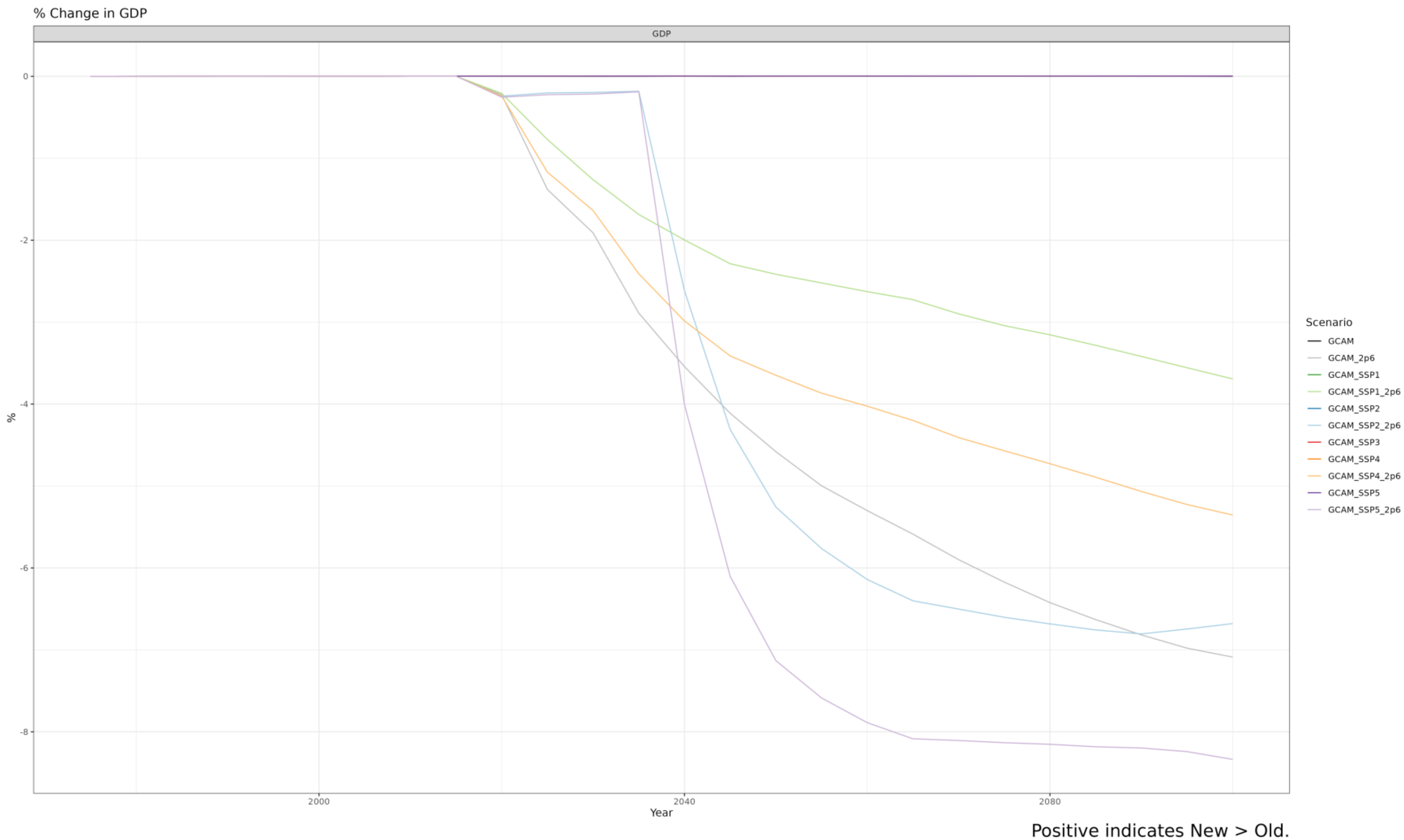


**Fig. 7** Changes in GDP projection in SPA runs using the "Open" mode relative to the "Fixed" mode

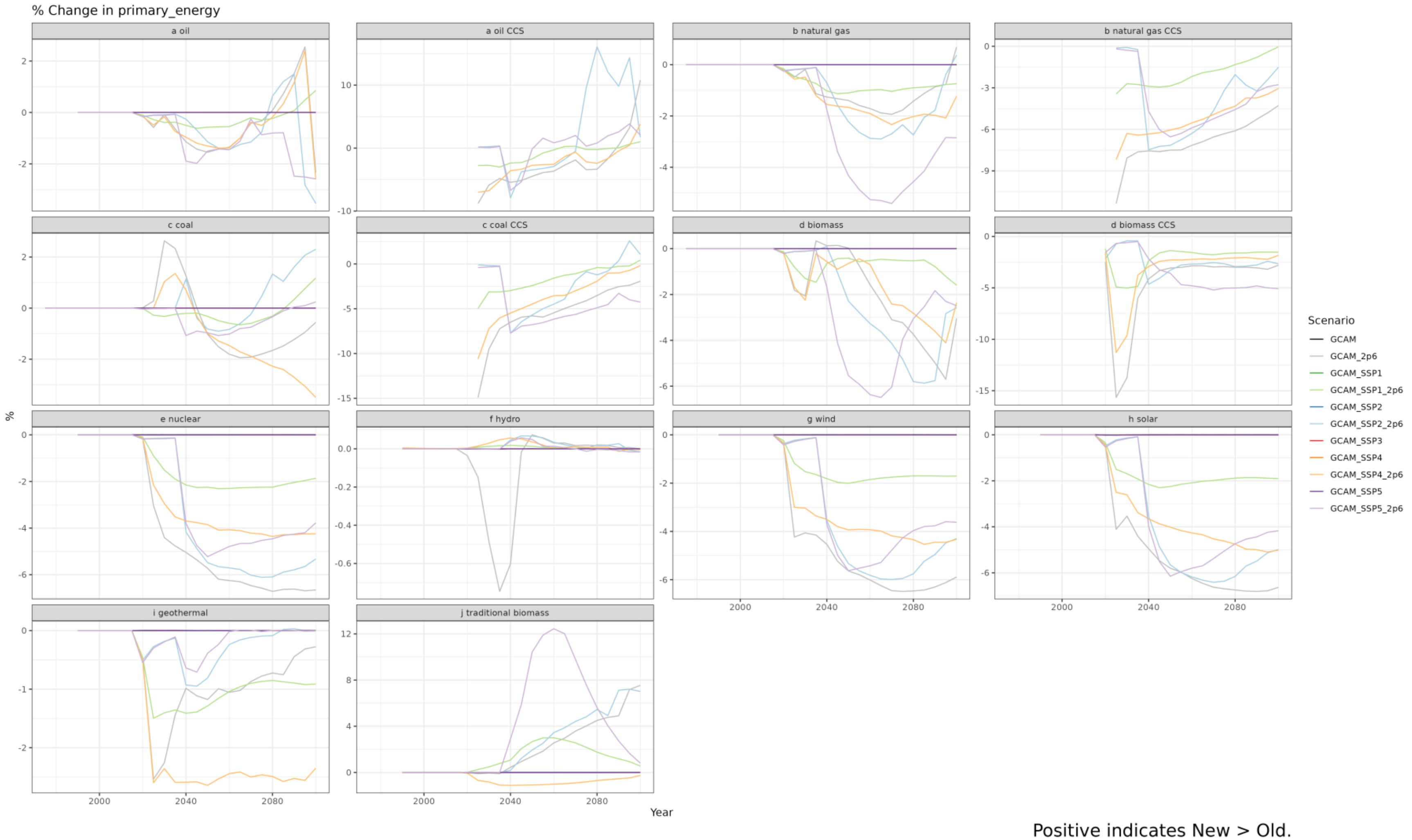


**Fig. 8** Changes in primary energy projection in SPA runs using the "Open" mode relative to the "Fixed" mode

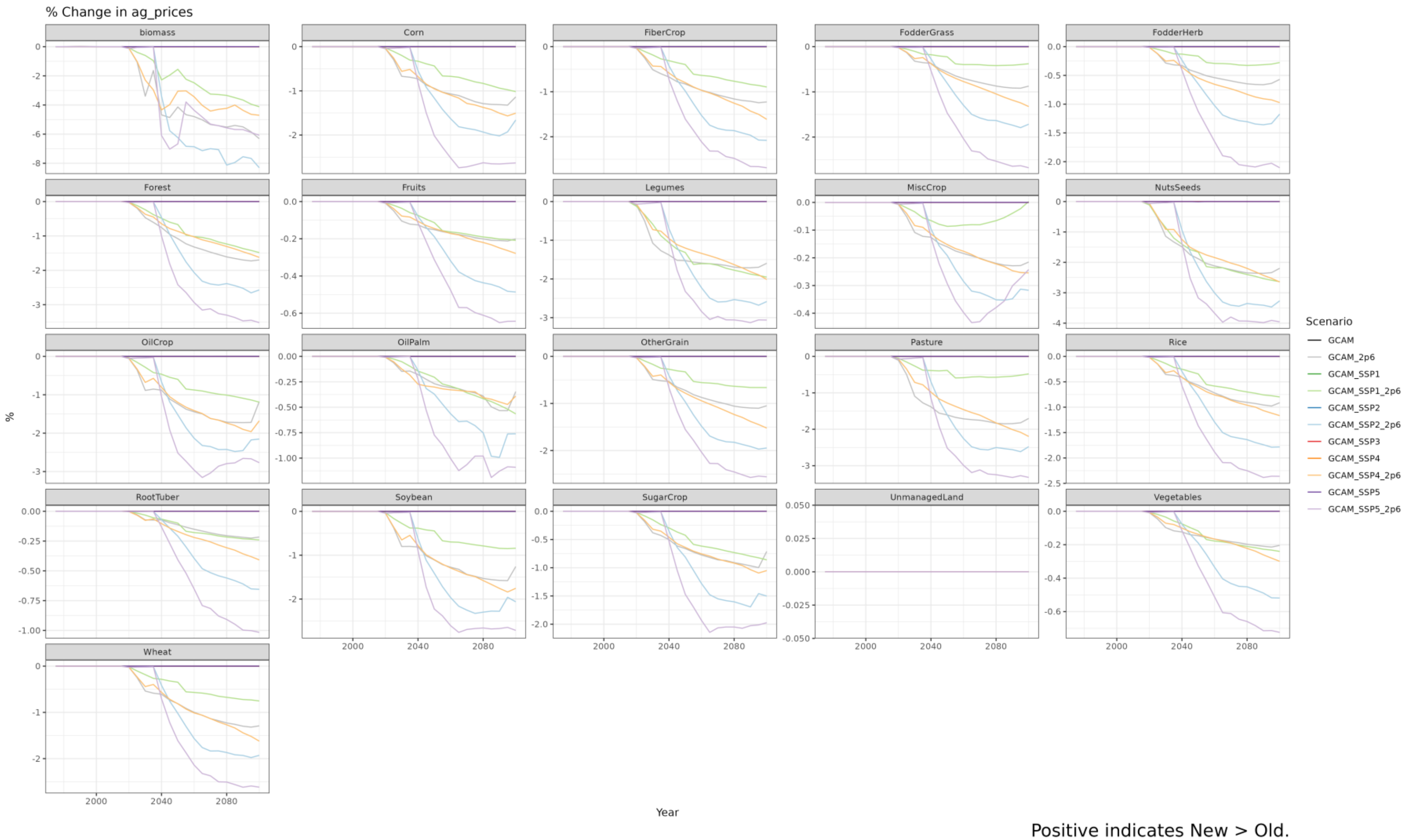


**Fig. 9** Changes in agricultural price projection in SPA runs using the "Open" mode relative to the "Fixed" mode

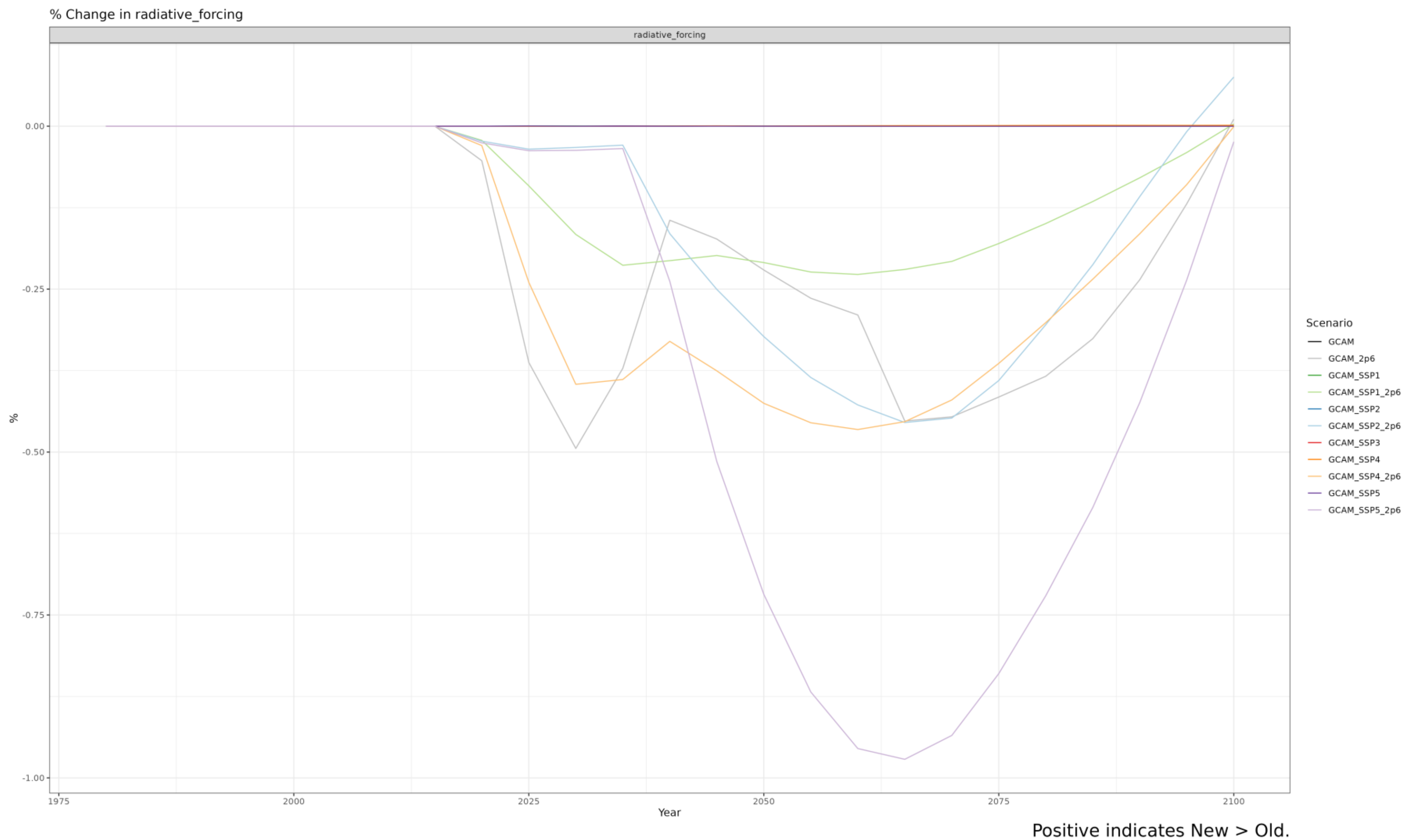


**Fig. 10** Changes in radiative forcing projection in SPA runs using the "Open" mode relative to the "Fixed" mode

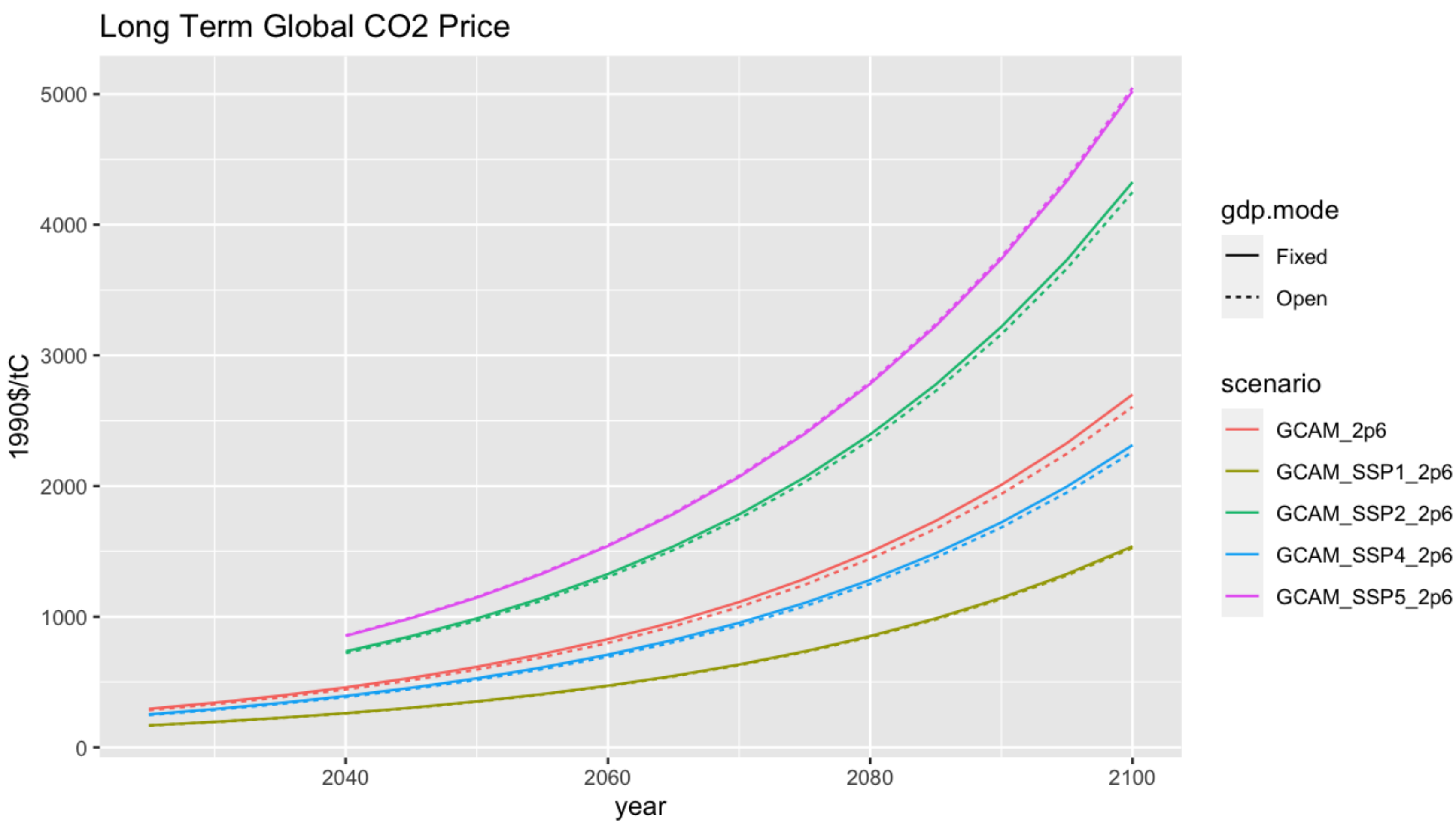


**Fig. 11** Carbon prices in SPA runs, “Open” mode vs. “Fixed” mode

### 4.2. Additional validation scenarios

The following set of diagnostic figures have been helpful to more directly perturb the Macro and check its response. These scenarios include the Reference (Ref), changing the productivity for each labor (L), capital (K), and energy (E). In addition, we include the RCP 2.6 scenario as well as a scenario where we remove a major energy-exporting region from the trade network (X).

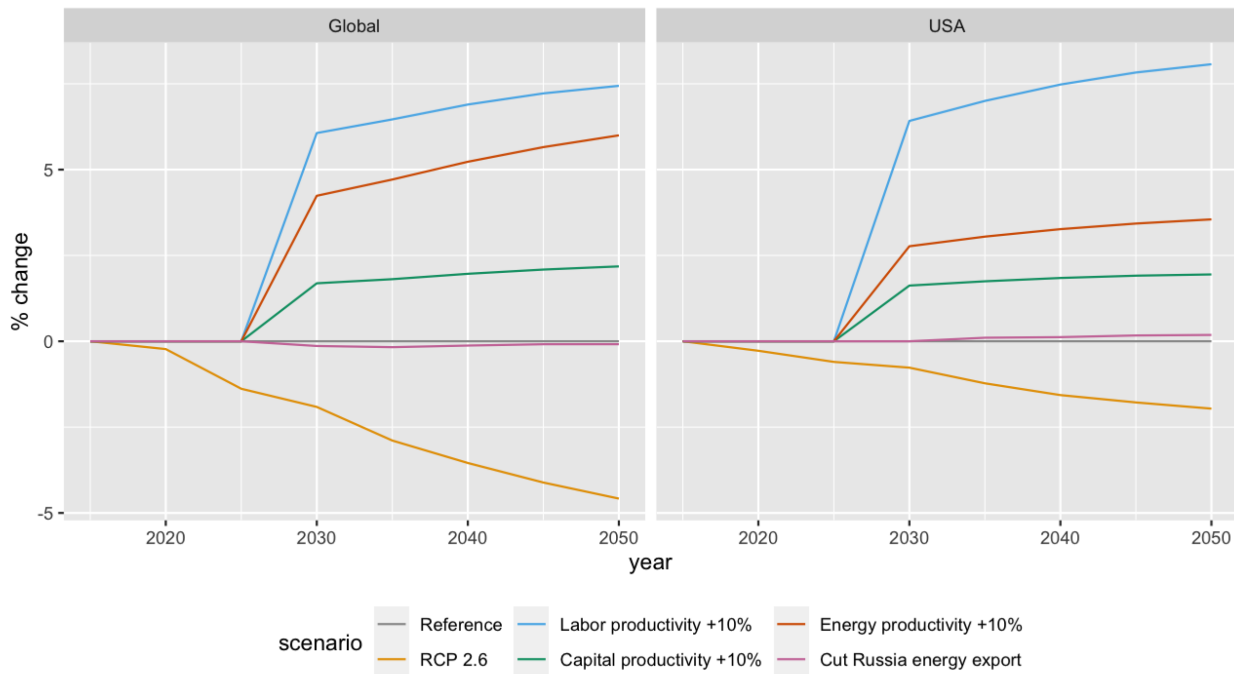


**Fig. 12** Global and US GDP changes by 2050 relative to the base year across the scenarios

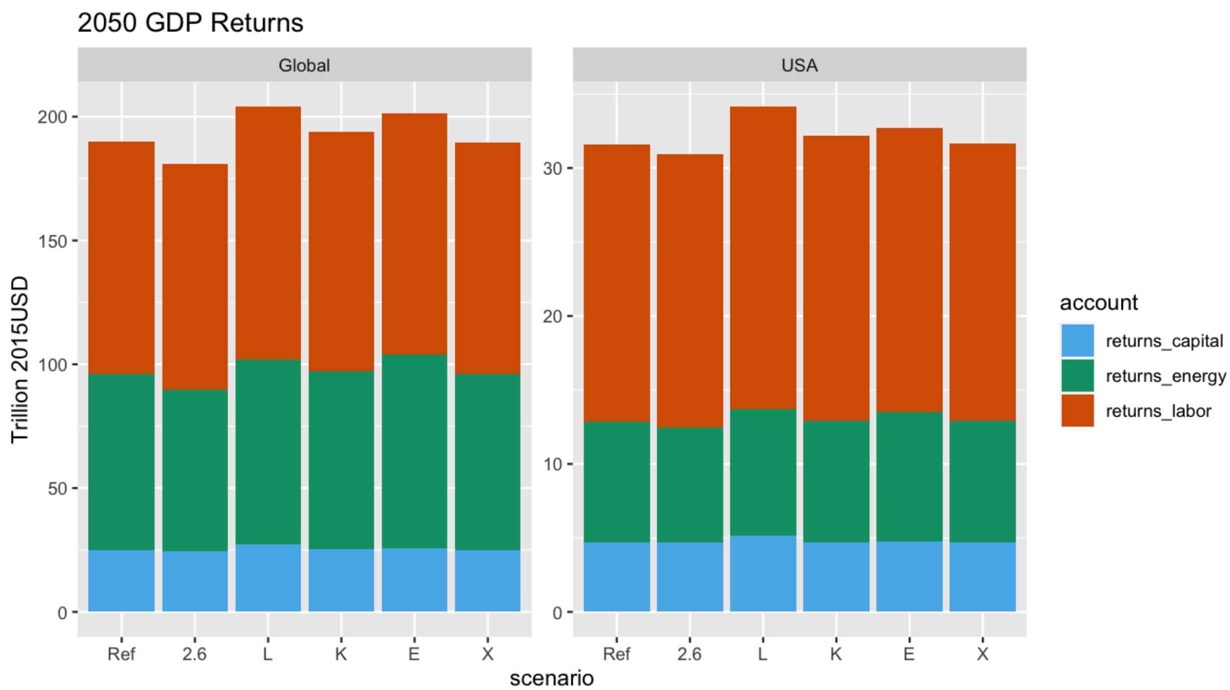


**Fig. 13** Decomposition of 2050 GDP by factor income

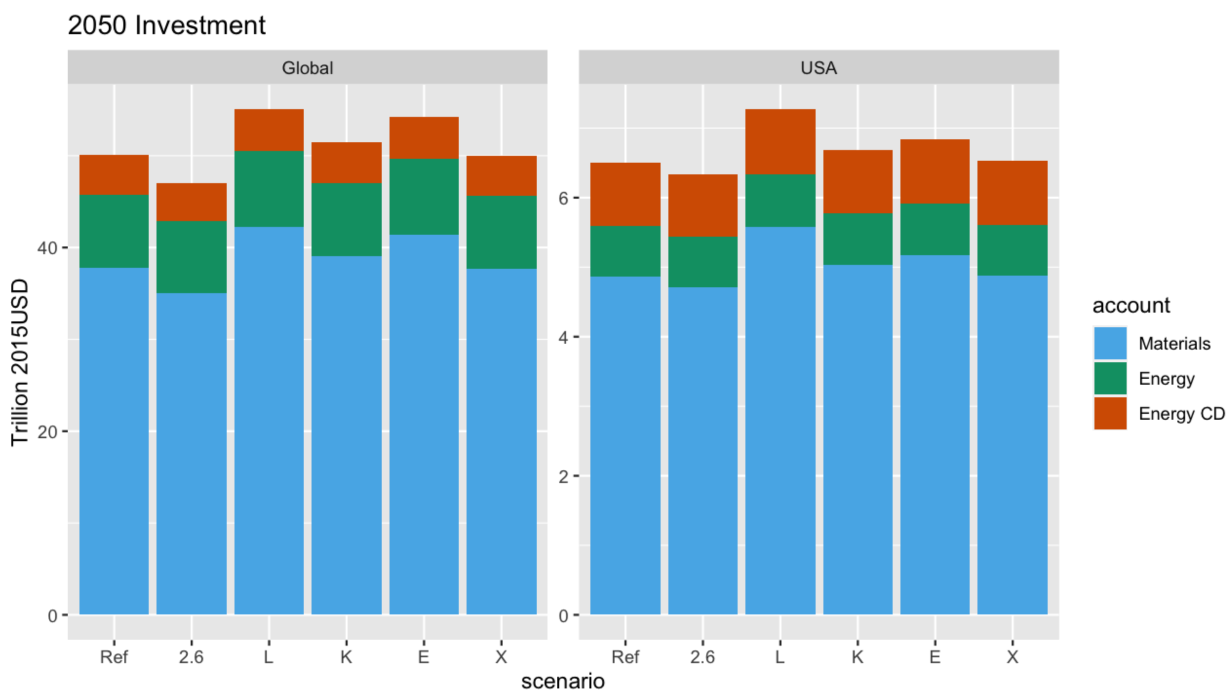


**Fig. 14** Decomposition of 2050 investment

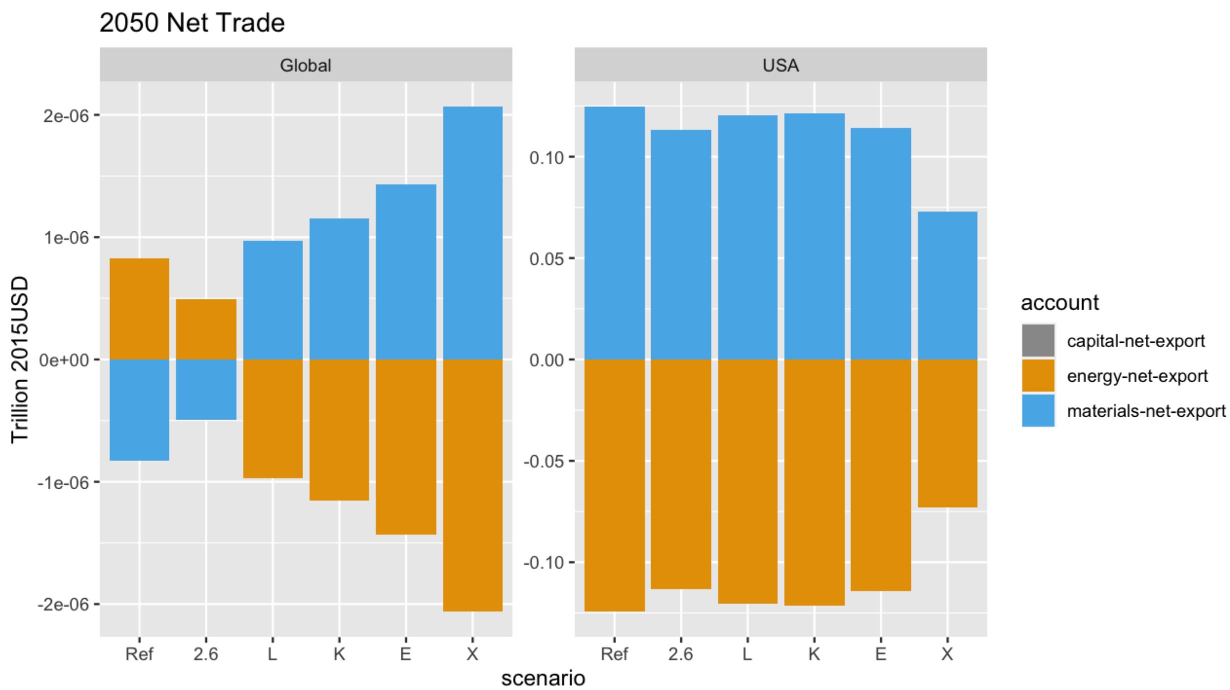


**Fig. 15** Decomposition of 2050 net trade

## 4.3. Comparison of GDP changes to literature (IPCC)

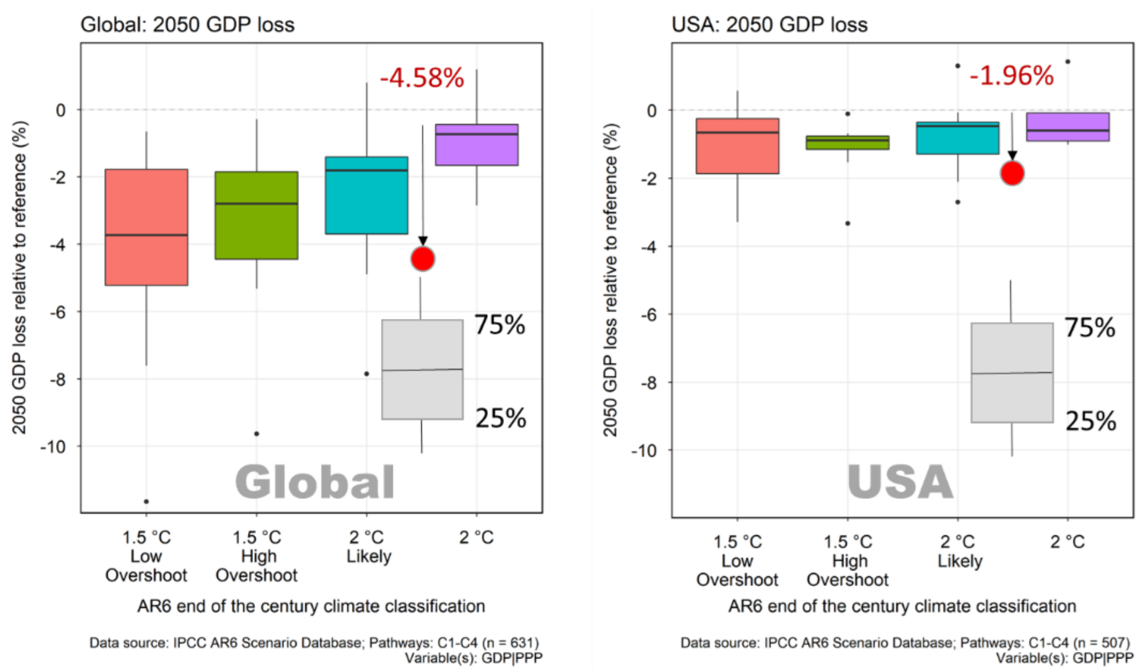


**Fig. 16** Comparing GDP impacts with the IPCC AR6 scenarios. GCAM results are shown as red dots.

## References


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., Wise, M., 2019. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. Geoscientific Model Development 12, 677–698. https://doi.org/10.5194/gmd-12-677-2019

Edmonds, J., Reilly, J., 1983. A long-term global energy-economic model of carbon dioxide release from fossil fuel use. Energy Economics 5, 74–88.

Edmonds, J.A., Reilly, J., 1985. Future global energy and carbon dioxide emissions. Atmospheric carbon dioxide and the global carbon cycle 215–246.

Feenstra, R.C., Inklaar, R., Timmer, M.P., 2015. The next generation of the Penn World Table. American economic review 105, 3150–3182.

Hogan, W.W., Manne, A.S., 1977. Energy-Economy Interactions: TheFable of the Elephant and the Rabbit? Advances m the Economicsof Energy and Resources 1.

IEA, 2015. World energy balance.

IIASA, 2018. SSP Database.

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., 2011. Description of the ReMIND-R model.

Manne, A.S., Richels, R.G., 1990. CO2 emission limits: an economic cost analysis for the USA. The Energy Journal 11.

Messner, S., Schrattenholzer, L., 2000. MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 25, 267–282. https://doi.org/10.1016/S0360-5442(99)00063-8

Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., 2014. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).