The Role of Three Key Emitters in Meeting Minimal Paris Agreement Emissions Targets in a Global Energy and Trade Model

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Abstract

Meeting net-zero emissions targets requires major and ongoing reductions in the use of fossil fuels. We focus on the role of three key emitters in a large dimensional, 30 country/region energy and trade model, designated as GTAP-R, to meet minimal Paris Agreement targets, illustrating the path in emissions reduction and the shift in energy mix from coal, oil and gas to renewables. The model incorporates changes in energy efficiency, energy intensity, increases in the demand for renewables and the use of a price on carbon to reach a minimal Paris target, comparing emissions (as a result of fossil fuel consumption only) along comparable transition pathways SSP2-RCP4.5 (Base Case) to (better than) SSP1-RCP2.6. Results show that the use of fossil fuels needs to be reduced substantially by 2050, for coal alone by 90–100% in India, China and the USA, compared to 2019, with a sustained transition to renewable energy. Globally, model results show reductions in fossil fuel carbon emissions overall must decrease by at least 3% per year, on average, to meet (or exceed) a minimal Paris Agreement target of less than 2^oC warming and domestic coal consumption must fall continuously from 2022 forward. As an addendum to the main results, we also show that limited carbon sequestration from forestry and land use change can help generate a near global net zero model outcome in 2050, albeit with marked uncertainty. Overall, the results indicate the need to dramatically reduce fossil fuel consumption (especially coal), showing the feasibility of meeting a better than SSP1-RCP2.6 emissions reduction target with increases in renewable energy, while still allowing for 'green growth' or increases in GDP.

Keywords: GTAP-R; energy mix; emissions reduction; renewable energy; Paris targets.

JEL classification: C68, D58, Q4, Q54, O13.

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February 4, 2022

1. Introduction

The transformation of the global energy system needs to accelerate substantially to meet the Paris Agreement objectives. If not, the potential impacts from global warming are enormous, with economic damages of more than $271 trillion USD in cumulative losses from now to 2100 at 3^oC warming, and annual country losses in GDP that range from less than 1% to over 17% in 2100, even with very limited damage functions (due mainly to losses in agricultural and labour productivity from rising temperatures) (Kompas et al., 2018). Additional damages from sea level rise and storm surge, extreme weather effects, bushfires, flooding, damages to human health and losses in biodiversity will only add to these dollar amounts, with enormous differences in impact across countries and regions (Piontek et al., 2021).

Despite the growing concern over the effects of global warming that result from the rapid growth in greenhouse gas emissions (GHG), these emissions have continued to increase, save for the now temporary impacts of COVID–19 in 2020 (UNFCCC, 2021). A large proportion of global GHG is due to the release of carbon dioxide, about 85% of which is due to the burning of fossil fuels with the remaining 15% generated from agriculture, deforestation and land degradation (IPCC, 2021).

While energy is needed to power economic growth and maintain standards of living, it is clear that the energy mix must move away from fossil fuels (especially coal) to reduce carbon emissions. This paper presents a novel computable general equilibrium (CGE) energy and trade model using the GTAP-P database (Hertel (1997); GTAP (2021); Chepeliev (2020)), for 30 countries/regions and 28 commodity sectors, designated as GTAP-R, to determine the needed change in energy mix and fall in carbon emissions to meet a minimal Paris target consistent with or better than SSP1-RCP2.6 (IPCC, 2021). Although GTAP-R provides model results for 30 countries/regions, we concentrate on three key emitters, China, the USA and India (with results also reported for the G7, BRICS and the World as a whole).

Generally speaking, CGE models are not able to adequately capture changes in the energy mix or rapid changes in technology or the demand for energy. We overcome this by adding two components not normally found in GTAP models, using GTAP-E (Burniaux and Truong (2002) and Truong et al. (2007)) to incorporate carbon-based fossil fuels, energy substitution and carbon pricing and GTAP-P (Chepeliev, 2020), an updated version of Peters (2016), which allows for a decomposition of the electricity sector in terms of fossil fuels and renewable energy (e.g., wind, solar, nuclear and hydro power). The combination allows for a unique representation of changes in energy mix (produced for export or consumed domestically), carbon emissions and trade patterns between countries and regions. With this, we incorporate changes in energy efficiency and intensity, a falling price for renewable energy, increases in the demand for renewables, policy changes and a price on carbon to generate the needed change in energy mix to meet (or exceed) a minimal Paris target. The technical set-up builds on the modelling approach in Kompas and Van Ha (2019), but instead employs a dynamic adaptive framework based on a disequilibrium approach to modelling capital mobility across regions (Ianchovichina et al., 2000), while still allowing for growth in population and country/region GDP to 2050. An addendum to the main results tracks the impact of limited changes in carbon sequestration from forestry, albeit with considerable

uncertainty.

The focus on a comparable SSP1-RCP2.6 transition path in GTAP-R is intended to indicate the minimum pathway for less than 2^oC warming by 2100, with the needed change in the energy mix to 2050. Although SSP1 allows for population and growth in country/region GDP, the RCP 2.6 scenario is designed to represent very low GHG emissions. Using a statistically based probabilistic framework indicates that having just a 50% chance of staying below 2^oC warming requires an average rate of decline in emissions of roughly 1.8% per year (Liu and Raftery (2021) and Raftery et al. (2017)), with net zero reached between 2065 and 2080 (van Soest et al., 2021). But these targets vary considerably by country/region and substantially lower emissions from China, the USA and India are key to any success. This is detailed in GTAP-R, achieving a target in emissions reductions better than SSP1-RCP2.6 and annual average falls in fossil fuel emissions of greater than 3%, relative to 2015.

Section 2 of the paper provides the background in terms of energy use for the three key emitters, China, the USA and India. Section 3 provides a general discussion of the methods used to generate results and section 4 details model structure. Unlike basic integrated assessment models (e.g., Hope et al. (1993) and Rezai and van der Ploeg (2017)), or far less flexible, at least in terms of changes in energy mix, 'bottom-up' or hybrid approaches such as GTEM models (e.g., Cai et al. (2015)), GTAP-R is a disaggregated, 'top-down', country and region specific model of production, trade, and changes in energy mix that adequately accounts for inter-fuel substitution and increases in renewable energy.[1] Section 5 outlines data sources and key assumptions and Section 6 provides model results. We characterise the impact of carbon sequestration from forests as an addendum to the main GTAP-R model in Section 7 and section 8 provides concluding remarks.

2. Background: Energy Use for the Key Emitters (China, the USA and India)

According to the IEA (2021*c*) and (BP, 2020), fossil fuels as an energy share accounted for more than 80% of global production in 2019. However, the share of non-fossil fuels (nuclear energy, hydroelectric, and renewables) in the total fuel-mix supply has been increasing rapidly from less than 3% a decade ago to 15.7% in 2019 (BP, 2020). As the primary source of fuel consumption, carbon dioxide from fossil fuel use has also been increasing, especially over the past two decades (with the average annual growth rate from 1.1% in the 1990s to 1.94% in the 2000s (computed from BP (2020)). In 2019, the three largest emitters were China, the USA, and India, accounting for 29.0%; 14.5%; and 7.3% of global carbon emissions, respectively (BP, 2020).

These three key emitters, China, the USA and India, account for more than 40% of world population, 45% of global GDP (IMF, 2021), and 51% of carbon emissions (BP, 2020). China alone accounted for 51.7% of global coal use in 2019 (BP, 2020), increasing by nearly fourfold

[1] A full review and assessment of physical and economic models of climate change is provided in Piontek et al. (2021). Along with a comparison of different approaches to the economic modelling of climate change, figure 4 in this work illustrates the considerable heterogeneity in potential damages from global warming across countries in terms of relative losses in GDP.

from 1990 to 2014, although relatively stable since 2015 (BP, 2020). The second-largest fuel use in China was petroleum, crude oil, LPG and other refined oil products accounting for over 20% of total energy consumption in 2019. Although China has diversified its energy supplies and cleaner-burning fuels have replaced some coal and oil use in recent years, hydroelectric sources (8%), natural gas (8%), nuclear power (2%), and other renewables (nearly 5%) accounted for a relatively small albeit growing share of China's energy consumption (EIA, 2021*a*).

According to EIA (2021*d*), the USA's primary energy consumption by energy source in 2020 was petroleum (35%), natural gas (34%), renewables (12%), coal (10%), and nuclear power (9%). Coal was the leading source of USA fossil fuel production during the mid-1980s through to 2010, but coal production has since been surpassed by natural gas (in 2011) and crude oil (in 2015). In 2020, the USA produced twice as much energy from crude oil (24 quadrillions Btu) than coal (11 quadrillions Btu) and three times as much energy from natural gas (35 quadrillions Btu) (EIA, 2021*b*).

India is the third-largest energy consumer in the world and also the third largest carbon emitter in the world (after China and the United States) (BP, 2020). Primary energy consumption in India nearly tripled during 1990-2019, estimated at 937 million tons of oil equivalent (Mtoe) in 2019. During 2000-19, coal, petroleum, and gas consumption all increased by a factor of 2.5 (BP, 2020). In 2019, coal continued to supply most (54.6%) of India's end-use energy consumption, followed by petroleum and other refined liquids (30%), and traditional biomass and waste (20%). Although natural gas accounts for 6% of total energy consumption, India plans to increase the natural gas market share to 15% by 2030 as part of the country's plan to reduce air pollution and use cleaner-burning fuels. Other renewable fuel sources make up a small share of primary energy consumption, although the potential capacity is significant for solar, wind, and hydroelectric sources of energy (EIA, 2021*c*). Over the past decade, nuclear, renewables, and solar energy have grown rapidly at an annual rate of 9.2%, 16.0%, and 27.3%, respectively (BP, 2020).

In 2019, India was the third-largest consumer of crude oil and petroleum products after the USA and China. The gap between India's oil demand and supply is widening. In 2019, demand and domestic supply were 4.9 and 1 million barrels per day (b/d), compared to less than 1 million b/d of total domestic oil liquid production. Diesel, which is used primarily for commercial transportation, and to a lesser degree in the industrial and agricultural sectors, remains the most consumed oil liquid in India, accounting for 39% of oil refinery product consumption in 2019. Gasoline consumption, which accounts for 14% of total oil liquid consumption, has also increased rapidly over the past few years (EIA, 2021*c*).

3. Methods

Our GTAP-R model is a large dimensional Computable General Equilibrium (CGE) model essentially based on an extensive data set developed by the Global Trade Analysis Project (GTAP), which is an essential tool for researchers and policy makers conducting quantitative analysis of changes in produced output, trade patterns and commodity flows (Hertel, 1997; GTAP, 2021). In its current form, a GTAP model (and its accompanying database) is a trade

model where countries/regions can buy and sell goods and services from each other. In each country, there are several producers, each one produces a single good or service, which is consumed domestically by regional households (i.e., final consumption) and producers (i.e., intermediate demand for products as inputs in the production of other commodities), or will be exported to other international regional households or producers. In the production process, firms employ or rent inputs (capital, land, labour and natural resources) from households and purchase intermediate products from other producers. Producers maximise their current profits given inputs and output prices. Regional households earn income from selling productive inputs and allocate this income to consumption expenditures and savings. Governments, with associated expenditures and tax revenues, are also included and inter-regional or cross-country flows of exports and imports of commodities is modelled.

In GTAP-R, we add two components not normally found in GTAP models. First, GTAP-R builds on GTAP-E (Burniaux and Truong (2002) and Truong et al. (2007)), which incorporates primary carbon-based fossil fuels, energy substitution and carbon pricing into the standard GTAP model. Second, since GTAP-E uses an aggregate of the electricity sector, with no allowance for substitution between fossil fuels and renewable energy, we also build on GTAP-P (Chepeliev, 2020), an updated version of Peters (2016), which allows for a decomposition of fossil fuels and renewable energy (e.g., wind, solar, nuclear and hydro power). The combination allows, in particular, for a unique representation of changes in energy mix (produced for export or consumed domestically), carbon emissions and energy and trade patterns between countries and regions. GTAP-R also incorporates changes in energy intensity and efficiency and, as an addendum to the main model, potential changes in carbon sequestration from forestry.

The model set-up employs a dynamic adaptive modelling framework based on a disequilibrium approach to modelling capital mobility (Ianchovichina et al., 2000). The disequilibrium approach provides the added realism needed to reconcile changes in savings with the movement of investment funds across regions and countries. Given the saving is allocated across regions to those investments with the highest rate of return, flows of capital and foreign asset ownership over time ensure that rates of return tend to converge in the long run (Ianchovichina and McDougall, 2000). Specific detail on model structure and the dynamic adaptive framework is detailed below. Finally, the model aggregates the global economy into 30 countries/regions with 28 commodity sectors (e.g., agriculture, livestock, forestry, crops, chemical products, manufacturing, services, transport, energy, etc.). We report mainly on major carbon emitters, China, the USA and India, although aggregates for the G7, BRICS and the World are also indicated. Details of the regions and sectors are contained in the Appendix.

Essentially, the overall approach in GTAP-R is GTAP, with GTAP-P included, to form a large dimensional energy and trade model with a focus on the decomposition of the electricity sector in terms of fossil fuels and renewables, accounting for changes in the energy mix over time. For emissions reduction modelling, we take growth paths in GDP for all countries to 2050 as exogenous and model the change in energy mix from fossil fuels to renewable energy needed to meet a minimal Paris target, given changes in demands for renewable energy,

trends in energy efficiency and intensity and policy levers (e.g., government mandates for clean energy, subsidies for renewables and a price on carbon). Results are reported for years 2022 to 2050, comparing (better than) SSP1-RCP2.6 to SSP2-RCP4.5 (Base Case), with 2015 as the base year for emissions (from fossil fuel consumption only). The key is the change in the energy mix. In effect, GTAP-R characterises a 'green growth' outcome, computationally determining the needed transtion from fossil fuels to renewables and the resulting emissions reduction pathway that gives (better than) SSP1-RCP2.6 while still maintaining economic growth.

4. Model Structure

4.1. Energy production

Along with the standard GTAP model structure for the production and trade of consumer and investment goods, GTAP-R follows a 'top-down' approach which starts with a detailed description of the macro (and international) economy and then derives the demand for energy inputs in terms of the demand for various sectoral outputs relative to a series of production and cost functions. As indicated, GTAP-R is initially based on a GTAP-E structure with inter-fuel (across various alternative fuels) and fuel-factor substitution (between fuels and labour and capital) (Burniaux and Truong, 2002), allowing for induced and exogenous changes in energy mix and energy-capital substitutability.[2]

In terms of production structure for energy components, energy inputs are taken out of the intermediate input 'nest' and incorporated into the 'value-added' nest as a capital-energy composite. The incorporation of energy into the value-added nest is in two steps. First, energy commodities are first separated into 'electricity' and 'non-electricity' groups, with an associated elasticity of substitution. Second, an energy composite is then combined with capital to produce an energy-capital composite, which is in turn combined with other primary factors in a value-added-energy nest through a standard structure. The elasticity of substitution between capital and the energy composite is assumed to be positive, with all elasticities of substitution used in GTAP-R based on Burniaux and Truong (2002) and Truong (2007).

The demand for composite energy is structured as a constant elasticity substitution (CES) production function. The demand for composite energy EN_j in sector j is a function of the sector output Q_j, the sector unit cost CE_j, and the composite energy price PEN_j, or

$$EN_j = aQ_j \left(\frac{CE_j}{PEN_j} \right)^{\sigma} \tag{1}$$

[2]The 'bottom-up' (engineering) approach, on the other hand, often starts with a detailed treatment of energy-producing processes or technologies, and then asks the question, given a particular level of demand for energy to produce various outputs, what is the most efficient, cost-minimising way of meeting these demands in terms of the energy technologies employed and the level and mix of inputs needed to produce energy (Burniaux and Truong, 2002).

for a a constant and σ the own-price elasticity of demand for composite energy. Letting $\overline{EN_j}$, $\overline{C_j}$, and $\overline{PEN_j}$, be the 'reference level' for these variables, the demand for composite energy EN_j at time t is given by the relative changes in energy price and unit cost, so that

$$EN_j = \overline{EN_j}\left(\frac{PEN_j}{\overline{PEN_j}}\frac{\overline{C_j}}{C_j}\right)^{\sigma} \tag{2}$$

where PEN_j is a function that depends on the prices of electric and non-electric energy, tax rates, and the distribution margins on the unit cost of electric and non-electric energy.

4.2. Decomposition of the Electricity Sector

As noted, the 'bottom up' approach to CGE energy modelling disaggregates the energy sector into different technologies and then recombines the outputs (or costs) into that of a single sector using an aggregate production function which generally assumes no substitution between existing technologies, but instead uses a nested logit choice model for new installations (Peters, 2016). For our purposes, these approaches are not useful, since they do not explain why the outputs of different technologies are only 'imperfectly substitutable' while electricity is a homogeneous commodity (Truong and Hamasaki, 2018). For GTAP-R, instead, we use the GTAP-Power (GTAP-P) v10a (Chepeliev, 2020) approach as the most relevant representation for analysing energy and carbon emissions given its dynamic change in fuel-mix (or substitution among energy sources), the potential move to low-carbon sources of energy and the role of renewables.

The disaggregation of the electric sector in GTAP-P is based on the top-down approach of GTAP-E developed by Peters (2016) and Chepeliev (2020). GTAP-E and GTAP-P decompose the original set of 57 GTAP commodities into a group of individual commodities and twelve energy commodity sectors: Transmission and Distribution, Nuclear base-load, Coal base-load, Gas base-load, Wind base-load, Hydro base-load, Oil base-load, Other base loads, Gas peak load, Hydro peak load, Oil peak load, and Solar peak load. The approach in GTAP-P v10a has three key elements: (a) it implements an additive constant elasticity of substitution specification in the power sector that ensures the sum of inputs (measured in GWh) sums to total output; (b) in GTAP-P v9, the output of the electricity was split using electricity generation data only; in GTAP-P v10a, heat generation volumes are employed to provide a more representative sectoral split and to better line-up with GTAP sectoral definitions; and (c) GTAP-P v10a introduces data on the country and year-specific shares of transformation and distribution costs in electricity use and trade for up to 80 different countries (Chepeliev, 2020).

4.3. Dynamic Adaptative Structure

The dynamic adaptive structure in GTAP-R follows the disequilibrium approach in Ianchovichina et al. (2000), adding realism to the how expectations are formed and how quickly the economy adjusts. There are two main components. The first is the assumption of adjustment costs to changing the capital stock (including changes to the energy mix) given by C or:

$$C = \pi^e \frac{\Phi}{2}\Big(\frac{I}{K}\Big)I \tag{3}$$

where e denotes an expectations operator, π is the price of capital goods measured in US dollars, K is capital stock, I denotes investment goods or additions to the capital stock measured in the same physical units, and Φ is a constant with respect to time. Firms producing investment goods in each region, augmenting the stock of capital goods to all other firms, maximises intertemporal profits subject to prices and the rental costs for capital, noting again that changes in the physical capital stock invoke a cost, so that:

$$max \int_t^\infty \left[q^e(s)K(s) - P^e(s)I(s) - \pi^e(s)\frac{\Phi}{2}\left(\frac{I(s)}{K(s)}\right)I(s)\right] e^{-R_s(s-t)}ds \tag{4}$$

subject to $\dot{K}(t) = dK/dt = I(t) - \delta K(t)$ for q is the rental price of capital in dollar terms, P the price of capital goods, δ the rate of depreciation and R a discount factor Ianchovichina et al. (2000).

The second main component assumes an initial target rate of return on investment, defined as the expected global rate of return which clears the market for global investment funds, adjusted by a region-specific risk premium. Errors in expectations or differences between actual and expected returns on investment drive the allocation of investment funds globally, assuming that investors' expectations are 'sluggish', adjusting their expectations of future rates of return and differences between actual and expected rates slowly. Eventually, expected and actual rates are equalised and a new composition of the global capital stock is realised. The process is not instantaneous with changes in capital and the regional and global energy mix dependent on errors in forecasts of expected returns and slow adjustment (with costs) of the physical capital stock.

4.4. Energy Flows and Energy Balance

Future energy flows and energy balances in quantity are estimated from calibrated results (percentage change) in GTAP-R and a base quantity from IEA (2021*c*), IEA (2021*a*) and BP (2020). The demand or consumption of energy resource i at time t is given by $D_t(i) = D_0(i) * d_t(i)$ where $D_0(i)$ and $d_t(i)$ is the quantity consumed at year 0 and the percentage change from the base year of consumption at time t given model outcomes. A similar equation applies to the supply of resource i or $S_t(i) = S_0(i) * s_t(i)$.

In GTAP-R, global energy flows balance consumption, production and net trade, or $NT_t(i)$, as the difference between exports (EX) and imports (IM), so that

$$D_t(i) = S_t(i) + (IM_t(i) - EX_t(i)) = S_t(i) + NT_t(i) \tag{5}$$

with the condition that globally

$$NT = \sum_{i=1}^{N} EX_i - \sum_{i=1}^{N} IM_i = 0 \tag{6}$$

so that both global consumption and supplies as well as global imports and exports balance.

5. Data and Key Assumptions

As indicated, along with GTAP-E, the GTAP-P data base, version 10a (Chepeliev, 2020) in the Global Trade Analysis Project (GTAP) data base, version 10 (also referred to as GTAP 10) are the main GTAP databases used in this study (Aguiar et al., 2019). The data bases are calibrated with base year 2014 describing the world economy across 65 (tradable) commodity sectors for 141 countries/regions. These 141 countries/regions account for 98% of world GDP and 92% of the world's population (Aguiar et al., 2019). In our study, the countries/regions and commodity sectors are aggregated to 30 countries/regions and 28 sectors (see the Appendix for details). The GTAP 'electricity' sector is disaggregated into transmission & distribution, nuclear, coal, gas (base and peak load), oil (base and peak load), hydroelectric (base and peak load), wind, solar, and other technologies. The specific methodology we use has been revised and is documented in Chepeliev (2020). Note that the electricity sector ('ely') includes both electricity and heat generation. This sector combines heat and power plants (CHP), public heat plants, auto-producer heat plants, heat pumps, and CHP and heat plants (Chepeliev, 2020).

Data for fuel use and carbon emissions is complex. For our purposes, we focus on fossil fuel combustion only. The data sources for regions in GTAP-R, fuel use and fuel unit conversions are drawn from BP (2020), Chepeliev (2020), and IEA (2021*c*). Carbon dioxide emission coefficients for fossil fuels are based on EIA (2016) and supporting energy data is obtained from IEA (2021*c*), BP (2020) and OWD (2021).

5.1. GDP and Population Growth

In terms of the macro economy, GDP and population growth are taken as given for each of the 30 countries/regions. Population growth to 2050 is based on United Nations (2019). The global population is projected to grow to 8.5 billion in 2030 and 9.7 billion in 2050. The medium-term outlook for global economic growth for the period from 2026-50 is based on IMF (2021) forecasts to 2026, projected forward, with an assumption of gradual 'slowing' after 2030 and (near) convergence across countries/regions by the end of the century. The assumed average annual growth rate in GDP for key emitters from 2022 to 2050 is 1.8% (USA), 4.5% (China), and 2.7% (India). Global economic growth is assumed to be 1.7% per year, on average, and 1.4% and 3.8% for the G7 and BRICS.

5.2. Growth of Renewables and Improvement of Energy Intensity and Efficiency

The shift in fuel-mix toward renewable energy is driven by falling renewable prices and policy measures to reduce carbon emissions (e.g., subsidies for renewables, enforced renewable or emissions reduction targets, or a price on carbon). The shift in demand for clean energy has indeed been profound. Over the past decade, global renewables have increased steadily at an average annual rate of 5%. In 2019, electricity generated from renewables was 6,963 TWh, contributing 25.8% of global electricity generation, and renewable hydro accounted for about 61% of this (4,207 TWh), followed by wind energy (20.3%), solar energy (10%),

bioenergy (8%), geothermal energy (1.3%) and marine energy (0.01%) (IRENA, 2021). In 2019 alone, renewable electricity generation increased by 5.5%. Solar and wind generation increased by 23% and 12% respectively. Together, these two sources of energy continue to dominate the growth in renewable energy, accounting for 71% of the overall growth since 2015 (IRENA, 2021).

According to IRENA (2020), renewable power generation costs have fallen sharply over the past decade, driven by steadily improving technologies, economies of scale, competitive supply chains, and growing developer experience. Costs for electricity from utility-scale solar photovoltaics (PV) alone fell 82% between 2010 and 2019. In general, increases in demand for renewable energy depend on falls in renewable prices and policy instruments as indicated above. GTAP-R uses a combination of trend changes in the demand for renewables and a price on carbon to characterise the minimal Paris target transition path.

Energy intensity is measured by the quantity of energy required per unit of output, whereas energy efficiency is enhanced when a given level of output or service is provided with reduced amounts of energy inputs. Energy intensity levels and trends differ widely across regions, reflecting differences in economic structure and energy efficiency outcomes (Enerdata, 2021). For example, high energy intensity in the Commonwealth of Independent States (CIS), the Middle East, China, and some Asian countries (e.g., Taiwan and South Korea) is driven by the dominance of energy-intensive industries, commodity export-based economies, and relatively lower energy prices that do not encourage energy efficiency (Enerdata, 2021). Overall, during the past decade, with the improvement of energy efficiency and economic structural changes toward lower energy intensity sectors (such as high technology, services, etc.), energy intensity has decreased. More precisely, according to Enerdata (2021), energy intensity (measured as total energy consumption per unit of GDP) decreased by -1.5%/year on average between 2000 and 2019. We calibrate GTAP-R with this rate, noting and using regionally specific measures (e.g., since 2000, the USA and the EU have cut their energy intensity by roughly 2%/year, with China's energy intensity also improving at a rate of 2.9%/year over the 2000-19 period). Energy intensity for coal, crude oil, oil refinery products also shows a declining trend at an annual average of 1-5% during 1990-2019 based region and the analysis contained in Enerdata (2021).

5.3. Carbon Prices

According to the World Bank (2020), an effective carbon price is an essential tool to reduce carbon emissions. In 2020, there were 61 carbon pricing initiatives in place or scheduled for implementation, consisting of 31 emissions trading schemes and 30 carbon pricing mechanisms, covering 12 gigatonnes of carbon dioxide equivalent (GtCO2e) or about 22 percent of global GHG emissions (World Bank, 2020). The carbon price per ton of carbon varies worldwide: $USD119 (Sweden); $USD99 (Switzerland, Liechtenstein); $USD58-68 (Finland); $USD53 (Northway); $USD49 (France), and ranges from $USD1-10 for countries such as Mexico, Columbia, Japan, Ukraine, Poland, Singapore, Shanghai, and Iceland (World Bank, 2020).

As usual, the price on carbon (per ton) in GTAP-R depends on country and region and is assumed to increase over time. Given increases in the demand for renewables (given falling

renewable prices, changes in energy efficiency and intensity and policy changes) the cost of a carbon tax and the price on carbon to reach a given target is moderated going forward. For the USA, carbon prices (in nominal terms), on average, are calibrated in GTAP-R to increase from $USD20 during 2022-30 to $USD36 in 2030-40, and $USD93 in 2041-50. For China, the price of carbon increases from $USD20 during 2022-30 to $USD33 in 2030-40, and $USD88 in 2041-50. For India, the carbon price is assumed to increase from $USD8 during 2022-30 to $USD14 in 2030-40, and $USD36 in 2041-50. We also assume no fossil fuel subsidies in any country/region or at any time period.

6. Model Results

As indicated, key model results from GTAP-R are presented for two scenarios of future development, a comparable 'Baseline (Base Case)' path (SSP2-RCP4.5) and a minimal 'Paris Transition Path' (PTP) (SSP1-RCP2.6), calibrated for emissions from fossil fuel consumption only. Emissions reduction from land use change are treated separately in Section 7. Although model results are available for 30 countries/regions we principally report for China, the USA and India, and less so for the G7, the World and BRICS, with a focus on coal consumption, oil liquids and natural gas consumption and renewables. We also highlight the economy or welfare cost of a price on carbon. The combination of falls in renewable prices, increases in demand for renewables, improvements in energy efficiency and intensity, policy changes and a price on carbon, all combined, generate the model results.

Figure 1 provides a general overview of the comparable Base Case carbon (SSP2-RCP4.5) transition path, the (at least) PTP (minimal Paris Agreement transition path or SSP1-RCP2.6) and coal consumption for the World, China, the USA and India, from the year 2022. As illustrated in Figure 1, with PTP the resulting global carbon emissions are roughly 12,647 Mt in 2050 or a 61% reduction in comparison with 2015 CO_2 emission levels of 32,787 Mt (IEA (2021*b*) and BP (2020)). This represents an average annual decrease of 3.13% in emissions from fossil fuel consumption from 2022 to 2050.

Keep in mind that the measure of 12,647 Mt is carbon emissions from fossil fuel consumption only, excluding other sources. It follows that if carbon from fossil fuel consumption is roughly 90% of total CO_2 emissions (IPCC, 2018), the equivalent non-fossil fuel emissions added to the GTAP-R results are 1,391 Mt or 14,038 in total, assuming that the proportion of carbon emissions from fossil fuel consumption to non-fossil fuel sources remains unchanged over time. If, on the other hand, carbon emissions from non-fossil fuels remain unchanged over time from the base year, the total is 17,047 Mt. In either case, the 12,647 Mt in emissions from fossil fuel consumption drawn from GTAP-R model results is better than the stated SSP1-RCP2.6 combined carbon emissions of roughly 20,000 Mt (IPCC, 2021)

Overall, for key emitters, using the year 2015 for comparison, carbon emissions from fossil fuel consumption in 2050 in GTAP-R are 93.1% lower for the USA, 88.6% lower for China, and 75.7% lower for India. The companion 2030 target is roughly 28,825 Mt in 2030 or a 15% reduction in comparison the 2015. For the minimal 2030 target, again using 2015 for comparison, emissions reduction is 38% for the USA, 21% for China, and 14% for India. Coal consumption falls from 2022 and throughout in all cases to meet these targets. For

the three major emitters, the decrease in emissions track the fall in coal consumption. The exact or model output transition paths for the major energy sources for the World, the G7 and BRICS, along with the three key emitters, are further discussed below.

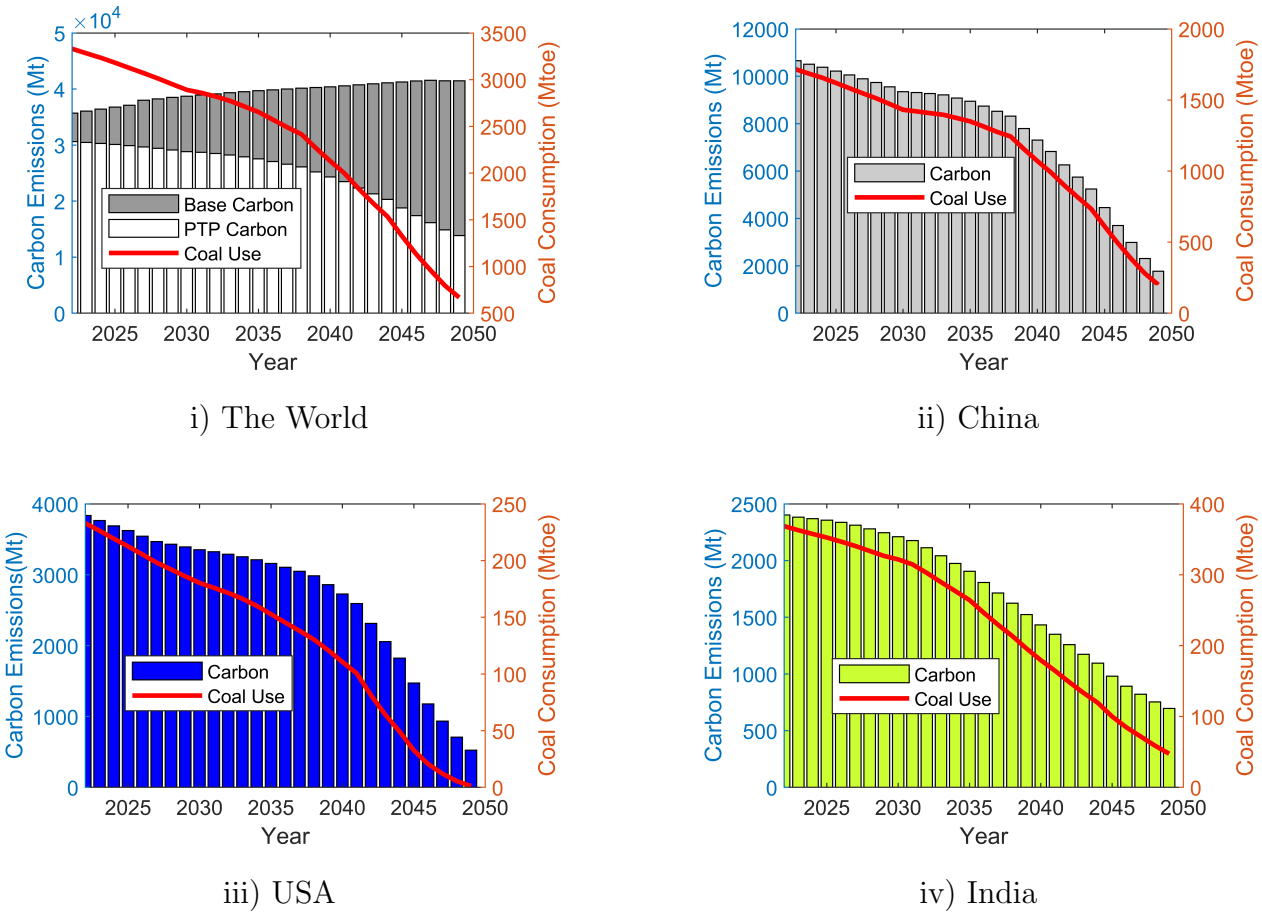
6.1. The Needed Change in Energy Mix to 2050 for PTP

Table 1 to Table 4 provides model results for the needed change in energy mix to obtain the PTP transition path (better than SSP1-RCP2.6) for the World, the G7, BRICS and the three key emitters, China, the USA and India. Of the 28 commodity sectors in GTAP-R, model output is reported for coal (Mtoe), oil liquids (Mtoe), and natural gas (Billion cubic metres) consumption and energy from renewables (Exajoules) for each country or region.

To meet the minimal target, coal consumption must decline steadily for all countries and regions. For the World, the G7 and BRICS, the average annual growth rate of coal use is -5.2%, -7.1% and -6.4%, respectively. For the USA, China and India, the growth rate is -17.3, and -6.5 and -7.1% (see Table 1). Coal consumption for the USA, in particular, reaches (virtually) zero in 2050 and coal consumption for the World falls by nearly 86% by 2050 compared to 2019.

Both oil liquids (which includes crude oil for refinery and refinery products) and natural gas consumption tend to increase initially but fall eventually. For the World, the G7 and BRICS, the average annual growth rate of oil liquids consumption is -1.3%, -3.0% and -2.4%, respectively. For the USA, China and India, the growth rate is -5.7, and -4.6 and -0.7% (see Table 2). For the World, the G7 and BRICS, the average annual growth rate of natural gas use is -0.5%, -1.8% and -0.3%, respectively. For the USA, China and India, the growth rate is -3.7, and 0.2 and -1.5% (see Table 3). It is notable that although coal consumption falls throughout the period to 2050, oil liquids and natural gas consumption increase for some time, and then fall rapidly. This especially the case for China and India, but not for the USA or the G7 where oil liquids and natural gas consumption fall continuously.

Figure 1: Annual Carbon Emissions and Coal Consumption to 2050



i) The World

ii) China

iii) USA

iv) India

Note: 'Base Carbon' is annual carbon emissions from fossil fuel consumption/combustion in a 'business as usual' scenario, comparable to SSP2-RCP4.5 (Base Case) and 'PTP Carbon' is carbon emissions under the (better than) SSP1-RCP2.6 scenario (left-hand vertical axis); 'Coal Use' (right-hand vertical axis) is coal consumption for The World, China, the USA and India from 2022 to 2050. Carbon emissions are in Mt-CO_2 and coal consumption is in Mtoe (Million tons of oil equivalent) units.

Table 1: Coal Consumption of PTP, 2022-50 *(Mtoe)*

Year	**World & Country Groups**			**Key Emitters**		
	World	G7	BRICS	USA	China	India
2022	3,331.2	409.2	2,173.8	233.0	1,716.6	368.6
2023	3,282.4	399.1	2,136.2	226.3	1,685.6	362.8
2024	3,235.1	388.4	2,100.6	219.3	1,656.1	357.7
2025	3,181.6	377.9	2,058.8	212.6	1,620.3	352.5
2026	3,125.5	367.3	2,015.0	205.4	1,583.3	346.7
2027	3,070.3	356.9	1,971.7	198.2	1,547.2	340.6
2028	3,012.7	347.9	1,928.1	192.3	1,512.0	333.6
2029	2,951.2	339.1	1,880.3	186.1	1,472.4	326.6
2030	2,891.0	330.7	1,832.9	180.3	1,431.4	321.7
2031	2,860.0	323.7	1,813.4	176.0	1,420.2	314.7
2032	2,820.4	316.4	1,787.4	171.5	1,407.7	302.7
2033	2,774.1	307.0	1,761.3	166.3	1,396.3	289.6
2034	2,714.8	296.7	1,723.8	160.1	1,373.1	277.0
2035	2,654.0	285.3	1,685.8	152.8	1,349.6	264.3
2036	2,572.5	273.6	1,630.0	145.4	1,313.6	246.4
2037	2,491.3	262.1	1,573.5	138.1	1,275.8	229.5
2038	2,415.4	250.1	1,523.6	130.4	1,243.8	213.6
2039	2,268.6	235.1	1,414.0	121.0	1,154.4	195.9
2040	2,129.0	219.3	1,311.4	110.6	1,070.7	179.4
2041	1,996.9	204.2	1,214.6	100.5	991.2	164.5
2042	1,830.3	178.2	1,104.0	81.3	899.8	148.4
2043	1,677.1	154.9	1,002.2	64.1	816.1	133.2
2044	1,533.9	134.4	903.7	49.2	734.5	119.2
2045	1,327.3	108.7	757.3	32.6	611.2	100.0
2046	1,131.4	87.4	616.8	20.5	491.3	84.6
2047	959.7	71.2	489.3	12.1	381.0	71.8
2048	795.8	57.1	371.2	5.5	280.0	58.9
2049	668.1	46.2	276.0	1.2	200.2	47.5
2050	559.0	37.3	205.1	0.0	142.0	38.0
	Average Annual Growth Rate (%)					
	-5.2	-7.1	-6.4	-17.3	-6.5	-7.1

Table 2: Oil Liquid Consumption of PTP, 2022-50 *(Mtoe)*

Year	**World & Country Groups**			**Key Emitters**		
	World	G7	BRICS	USA	China	India
2022	4,058.2	1,345.6	1,149.6	752.9	674.3	212.5
2023	4,080.9	1,332.1	1,160.2	739.3	677.7	217.2
2024	4,101.5	1,314.2	1,171.6	723.3	681.2	222.3
2025	4,137.5	1,301.3	1,190.8	712.4	691.8	228.0
2026	4,163.0	1,280.2	1,210.1	693.6	704.3	232.5
2027	4,180.9	1,258.2	1,226.2	674.3	715.6	235.6
2028	4,208.5	1,256.1	1,241.6	674.4	727.6	237.3
2029	4,232.1	1,255.1	1,253.0	675.2	737.0	237.9
2030	4,240.8	1,251.4	1,254.4	674.0	742.4	232.9
2031	4,258.7	1,249.2	1,266.9	674.2	753.1	233.7
2032	4,271.3	1,245.5	1,276.5	673.0	761.5	233.4
2033	4,265.4	1,241.0	1,271.2	672.7	757.0	231.9
2034	4,255.1	1,236.6	1,261.0	671.9	747.2	230.6
2035	4,245.1	1,232.9	1,249.9	671.7	736.4	229.3
2036	4,229.5	1,227.3	1,234.9	670.7	723.6	226.9
2037	4,212.9	1,221.6	1,218.8	669.4	709.9	224.6
2038	4,173.1	1,211.1	1,188.5	665.2	683.7	221.2
2039	4,099.6	1,169.9	1,153.1	629.7	652.2	217.9
2040	4,029.5	1,130.1	1,119.2	595.2	621.5	215.4

Table 2 – *Continued from previous page*

Year	World & Country Groups			Key Emitters		
	World	G7	BRICS	US	China	India
2041	3,961.0	1,091.3	1,084.3	561.1	589.8	213.2
2042	3,827.4	1,010.9	1,028.6	486.3	539.3	209.8
2043	3,695.0	942.1	969.1	422.5	485.1	206.7
2044	3,576.3	883.2	913.7	368.0	434.7	203.9
2045	3,395.5	784.7	835.3	290.6	365.3	197.7
2046	3,235.9	701.8	762.8	229.1	301.6	194.3
2047	3,105.9	635.4	700.6	182.3	249.6	192.5
2048	2,949.2	575.1	635.6	143.0	197.1	193.2
2049	2,821.3	526.5	581.8	112.6	155.4	194.4
2050	2,706.4	486.5	527.7	89.6	123.2	185.9
	Average Annual Growth Rate (%)					
	-1.3	-3.0	-2.4	-5.7	-4.6	-0.7

Table 3: Natural Gas Consumption of PTP, 2022-50 *(Billion Cubic Metres)*

Year	World & Country Groups			Key Emitters		
	World	G7	BRICS	USA	China	India
2022	4,203.5	1,504.6	1,005.3	892.1	376.7	59.3
2023	4,230.9	1,501.5	1,014.3	886.7	382.9	60.6
2024	4,256.5	1,495.1	1,025.1	880.0	391.1	61.8
2025	4,278.3	1,489.4	1,030.7	873.9	393.9	63.2
2026	4,297.3	1,486.0	1,032.2	869.9	394.2	64.2
2027	4,317.2	1,486.5	1,032.1	869.8	394.2	64.9
2028	4,314.8	1,482.5	1,031.7	865.0	395.0	65.1
2029	4,307.0	1,477.2	1,027.4	858.5	392.8	65.2
2030	4,290.1	1,468.9	1,018.4	850.6	387.6	65.4
2031	4,284.8	1,464.7	1,019.0	846.6	391.4	65.6
2032	4,270.7	1,455.8	1,016.9	838.7	393.6	65.1
2033	4,260.9	1,446.4	1,020.9	831.9	402.9	64.3
2034	4,247.2	1,435.4	1,021.7	823.3	408.6	63.6
2035	4,232.1	1,422.4	1,022.8	812.3	414.3	62.8
2036	4,214.5	1,409.4	1,020.6	800.9	417.2	61.5
2037	4,195.8	1,395.4	1,017.8	788.6	419.5	60.2
2038	4,184.1	1,378.9	1,026.2	774.8	433.8	58.8
2039	4,173.1	1,374.1	1,021.1	772.3	434.0	57.2
2040	4,159.9	1,366.2	1,015.9	766.7	433.6	55.8
2041	4,144.4	1,354.7	1,009.7	756.7	431.9	54.7
2042	4,127.3	1,328.4	1,012.3	732.9	439.2	53.3
2043	4,117.4	1,296.9	1,025.2	702.4	455.1	52.6
2044	4,103.0	1,258.6	1,039.0	665.4	471.8	52.0
2045	4,023.6	1,169.0	1,029.7	579.2	466.8	48.8
2046	3,943.7	1,077.5	1,017.3	491.5	457.5	47.3
2047	3,849.1	992.8	978.1	407.2	423.4	45.8
2048	3,718.3	898.6	930.3	315.7	383.8	43.8
2049	3,602.2	812.0	887.7	234.6	345.3	42.4
2050	3,475.3	730.5	825.4	159.3	298.8	35.9
	Average Annual Growth Rate (%)					
	-0.5	-1.8	-0.3	-3.7	0.2	-1.5

Renewables, or renewable consumption, in GTAP-R results increases rapidly at the global level and for the key emitters, China, the USA and India, as well as for the G7 and BRICS (see Table 4). Average annual increases are World (5.3%), G7 (5.9%), BRICS (5.7%), the USA (7.9%), China (6.3%) and India (4.5%). Given model structure and assumptions, as well

as practical experience, this is not unexpected. As indicated, renewable power generation technologies have become the least-cost option for new capacity in almost all parts of the world. Solar cost per kWh has been falling rapidly over the past ten years from $0.35 to less than $0.10 in China, the USA, and India (Naam, 2020). Overall, electricity costs per kilowatt-hour (kWh) for solar PV and concentrating solar power fell from $USD0.35 and 0.346 in 2010 to $USD 0.068 and 0.182 in 2019, respectively. For offshore and onshore wind, costs and concentrating wind power have fallen from $USD0.161 and 0.086 in 2010 to $USD 0.115 and 0.053, respectively (IRENA, 2020). In 2019, except for concentrating solar and offshore wind, on average, the electricity cost of fossil fuels per kWh ($USD0.066) was only slightly better than solar PV ($USD0.068), but much less competitive than geothermal ($USD0.049), hydro ($USD0.037), and onshore wind power ($USD0.053). The electricity costs ($USD/kWh) of fossil fuels have also decreased from $USD0.076 in 2010 to $USD0.066 in 2019, but at a lesser rate than renewables. As it stands, the rapid fall in renewable-energy costs and the fast-growing opportunities to electrify other energy end-uses (such as transportation and heating) (IRENA, 2019) have reduced the cost of climate change mitigation over time considerably. For example, during 2007-17, the cost of solar electrification fell by more than 70 percent for significant energy consumers and the cost of renewables in general are expected to keep falling at comparable rates (IRENA, 2020).

Figure 2 shows the growth of renewables to 2050 comparing the PTP target (better than SSP1-RCP2.6) to the Base Case (comparable to SSP2-RCP4.5) for the World, China, the USA and India. The results show substantial increases in renewable energy, with the increase in India still accelerating in 2050.

Table 4: Renewable Consumption of PTP, 2022-50 *(Exajoules)*

Year	**World & Country Groups**			**Key Emitters**		
	World	G7	BRICS	USA	China	India
2022	121.0	40.3	48.6	19.7	33.5	5.7
2023	125.9	41.7	51.0	20.7	35.3	6.0
2024	131.0	43.0	53.6	21.6	37.3	6.3
2025	136.7	44.5	56.5	22.7	39.6	6.6
2026	142.5	45.9	59.5	23.7	42.1	7.0
2027	148.5	47.4	62.6	24.8	44.6	7.3
2028	155.0	49.4	65.8	26.3	47.3	7.6
2029	161.7	51.6	69.0	28.0	49.9	7.8
2030	168.3	53.9	72.0	29.9	52.5	8.0
2031	175.8	56.4	75.7	31.8	55.6	8.4
2032	183.5	59.0	79.4	33.9	58.7	8.7
2033	190.8	61.8	82.5	36.3	61.3	9.0
2034	198.4	64.8	85.6	38.8	63.8	9.3
2035	206.5	68.1	89.0	41.6	66.4	9.7
2036	217.0	71.9	94.0	45.0	70.7	10.1
2037	231.4	77.0	101.5	49.5	77.4	10.4
2038	246.6	82.6	109.2	54.4	84.3	10.8
2039	261.4	88.2	116.2	59.3	90.6	11.1
2040	281.1	95.7	125.9	66.1	99.1	11.7
2041	304.5	105.7	136.5	75.3	108.6	12.3
2042	327.9	116.1	146.9	85.0	117.9	12.8
2043	353.3	128.2	157.3	96.2	127.2	13.5
2044	381.5	141.7	169.1	108.6	137.6	14.2
2045	396.8	147.1	175.8	113.2	143.5	14.4
2046	412.8	151.9	183.7	117.2	149.6	15.3

Table 4 – *Continued from previous page*

Year	World & Country Groups			Key Emitters		
	World	G7	BRICS	US	China	India
2047	427.7	156.7	190.1	120.9	154.1	16.7
2048	442.4	162.7	195.9	125.3	157.3	18.9
2049	457.1	167.8	201.6	129.0	160.1	21.3
2050	472.8	172.8	208.5	131.7	165.7	22.1
	Average Annual Growth Rate (%)					
	5.3	5.9	5.7	7.9	6.3	4.5

6.2. The Change in Energy Mix and Fuel Consumption to 2050

Figure 3 provides a graphical representation of the change in energy mix and fuel consumption to 2050, compared to 2019. It compares fuel consumption in 2019 to the Base Case in 2050 (comparable to SSP2-RCP4.5) and the PTP transition path to 2050 (better than SSP1-RCP2.6), for the World, the G7, BRICS, the USA, China and India. The reference year 2019, is based on reported data (BP, 2020; IEA, 2021*c*). Coal, oil liquid, and natural gas measures for the USA, China and India in 2019, for example, are 283.8, 2050.5 and 419.4 Mtoe for coal respectively, 925.7, 720.2 and 230.6 Mtoe for oil liquids, and 1,084.8, 397.8 and 68.8 (Bcm) for natural gas. All other data is drawn from GTAP-R model results as given in Tables 1 to 4.

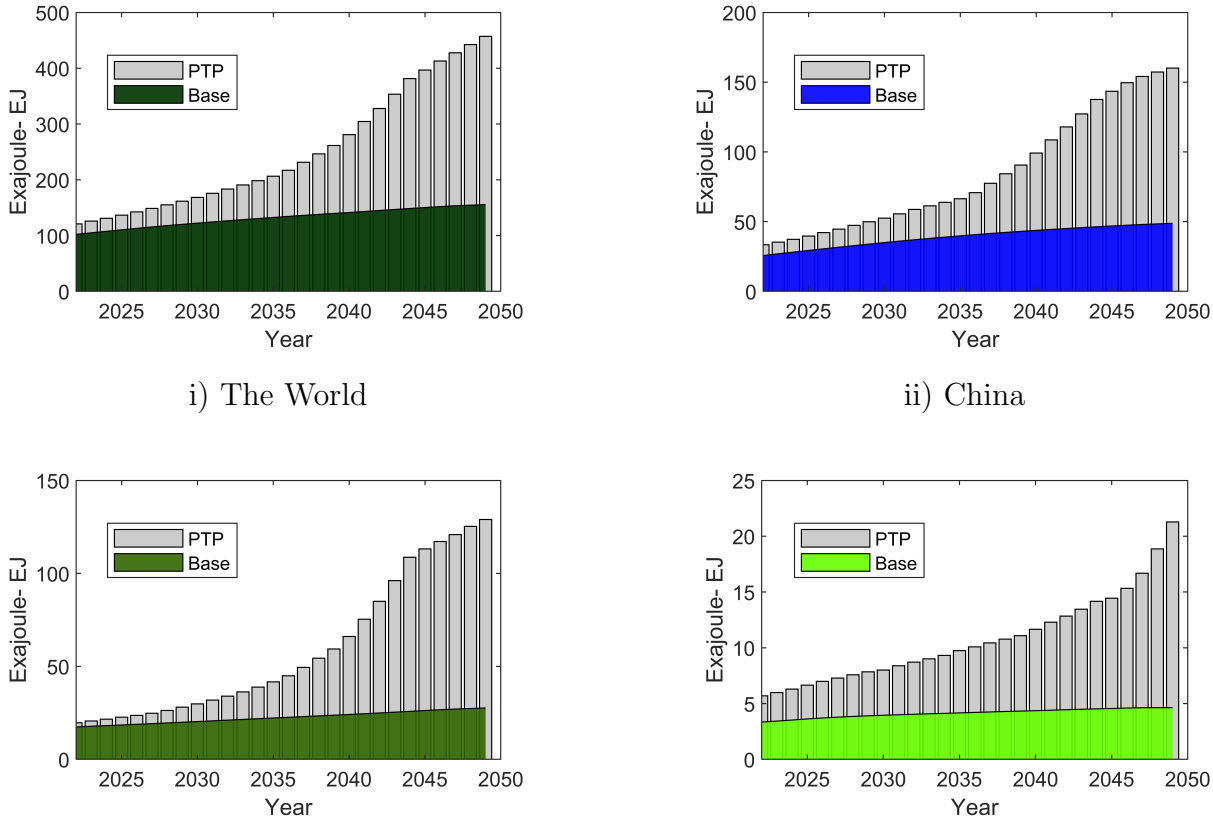
The changes in energy mix are profound, even to meet a minimal Paris target. The use of fossil fuels decreases significantly, especially for coal. In particular, for the Base Case, global coal use increases by roughly 10% on average from 2019 (3,900 Mtoe to 4,300 Mtoe), but for PTP it falls dramatically by 86%, 100%, 93% and 91% for the World, the USA, China, and India, respectively.

Global oil consumption increases from 4,718 Mtoe in 2019 to 6,275 Mtoe for the Base Case in 2050 and decreases to 2,706 Mtoe for PTP in 2050. In 2050, compared to 2019, the percentage increase in oil consumption is 33% for the Base Case, but decreases significantly by 43%, 90% 83% and 19% for the World, the USA, China, and India.

Global gas consumption increases from 4,980 Bcm in 2019 to 5,760 Bcm for the Base Case in 2050 and decreases to 3,470 Bcm for PTP in 2050. In 2050, compared to 2019, the percentage increase in gas consumption for the Base Case is 16%, but for PTP gas consumption falls by 30%, 85%, 25% and 48% for the World, the USA, China, and India, respectively.

In contrast with fossil fuels, renewables consumption increases dramatically, especially for the PTP case. For Base Case the increase is from 99.4 Ej in 2019 to 157 Ej in 2050, and for PTP renewables consumption in 2050 is 473 Ej for the World. For PTP, in particular, compared to 2019, the percentage increase is 375%, 665%, 624%, and 371% for the World, the USA, China, and India, respectively.

Figure 2: Growth of Renewables to 2050



i) The World

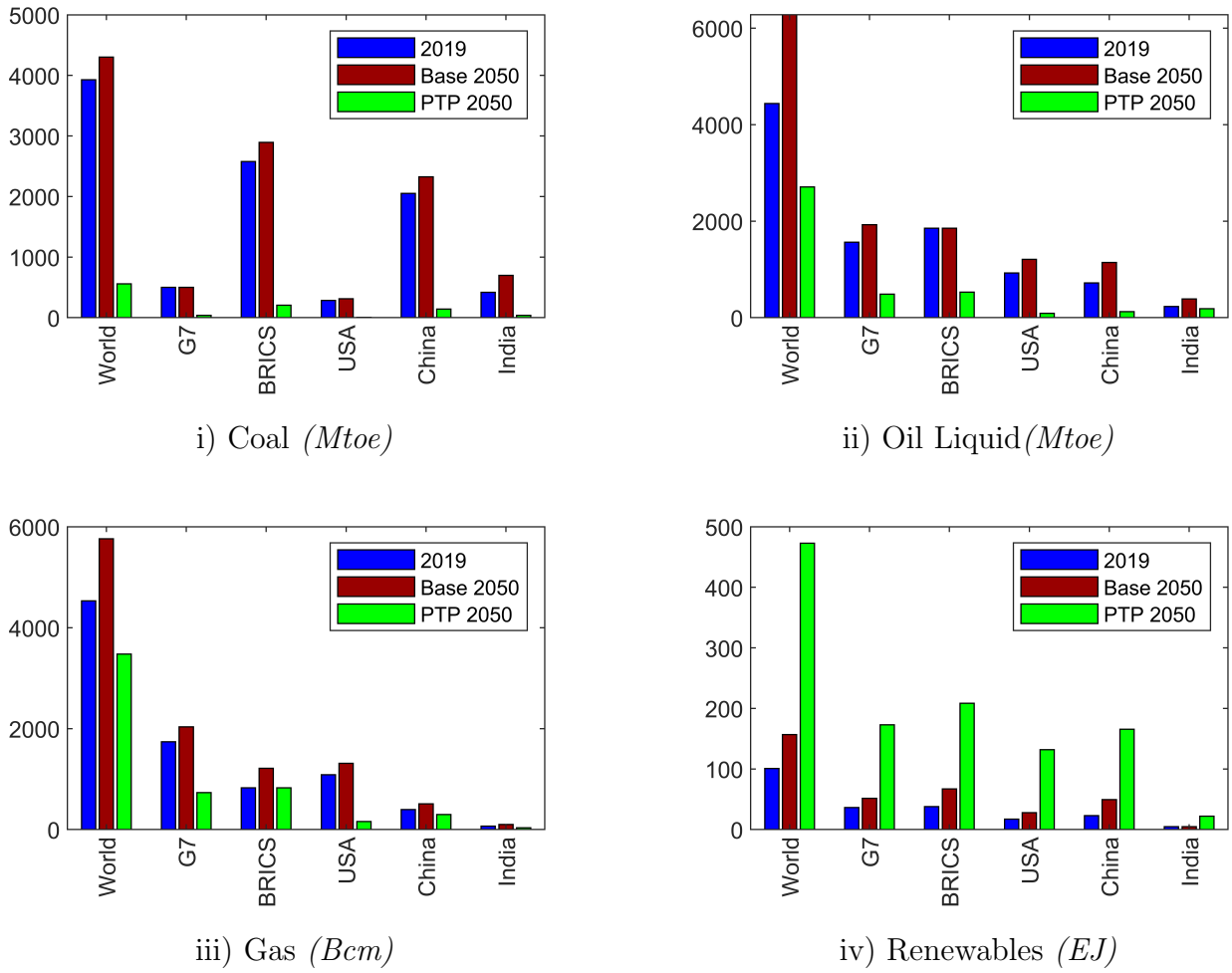
ii) China

iii) USA

iv) India

Note: Initial reporting year for renewables consumption is 2022. Base is Base Case or the 'business as usual' scenario (comparable to SSP2-RCP4.5). PTP is the Paris (Agreement) Transition Path (or better than SSP1-RCP2.6) for renewables consumption. EJ: Exajoule.

Figure 3: Fuel Consumption by Scenario in 2050



i) Coal *(Mtoe)*

ii) Oil Liquid*(Mtoe)*

iii) Gas *(Bcm)*

iv) Renewables *(EJ)*

*Note: Reference year is 2019 (BP, 2020; IEA, 2021*c*). Base 2050 is fuel consumption for the Base Case. PTP 2050 is the Paris (Agreement) Transition Path (for better than SSP1-RCP2.6). Mtoe: Million Tons of Oil Equivalent; Bcm: Billion Cubic Meters; EJ: Exajoule.*

6.3. The Cost of a Price on Carbon

Despite for the rapidly falling prices for renewables captured in GTAP-R, the transition path to shift the energy mix away from fossil fuels can be costly. To measure the cost of a price on carbon, we relax the assumption of exogenous GDP and follow Huff and Hertel (2000) by developing a decomposition of the change in global welfare in GTAP with the imposition of a price on carbon emissions (all else equal) as a shock to GDP on SSP2-RCP4.5 (Base Case). We assume no subsidies for fossil fuels or international trades in emissions reduction, and the revenue from the carbon tax is assumed to be captured (and redistributed) by government. The welfare loss from a carbon tax from 2022 to 2050, globally, on average, is less than 0.5% of projected GDP, although this varies by country or region. The cumulative dollar cost of the carbon price to 2050 is roughly $USD13.3 billion, with the cost as a fraction of GDP that decreases from over 0.6% in the 2020s and 2030s to 0.1% in 2050. Note this is a welfare reduction in GDP relative to what it would have been under a comparable SSP2-RCP4.5 scenario, not an absolute loss in income. The welfare cost is higher for fossil-fuel dependent countries and the total annual cost of the carbon tax falls, even though the price on carbon rises, since the shift to renewables results in less emissions. The main cost occurs before 2040 given the shift in energy mix, and the percentage welfare losses fall for every country and region over time.

7. Land Use Change and Carbon Sequestration from Forests

According to the IPCC (2019), Agriculture, Forestry and Other Land Use (AFOLU) activities contributed roughly 13% of CO_2, 44% of methane (CH_4), and 82% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, accounting for 23% (12.0 +/- 3.0 $GtCO_2e$ yr-1) of total net anthropogenic emissions of GHGs. However, land is potentially both a source and a sink of greenhouse gases (GHGs) and plays a key role in the exchange of energy, water and aerosols between the land surface and the atmosphere. Sustainable land management can contribute to reducing some of the negative impacts of global warming as well as potential damage to ecosystems and biodiversity (IPCC, 2019).

That said, carbon sequestration from forests is very complex, with rates that vary greatly in terms of forest age, composition, location and soil type (Toochi, 2018). A study by Harris et al. (2021) integrates ground and Earth observation data to map annual forest-related greenhouse gas emissions and removals globally at a spatial resolution of 30 meters over the years 2001-2019. During that time, global gross emissions from forestry (from deforestation and other satellite-observed forest disturbances) were estimated to be 8.1 $\pm$ 2.5 Gt CO_2e per year (CO_2 equivalent) (mean $\pm$ deviation). Over the same period, gross carbon removals by forest ecosystems were -15.6 $\pm$ 49 Gt CO_2e per year. Taken together, the balance of these opposing effects yields a global net GHG forest sink of -7.6 $\pm$ 49 Gt CO_2e per year on average over the past two decades (Harris et al., 2021). The large uncertainty is largely due to extremely high uncertainties in removal factors from the IPCC Guidelines applied to old secondary temperate forests outside the United States and Europe (Harris et al., 2021). Overall, using the mean value, the world's forests sequestered about twice as much carbon

dioxide as they emitted between 2001 and 2019. In other words, forests provided a 'carbon sink' that absorbed a net 7.6 billion metric tonnes of CO_2e per year (Harris et al., 2021).

In this section we concentrate on LUC and carbon sequestration from forests in a GTAP framework to partially offset the carbon emissions outlined in the previous sections. We take a more straightforward approach in GTAP-R, compared to (Burniaux and Lee, 2003), by simply introducing a shock to the type and location of forests by land area at an increasing rate of 1% per year from 2022 to 2050. In terms of forest type, which largely determines the extent of sequestration, we focus on young and secondary forests (leaving aside primary and plantation/tree crops) following the categorisation in Harris et al. (2021). The four major forest domains we model are (a) boreal, (b) temperate, (c) subtropical, and (d) tropical. The regions specified in GTAP-R are matched to classified forest domains based on FAO (2020).

7.1. Projection of Gross Carbon Reduction from Forests in GTAP-R

Projecting carbon reduction in GTAP-R is specified by a LUC relationship for forest area in region i, with forest domain j at time t, or:

$$LUC(i,j,t) = L(i,j,0)[(1+g)^t - 1] \tag{7}$$

where $L(i,j,0)$ is forest land at year 0, g is the growth of forest land, which we take initially at $g = 1\%$, and j is the forest domain, again mapped to regions in GTAP-R based on FAO (2020).

Forest land ($L(i,j,t)$) at time t, however, contains overlapping cohorts m of forest ages or vinatges. In our study, they are: (i) from 1-9 years old, (ii) 10-19 years old, and more than 20 years old. After year 9, a young forest area becomes the part of the young secondary group. After 19 years, that area belongs to the old secondary forest area. At the time t, the forest areas by type for region i with a forest domain j are thus given by

$$LUC(i,j,t,m) = \overbrace{LUC(i,j,(t \leq 9))}^{m1} + \overbrace{LUC(i,j,(9 < t \leq 19))}^{m2} + \overbrace{LUC(i,j,(t > 19))}^{m3} \tag{8}$$

where $m1$ is the young forest ($<$ 10 years old); $m2$ is the young secondary forest (10-19 years old); and $m3$ is the old secondary forest (>20 years old).

Carbon sequestration by new forest area at time t in the region i thus depends on the forest area, the forest domain j, and the average 'Net carbon or GHG flux' (NCR) of the forest type m ($nf(i,j,m)$) (as the difference between carbon removal and carbon emissions for the forest), so that:

$$NCR(i,j,t) = \sum_{m=1}^{3} LUC(i,j,m) * nf(j,m) \tag{9}$$

where the average NCR is given by

$$nf(j,m) = gcr(j,m) - ce(j,m) \tag{10}$$

where $gcr(j, m)$ and $ce(j, m)$ is the gross carbon removal and the carbon emissions of the forest in forest domain j and cohort m. As indicated, the value of $nf(j, m)$ is a complex estimation given the uncertainties. Given the complexity we apply an approximate or simple calculation and set aside potential deforestation and forest disturbance (e.g., damage from fires and floods). For the old secondary forest, net GHG flux is equal to the mean value of net GHG flux by total forest land for each forest domain in Harris et al. (2021) and, as adapted from Phillips et al. (2009) and Kohl et al. (2017), we assume the forest cohort $m1$ has zero Net GHG flux, and the forest cohort $m2$ provides a Net GHG flux of roughly 25% of the old secondary forest. Total net carbon removal (TNCR) at time t is simply given by the sum of all NCR by all forest domains for all regions, or:

$$TNCR(t) = \sum_{j=1}^{4} \sum_{i=1}^{30} \left[CR(i, j, t) \right] \tag{11}$$

where region i represents the 30 regions in our study and j is (again) forest domain.

7.2. Gross Carbon Reduction of Forest Growth

Figure 4 represents the carbon reduction by forest sequestration. Potential global total net carbon removal (TNCR) increases from roughly 500 Mt in 2033 to 7,606 Mt in 2050 driven by an increase of land use for forests and changes in tree age.

In section 6 above, the PTP path generated 12,647 Mt carbon emissions in 2050 or a 61% reduction in comparison with 2015 CO_2 emission levels (from fossil fuel consumption only). Given TNCR, mean value forest sequestration thus results in total carbon emissions of 5,041 or an 84% reduction compared to 2015 emissions.

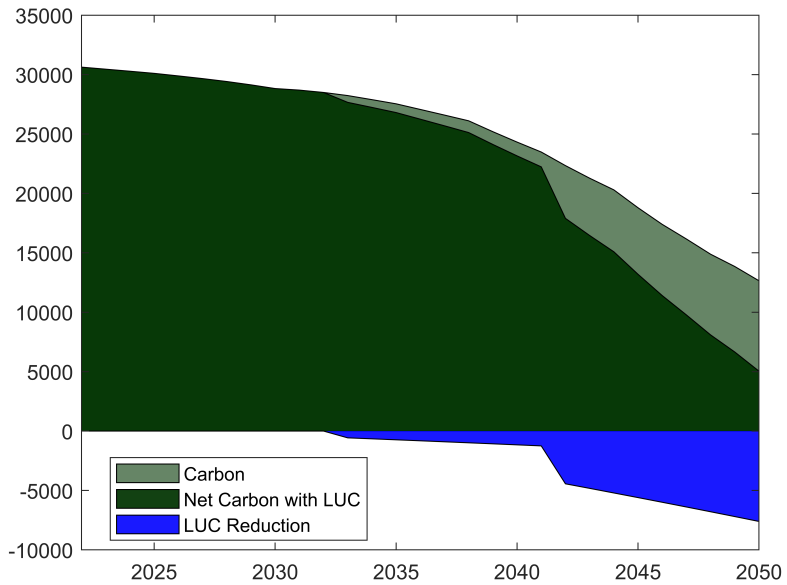
However, considerable caution is needed here given the range of uncertainty in the global net GHG forest sink of -7.6 $\pm$ 49 Gt CO_2e per year (CO_2 equivalent, on average over the past two decades), as estimated by (Harris et al., 2021). The range of uncertainly could include periods and regions as carbon sources, rather than forest carbon sinks. The key determinant of a fall in carbon emissions is thus a decrease in the consumption of fossil fuels.

8. Concluding Remarks

The transformation of the global energy system needs to accelerate rapidly to offset the effects of global warming. The GTAP-R framework presented here provides an essential tool to model the needed changes in the energy mix and emissions reduction from fossil fuel consumption to meet this challenge, concentrating on three key emitters, China, the USA and India. The key to meeting minimal Paris Agreement targets in our framework is a change in the energy mix. In effect, GTAP-R characterises a 'green growth' outcome, computationally determining the needed transition from fossil fuels to renewables and the resulting emissions reduction, while still allowing for increases in GDP. The changes in the energy mix are indeed profound, even to meet a minimal Paris target.

Overall, GTAP-R results deliver better than a SSP1-RCP2.6 outcome, with resulting carbon emissions of 12,647 Mt in 2050 (from fossil fuel consumption only). The decrease

Figure 4: Global Carbon Path with Carbon Reduction from Forest Sequestration and Land Use Change (LUC) (CRFL)(*Mt of CO2e*)



in the use of fossil fuels to achieve this outcome is considerable, posing a major challenge even for this relatively 'mild' target (i.e., global net zero emissions are not reached in 2050 even with the impacts of carbon sequestration). Nevertheless, carbon emissions in 2050 are dramatically lower for the key emitters, or a 93.1% reduction for the USA, 88.6% lower for China, and 75.7% lower for India. Overall, the global average annual decrease in carbon emissions from fossil fuel consumption from 2022 to 2050 is 3.13%.

Although all fossil fuel consumption decreases from 2022 to 2050, the main driver of the fall in emissions is the decrease in coal. Coal consumption falls dramatically in the PTP scenario, by 86%, 100%, 93% and 91% for the World, the USA, China, and India, respectively. This dramatic fall partly explains the limited increases in oil liquids and natural gas consumption over the period to 2037, as 'transitional fuels' in the energy and trade model, but overall these fuels also fall by 43% and 30% for the World with, given the differing production technologies in each country embedded in GTAP-R, even larger falls for China and the USA for oil consumption and for all the USA and India for gas consumption.

A further dramatic change in the GTAP-R results is the percentage increase in renewables at 375%, 665%, 624%, and 371% for the World, the USA, China, and India, respectively. Model results show that this is what is required to reach a better than a SSP1-RCP2.6 emissions pathway and potentially generate a 'green growth' outcome.

Appendix: Sectors and Regions in GTAP-R

Table A1: GTAPR Regions

No	Region	Countries included
		North America
1	USA	United States
2	CAN	Canada
3	MEX	Mexico
		South & Central America
4	BRA	Brazil
5	AMC	**Central America:** Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominica, Jamaica, Puerto Rico, Trinidad and Tobago
6	AMNS	**Northern South America:** Bolivia, Colombia, Ecuador, Paraguay, Peru, Venezuela
7	AMSS	**South South America:** Argentina, Chile, Uruguay
		Europe & Eurasia
8	CEU	**Central Europe:** Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Bulgaria, Croatia, Romania
9	DEU	Germany
10	EUE	**East Europe & West Asia:** Albania, Belarus, Ukraine, Rest of Eastern Europe, Kazakhstan, Kyrgyztan, Tajikistan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia
11	FRA	France
12	GBR	United Kingdom
13	ITA	Italy
14	TUR	Turkey
15	RUS	Russia
16	WEU	**Other Western Europe:** Austria, Belgium, Denmark, Finland, Greece, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Spain, Malta, Sweden, Switzerland, Rest of Western Europe
		Middle East
17	ME	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, UAE
		Africa
18	AFC	**Central Africa:** Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Kenya, Rwanda, Tanzania, Uganda, Rest of Eastern Africa
19	AFN	**North Africa:** Egypt, Morocco, Tunisia, Rest of North Africa, Ethiopia
20	AFO	**Other Africa:** Madagascar, Malawi, Mauritius, Mozambique, Zambia, Zimbabwe, Botswana, Namibia, Rest of Africa
21	ZAF	South Africa
		Asia-Pacific
22	ASEAN	Brunei, Cambodia, Lao, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest
23	AUS	Australia
24	CHN	China & Hongkong
25	IND	India
26	JPN	Japan
27	KOR	Korea
28	NZL	New Zealand
29	SAS	**South Asia:** Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia
30	ASO	Rest of Oceania, Mongolia, Taiwan, Rest of East Asia

Table A2: GTAPR Sectors

No	Sectors	Contents
1	Crops	Paddy rice; Wheat; Cereal grains nec; Vegetables, fruit, nuts; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec
2	Livestock	Bovine cattle, sheep and goats; Animal products nec; Raw milk; Wool, silk-worm cocoons; Bovine meat products; Meat products nec; Dairy products; Leather products
3	Forestry	Forestry
4	Fishing	Fishing
5	Coal	Coal
6	Oil	Oil
7	Gas	Gas
8	OtherMin	Minerals nec
9	CropPrd	Vegetable oils and fats; Processed rice; Sugar; Food products nec; Beverages and tobacco products
10	Manufactures	Textiles ; Wearing apparel;Metal products; Computer, electronic and optic; Electrical equipment;Machinery and equipment nec; Motor vehicles and parts;Transport equipment nec; Manufactures nec
11	WoodPaperPrd	Wood products; Paper products, publishing
12	Oil pcts	Petroleum, coal products
13	ChemRubPlast	Chemical products; Basic pharmaceutical products; Rubber and plastic products
14	NonMetalMin	Mineral products nec
15	IronSteel	Ferrous metals
16	NonFerMetal	Metals nec
17	Utilities	Gas manufacture, distribution; Water
18	Construction	Construction
19	LandTpt	Road transport
20	WaterTpt	Sea transport
21	AirTpt	Air transport
22	Services	Trade; Accommodation, Food and services; Warehousing and support activities; Communication; Financial services nec; Insurance; Real estate activities; Business services nec; Recreational and other service
23	DefcGovSrv	Public Administration and defence; Education; Human health and social work activities
24	Dwellings	Dwellings
25	TnD	Electricity transmission and distribution
26	efoss	Coal base load; Gas base load; Oil base load; Gas peak load; Oil peak load
27	renew	Nuclear base load; Wind base load; Hydro base load; Other base load; Hydro peak load; Solar peak load
28	CGDS	Capital good commodities

Supplementary Information

Model code and supporting data can be obtained at https://osf.io/mrbuh/. Please acknowledge any use of these materials and the accompanying manuscript/paper. Users will also require GTAP data.

References

Aguiar, A., Chepeliev, M., Corong, E., McDougall, R. and van der Mensbrugghe, D. (2019), 'The GTAP Data Base: Version 10', *Journal of Global Economic Analysis* **4**(1), 1–27.

BP (2020), 'BP Global Energy Database', British Petroleum. Statistics 2020. Available at https://www.bp.com/.

Burniaux, J.-M. and Lee, H.-L. (2003), 'Modelling land use changes in GTAP', Purdue Working Paper 1509. University of Purdue.

Burniaux, J.-M. and Truong, T. (2002), 'GTAP-E: An Energy-Environmental Version of the GTAP Model', GTAP Technical Paper n.16.

Cai, Y., Newth, D., Finnigan, J. and Gunasekera, D. (2015), 'A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation', *Applied Energy* **148**, 381–395.

Chepeliev, M. (2020), 'GTAP-Power 10a Database: a Technical Note', Research Memorandum No. 31. Available at https://www.gtap.agecon.purdue.edu.

EIA (2016), 'Carbon Dioxide Emissions Coefficients', US Energy Information Administration. Available at https://www.eia.gov/.

EIA (2021*a*), 'China', US Energy Information Administration. Available at https://www.eia.gov/.

EIA (2021*b*), 'Fossil fuel production expected to increase through 2022 but remain below 2019 peak', US Energy Information Administration. Available at https://www.eia.gov/.

EIA (2021*c*), 'India', US Energy Information Administration. Available at https://www.eia.gov/.

EIA (2021*d*), 'U.S energy facts explained', US Energy Information Administration. Available at https://www.eia.gov/.

Enerdata (2021), 'Energy intensity- Global Energy Statistical Yearbook 2021', Publication by the Departement of Industry, Science, Energy and Resources of Australia (DISER). Available at https://yearbook.enerdata.net.

FAO (2020), 'The State of the World's Forests 2020', Food and Agriculture Organization of the UN. Available at http://www.fao.org/.

GTAP (2021), 'GTAP (Global Trade Analysis Project)', Global Trade Analysis Project. Available at https://www.gtap.agecon.purdue.edu/.

Harris, N, L., Gibbs, D, A., Baccini, A. and et al. (2021), 'Global maps of twenty-first century forest carbon fluxes ', *Nature Climate Change* **11**(3), 224–240.

Hertel, T. W., ed. (1997), *Global Trade Analysis: Modeling and Applications*, Cambridge University Press, Cambridge, New York.

Hope, C., Anderson, J. and Wenman, P. (1993), 'Policy analysis of the greenhouse effect: an application of the PAGE model', *Energy Policy* **21**(3), 327–338.

Huff, K. and Hertel, T. (2000), 'Decomposing Welfare Changes in the GTAP Model', GTAP Working Paper No. 5 2000. Available at https://www.gtap.agecon.purdue.edu/.

Ianchovichina, E. and McDougall, R. (2000), 'Theoretical Structure of Dynamic GTAP', GTAP Working Paper No. 17 2000. Available at https://www.gtap.agecon.purdue.edu/.

Ianchovichina, E., McDougall, R. and Hertel, T. (2000), 'A Disequilibrium Model of International Capital Mobility ', GTAP Working Paper No. 10 2000. Available at https://jgea.org/resources/download/2870.pdf.

IEA (2021*a*), 'Global-Energy-Review-2021', International Energy Agency. Statistics Database. Available at https://www.iea.org/reports/global-energy-review-2021/.

IEA (2021*b*), 'Global Energy Review: CO2 Emissions in 2020', International Energy Agency. Articles. Available at https://www.iea.org/articles.

IEA (2021*c*), 'World Energy Balances', International Energy Agency. Statistics Database. Available at https://www.iea.org.

IMF (2021), 'World Economic Outlook', WEO Report. Available at www.imf.org .

IPCC (2018), 'Global warming of 1.5^0C 2018: Synthesis Report', An IPCC Special Report on the impacts of global warming of 1.5^0C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. IPCC, Geneva, Switzerland, 616 pp.

IPCC (2019), 'Climate change and land', An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

IPCC (2021), 'Climate change 2021: The physical science basis', Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press.

IRENA (2019), 'Global Energy Transformation: A Roadmap to 2050 (2019 edition)', Available at www.irena.org.

IRENA (2020), 'Renewable Power Generation Costs in 2019', Available at www.irena.org.

IRENA (2021), 'Renewable energy statistics 2021', Available at www.irena.org.

Kohl, M., Neupane, P. and Lotfiomran, N. (2017), 'The impact of tree age on biomass growth and carbon accumulation capacity: A retrospective analysis using tree ring data of three tropical tree species grown in natural forests of suriname', *PLOS One* **12**(8).

Kompas, T., Pham, V. H. and Che, T. N. (2018), 'The effects of climate change on GDP by country and the global economic gains from complying with the Paris climate accord', *Earth's Future* **6**(8), 1153–1173.

Kompas, T. and Van Ha, P. (2019), 'The 'curse of dimensionality' resolved: The effects of climate change and trade barriers in large dimensional modelling', *Economic Modelling* **80**, 103–110.

Liu, P. R. and Raftery, A. E. (2021), 'Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2C target', *Communications Earth and Environment* **2**(1), 1–10.

Naam, R. (2020), 'Solar's Future is Insanely Cheap (2020)', Ramez Naam. Available at https://rameznaam.com.

OWD (2021), 'CO2 Emissions', Our World in Data. Prepared by Hannah Ritchie and Max Roser. Available at https://ourworldindata.org/.

Peters, J. (2016), 'GTAP-E-Power: An Electricity-Detailed Economy-Wide Model', *Journal of Global Economic Analysis* **1**(2), 156–187.
URL: *https://jgea.org/resources/jgea/ojs/index.php/jgea/article/view/27*

Phillips, O. L., Aragao, L. E. O. C., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C., Almeida, S., Meir, P., Amaral, I. and Brando, P. M. (2009), 'Drought sensitivity of the amazon rainforest', *Science* **323**, 1344–1347.

Piontek, F., Drouet, L., Emmerling, J., Kompas, T., Méjean, A., Otto, C., Rising, J., Soergel, B., Taconet, N. and Tavoni, M. (2021), 'Integrated perspective on translating biophysical to economic impacts of climate change', *Nature Climate Change* **11**, 563–572.

Raftery, A. E., Zimmer, A., Frierson, D. M., Startz, R. and Liu, P. (2017), 'Less than 2 c warming by 2100 unlikely', *Nature Climate Change* **7**(9), 637–641.

Rezai, A. and van der Ploeg, F. (2017), 'Climate policies under climate model uncertainty: Max-min and min-max regret', *Energy Economics* **68**, 4–16.

Toochi, E. (2018), 'Carbon sequestration: how much can forestry sequester CO2', *Forestry Research and Engineering: International Journal* **2**(3), 148–150.

Truong, T. (2007), 'GTAP E: An Energy-Environmental Version of the GTAP Model with Emission Trading', GTAP Technical Paper: User's Guide.

Truong, T., Kemfet, C. and Burniaux, J. (2007), 'GTAP-E: An Energy-Environmental Version of the GTAP Model with Emission Trading', Working Paper No.668. German Institute for Economic Research.

Truong, T. P. and Hamasaki, H. (2018), 'Disaggregating the electricity sector in a CGE model to allow competition theory to explain the introduction of new technologies to the sector', Research Working Paper. University of Sydney NSW.

UNFCCC (2021), 'Greenhouse Gas Inventory Data - Detailed Data by Party', the United Nations Framework Convention on Climate Change (UNFCCC). Available at https://unfccc.int.

United Nations (2019), 'World Population Prospects 2019', World Bank Report. Available at https://population.un.org.

van Soest, H. L., den Elzen, M. G. and van Vuuren, D. P. (2021), 'Net-zero emission targets for major emitting countries consistent with the Paris Agreement', *Nature Communications* **12**(1), 1–9.

World Bank (2020), 'State and Trends of Carbon Pricing 2020', World Bank. Available at https://openknowledge.worldbank.org/.