Annex

This appendix to Chapter 3 of the October 2022 World Economic Outlook provides documentation of the model structure, data sources, and additional details on simulations presented in Chapter 3. Section 3.1 describe the structure of the Global Macroeconomic Model for the Energy Transition (GMMET) model and documents some elements of its calibration. Section 3.2 sheds a light on factor reallocation during the transition. Section 3.3 investigates the external sectors during the transition. Section 3.4 provides impact of delayed climate policies for the different regions.

Annex 3.1 Description of the Global Macroeconomic Model for the Energy Transition

The Global Macroeconomic Model for the Energy Transition (GMMET) is a multi-region model configured for four regions – the United States, the euro area, China, and a fourth block for the rest of the world.[1] It belongs to the class of large-scale structural New-Keynesian dynamic general equilibrium models that are traditionally used for the quantitative short- and medium-term analysis of monetary and fiscal policy. The model's macroeconomic core is inherited from GIMF (the IMF's Global Integrated Monetary and Fiscal Model; see Kumhof and others 2010 and Anderson and others 2013). Consequently, it includes tradable and non-tradable goods sectors, liquidity-constrained and overlapping-generations households, a wide menu of real and nominal rigidities, a fiscal sector with a variety of fiscal instruments, and a simple monetary policy rule.

The Structure of GMMET

With the presence of overlapping generations households, each region's outcomes will be affected by the level of government debt held – in other words, the model exhibits non-Ricardian behavior even in the long term (Blanchard 1985). These non-Ricardian impacts are amplified in the short term by the presence of liquidity-constrained households which consume all income each period and have no savings. Because of the long-term non-Ricardian impacts, regions can have permanent variations in their current account balances. Therefore, net foreign asset positions have a meaningful role, driving real exchange rate and global real interest rate movements that help reconcile regional and global saving-investment balances.

Firms in non-energy sectors produce tradable and nontradable goods based on energy inputs (outlined further below in Annex Figure 3.1.4) and labor and capital services. Capital services are provided capital stocks that accumulated by investment, which is financed by a financial sector as found in Bernanke, Gertler and Gilchrist (1999). This employs a procyclical financial accelerator, with the cost of borrowing costs facing firms rising with their level of debt relative to the net worth of their firms. Since firms are represented at the highly aggregated level of tradable and nontradable goods, there is no distinction between financing "green" or "dirty" firms.

[1] See Carton and others (2022) for a detailed description of the model.

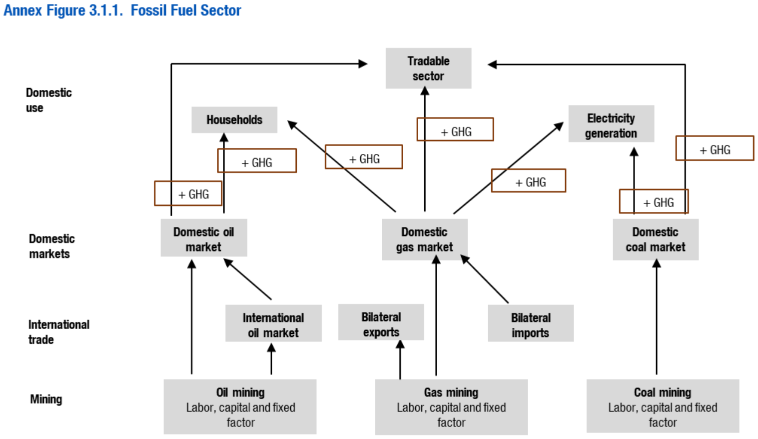
The purpose of GMMET is to analyze the short- and medium-term macroeconomic impact of curbing GHG emissions, rather than taking a long-term perspective as done in integrated assessment models (IAMs) or computable general equilibrium (CGE) models, such as the combination of models used by the Network for Greening the Financial System (NGFS).[2] This shorter-term focus means GMMET is able to exclude certain features related to emissions and emissions-reducing technologies. First, GMMET does not model the prospective longer-term increases in firm or sectoral productivity that is expected to result from constantly improving emissions reduction technologies, whether it is related to electricity production, manufacturing or agricultural processes, or electric vehicle production. Second, GMMET's structure does not account for damages from warming produced by damage functions. Consequently, the benefits from mitigation—avoided warming damages— are also not included. This is admissible because the stock of GHG emissions in the atmosphere is accumulated over a long time horizon and does not adjust significantly to mitigation polices over the limited time span of eight years considered in this exercise. On the other hand, analyzing the macroeconomic impact of mitigation requires a detailed description of GHG-emission-generating activities, particularly energy, transportation, and the production of goods associated with other GHG emissions, and their interaction with the rest of the economy. These elements, which are novel relative to GIMF, are outlined in the next subsection.

The Structure of the Energy Sectors and Interactions with the Rest of GMMET

Energy originates from three fossil fuel mining sectors – coal, gas, and oil – each combining capital and labor with a resource available in fixed supply (such as coal mines or gas deposits or oil wells and tar sands). The calibrated model reproduces empirical estimates of the supply elasticity at various time horizons. In the case of coal, for example, the elasticity was estimated with the empirical strategy in Boer, Pescatori and Stuermer (2021). The calibration of mining supply elasticities is crucial for a meaningful analysis of the transition to lower emissions, since they govern to what extent the GHG price burden is borne by customers—for example, electricity utilities—which in turn determines the magnitude of the resulting switch to cleaner fuels.

The bottom half of Annex Figure 3.1.1 shows all three mining sectors. There are the domestic markets, and

Annex Figure 3.1.1. Fossil Fuel Sector



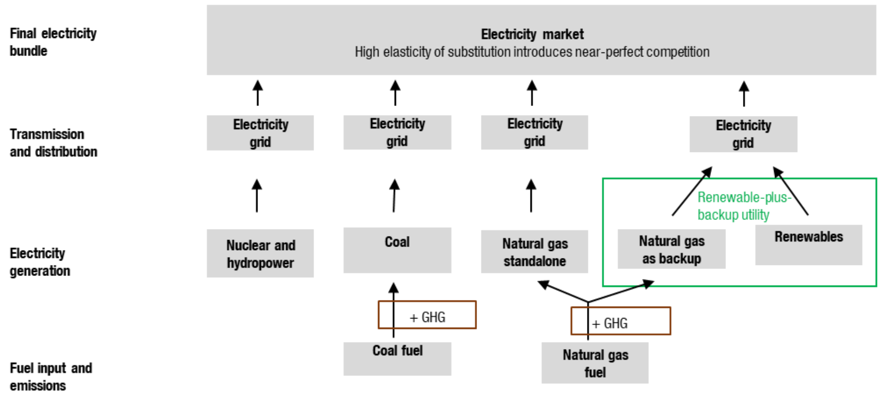
Source: IMF staff.
Note: Fixed factor in the three mining sectors refers to the deposits of either coal, fossil gas or oil for their respective sectors. GHG = greenhouse gas.

2 Integrated assessment models are typically based on single observations covering five or more years (called resolution units). The macroeconomy is represented by a Ramsey-type growth model where output is entirely determined by the supply side. Computable general equilibrium models feature a high number of regions and sectors but only allow comparison across different static equilibria. The energy transition can in principle be analyzed in dynamic CGEs, but their recursive solution method neglects the role of forward-looking expectations (which are especially important for investment decisions).

international markets for oil (with an integrated global market tracking each region's total exports and imports) and gas (tracking bilateral trade among all of the regions).[3] In those markets, all three fuels are sold to the tradable sector as an intermediate input. In addition, oil and gas are also consumed by households (as car gasoline and fuel for home heating, respectively), and gas and coal are also sold as fuel for electricity generation. In this figure and in the following, the label "+GHG" indicates GHG emissions from burning these fossil fuels.

The electricity generation sector features five technologies: coal, gas, nuclear power, hydroelectric power, and renewables. It is depicted in Annex Figure 3.1.2, where the supply chain runs from the fuel inputs at the bottom to the final electricity output at the top. The five technologies differ in their cost structures and emission intensities, and each has a technology-specific capital stock.

Annex Figure 3.1.2. Electricity Generation Sector



Source: IMF staff.
Note: GHG = greenhouse gas.

Nuclear and hydroelectric power are grouped into one and its investment is decided exogenously, reflecting that nuclear investment is determined by politics rather than market forces, and that sites for hydroelectric power generation are limited. Therefore, any change in investment in that sector in the policy packages of the main text reflects decisions taken by the government or private sector measures with government financing, not a behavioral response to demand or supply conditions.

A key obstacle to the mass deployment of renewable sources for electricity is that its generation is intermittent. That is, electricity generation from renewable sources is subjected to uncontrollable weather-dependent fluctuations (Bistline and others 2021, for a recent literature overview and Box 3.3 in the main text). To capture this aspect in a stylized fashion, it is assumed that a so-called "renewables-plus-backup" utility pairs wind and solar power generation with a flexible back-up capacity based on gas that covers periods of shortfalls in electricity generation.[4] The size of the back-up capacity relative to the renewable capacity is endogenously determined by a cost-minimization problem based on the degree of intermittency and the relative costs of both generation technologies.

[3] Currently, international trade in coal is not modeled because the observed trade shares are low.

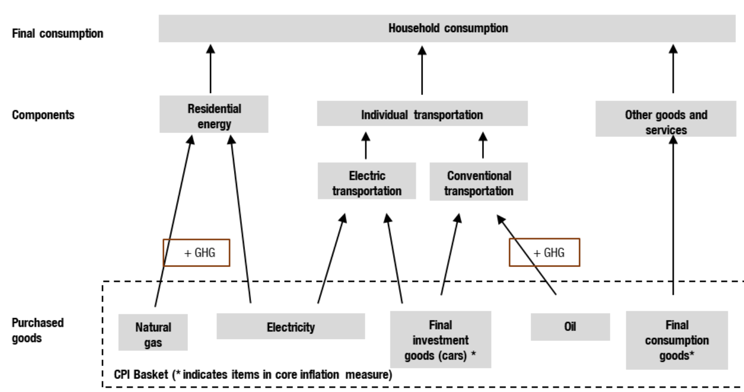
[4] Grid-scale electricity storage, a key option to alleviate the intermittency problem, is not accounted for since the model is based on currently available technology.

The electricity output of all technologies is individually paired with grid capital and combined into a final electricity bundle. As they are assumed to be very close substitutes they are subject to a very high elasticity of substitution.

The model's transportation sector distinguishes between the fleets of conventional cars burning gasoline (that comes from oil) and electric vehicles running on electricity. For each type, the net inflow to the fleet corresponds to the balance of newly purchased and scrapped cars. The share of both types in newly purchased cars depends on relative vehicle prices and the associated elasticity of substitution of 3.3 (Holland, Mansur and Yates 2021), relative to expected fuel costs over a car's lifecycle, and the size of charging and fueling networks. An explicit role for the latter is crucial for a realistic assessment of the efficacy of policies aimed at the electrification of transportation. Therefore, network externalities are modelled between electric vehicle adoption and the deployment of charging stations in the spirit of Li and others (2017). A higher number of electric vehicles encourages the construction of new charging stations, while a higher density of the charging station network incentivizes the purchase of electric vehicles by households. The resulting positive feedback loop amplifies the impact of mitigation policies to shift away from conventional cars.

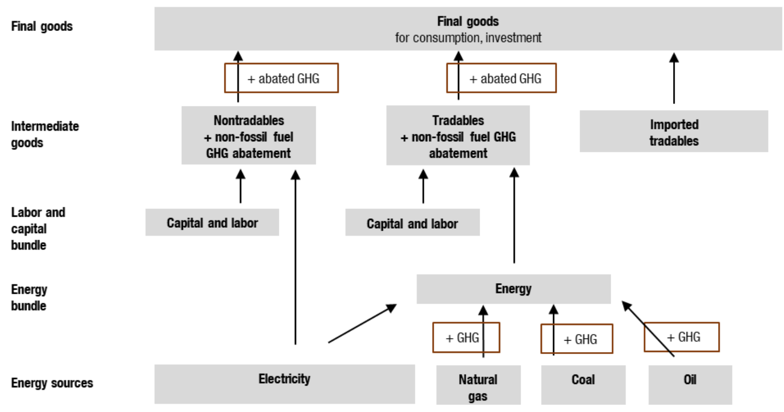
Annex Figure 3.1.3 shows in detail the components of household consumption and shows that cars of both types are treated as investment goods (to account for a high import share), while their fuels – either gasoline (oil) or electricity – are explicitly accounted for in the consumption bundle. The box in dashed lines indicates the composition of the consumer price index (CPI). Only cars and the final consumption good are included in the core inflation measure. "Residential heating" is a composite of electricity and gas, and "Other goods and services" denotes the standard GIMF consumption bundle of a final good made up of tradable and nontradable goods, as described in the following figure.

Annex Figure 3.1.3. Household Consumption



Source: IMF staff.
Note: GHG = greenhouse gas.

Annex Figure 3.1.4. Production Sector



Source: IMF staff.
Note: GHG = greenhouse gas.

Annex Figure 3.1.4 shows that the nontradable sector (mostly services) only uses electricity as an input factor alongside a bundle of capital and labor. The tradables (mostly manufacturing) sector, in contrast, combines the capital and labor bundle with an energy bundle that in turn comprises electricity and the three fossil fuels, oil, gas, and coal. This corresponds to the demand from tradables in the fossil fuel sector shown in Annex Figure 3.1.1. The production of nontradables and tradables is combined with imported tradables to create the final good. Final goods are used for investment and consumption (both private and public), and their respective demand determines the share of imported tradables, which is higher for investment than for consumption.

A special feature of the nontradables and tradables sectors is that their production is linked to GHG emissions not resulting from fossil fuel combustion, such as methane from agriculture. Whereas other sectors adjust their reliance on fossil fuels to reduce emissions in response to a GHG tax, in these two sectors, non-fossil-fuel emissions are not modelled explicitly, hence requiring an additional representation of emissions reduction, called abatement. Both sectors can employ emission abatement technology (the use of alternative, greener production processes) that allows producers to reduce emissions at the expense of the sector's total factor productivity. It is implemented in a reduced-form fashion and calibrated to be in line with sector-specific estimates of marginal abatement cost curves (that is, for all abatement levels, productivity costs of abating another unit of emissions correspond to empirical estimates). Given this technology, both sectors chose their optimal abatement level in order to equate tax savings from abating a marginal unit of emissions with marginal abatement costs. These non-fossil fuel emissions are labeled "+ abated GHG" in the Annex Figure 3.1.4 above.

To allow for the introduction of economy-wide GHG prices, the government can levy sector-specific per-unit GHG taxes that depend on the respective sector's carbon intensity. The government can also subsidize green technologies such as renewables or electric vehicles and expand investment in nuclear power generation. The government can also wield regulatory instruments to mitigate GHG emissions. In GMMET, regulations are introduced as revenue-neutral tax-subsidy combinations where one or more inputs of a sector are taxed, and the revenues used to subsidize the remaining inputs. These imposed relative price shifts lead to expenditure switching that mimic a regulation that forces an adjustment of relative quantities, such as favoring renewables power generation in the electricity over coal and gas, for example.

Calibrating The Energy Sectors

The overall calibration of GMMET and its four regions is based on a variety of data sources. In the initial state of the model before a policy is implemented, the size of the different sectors, and the trade structure is informed by the OECD's Inter-Country Input-Output Tables (OECD 2021), while more granular calibration aspects pertaining to the different fossil fuels are based on the World Energy Balances by the International Energy Agency (IEA 2021). Annex Table 3.1.1 compares the extraction and use of fossil fuels across regions in GMMET, based on data from 2018. Fossil fuel extraction as a share of GDP (grouping coal, gas and oil) is by far the greatest in the rest of the world block, with roughly a quarter being exported. China is especially dependent on coal, which comprises the largest portion in electricity generation and second largest (after oil for petrochemicals) in highly energy-intensive manufacturing.

Annex Table 3.1.1 Fossil Fuel Supply and Use

(Percent of region's GDP, unless noted otherwise)

	China	Euro Area	Rest of the World	United States
GDP (percent of world)	16.4	15.5	43.7	24.4
Fossil fuel extraction	3.3	0.2	6.1	2.6
Coal	2.5	0.2	0.7	0.3
Fossil gas	0.2	0.0	1.5	0.8
Oil	0.6	0.0	4.0	1.4
Fossil fuel net imports	1.6	1.9	-1.5	0.4
Fossil gas	0.2	0.5	-0.2	0.0
Oil	1.4	1.4	-1.3	0.5
Fossil fuel in electricity	1.8	0.3	1.1	0.6
Coal	1.7	0.1	0.5	0.3
Fossil gas	0.1	0.2	0.6	0.3
Energy in tradables	5.7	2.0	3.9	1.6
Coal	0.8	0.0	0.2	0.0
Fossil gas	0.2	0.2	0.4	0.3
Oil	1.5	0.7	1.7	0.9
Electricity	3.2	1.0	1.6	0.3
Electricity in nontradables	0.3	0.8	0.8	0.5
Energy in household consumption	1.3	1.5	2.1	1.8
Fossil gas	0.1	0.1	0.2	0.1
Oil	0.5	0.6	0.9	1.0
Electricity	0.7	0.8	1.0	0.6

Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff calculations.
Note: Expenditures on energy do not include refining, transportation/transmission, and distribution margins. Accounting errors due to rounding.

Initial GHG emissions, including other gases than CO_2, reflect data from the European Commission's EDGAR database (European Commission Joint Research Centre 2022), while marginal abatement costs for non-CO_2 emissions are calibrated on country-specific estimates from the US Environmental Protection Agency (US EPA 2019).

Key values in the benchmark calibration for the use of energy as well as in the alternative calibration (see section "Energy Transition: How Quickly Can It Be Achieved?" in the main text) are shown in Annex Table 3.1.2. Renewables can be treated as just as substitutable as coal, gas and nuclear power in electricity generation because the model addresses the issue intermittency of renewable energy by including a gas backup. Therefore, the benchmark elasticity is quite high at 20. By contrast, price elasticities of demand are low. For manufacturing, energy is being used for disparate outputs such as chemicals, cement, and steel. Residential energy is somewhat more flexible with a price elasticity of demand of 1.5, reflecting the ability to convert between the use of gas and electricity. When considering using the use of energy relative to labor and capital, the elasticity is sensibly low (0.4 for tradables and 0.5 for nontradables).

Annex Table 3.1.2. Benchmark and Lower Elasticities of Substitution

	Benchmark	Lower
Elasticity between:		
Four types of generation in electricity	20.0	5.0
Four types of energy in manufacturing	0.5	0.2
Energy and other factors in manufacturing	0.4	0.2
Electricity and other factors in services	0.5	0.2
Electricity and fossil gas in residential	1.5	1.2

Source: Global Macroeconomic Model for the Energy Transition.

Dynamic model parameters are calibrated as in GIMF, while long-term elasticities of substitution between different fossil fuels—when there is no gradual modelling as in electricity generation or transportation— are taken from the literature (Fally and Sayre, 2018 provide a recent survey).

Nominal Rigidities and Monetary Policy Rule

In GMMET, the wage and price inflation Phillips' curves are implicit in several equations. However, for illustrative purposes, they can be represented in a linearized form that includes past and expected future inflation, and the deviation of firms' markups (the wage to marginal rate of substitution ratio for labor or price to marginal cost ratio for all other sectors) from their equilibrium level ($\hat{\mu}_t$):

$$(1+\beta)\pi_t = \pi_{t-1} + \beta\, E(\pi_{t+1}) + \frac{\sigma - 1}{\phi}\hat{\mu}_t$$

where the default value of β is 0.97. The scenario assuming lower central bank credibility introduces more sluggish inflation expectations by setting β=0.2. In addition, the wage inflation Phillips curve is modified so that it partially indexes wage inflation to consumer price inflation:

$$(1+\beta\,)\pi_t^w = \pi_t^c + \beta\, E(\pi_{t+1}^w) + \frac{\sigma - 1}{\phi}\hat{\mu}_t^w$$

The monetary policy rule sets the interest rate as a function of the deviation of a measure of inflation from an inflation target. For illustrative purposes, it can be written so that its log-linearized form is:

$$i_t = \varrho i_{t-1} + (1-\varrho)\alpha i[(\chi\pi_t + (1-\chi)E(\pi_{t+1})) - \bar{\pi}]$$

The measure of inflation is a weighted average (using χ) of current and (perfect foresight) expected inflation (which is either headline or core inflation, depending on the scenario). Core inflation is defined from a subset of consumption expenditures that excludes energy consumption (oil, gas and electricity; see Annex Figure 3.1.3).

Simulation Techniques

GMMET has many nonlinearities, including related to its energy sectors, typically rising marginal abatement costs, linkages between GHG emissions and taxation, and standard nonlinearities related to investment and the financial accelerator. For example, during the gradual increase of a GHG tax, the output of a region's coal mining sector can fall to almost zero long before other energy sectors' production reach their maximal emissions reduction. This introduces a nonlinearity, or even a discontinuity, in the mathematical solution of the model. These sorts of nonlinearities produce rich results but would be lost if the model was solved using a linear approximation method.

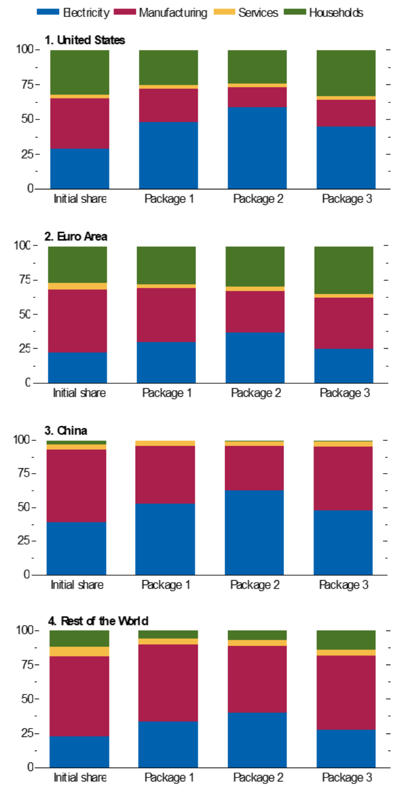
The solution algorithm employed attempts to solve the full nonlinear model but might need to partially approximate the full solution due to computational constraints. For example, perhaps 75 percent of a GHG price shock can be solved, but the remaining 25 percent of the solution is based on the difference between solving 75 and 74 percent of the GHG price. This partial numeric linearization method will capture a significant portion of the nonlinearities of the model. More concretely, if the economy-wide GHG price is doubled, the impacts often more than double depending on the sector, results which are often lost under a linear approximation method. Employing this methodology also allows permanent shocks to be solved (such as a permanent increase in GHG taxation), instead of only being able to consider temporary shocks.

Annex 3.2 Resources Reallocation under Rising GHG Taxes

To detail the impact of carbon pricing on the use and reallocation of resources, this annex focuses on scenarios where GHG taxes are gradually introduced in all regions simultaneously. Reducing GHG emissions by 25 percent in less than a decade constitutes a deep transformation of the economy in which every sector plays a role.

Not all sectors participate proportionally in the reduction of emissions. Electricity generation – where fossil fuels, in particular coal, are quickly replaced by renewables – is central to the transformation. Because the tax is levied proportionally to a fuel's CO_2 intensity, it penalizes coal the most. For instance, electricity generation accounts for 29 percent of initial emissions in the United States (see Annex Figure 3.2.1., first column in the first panel) but is expected to represent between 45 and 59 percent of their reduction depending on the scenario (emissions reductions for Policy Packages 1 to 3 are shown in columns 2 to 4, where a higher share than in the first column signals a more than proportional contribution to emissions reduction of the respective sector). Figures are very similar in China as electricity accounts for a third of GHG emissions and around half of their reductions depending on the scenario. In other sectors, emissions also fall via energy savings and the deployment of abatement technologies (that is, the shifting to lower-emission processes). The household sector plays a prominent role in the United States and in the euro area, as residential energy and individual transportation account for a large share of emissions. The manufacturing sector is particularly relevant for emissions reductions in China and the rest of the world.

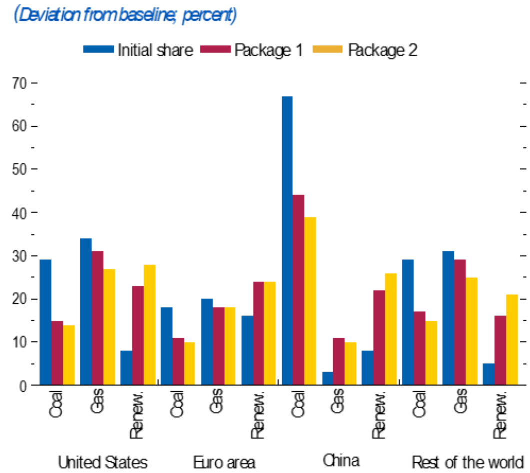
Annex Figure 3.2.1. Share in Initial GHG Emissions and Their Reduction by 2030 in the Three Policy Packages
(Percent)



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on benchmark elasticities. Package 1: one-third transfers to households, two-thirds labor tax cuts; Package 2: one-third transfers to households, one-third labor tax cut, one-third green subsidies; Package 3: production subsidies and transportation regulation. See Table 3.1. for the description of the three policy packages. GHG = greenhouse gas.

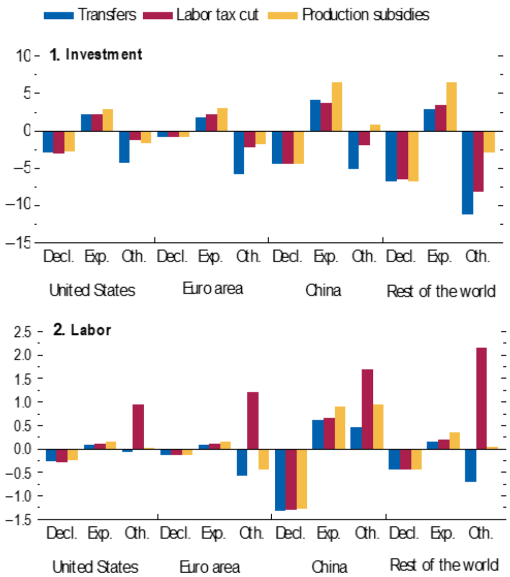
In the electricity sector, GHG emissions reductions are the result of a shift in the electricity mix as generation from coal is rapidly substituted by renewables with gas backup to compensate for intermittency. Policy Package 1, where the GHG price alone is implemented (see Table 3.1 in the main text for detailed description of the package), incentivizes a large reduction in generation from coal and a shift to generation from renewables (See Annex Figure 3.2.2.). Policy Package 2, that adds renewables subsidies on the top of Policy Package 1, is particularly well-designed to trigger an even larger fuel shift in electricity generation; it causes the share of renewables to increase by around 20 percentage points. The combination of both a GHG price, heavily targeting coal, and renewable subsidies is key to decarbonize the electricity sector swiftly and effectively.

Annex Figure 3.2.2. Electricity Generation Shares in 2030
(Deviation from baseline; percent)



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Package 1: two-thirds labor tax cuts and one-third transfers to households; Package 2: one-third transfers to households, one-third labor tax cut, one-third green subsidies. See Table 3.1. for the description of the three policy packages. Renew. = wind and solar generation.

Annex Figure 3.2.3. Contribution to Change in Regional Aggregate in 2030
(Deviation from baseline; percentage points)



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on Package 1 with benchmark elasticities. Decl. = declining energy sector - fossil fuel extractions and coal power plants; Exp. = expanding sectors - renewables, nuclear, hydro and fossil gas generation, electricity grid; Oth. = other sectors.

Underlying those structural changes are wide-ranging shifts in investment patterns. While investment falls to adjust the stock of capital in response to higher energy prices – capital and energy are generally complements in production – there is substantial heterogeneity across sectors. Investment in expanding energy sectors (renewables generation, gas power plants and the electricity grid) boom, while investment in declining energy sectors (fossil fuel extraction and coal power plants) drop (see Annex Figure 3.2.3.). Investment in non-energy tradables and nontradables (column "Oth." in Annex Figure 3.2.3.) usually drops as the cost of energy is higher. This reallocation of capital goes hand in hand with a reallocation of labor from declining to expanding sectors. In this context, the revenue recycling option matters most for non-energy tradables and nontradables, where employment expands significantly if an increase in GHG tax revenues is used to cut labor taxes. In contrast, employment declines if the tax revenue is transferred back to households in a lumpsum fashion.

Annex 3.3. External Impact of GHG Mitigation Policies: Do It Alone or Do It Together

Decarbonization In Different Regions: A Primer

Each region has a specific economic structure: the size of the fossil fuel extraction in the economy, the share of different technologies in electricity generation, the energy-intensity of production, the structure of household consumption, sectoral emission-intensities, etc. (see Annex Table 3.1.1 for details on initial fossil fuel use). As a result, policies reducing emissions by the same proportion in all regions require region-specific GHG prices, with macroeconomic implications that depend on each region's economic and energy structures. The differing GHG prices across regions introduce tax wedges that can have an impact on relative prices between domestic and imported goods.

The United States, for instance, has a high emissions-to-GDP ratio, but can easily reduce emissions in its electricity sector (thanks to a local abundance of gas to back up renewables) and in individual transportation (this sector represents a much larger share of emissions than in other countries and lower-emissions electric vehicle technology is more mature relative to some other regions). In comparison, the euro area has lower emissions per unit of GDP resulting from two decades of mitigation policies, so that fewer low-hanging fruits remain and a higher GHG price is required for the same emissions reduction (137 US dollars per metric ton of CO2 equivalent versus 85 US dollars per metric ton of CO2 equivalent in Policy Package 1 for example).

China also has a high emissions-to-GDP ratio, driven by concentrated emissions in electricity generation and manufacturing sectors while the household sector plays a relatively minor role. Those emission are driven by the heavy use of coal and fewer regulations on emissions in manufacturing relative to other countries. As coal has a very high emissions-to-value ratio, a relatively low GHG price (36 US dollars per metric ton of CO2 equivalent in Policy Package 1) is already sufficient to bring about the 25 percent overall emissions reduction (see Figure 3.2. Panel 1 in main text).

The rest of the world block aggregates very different economies and the presented simulation results should therefore not be thought of as applying to any particular member country. For example, a similar reduction of emissions in different economies requires differentiated GHG price increases, which is averaged out in the aggregate. Another example is that reduced demand for fossil fuels has potentially large wealth effects for oil exporters, and these effects are distributed across all countries subsumed in the aggregated region.

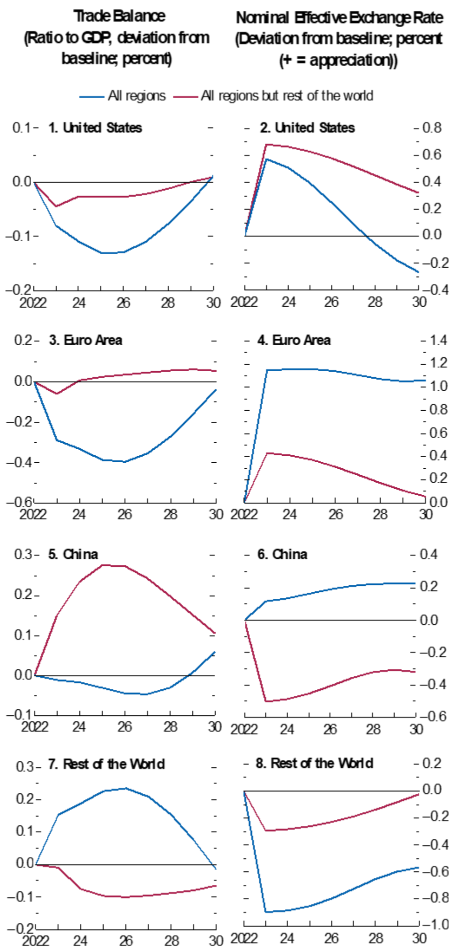
The block is unique in that it has a high share of energy in GDP, a high share of oil use, and is a large net exporter of fossil fuels. As a result, reducing emissions has a larger negative impact on both real GDP and investment. Less emissions-intensive fuels are dominant in electricity generation and manufacturing sector (oil and gas instead of coal as in China), so a higher GHG price is required (95 US dollars per metric ton of CO_2 equivalent in Policy Package 1), leading to a larger increase in energy prices for the manufacturing sector. A large increase in energy prices interacting with a high share of energy in production leads to a more pronounced decline in the return of capital and a very significant drop in investment in the near term.[5]

Do It Alone or Do It Together: Partial or Common Action

To investigate further how policies and their macroeconomic impact on each region shape the external sector and global interest rates, we compare the *common* action scenario, which is Policy Package 1 in the main text, where all regions implement GHG mitigation policies, to a *partial* action scenario, where only the United States, the euro area, and China implement the policy package.

[5] The analysis is consistent with IMF (2022).

Annex Figure 3.3.1. External Sector with Common and Partial Action



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on benchmark elasticities and Policy Package 1. See Table 3.1. for the description of the three policy packages.

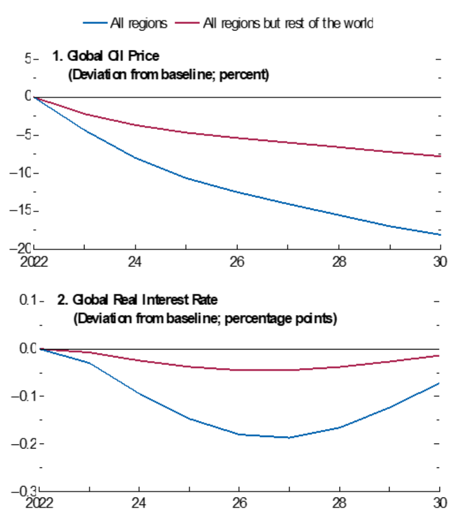
With common action, investment slows down in the near term, particularly in the rest of the world block, and the real global real interest rate falls. Capital flows out of the rest of the world, depreciates the effective exchange rate and improves the trade balance. Real effective exchange rates appreciate in the United States, the euro area and China (see Annex Figure 3.3.1., blue lines).

With partial action, it is no surprise that the global GHG emissions reduction is more muted compared to the common action scenario. The rest of the world no longer reduces its demand for fossil fuels, so there is less of a decline in global oil and gas prices. Therefore, regions that engage in GHG emissions reduction experience greater GDP losses, as the tax burden is not offset to the same extent by a reduction in producer prices (see Annex Figure 3.3.3).

Since the rest of the world is not introducing a GHG price, it does not experience direct impacts from decarbonization, facing only the spillovers from the other regions, primarily the impact of lower oil and gas prices and lower demand for their exports. The reduction of their investment is more muted relative to the common action scenario. Without the participation of the rest of the world, there is much less of a reduction of global investment, which leads to only a small reduction in global interest rates relative to the common action scenario (Annex Figure 3.3.2). These differences in external positions result in smaller appreciations of the effective exchange rates in China, the euro area and the United States (Annex Figure 3.3.1., red lines).

With partial action, the negative impacts of decarbonization policy in China, the euro area and the United States are magnified, relative to the common action scenario (Annex Figure 3.3.3.). With the smaller drop in the global real interest rate as well as less of a decrease in the global gas and oil prices partially offsetting the tax burden, the impact on GDP is magnified in all three regions (Annex Figure 3.3.2). In the United States, investment is slightly higher as the

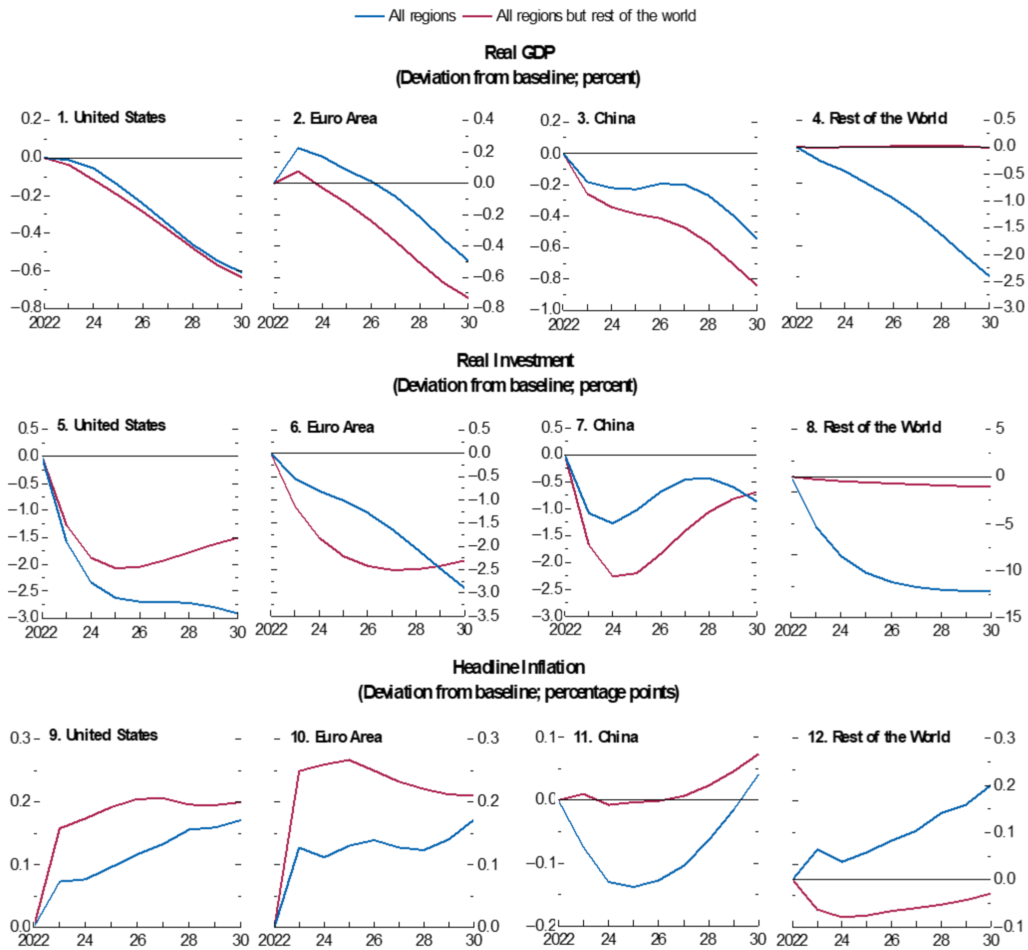
Annex Figure 3.3.2. External Sector with Common and Partial Action



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on benchmark elasticities and Policy Package 1. See Table 3.1. for the description of the three policy packages.

fossil fuel extraction industry avoids a large decline in output, thanks to higher demand for oil and gas than in the common action scenario. In the euro area, this channel is absent, and investment drops more rapidly. For China, investment still falls, as it is driven by the contraction of the coal sector, which continues to occur in the partial action scenario.

Annex Figure 3.3.3. Macroeconomic Impact with Common and Partial Action



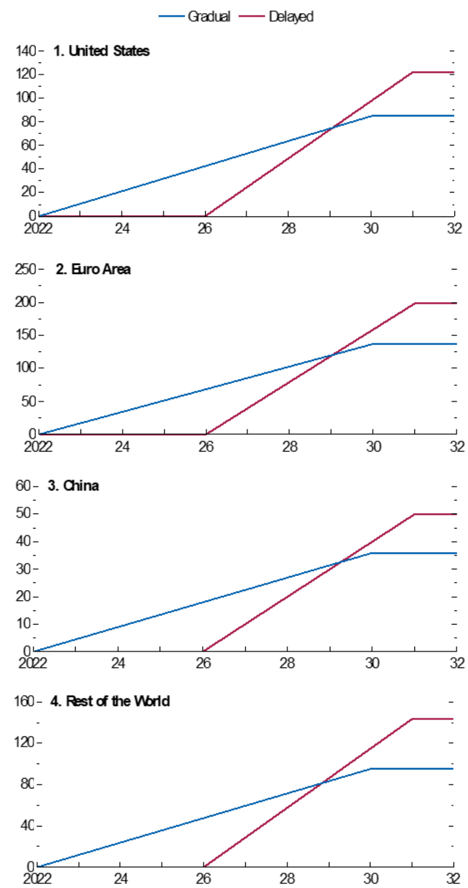
Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on benchmark elasticities and Policy Package 1. See Table 3.1. for the description of the three policy packages.

Annex 3.4 Delayed Mitigation Policies

To extend the analysis of delayed policies found in the main text, this section compares in all regions the immediate and gradual implementation of the Policy Package 1 with its delayed and more abrupt implementation. The delayed implementation keeps the same objective in emissions reduction by 2030 and targets similar cumulative emissions by 2045.

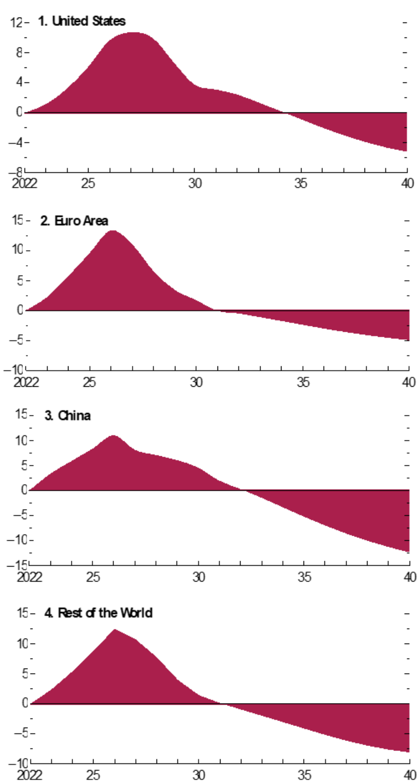
Delayed implementation requires a steeper rise in all regions' GHG prices and temporarily higher levels to bring about the same reduction of cumulative emissions in the medium term (Annex Figure 3.4.1). The GHG price increases from 2027 to 2030 to reach 50 US dollar per metric ton of CO_2 equivalent in China and climbs up to 200 US dollars in the euro area. Emissions decline rapidly starting in 2027 to reach the same level as under gradual implementation by about 2030, but the delayed scenario assumes that cumulative emissions reductions converge in 2045 (Annex Figure 3.4.2. shows the difference in emissions between both scenarios).

Annex Figure 3.4.1. GHG Price Path in the Gradual and Delayed GHG Mitigation Policies for Policy Package 1 and Benchmark Elasticities
(US dollars a tCO_2e)



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: GHG = greenhouse gas; tCO_2e = metric tons of carbon dioxide equivalent.

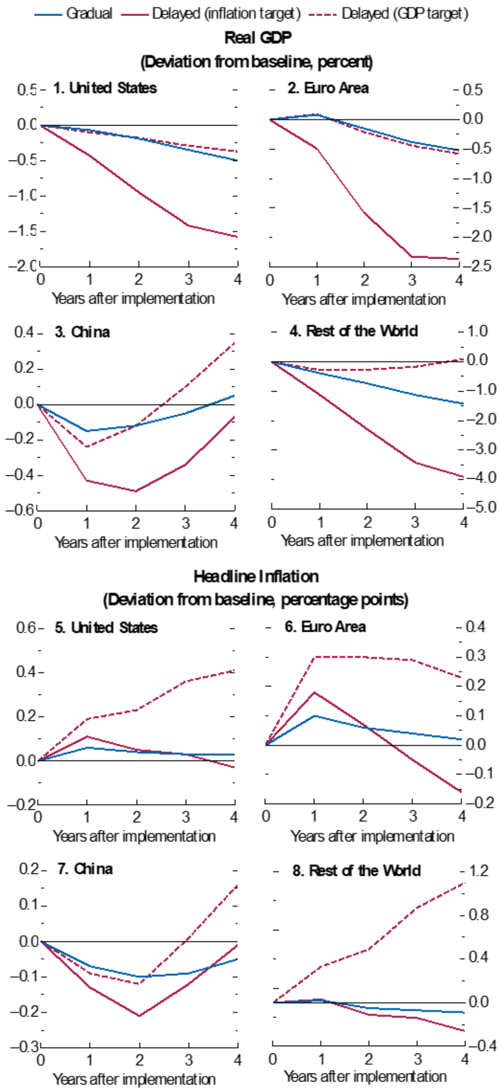
Annex Figure 3.4.2. Excess GHG Emissions from Delaying Policies
(Percent of baseline emissions)



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on Policy Package 1 and benchmark elasticities. GHG = greenhouse gas. See Table 3.1. for the description of the three policy packages.

The policy message for the United States, the euro area and the rest of the world block is similar: the need for rushed mitigation after further policy procrastination until 2026 greatly magnifies the costs (Annex Figure 3.4.3). The greater output-inflation tradeoff is illustrated by the high output costs of stabilizing headline inflation (with roughly the same magnitude as under immediately implemented mitigation policies), and the high level of inflation when output losses are limited (to about the same as under immediate policy action). The most extreme deterioration of the output-inflation tradeoff occurs in the rest of the world.

Annex Figure 3.4.3. Macroeconomic Effect of Gradual and Delayed GHG Mitigation Policies



Sources: Global Macroeconomic Model for the Energy Transition; and IMF staff estimates.
Note: Results based on Policy Package 1 with benchmark elasticities. Monetary policy targets core + GHG price under Gradual and Delayed under Delayed (GDP target), monetary policy targets the same GDP as in Gradual. GHG = greenhouse gas.

China stands aside as both the gradual and delayed mitigation policies generate little inflation. Low inflation in China is the result of a low direct impact of the GHG price on the CPI (energy use is low outside of the manufacturing sector in comparison to other regions) and the drop in the global prices of fossil fuel. During the first year of the GHG price increase, the producer price declines for each of the fossil fuels as global demand stalls. Fossil fuel user prices still increase globally because of the GHG price. Since China implements the lowest GHG price, it experiences the lowest increase in its user price. Delayed and more abrupt policies globally further accentuates the drop in China’s fossil fuel producer prices and further reduces inflation in China, at least in the near term. With the relatively lower impact of the GHG price on inflation in China, its output-inflation tradeoff is also smaller than in other regions.

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