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Getting to Know GMMET

The Global Macroeconomic Model for the Energy Transition

Benjamin Carton, Christopher Evans, Dirk Muir, and Simon Voigts

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Getting to Know GMMET: The Global Macroeconomic Model for the Energy Transition
Prepared by Benjamin Carton, Christopher Evans, Dirk Muir and Simon Voigts*

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ABSTRACT: This paper presents GMMET, the Global Macroeconomic Model for the Energy Transition, and provides documentation of the model structure, data sources and model properties. GMMET is a large-scale, dynamic, non-linear, microfounded multicountry model whose purpose is to analyze the short- and medium-term macroeconomic impact of curbing greenhouse gas (GHG) emissions. The model provides a detailed description of GHG-emitting activities (related to both fossil fuel and non-fossil-fuel processes) and their interaction with the rest of the economy. To better capture real world obstacles of the energy transition, GMMET features a granular modelling of electricity generation (capturing the intermittency of renewables), transportation (capturing network externalities between charging stations and electric vehicle adoption), and fossil fuel mining (replicating estimated supply elasticities at various time horizons). The model also features a rich set of policy tools for the energy transition, including taxation of GHG emissions, various subsidies, and regulations.

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WORKING PAPERS

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Introduction

The consensus view in climate science, summarized by the Intergovernmental Panel on Climate Change (IPCC), is that climate change poses immense risks to lives and livelihoods across the world (IPCC 2022). As the urgency to implement policies that can limit global warming grows, the likely economic effects of such policies are becoming a focal point of the global policy debate. The Global Macroeconomic Model for the Energy Transition (GMMET) presented in this paper seeks to shed light on the macroeconomic aspects of GHG emission mitigation in the short and medium term.

Enormous research efforts have been devoted to understanding how GHG emissions cause global warming, and how this warming interacts with the global climate system. These efforts have not been limited to climate science but have also aimed at shedding light on its social and economic implications, as well as on mitigation policies. Reflecting the slow-moving nature of climate change, most climate economic models take a long-term perspective on the closed loop between economic activity and its environmental implications: economic activity emits GHGs that accumulate in the atmosphere, which leads to global warming that in turn affects economic activity. GMMET, in contrast, is designed for the analysis of the short- and medium-term macroeconomic implications of reducing GHG emissions. The focus is on assessing potential costs of different mitigation polices, including the impact on output and employment, inflation, the external sector, and the fiscal accounts. Assessing these costs is crucial for designing policies that are efficient (minimizing economic costs for a given emissions reduction).

GMMET is a large-scale non-linear structural New-Keynesian dynamic general equilibrium model. These types of models are traditionally used for the quantitative short- and medium-term analysis of monetary and fiscal policy and a variety of macroeconomic shocks. GMMET builds on the IMF's workhorse Global Integrated Monetary and Fiscal model (GIMF).[1] In this model households and firms are forward looking and choose consumption, labor supply, asset holdings, and investment optimally, considering their preferences and expectations about the future. Nominal and real frictions as well as the explicit modeling of expectations allow the analysis of cyclical fluctuations and stabilization policies.

GMMET significantly extends GIMF to capture various aspects of energy production, trade, and use by various sectors, and their implications for emissions:

- The modelling of fossil fuel mining, and especially the implied supply elasticity, is a key determinant for the effectiveness of a GHG price in reducing emissions. The model features resource input factors whose volumes adjust to the price of the fuel output such that their fossil-fuel-specific supply elasticities align with empirical estimates.
- Regarding electricity generation, the model features five technologies that differ in their cost structure and emission intensities: Coal, fossil gas, nuclear power, hydroelectric power, and renewables.
- GMMET captures a key real-world obstacle to increasing the share of renewables in electricity generation, which is that their generation is subject to uncontrollable weather-related fluctuations – renewable energy generation is intermittent. Therefore, GMMET has so-called renewable-plus-backup utilities, which pair renewable generation with a flexible fossil-fuel-based backup. The structure of the

[1] For more details on GIMF, see Kumhof and others (2010) for the theoretical structure, and Anderson and others (2013) for the standard model properties.

utility is determined endogenously by a cost-minimization problem that accounts for the variable and fixed costs of both technologies as well as the distribution of weather regimes.

- The model also features a dedicated transportation sector that distinguishes between combustion engine cars burning fossil fuel and electric vehicles running on electricity. The sector has stock-flow accounting of vehicle fleets and newly purchased vehicles. It also features an explicit role for charging and fueling stations, capturing network externalities between electric vehicle adoption and the deployment of charging stations in the spirit of Li and others (2017).
- Finally, non-fossil fuel GHG emissions and the possibility to abate them are accounted for by sector-specific emission abatement technologies.

GMMET features a rich treatment of fiscal policy levers. To analyze to the macroeconomic impact of mitigation, the model allows for a wide set of GHG mitigation polices, including subsidies, regulatory measures, and GHG taxes that are sector-specific according to the respective GHG emissions intensity.

GMMET abstracts from the benefits of avoiding GHG emissions (mitigating warming damages). Taking as given that global warming exceeding the goal of the Paris Agreement is associated with the risk of irreversible and catastrophic damages to the climate system (IPCC 2022), the Paris agreement can be taken as the answer to the question of how much emissions must decline. The model focuses on the macroeconomic implications of different ways to achieve a given emission decline, not on assessing different emissions objectives.

The paper presents an exhaustive set of simulations to document GMMET properties and should be thought of as a reference guide. The emphasis is on energy transition policies, but other shocks are also considered, including various shocks to the energy sectors (in the body of the paper) and standard macro shocks (in Annex II). While there are too many results to preview here, a few insights emerge.

The first insight is that there is often a distinction between the sectoral and macro effects from climate policies. The sectoral effects focus on how the structure of energy generation, transmission, and consumption changes in response to climate policies, through their impact on relative prices. These are the changes that matter for achieving a reduction in GHG emissions. The sectoral effects have short-to-medium term macro costs, but the latter are also shaped by the broader macroeconomic policy response. On the fiscal side, how additional revenues (expenses) from climate policies are spent (financed) matters for the macro effects. For example, while the decline in coal and fossil gas use in electricity generation due to a rise in GHG prices is insensitive to a particular revenue recycling option, lump-sum transfer or labor income taxes, the impact on labor supply and therefore real GDP is markedly different (Figure 7). When the GHG price revenues are rebated through labor income tax cuts, net-of-tax wages rise, leading to higher consumption than when revenues are used to reduce lump-sum transfers. The former dampens the negative impact of the GHG price on real GDP. Similarly, the impact on inflation depends on the macro effects as well as the direct impact of the GHG tax on firms’ costs, and on the reaction of monetary policy.

The second insight is that there are important non-linearities in the impact of climate policies. In the initial stages of a GHG price rise, for example up to about US$50 per metric ton of CO_2 equivalent (tCO_2e) in the United States, total GHG emissions fall rapidly as the use of high-emitting coal in electricity generation is phased out (Figure 13). Once the reduction in coal has been exhausted the marginal impact on emissions of raising the GHG price higher becomes smaller. Beyond this point emission reductions are driven by the electrification of the transport sector and increasingly costly abatement of non-fossil fuel related emissions. The degree of non-linearity in the long-term effects differs across macroeconomic aggregates (Figure 12, Panel A). Emissions are the tax base for GHG prices; therefore, as emissions diminish so does the marginal increase in tax revenues. If revenues from the GHG tax are rebated through the labor income tax rate then their diminishing return leads to smaller reductions in the labor income tax (Figure 12, Panel E) and a more muted labor supply response.

The third insight is the impact of the global dimension of the model on outcomes for countries pursuing climate policies. The effects of climate policies depend on whether a country enacts them alone or in tandem with others. For example, if the United States raises GHG prices alone, their current account balance with the rest of the world will increase as aggregate investment falls (Figure 10). When all other regions also implement a GHG price, in contrast, current account dynamics depend on which region is most severely impacted. Since production outside of the United States is more energy-intensive, the impact on their investment from the GHG price is much larger, turning them into net capital exporters and lowering the US current account, which leads to an appreciation of the US dollar. Moreover, if the United States acts alone, producer prices of oil and fossil gas fall by less than under a global implementation, as demand for fuel outside of the United States does not decline (Figure 11).

GMMET relates to the growing literature on the macroeconomic modeling of climate policies as follows:

- In Integrated Assessment Models (IAMs) such as DICE, WITCH or REMIND (Nordhaus 2014, Bosetti and others 2009, and Leimbach and others 2010, respectively), the macroeconomy is typically represented by Ramsey-type growth models—where output is determined by the supply side—and the models have a temporal resolution of typically five or more years (that is, a model period corresponds to five years, instead of being annual or quarterly). The purpose of these models is to compute welfare-maximizing policies and the resulting allocation in the long term, as the lack of a Keynesian aggregate demand channel prevents the analysis of short-term output fluctuations. GMMET is an annual model that highlights the aggregate demand channel, in addition to its supply side features.
- Computable General Equilibrium (CGE) models, such as GTAP (Corong and others 2017), or ICES (Eboli and others 2010), feature many countries/regions and sectors and allow for extensive sectoral analysis of exogenous policy changes. These models do not typically feature however an explicit role for expectations, which are central to forward-looking investment decisions and to explore the role of policy credibility. Relative to CGE models, GMMET simplifies the sectoral breakdown of the economy and focuses instead on sectors that matter the most for mitigation policies (fossil fuel mining, electricity generation and transportation) while keeping the manufacturing and service sectors highly aggregated. Accordingly, fiscal instruments are more detailed for emitting sectors (different fossil fuels, targeted subsidies for renewables, etc.) than for other macroeconomic variables (labor, consumption, etc.). GMMET is also solved in a perfect foresight rational expectations environment, which allows for expectations of future policies or technical progress to affect today's decisions.
- The closest large-scale macroeconomic models to GMMET are G-CUBED (see McKibbin and Wilcoxen 1999; 2013) and E-QUEST (Varga, Roeger, and in't Veld 2022). These models use a new-Keynesian framework that shares various features with quantitative macroeconomic models used in policymaking institutions. The modeling of key sectors is different, however. GMMET also differs in that employs solution techniques that do not require the model to be fully linearized.

This working paper documents the current structure of GMMET model (Section 2) and its main economic properties. The calibration used (Section 3) divides the world in four regions. The main properties are illustrated with sets of analytical simulations related to responses to economy-wide mitigation policies (Section 4), sectoral mitigation polices (Section 5), and global energy shocks (Section 6). Analytical simulations presented aim to illustrate and discuss the properties of the model and do not represent policy recommendations. Section 7 concludes and outlines ongoing development of the model. Lastly, the annexes present the detailed model derivations, model properties of macroeconomic shocks standard to many large-scale economic models, and other technical details related to GMMET and its use.

Model Description

The following section provides a high-level description of GMMET that gives a sector-by-sector overview of the model structure. Elements that are novel in GMMET are outlined in more detail than elements shared with GIMF. Derivations of the underlying equations are provided in Annex I, which will be referenced throughout this section.

GMMET is an annual, multi-region model that belongs to the class of large-scale structural New-Keynesian dynamic general equilibrium models. These models are traditionally used for the quantitative short- and medium-term analysis of monetary and fiscal policy but have been expanded here to include elements that allow for the analysis of GHG emission mitigation policy. The model has a well-articulated steady state, and therefore also features stock-flow consistency, which is important when discussing investment, government debt, and international flows in general.

As noted in the introduction, GMMET is intended to address short- and medium-term questions related to climate policy. This shorter-term focus means GMMET can exclude certain features related to emissions and emissions-reducing technologies. GMMET does not explicitly model the prospective long-term increases in firm or sectoral productivity that are expected to result from constantly improving emissions reduction technologies, whether related to electricity production, manufacturing or agricultural processes, or electric vehicle production. As noted above, there is also no role in the model for warming damages and therefore GMMET does not account for avoided damages from mitigation policy. The model seeks to facilitate the design of mitigation policies by analyzing their short- and medium-term macroeconomic implications.

The version of GMMET discussed in this working paper is based on four regions – China, the euro area, the United States, and a “rest-of-the-world bloc” comprising all the remaining countries.[2] Some model features are simplified given this highly aggregated structure. For example, there is no international trade in coal.

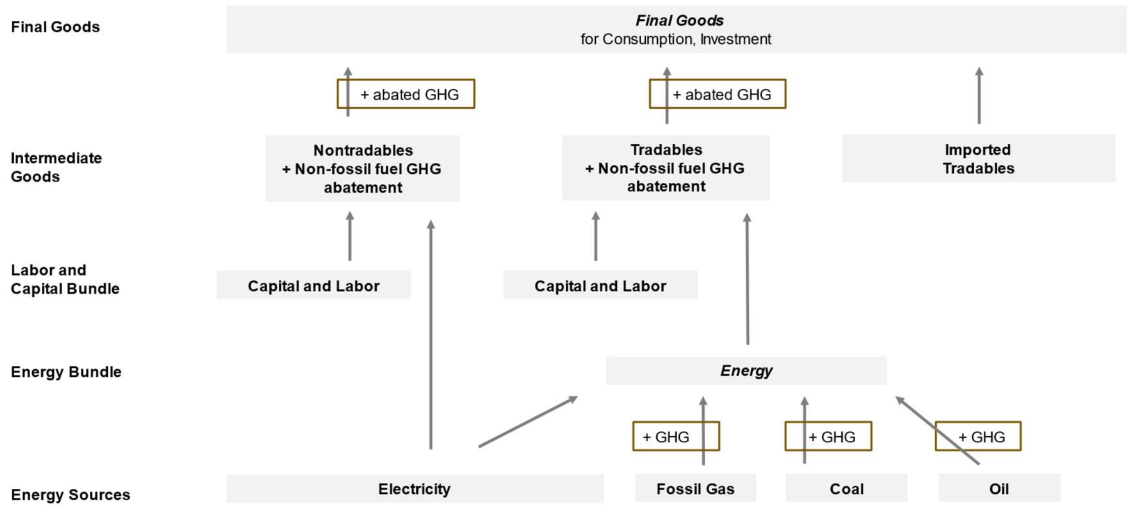
Supply Side

Figure 1 is an overview of each region’s supply of final goods. Primary production is carried out by a continuum of firms that belong either to a sector either tradable or nontradable goods. Firms in both sectors use a capital-labor bundle for production. To create that bundle, firms buy household labor inputs mediated by unions and capital services provided by capital stocks cumulated from investment. Investment is financed by a financial sector as found in Bernanke, Gertler and Gilchrist (1999), which introduces a procyclical financial accelerator, with the cost of borrowing facing firms rising with their level of debt. As in GIMF, GMMET relies on the full nonlinear version of the financial accelerator, not the linearized simplification suggested by Bernanke, Gertler,

[2] Results using this version of GMMET have been previously published in the International Monetary Fund’s October 2022 *World Economic Outlook* (IMF 2022).

Gilchrist (1999). All firms are perfectly competitive in their input markets but monopolistically competitive in their output markets, and their price setting is subject to nominal rigidities.

Figure 1: Production Sector



GMMET introduces additional energy-related inputs. Nontradables production consumes electricity, while tradables use an energy bundle that encompasses electricity and the model's three fossil fuels (fossil gas, coal and oil), corresponding to the demand from tradables shown in Figure 4 below. Figure 1 and all following figures indicate GHG emissions by "+ GHG" in the brown boxes. In the case of the energy bundles, the associated fossil fuel-related emissions are linked to the volume of the consumed fuel. 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, or CO_2 from curing concrete. These emissions are labeled "+ abated GHG" because they can be abated by means of an abatement technology that incorporates estimated abatement cost curves (described in the next section). To produce final goods, domestic nontradables are combined with domestic as well as imported tradables. This is carried out by competitive distributors in the same way as in GIMF.

In a second layer of trade, distributors combine domestically produced final goods with imported ones to produce consumption and investment goods, as in GIMF. The importation of consumption and investment goods, and of intermediate tradables, is facilitated by import agents that are owned by the exporting country but located in the respective export destination (importing) country. They price to the local market and are subject to nominal rigidities, while changes in the volumes of imported goods give rise to real adjustment costs. The purpose of the model's trade structure is to produce the high trade-to-GDP ratios typically observed in small, highly open economies, with a full accounting of the bilateral trade relationships, and captures the empirical regularity that investment goods typically contain a larger share of imports than consumption goods.

The model follows the traditional balance of payments identity, where the change in the US-dollar-denominated current account balance equals the change in the net foreign asset position. GMMET has incomplete international asset markets like GIMF, with international trade in assets limited to non-contingent US dollar-denominated bonds.

Fossil Fuel and Non-Fossil Fuel Emission Abatement

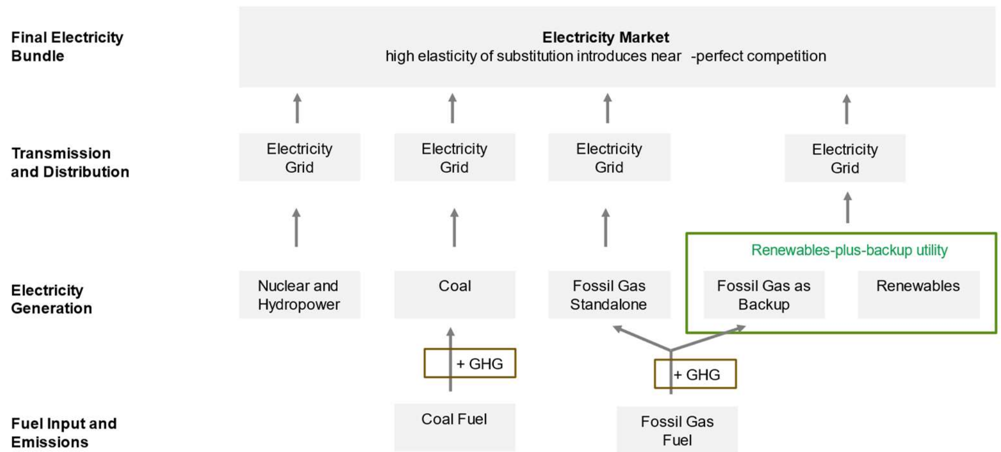
The process of GHG emission abatement differs between emissions from burning fossil fuels and emissions not associated with fossil fuels. Fossil fuel-related emissions are tracked by associating the volume of fossil fuel inputs with observed, input-specific emission intensities. For example, fossil fuel consumption in industrial processes is captured by the presence of fossil fuel inputs in the CES energy bundle (Figure 1). Emission abatement can occur if the volume of fossil fuel inputs adjusts to mitigation polices, either by substitution within the bundle, or by adjustment of the volume of the entire bundle. This also applies for abatement of fossil fuel emissions from electricity generation and transportation (both outlined below), although fossil fuel inputs are not simply included in CES bundles, but instead used as inputs in granular modelling of the electricity and transportation sectors.

Emissions other than those from fossil fuel use are not linked to the volume of fuel inputs, but instead to the output of the non-energy tradables and nontradables sectors (Figure 1). For example, agriculture is subsumed in the non-energy tradables sector, so agricultural methane emissions are associated with that sector's output (labelled as "+ abated GHG" in Figure 1). Firms with non-fossil fuel emissions can abate them according to sector-specific reduced-form emission abatement technologies. These technologies link emission abatement with a sectoral total factor productivity cost that depends nonlinearly on the share of abated emissions. The sector-specific abatement cost function is calibrated based on estimated marginal abatement costs curves: for all abatement levels, productivity costs of abating another unit of emissions correspond to empirical estimates. As detailed in Annex I, the form of the abatement cost function can replicate smooth steps and piecewise linearity in marginal abatement costs, which is crucial for representing discrete abatement technology options (Weitzel, Saveyn, and Vandyck 2019) and is more general than the functions used in Nordhaus (2014) and Varga, Roeger, and in 't Veld (2022). Given this technology, both sectors choose their optimal abatement level to equate tax savings from abating a marginal unit of emissions with marginal abatement costs.

Electricity Generation

Figure 2 provides an overview of the electricity generation sector, where the supply chain flows from the fuel inputs at the bottom to the electricity output at the top. There are five technologies – coal, fossil gas, nuclear power, hydroelectric power, and renewables – which are backed up by flexible gas generation capacity (the so-called renewable-plus-backup utility is discussed in the next section). The five technologies differ in their cost structures and emission intensities, and each has a technology-specific capital stock. Nuclear and hydroelectric power are grouped into one sector and investment in this sector is decided exogenously, reflecting that nuclear investment is not determined solely by economic considerations, and that sites for hydroelectric power generation are limited. Therefore, any change in investment in these sectors reflects decisions taken by the government or private sector measures undertaken with government financing, rather than a response to demand or supply conditions.

Figure 2. Electricity Generation Sector



The electricity output of all technologies is individually paired with capital services for the transmission grid and combined into a final electricity bundle, where they are assumed to be very close substitutes. While in principle the intermittency of renewables power generation would by itself limit the extent to which this technology can replace other sources, this is not the case since it is backed up by fossil gas, as explained below. Fossil fuel inputs (coal and fossil gas burned for stand-alone electricity generation and as backup) cause emissions proportional to their volume.

Renewable-Plus-Backup Utility

The costs of building the renewables generation capital stock have declined dramatically in the past decade, so that the remaining key obstacle to the widespread deployment of renewable sources for electricity is the problem of intermittent generation (Bistline and others 2021 and Ueckerdt and others 2017). This limits the role that renewables can play in the electricity mix since typically only a portion of intermittency is compensated by diversification of generation across space (via the electricity grid), across technologies (for example, wind and solar generation), and by storage technologies (mostly batteries).[3] GMMET captures this obstacle to decarbonizing electricity generation in a stylized fashion by assuming that renewable electricity is provided by a "renewables-plus-backup" utility. This utility manages intermittency by pairing wind and solar power generation with a flexible, non-renewable back-up capacity based on fossil gas that covers periods of uncontrollable generation shortfalls from renewables.

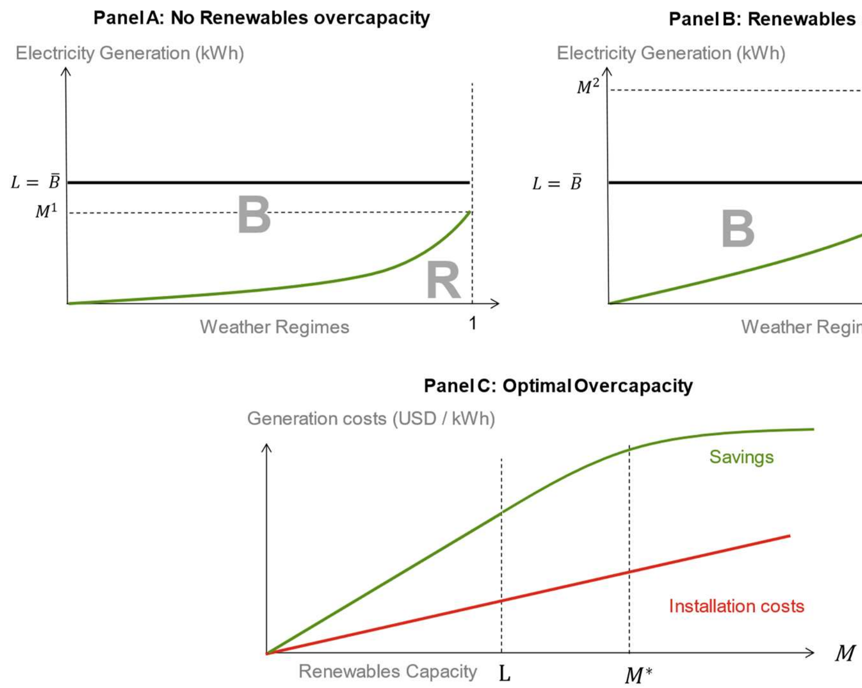
The size of the back-up capacity relative to the renewable capacity is endogenously determined by cost minimization in line with Figure 3.[4] The green curves in Panels A and B are illustrative generation duration curves associated with different levels of renewable capacities M^1 and M^2 respectively. Capacity describes the maximum output of an electricity generation technology, which in the case of renewables depends on the weather regime plotted on the horizontal axis. The best weather regime (where renewable generation reaches capacity) is to the right while the worst weather regime—neither sunlight nor wind—is to the very left, where renewables generation is zero. L is the volume of generated electricity, which is determined in the context of

[3] Grid-scale electricity storage, a key option to alleviate the intermittency problem, is not considered in GMMET, which is based on currently available technology, reflecting its focus on the short and medium term.

[4] See Annex I for an algebraic derivation of the underlying cost minimization problem.

the broader model as illustrated in Figure 3 and is identical in the two illustrative cases in Panels A and B. The stability required of electricity generation is captured by horizontal line L which is identical across weather regimes. $\bar{B}$ indicates installed backup capacity, which must equal L as constant output must be guaranteed also in periods when there is no sufficient generation from renewables. The area below L is the total expected electricity generation over the distribution of weather regimes. This area is split between expected generation from renewables (area R) and generation from the backup (area B).

Figure 3. Illustration of Cost-Minimization Problem of Renewable-plus-Backup utilities



To illustrate the utility's tradeoff, first consider the generation duration curve associated with renewables capacity M^1 in Panel A. For this limited generation capacity, renewables cover only roughly three quarters of output L during the best weather regime. If the utility deploys an additional unit of renewable capacity (raising M), it faces a tradeoff. It incurs fixed costs from buying the renewable capital but generates variable costs savings as renewables do not consume fuel and thus produce electricity at lower costs than the backup (graphically, increasing M enlarges area R the expense of area B). Under GMMET's assumptions on the cost structures after taxes and subsidies, variable costs savings are greater than the fixed costs, so the utility will raise M at least up to L, at which point overcapacity becomes relevant. This situation is illustrated in Panel B. Since M^2 is greater than L, peak generation exceeds the stable level of output so that excess electricity generation must be curtailed.

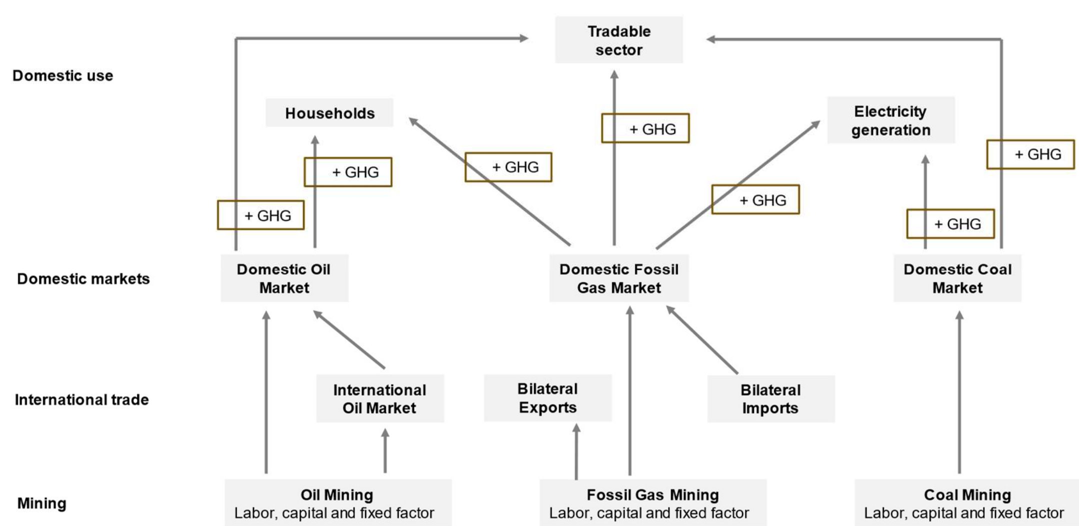
The expected volume of curtailed electricity corresponds to the "curtailment area" C . This mitigates costs savings from installing additional renewables since the curtailed portion of additional renewables generation does not replace backup generation (graphically, increasing M enlarges both areas R and C, but the growing area C does not shrink area B). The marginal increase of the curtailment area becomes greater in M, so variable costs savings shrink at an increasing pace when the utility installs additional renewable capacity. Panel C depicts variable costs savings as well as installation costs as a function of M. The rising marginal enlargement of the curtailment area when M surpasses L reflects in the flattening of the saving line's slope after L. Since installation costs of renewables generation capital are linear, there is a cost-minimizing capacity M^*, which implies overcapacity $(M^* - L)$ up to the point where marginal cost savings equal installation costs of additional renewable capital.

Fossil Fuel Mining and Trade

Energy originates from three fossil fuel mining sectors—coal, fossil gas, and oil. Each combines capital services and labor with an additional resource factor called "mines". These are loosely interpretable as a natural resource (coal mines, fossil gas deposits, or oil wells, oil shale deposits, and tar sands) but serve the purpose of introducing a time-variant price elasticity of each respective fossil fuel's supply. This approach can capture the time needed to close existing mines or open new ones. In particular, the volume of the resource factor is governed by a backward-looking moving average of the price of the mined fossil fuel output. The calibration of this moving average process influences the supply elasticity of the mined fossil fuel output and is chosen such that the elasticity corresponds to estimates (for given supply elasticities of the other two inputs, capital services and labor). Modelling empirically plausible fossil fuel supply elasticities at different time horizons is crucial for a meaningful analysis of the energy transition, since the elasticities 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 in response to GHG taxation.

Figure 4 provides a broader picture of the fossil fuel sector. The supply chain again flows from the bottom (where it starts with the mining sectors) to the top. Oil and fossil gas are both sold on domestic markets and traded internationally. Oil is traded exclusively on an international market and fossil gas is traded bilaterally, reflecting the assumption of a fixed pipeline infrastructure and the lower degree of transportability of fossil gas compared to oil.

Figure 4. Fossil Fuel Sector



Coal is not traded across regions, which is motivated by generally low observed trade volumes, and to help maintain the tractability of the model.[5] Tradable goods production is a source of demand for all three domestic fuel markets as already shown in Figure 4. Oil and fossil gas are also consumed by households, as car gasoline and fuel for home heating, respectively, as shown in Figure 5. Coal and fossil gas are also sold as fuel for electricity generation as shown in Figure 2 .

Household Sector

The household sector is very similar to that of GIMF. Like GIMF, GMMET features two types of households, both of which consume goods and supply labor. First, overlapping generations (OLG) households can accumulate and draw down domestic bonds (government and corporate) and a single internationally traded asset (US bonds). Their level of consumption depends on total wealth defined as the sum of human wealth (from labor income and net transfers from the government), financial wealth (from dividend income), and bond holding. The theory behind OLG households is broadly in line with the overlapping generations' model of Blanchard (1985), Buiter (1988), Weil (1987), and Yaari (1965). The key difference to a standard neoclassical household is both the limited lifespan of currently living households (leading them to discount future human wealth by a higher rate than the bond market rate) and the arrival of new households every next period (whose future wealth is irrelevant for current consumption decision). OLG households break Ricardian equivalence by making the tax payment profile over time matter for the stock of wealth. The second class of households are liquidity constrained (LIQ households). Their inability to save or access credit forces them to consume all their income (labor income plus net transfers from the government) in every period. The presence of LIQ households makes aggregate consumption less Ricardian.

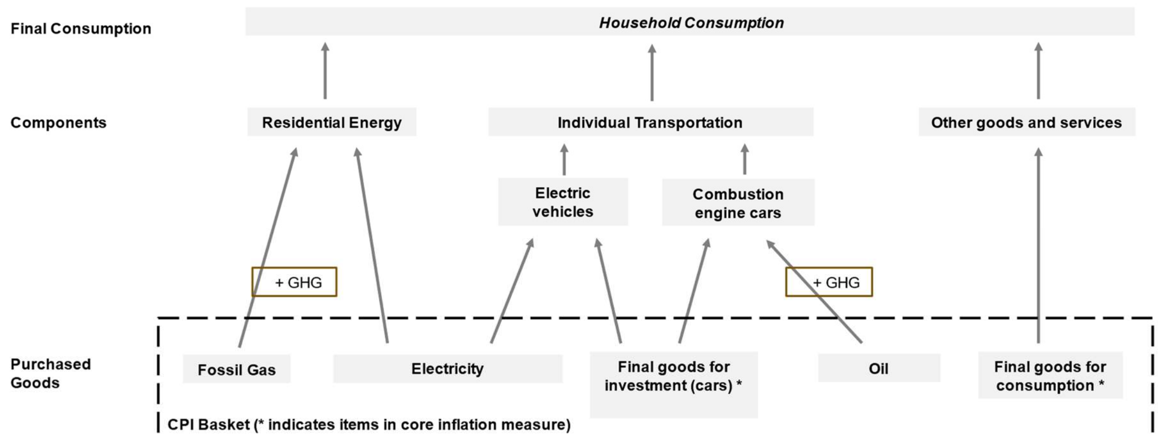
Both types of households supply the same number of hours, which is determined by the OLG households' consumption-leisure choice to maximize their utility, subject to their budget constraint. All households sell their labor to a union, which in turn sells it on to firms in a monopolistically competitive market. In the short term, wage setting is also subject to nominal rigidities.

Household Consumption

One significant difference is the composition of the household consumption bundle. While in GIMF households only consume the final consumption bundle, in GMMET they consume a broader range of goods that play a role in GHG emissions. The composition of the set of consumed goods, identical for both OLG and LIQ households, is shown in Figure 5.

[5] This simplification is not accurate for all regions, and the implementation of a more granular trade structure is planned for future development.

Figure 5. Household Consumption



"Residential heating" is a composite of electricity and fossil gas. "Individual transportation", discussed in detail below, encompasses cars, which are produced as final investment goods, as well as oil and electricity, which represent fuel for combustion engine cars (CCs) and electric vehicles (EVs) respectively. "Other goods and services" is the standard GIMF consumption bundle comprising nontradable goods and a CES aggregation of domestic as well as imported tradable goods. The box delineated by the dashed lines at the bottom of the figure indicates the components of the consumer price index (CPI) which are the basis for measuring headline inflation. However, only cars (final investment goods) and final consumption goods (marked by asterisks) are included in the core inflation measure.

Transportation

Transportation emits roughly a quarter of global energy-related carbon dioxide emissions (IEA 2021). Since about three quarters of these emissions originate from road transport (IEA 2022b), the model abstracts from all other modes of transportation. Households consume a transportation service provided by a vehicle fleet of CCs and EVs, fueled by gasoline (the same as oil in GMMET) and electricity respectively. As fleets of both types of vehicles are modelled as separate capital stocks, given by the balance of newly purchased and scrapped cars, shifts in new car purchases translate gradually into a changing composition of the overall fleet. Depending on the emissions intensity of electricity production, a shift from CCs towards EVs can reduce transport emissions.

To provide a realistic representation of tis possible pathway for decarbonization, two key determinants of the choice are captured between purchasing an CC or an EV. First, the decision is not only based on current vehicle and fuel prices, but also on expected future fuel prices during the lifespan of the vehicle. Second, network externalities between EV adoption and the deployment of EV charging stations are explicitly modeled in the spirit of Li and others (2017). This captures how a lack of EV charging stations curbs EV adoption, but at the same time allows for a positive feedback loop that amplifies the impact of mitigation policies aimed at incentivizing a shift towards EVs. A higher number of EVs makes it more lucrative to build new EV charging stations, while a higher density of the EV charging station network incentivizes the purchase of EVs by households. The resulting positive feedback loop allows for a more comprehensive shift from CCs towards EVs, which is difficult to attain under a standard CES framework bundling both types of cars for household demand. For simplicity, symmetric network effects for CCs and their fueling stations are assumed.

Monetary Policy

Monetary policy is represented by an interest rate reaction function. The standard form is an inflation-forecast-based rule operating under a flexible exchange rate, but a fixed exchange rate regime can be implemented as well. There can also be a role for the output gap. GMMET differs from GIMF in that the household consumption basket does not only include consumption goods, but also additional items that have an explicit role in the mitigation of GHG emissions. In addition to standard definitions of headline and core (non-energy) inflation, it is also possible to define an expanded measure of core inflation that includes GHG taxes. In this alternate measure of core inflation, higher fossil fuel prices only count towards inflation when they are caused by a GHG tax, but not by, for example, an adverse supply shock in the fossil fuel sectors.

Fiscal Policy

The government conducts fiscal policy as in GIMF, but with additional features related to GHG-emissions taxation and regulation and subsidization for mitigation policy. As in GIMF, there is government spending on current consumption and on investment in public infrastructure. Spending on public infrastructure augments a public infrastructure capital stock, a public good whose services add to the productivity of final goods production in the economy as it increases. Also, in line with GIMF, there are two instruments related to lumpsum transfers to households (transfers distributed to all households or those targeted exclusively to either OLG or LIQ households), and four tax instruments: on household consumption (a value-added tax), on labor income, on corporate income, and a general lumpsum tax, plus the ability to levy tariffs on international trade.

In GMMET, additional instruments are modeled for climate mitigation. The government can subsidize green technologies such as renewable power generation or the purchase price of EVs, and it can expand investment in nuclear power generation. There is a tax on GHG emissions, which can be applied on each sector or can follow from a regional GHG price. GHG prices translate into sector-specific per-unit taxes according to a sector’s GHG emission intensity.

The government can wield regulatory instruments to mitigate GHG emissions. 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. This can be done implicitly using what are called “shadow prices.” 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 fossil gas, for example. There is also an explicit mechanism where GHG prices (sectoral or regional) are matched by the distribution of their revenues to other sectoral inputs – similar in concept to what are popularly referred to as “feebates.”

To ensure well-defined steady state ratios, the government targets a long-term level of debt relative to GDP, which is typically achieved through adjustment in lumpsum transfers but can rely on other fiscal instruments instead. In the short term, fiscal policy also features automatic stabilizers to dampen the business cycle and counterbalances the procyclical nature of fiscal policy associated with a debt target.

Model Calibration

This section describes the salient great ratios and selected parameter values for the four-region version of GMMET used here. Several parameters have the same calibration across all regions. Some of the benchmark data is also key for the behavior of the different regions, such as the output and use shares of the fossil fuel sectors in each region, the bilateral trade relationships among regions, and each region's openness to trade. For the steady state of GMMET, calibration is based on data from OECD (2021), stylized facts, and properties of the IMF's other structural macroeconomic models, such as GIMF. The goal is to obtain sensible system-wide properties. Given that the calibration is for a steady state in the model, the numbers may not match raw data in quantity, but should qualitatively capture their significance. Dynamic model parameters are based on a variety of sources, further discussed below.

Domestic Economy

Each region's economy is calibrated using the OECD inter-country input-output database for 2018 (OECD 2021), drawing on national accounts and fiscal ratios (Table 1). Differences across countries provide a source of variation in the regional responses to the same economic shock.

Table 1. Domestic Sector Calibration

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

	China	Euro Area	United States	Rest of the World	Global Average
GDP (percent of world)	16.3	15.5	24.4	43.8	*100.0*
Consumption	52.2	54.7	65.7	57.9	*58.4*
LIQ households	7.3	7.5	8.4	12.2	*9.7*
OLG households	44.9	47.2	57.3	45.7	*48.6*
Private Investment	22.3	20.7	16.6	21.6	*20.4*
non-energy	20.3	19.3	15.3	17.1	*17.5*
energy	2.0	1.4	1.3	4.5	*2.8*
Government	25.2	24.6	17.7	20.6	*21.3*
consumption	16.2	21.8	14.4	17.1	*17.0*
investment	9.0	2.8	3.3	3.5	*4.2*
Net Exports	0.0	0.0	0.0	0.0	*0.0*

Sources:OECD Inter-Country Input-Output Database, using 2018 data; and authors' calculations.
Note: Accounting errors are due to rounding.

For household consumption, the intertemporal elasticity of substitution, which among other features governs the dynamics and speed of the current account response, is set at 0.2 for all countries. There is differentiation in the share of LIQ households. This share is set at 40 percent for the rest-of-the-world bloc as it contains many emerging markets and low-income countries with less sophisticated financial sectors and saving vehicles. The share of LIQ households is smaller in the United States, the euro area, and China at 25 percent, due to their (more) mature financial markets.

Investment has the same depreciation rates across regions but differs by sector (Table 2) – 10 percent for non-energy tradable and nontradable goods, 12.5 percent for all vehicles, and varying amounts for energy mining and generation, electricity sector, and transmission investments.

Table 2. Depreciation Rates for Investment

(percent)

	Rates
Non-energy tradables	10.00
Nontradables	10.00
Infrastructure stock	4.00
Mining sectors	
Coal (*max / min*)	3 (*10/2*)
Fossil gas (*max / min*)	3 (*10/2*)
Oil (*max / min*)	3 (*10/2*)
Electricity generation	
Coal (*max / min*)	3 (*5/2*)
Fossil gas (*max / min*)	3 (*5/2*)
Nuclear and hydroelectric	2.00
Renewables	3.00
Transmission	3.33
All vehicles	12.50

Source: Authors' calculations

External Sector

The degree of openness and structure of bilateral trade across regions, which is key for assessing spillovers, is provided in Table 3. The calibration assumes balanced trade, which implies aggregate export and import shares are the same in each region. The Euro area is the most open region out of the four currently in the model, with trade shares (excluding intra-regional trade) at around 24 percent of GDP, followed by the rest-of-the-world bloc (18 percent, again excluding intra-regional trade), China (17 percent), and the United States (12 percent).

Bilateral non-energy trade flows across regions are drawn primarily from the OECD inter-country input-output database and the CEPII CHELEM for 2018.[6] They are sizable, with most trade consisting of intermediate and consumption goods. Regarding energy, bilateral trade flows of fossil gas are relatively small, except for the

[6] CHELEM (*Comptes Harmonisés sur les Échanges et L'Economie Mondiale*) is derived largely from the UN COMTRADE database. Its construction is discussed in de Saint Vaulry (2008).

euro area which is a net importer of fossil gas. The model does not track bilateral trade flows of oil, as these are aggregated into a global oil market, but overall oil trade flows are larger and considerably more imbalanced. Most oil exports come from the rest-of-the-world bloc, as the latter contains OPEC+ and other producers like Canada and Norway. China and the euro area's oil imports are sizable. The United States is both an importer and exporter, while and its net oil trade balance is small.

Table 3. External Sector Calibration

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

	Exporter				Importer			
	China	Euro Area	United States	Rest of the World	China	Euro Area	United States	Rest of the World
GDP (percent of world)	16.3	15.5	24.4	43.8	16.3	15.5	24.4	43.8
Aggregate	17.1	24.2	11.5	18.0	17.1	24.2	11.5	18.0
China	. . .	2.5	1.2	4.1	. . .	2.5	1.8	4.4
Euro Area	2.4	. . .	2.2	5.8	2.3	. . .	1.8	6.6
United States	2.8	2.8	. . .	3.7	1.8	3.4	. . .	4.4
Rest of the World	11.9	18.9	7.4	. . .	11.0	16.6	6.6	. . .
Consumption goods	5.0	7.6	3.5	4.2	4.6	7.5	2.9	4.7
China	. . .	0.7	0.5	1.2	. . .	1.0	0.5	1.2
Euro Area	1.0	. . .	0.6	2.0	0.6	. . .	0.6	2.1
United States	0.8	0.9	. . .	1.0	0.7	0.9	. . .	1.3
Rest of the World	3.3	6.0	2.4	. . .	3.3	5.6	1.8	. . .
Investment goods	3.3	3.9	1.6	1.6	1.5	3.3	1.4	2.6
China	. . .	0.4	0.1	0.3	. . .	0.4	0.3	0.9
Euro Area	0.4	. . .	0.4	0.8	0.4	. . .	0.2	1.1
United States	0.4	0.3	. . .	0.5	0.2	0.6	. . .	0.9
Rest of the World	2.4	3.2	1.1	. . .	0.9	2.3	0.9	. . .
Intermediate goods	8.8	12.8	5.5	7.5	8.8	11.2	5.9	7.8
China	. . .	1.4	0.6	2.5	. . .	1.1	1.0	2.3
Euro Area	1.0	. . .	1.2	2.9	1.3	. . .	1.0	3.4
United States	1.6	1.6	. . .	2.1	0.9	1.9	. . .	2.1
Rest of the World	6.2	9.7	3.8	. . .	6.6	8.2	3.8	. . .
Fossil gas	. . .	. . .	0.1	0.3	0.2	0.5	0.1	0.1
China	. . .	. . .	<0.1	0.1	. . .	. . .	. . .	. . .
Euro Area	. . .	. . .	<0.1	0.1	. . .	. . .	. . .	. . .
United States	. . .	. . .	. . .	0.1	<0.1	<0.1	. . .	0.1
Rest of the World	. . .	. . .	0.1	. . .	0.2	0.5	0.1	. . .
Oil	. . .	. . .	0.9	4.5	2.1	1.7	1.3	2.8

Sources: CEPII CHELEM Database, IEA World Energy Balances, and OECD Inter-Country Input-Output Database, all using 2018 data; and authors' calculations.

The dynamics of trade in response to domestic and external shocks are also influenced by real adjustment costs on bilateral import volumes and nominal rigidities on bilateral import prices. The calibration of adjustment costs is in line with the calibration in GIMF. Calibration of nominal rigidities on bilateral import prices is presented in Table 3 and is also broadly in line with GIMF. The extent of nominal rigidities for imports, which among other features determines the degree of pass-through of exchange rate fluctuations, is positively related to the size of the import market and inversely related to market power. It is harder for individual import price changes to influence the overall price in larger, more competitive, import markets.

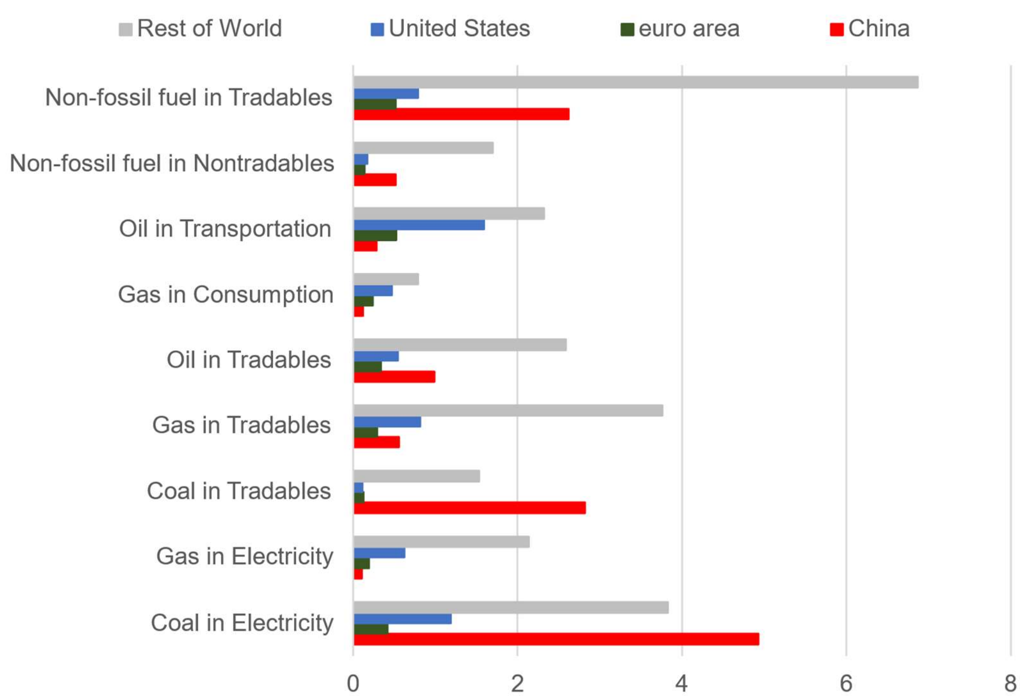
All the simulations proposed in the paper show deviations from a balanced-growth path where all macroeconomic variables, including GHG emissions grows at a constant rate. The design of a baseline scenario for macro variables is not documented in this working paper.

GHG Emissions

The steady-state calibration of GHG emissions is based on data from the International Energy Agency's "Greenhouse gas emissions from energy" database (IEA 2021) and the European Commission's EDGAR database (European Commission Joint Research Centre 2022). The former breaks down fossil fuel emissions by the type of fuel. The EDGAR database includes non-fossil fuel emissions, which are also captured in the model (see the subsection "Supply Side: Fossil Fuel and Non-Fossil Fuel Emission Abatement" above). Non-CO_2 emissions not already expressed as metric tons of CO_2 equivalent (tCO_2e) are converted on the basis of their global warming potential over a 100-year time horizon provided by the IPCC (IPCC 2022). Figure 6 illustrates GHG emissions in the steady state of the model, where China emits 13.0 billion tCO_2e, the euro area emits 2.8 billion tCO_2e, the United States emits 6.3 billion tCO_2e, and the rest-of-the-world bloc emits 25.5 billion tCO_2e.

Figure 6. Initial GHG Emissions

(billions of metric tons of CO_2 equivalent)



Sources: IEA (2021) and European Commission Joint Research Centre (2022).

Along with non-CO_2 emissions, the model requires related marginal abatement cost curves. These are calibrated using the country-specific estimates from the US Environmental Protection Agency (US EPA 2019).

Energy and Electricity Sectors

Fossil fuel (coal, fossil gas and oil) data are primarily derived from the International Energy Agency's World Energy Balances (IEA 2022a). The calibration, presented in Table 4, is based on 2018 data. Accounting for balanced trade in the steady state of GMMET and the lack of global trade in coal leads to some modifications of the data. Fossil fuel extraction as a share of GDP is by far the greatest in the rest-of-the-world bloc, 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 (the tradables sector in GMMET).

Table 4. Fossil Fuel Supply and Use

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

	China	Euro Area	United States	Rest of the World	Global Average
GDP (percent of world)	**16.4**	**15.5**	**24.4**	**43.7**	***100.0***
Fossil fuel extraction	3.3	0.2	2.6	6.1	*3.9*
Coal	2.5	0.2	0.3	0.7	*0.8*
Fossil gas	0.2	0.0	0.8	1.5	*0.9*
Oil	0.6	0.0	1.4	4.0	*2.2*
Fossil fuel net imports	1.6	1.9	0.4	-1.5	*0.0*
Fossil gas	0.2	0.5	0.0	-0.2	*-0.2*
Oil	1.4	1.4	0.5	-1.3	*-1.3*
Total Supply (above) = Total Demand (below)	**4.9**	**2.0**	**3.0**	**4.6**	***3.9***
Fossil fuel in electricity	1.8	0.3	0.6	1.1	*1.0*
Coal	1.7	0.1	0.3	0.5	*0.6*
Fossil gas	0.1	0.2	0.3	0.6	*0.4*
Fossil fuel in tradables	2.6	1.0	1.2	2.4	*1.9*
Coal	0.8	0.0	0.0	0.2	*0.2*
Fossil gas	0.2	0.2	0.3	0.4	*0.3*
Oil	1.5	0.7	0.9	1.7	*1.3*
Fossil fuel in household	0.5	0.8	1.2	1.1	*1.0*
Fossil gas	0.1	0.1	0.1	0.2	*0.1*
Oil	0.5	0.6	1.0	0.9	*0.8*

Sources: IEA International Energy Balances and OECD Inter-Country Input-Output Database, both using 2018 data; and authors' calculations.
Note: Expenditures on energy (demand) do not include refining, transportation/transmission, and distribution

Table 5 shows how energy use is derived from fossil fuel use in tradables and electricity production and household consumption, and electricity use in tradables and nontradables production, and household consumption of transportation. China has the highest energy use as a share of GDP due to its energy-intensive use in production, and relatively low per capita share of GDP. The relatively high per capita share of GDP, focus on services and low share of renewable and nuclear energy in electricity generation is why the United States has the lowest energy use as a share of GDP.

Table 5. Energy Use

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

	China	Euro Area	United States	Rest of the World	Global Average
GDP (percent of world)	**16.4**	**15.5**	**24.4**	**43.7**	***100.0***
Energy in tradables	5.7	2.0	1.6	3.9	*3.3*
Fossil fuels	2.6	1.0	1.2	2.4	*1.9*
Electricity	3.2	1.0	0.3	1.6	*1.4*
Energy in nontradables					
Electricity	0.3	0.8	0.5	0.8	*0.7*
Energy in household consumption	1.3	1.5	1.8	2.1	*1.8*
Fossil fuels	0.5	0.8	1.2	1.1	*1.0*
Electricity	0.7	0.8	0.6	1.0	*0.8*
Aggregate energy use	**7.4**	**4.3**	**3.9**	**6.8**	***5.8***
Electricity	4.2	2.6	1.5	3.3	*2.9*
From fossil fuels	1.8	0.3	0.6	1.1	*1.0*
Fossil fuels	4.9	2.0	3.0	4.6	*3.9*

Sources: IEA International Energy Balances and OECD Inter-Country Input-Output Database, using 2018 data; and authors' calculations.
Note: Expenditures on energy do not include refining, transportation/transmission, and distribution margins. Expenditures on electricity include transmission and distribution margins. Accounting errors are due to rounding.

Table 6. Elasticities of Substitution for Energy and Electricity

	Value
Elasticity between:	
Four types of generation in electricity	20.0
Four types of energy in tradables	0.5
Energy and other factors in tradables	0.4
Electricity and other factors in nontradables	0.5
Electricity and fossil gas in residential energy	1.5

Source: Authors' calculations.

Table 6 presents the calibration of key elasticities for energy and electricity use. Renewables is treated as a close substitutable for coal, fossil gas and nuclear power in electricity generation, as GMMET addresses the issue of intermittency of renewable energy generation as discussed above. Therefore, the elasticity is set to 20. By contrast, price elasticities of demand are low.

In the tradables sector, energy is being used for disparate outputs such as chemicals, cement, and steel, hence the assumption of a much lower elasticity of substitution between different sources of energy in the sector (0.5). Residential energy is somewhat more flexible, with a price elasticity of demand of 1.5, reflecting the ability to switch between using of fossil gas and electricity. When considering the use of energy relative to labor and capital services, the elasticity is sensibly low (0.4 for tradable goods and 0.5 for nontradable goods).

A key set of elasticities are the supply elasticities for mining (Table 7). The model is calibrated such that, following a permanent increase in the market price of a given commodity, the supply of commodity in the short and long term follows the estimates given from Fally and Sayre (2019) for oil and fossil gas, and Boer, Pescatori, and Stuermer (2021) for coal. In the case of oil, for instance, a one percent increase in market price increases supply by 0.14 percent the first year (labor and capital utilization rate are flexible at this horizon) and 1.3 percent in the long term (labor, the capital stock, and the number of active oilfields) are flexible.

Table 7. Effective Price Elasticities of Fossil Fuel Supply in the United States

	After 1 year	After 7 years	Long term
Coal	0.17	0.4	0.6
Fossil Gas	0.18	0.3	0.5
Oil	0.14	0.5	1.3

Sources: Fally and Sayre (2019); Boer, Pescatori and Stuermer (2021) and related calculations; and authors' calculations,

Note: Each elasticity is the outcome of several parameters in the model.

Transportation

Transportation, which consists of EVs and CCs, is calibrated along several dimensions. The steady-state shares of EVs in the overall market are calibrated consistent with their share in new vehicle purchases. The relative price of EVs to CCs comes from American Automobile Association (2021), while the elasticity of substitution of 5.5 between the two types of vehicles is the third largest out of the four values considered in Holland, Mansur, and Yates (2021). This choice reflects that technological improvements are likely to make EVs and CCs closer substitutes in the future. The acceleration of EV purchases over time is related to growth in the charging station network, based on Li and others (2017).

Fiscal and Monetary Policy and Prices

As mentioned above in the model description, the benchmark fiscal rule’s primary function is to stabilize the debt-to-GDP ratio at its targeted level, based on 2021 data. Recall that the rule also contains an automatic stabilizer (Table 8), whereby the level of general lumpsum transfers is negatively correlated with the output gap, given shifts in other tax bases and spending components, derived from Price, Dang and Botev (2015).

Table 8. Automatic Stabilizer for the Output Gap

(percent of GDP)

	Value
China	0.25
Euro Area	0.55
United States	0.32
Rest of the World	0.50

Sources: Price, Dang, and Botev (2015), Table 10; and authors' calculations.

The benchmark monetary policy rule only has a weight (1.5 for the euro area, 1 elsewhere) on a forward-looking core inflation measure, which is a weighted average of contemporaneous core inflation (0.25) and one-year-ahead core inflation (0.75).

The calibration of the monetary policy rule works in tandem with nominal rigidities on prices, both the short-term parameters and the long-term values assigned to the steady-state markups. Short-term nominal rigidities follow the Ireland (2001) implementation of Rotemberg (1982) pricing, which means that the numeric values of the parameters have no particular structural meaning; it is their ability to match stylized facts on inflation dynamics that determine their values. These values are in line with those previously used in GIMF. The relative magnitudes between regions are also a good indication of the sluggishness or speed or price movements in different regions (while still needing to account for sectoral sizes and the degree of influence of foreign price dynamics through trade). Generally, the euro area has more sluggish price adjustment, so their rigidity parameters are 1.5 times higher than that of the United States. For imports, regions which are price takers should have low nominal rigidity parameters – hence 0.1 for the remaining countries bloc, which comprises mostly small open economies.

Table 9. Steady-State Markups and Short-Term Nominal Rigidities

(percent over price for markups; relative strength of adjustment for nominal rigidities)

	China	Euro Area	United States	Rest of the World
Final consumption goods				
Markup (%)	10	10	10	10
Nominal rigidity	1.00	1.50	1.00	1.00
Final investment goods				
Markup (%)	5	5	5	5
Nominal rigidity	1.00	1.50	1.00	1.00
Tradable intermediate goods				
Markup (%)	20	20	20	20
Nominal rigidity	1.00	1.50	1.00	1.00
Imported consumption goods				
Markup (%)	5	5	5	5
Nominal rigidity	0.33	0.50	1.00	0.10
Imported investment goods				
Markup (%)	5	5	5	5
Nominal rigidity	0.33	0.50	1.00	0.10
Imported intermediate goods				
Markup (%)	5	5	5	5
Nominal rigidity	0.33	0.50	1.00	0.10
Nontradable intermediate goods				
Markup (%)	20	20	20	20
Nominal rigidity	1.00	1.50	1.00	1.00
Wages				
Markup (%)	10	10	10	10
Nominal rigidity	2.50	3.75	2.50	2.50

Sources: Authors' calculations.

Note: Nominal rigidities are normalized to 1 for the strength of the Ireland (2001) form of nominal rigidities for tradable goods in the United States.

Economy-Wide Mitigation Policies

This section begins the discussion of the macroeconomic impact of different GHG emission mitigation policies, for the most part using the United States as an illustrative example. Mitigation policies are implemented as an exogenous, permanent variation of a policy instrument, such as the GHG price, a subsidy rate, or a regulation-induced expenditure shift. Alternatively, a mitigation policy could also be calibrated to bring about an exogenously chosen reduction in emissions.

This set of mitigation policies employs economy-wide GHG prices, which disincentivize emitting activities in proportion to their emissions intensity. For instance, the GHG tax on generating electricity from coal includes both the direct carbon emissions from burning coal at the power plant as well as upstream emissions of the capital stock.[7] This working paper does not document the impact of quantity-based policies, like the one implemented by an emission trading system (ETS) without free allocation of credits, as those policies share most of the properties of a GHG price.

This section has three simulations centered around GHG prices: First is the introduction of a simple GHG price. The second exercise compares a global and a unilateral introduction of the same GHG price. The final exercise takes a long-term perspective on the impact of the policy. All policies presented are illustrative, with the intention of documenting the properties of the model, and do not represent policy recommendations.

Global Increase in the GHG Price with Different Recycling Options

Figure 7 depicts the impact on the US economy of a gradual introduction of a US\$50/tCO_2e GHG price over the course of 8 years in all regions (Panel A). Revenue from the increase in the GHG price is recycled either by lowering the labor income tax or by increasing general lumpsum transfers to households (depicted in dashed red and solid blue lines respectively).

The negative impact of introducing a GHG price on real GDP is weaker when revenues are rebated through labor income tax cuts (Panel B) because it increases net-of-tax wages and labor supply (Panel D). Relative to the other recycling option, this causes consumption of LIQ households to be higher, which leads to more aggregate household consumption (Panel C). The negative response of investment from the gradual increase in GHG price is dampened when the revenue is recycled through labor income tax, compared to general lumpsum transfers, as the economy is expected to be buoyed by higher employment and growth (Panel E).

The GHG price has a very similar impact on inflation under the two recycling options (Panel I), reflecting the central bank's credibility that it will respond to inflation and keep firms' and households' inflation expectations anchored. The GHG price increases the price of fossil fuels, which affects the CPI directly via household consumption of fossil gas and oil (gasoline), and indirectly via higher input prices for electricity generation and the production of tradable and nontradable goods. However, given the gradual nature of the GHG price implementation, the impacts on the headline CPI inflation and thereby on the policy rate are limited (Panel H). There is no significant adjustment of the real effective exchange rate and the current account, owing to the symmetric nature of the global policy shock (Panels G and F).

[7] The model does not differentiate investment goods by their GHG content. All investment goods share the same average GHG content inherited from their production process.

When interpreting the macroeconomic impact of the GHG price, it is crucial to remember that, given the model's lack of a role for warming damages, the simulated decline in output and household consumption does not necessarily mean that the policy reduces welfare. A welfare analysis would need to balance the GHG price's costs with its benefit from mitigating warming damages, which is beyond the scope of GMMET. The model evaluates the impact of mitigation policies while ignoring the impact of foregone climate change.

Figure 8 provides an overview of the adjustment of GHG-emitting sectors. Since it is almost identical under the two revenue recycling options—how revenues are rebated matters mostly for macroeconomic outcomes—the figure only shows the adjustment in the case of revenue recycling through labor income tax cuts.

The size of the rising tax burdens on the three fossil fuels is linked to their emission intensities, while the distribution of the tax wedges between the respective mining sectors and their consumers is determined by relative elasticates of supply and demand (Panels A and B). For fossil gas and oil, most of the tax burden is borne by consumers. The burden on coal is roughly split evenly between both sides (demand for coal is relatively elastic since coal in electricity generation can relatively easily be substituted for by other technologies). The consumer price of coal rises the most, owing to its high emissions intensity. These large differences in the GHG price incidence across fossil fuels highlight the central role of supply elasticities in quantifying the effectiveness of GHG prices in reducing emissions.

There is significant adjustment in the electricity generation sector. The GHG price alters relative prices of different fuels to the disadvantage of relatively more polluting ones, which leads to a crowding out of generation from coal, and, to a lesser extent, of fossil gas (Panel D, blue and red lines). Since nuclear generation is exogenous, only generation from renewables is crowded in, which contributes towards stabilizing fossil gas generation that is used as a backup for intermittent renewables generation. In the long term, electricity generation from fossil fuels is almost eliminated by the GHG price. The electricity price rises gradually in line with the growing GHG price as the tax burden is (partially) passed on (Panel E). However, the overall generation volume barely declines, in part because it is stabilized by higher demand from a growing share of EVs.

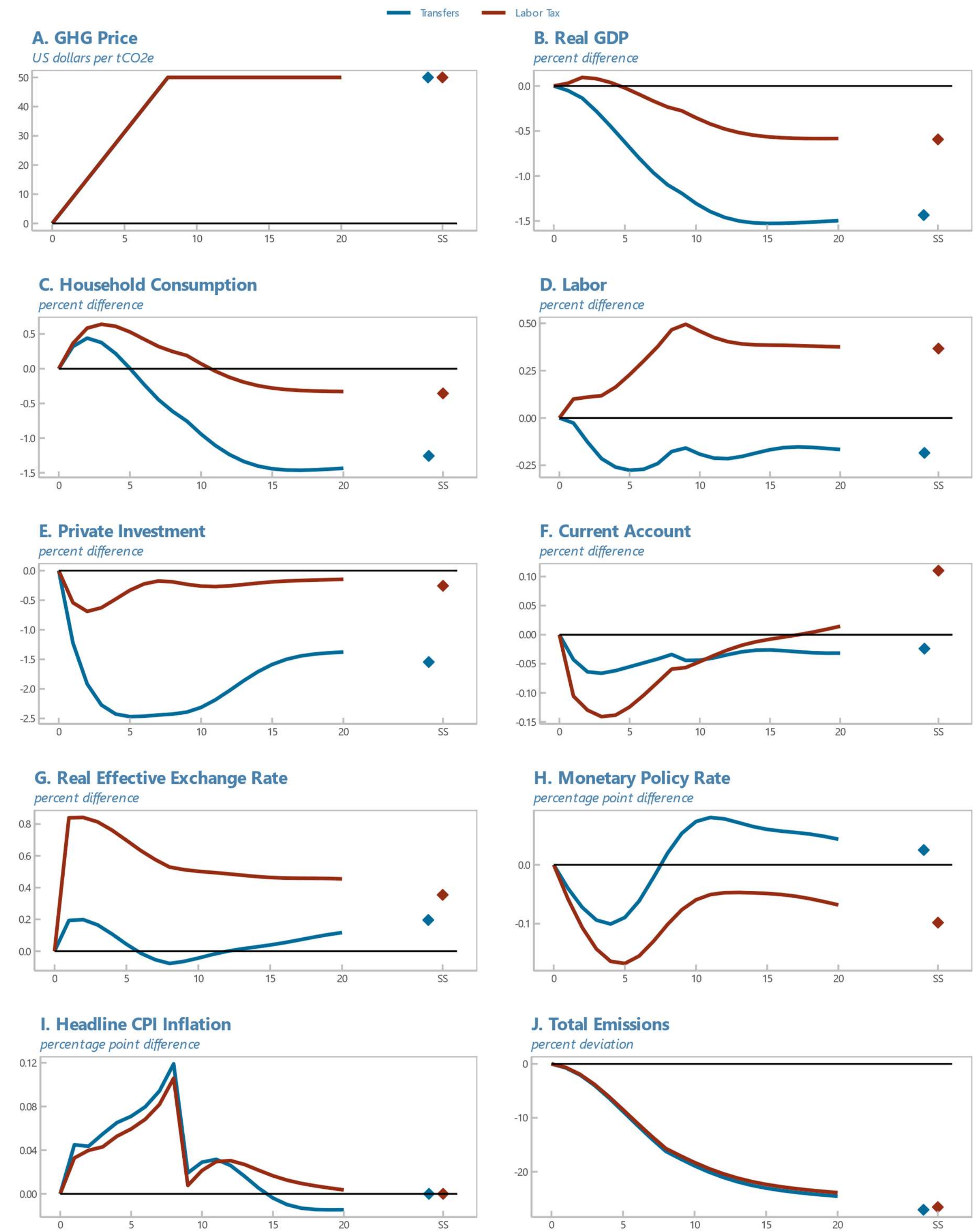
There is also some adjustment in the transportation sector. Fuel costs over a car's life cycle increase for both EVs and CCs, reflecting the higher electricity price and the tax burden on oil respectively (Panel F). The (tax-inclusive) oil price rises by more than the electricity price, but the induced shift towards EVs in newly purchased cars remains modest in size (Panel G), since a car's purchase price—but not fuel costs—dominates the total usage costs over its life cycle. However, the price-induced shift towards EVs incentivizes the deployment of EV charging stations, and the emerging positive feedback loop further increases the share of EVs (Panel H).

The prices of the energy bundles used as fuel for the tradables sector (comprising electricity, coal, fossil gas, and oil) and by households (comprising of electricity and fossil gas) both increase when the GHG price is gradually introduced, and the volumes decline accordingly (Panel I). In the tradables sector, this reduction in fossil fuel use lowers the demand for labor and capital services. The use of oil does not decline significantly (Panel J), as the oil price increases the least among the components of the energy bundle.

The use of abatement technologies for non-fossil-fuel emissions in the tradable and nontradable sectors are shown in Panels K and L. In the case of tradables, around 20 percent of non-fossil-fuel emissions can be abated at less than US\$50/tCO_2e, making it profitable to realize this abatement share once the GHG price is fully phased in. For nontradables, abatement is more costly, so the US$50/t$CO_2$e GHG price only reduces non-fossil-fuel emissions by about 5 percent. The abatements costs are minor for both sectors though they may be large in the specific subsectors responsible for non-fossil-fuel emissions such as agriculture or cement.

Overall, the higher GHG price reduces total US GHG emissions by close to 30 percent (Figure 7, Panel J). The detailed breakdown of emission reductions by sector and fuel in Figure 9 shows for each emissions source the proportional (Panels A and B), and absolute level (Panels C and D) adjustments. Emissions from burning coal for electricity generation exhibit a decline of almost 100 percent, while emissions from gas in electricity generation pick up mildly, reflecting their use as a backup for renewables (Panel A). Emissions from gas used for home heating decline by about 40 percent, pointing to a substantial substitution towards electricity (Panel B). The largest share of the level of emission reductions comes from eliminating coal in electricity generation (Panel C).

Figure 7: Gradual Introduction of a US$50/tCO$_2$e Global GHG Price — Macroeconomic Impact in the United States

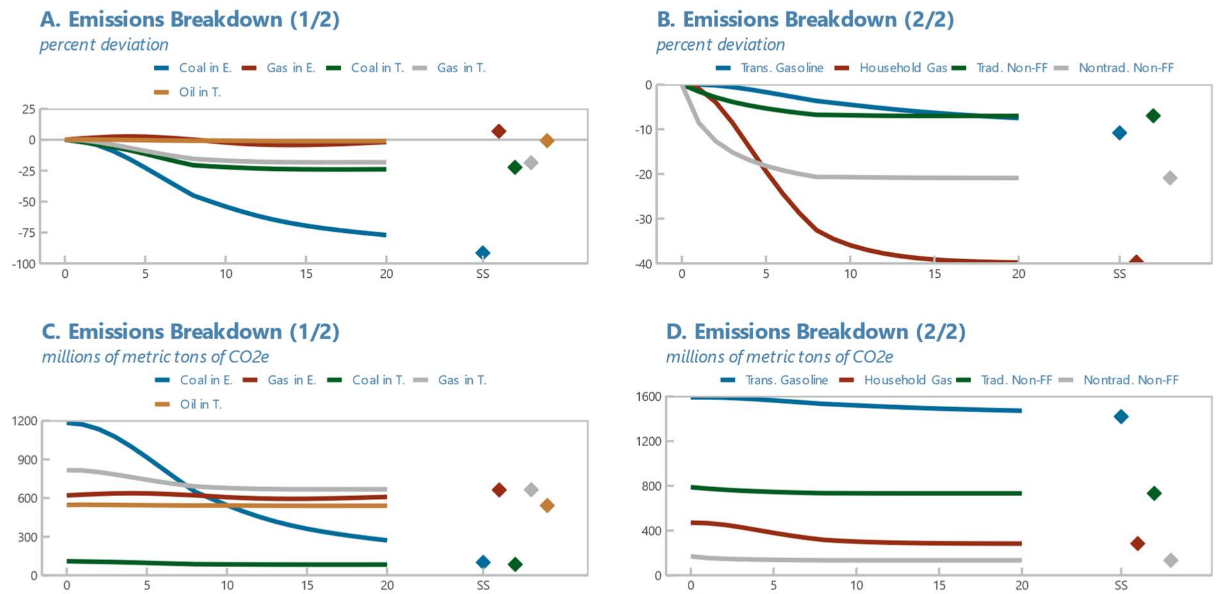


Source: Authors' calculations

Figure 8. Gradual Introduction of a US$50/t$CO_2$e Global GHG Price — Emitting Sectors in the United States

Source: Authors' calculations

Figure 9. Gradual Introduction of a US$50/$tCO_2e$ Global GHG Price — Emissions in the United States



Source: Authors' calculations

Global vs. Unilateral Increase in the GHG Price

The red lines in Figures 10 and 11 depict the impact on the United States of the same policy shock as analysed in the previous subsection – the gradual introduction of a global US$50/tCO2e GHG price over the course of 8 years. It is assumed that the revenue generated from the GHG price is rebated through lowering the labor income tax. Blue lines show the impact of the same policy but enacted in the United States only (Figure 11, Panel A).

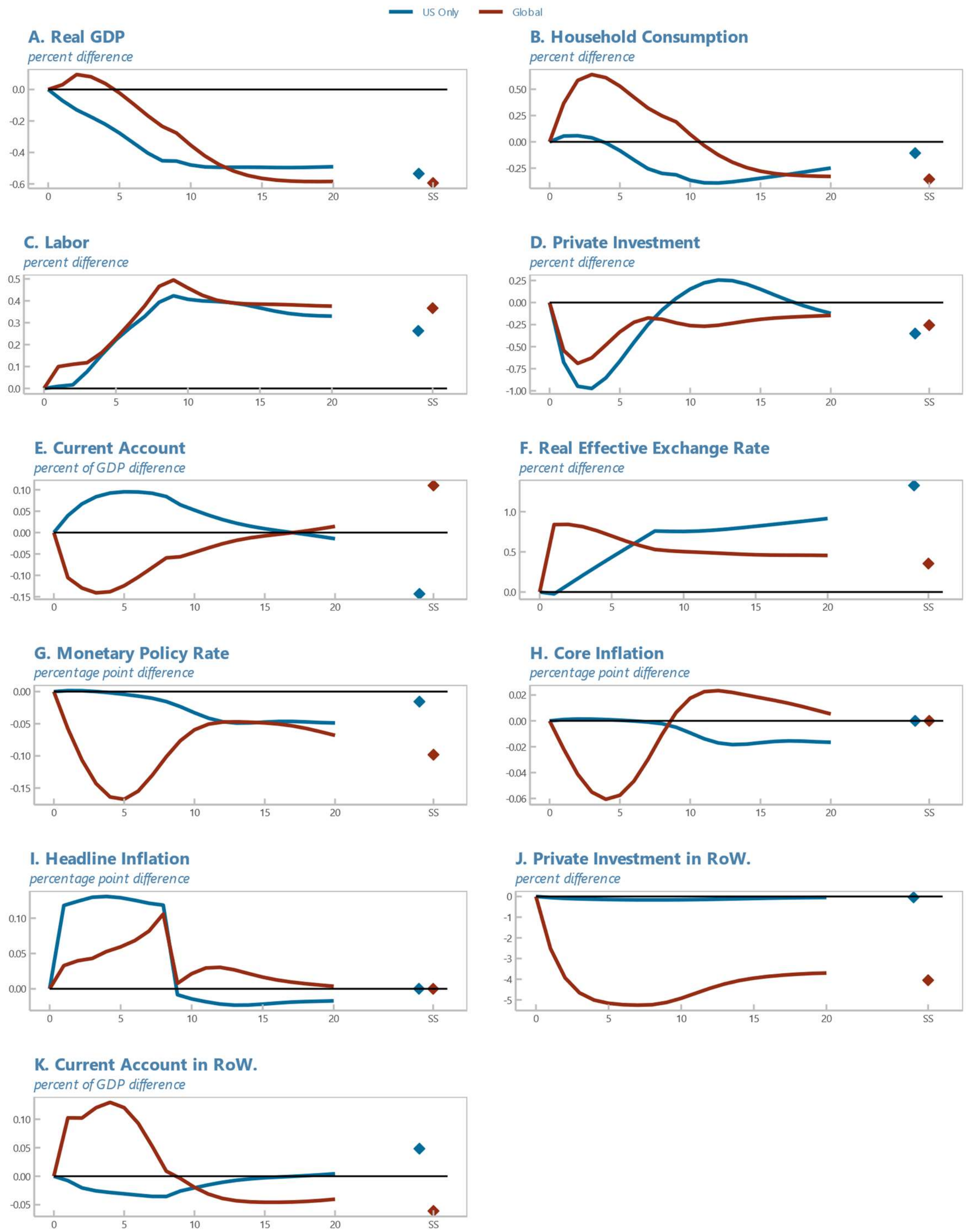
Differences in the macroeconomic adjustment between the global and unilateral scenarios (Figure 10) start with the external sector and the current account response. The current account reflects the difference between a country's saving and investment balance and that of the rest of the world. The US current account (Panel E) increases when the United States is the only country that implements a GHG price, following the policy-induced decline in US investment in fossil fuels. When all countries implement a GHG price, in contrast, current account dynamics depend on which region is most severely impacted. Since production in the rest-of-the-world bloc (an aggregate of all countries other than the United States, China, and the euro area) is more energy intensive, the impact on investment from the GHG price is much larger in that bloc (Panel I), multiple times greater than that in the United States (Panel D). This turns the rest-of-the-world bloc into a net capital exporter, lowering the US current account and leading to an appreciation of the US dollar (Panel F).

The impact on headline and core inflation (Panels I and H) is also noticeably different between the two scenarios, even though the magnitude of the effects remains relatively small in both cases. When the United States acts alone, there is a direct effect on headline inflation, reflecting the gradual introduction of the GHG price in a stepwise fashion, but there is no visible impact on core inflation. Instead, when all countries implement the GHG price there is a large reduction in world fossil fuel prices, especially oil, as global demand for fossil gas and oil falls (Figure 11, Panels D and E) so that there is a decline in US core inflation and a smaller increase in US headline inflation.

Differences in the inflation response also have implications for the reaction of US monetary policy and for the macroeconomic effects of the GHG price on the US economy. In the global scenario, the decline in core inflation elicits a loosening of monetary policy (Figure 10, Panel G), which results in a temporary increase in household consumption (Panel B) and a milder decrease in private investment (Panel D). As a result, the implementation of the GHG price has a short-lived expansionary effect on GDP (Panel A).

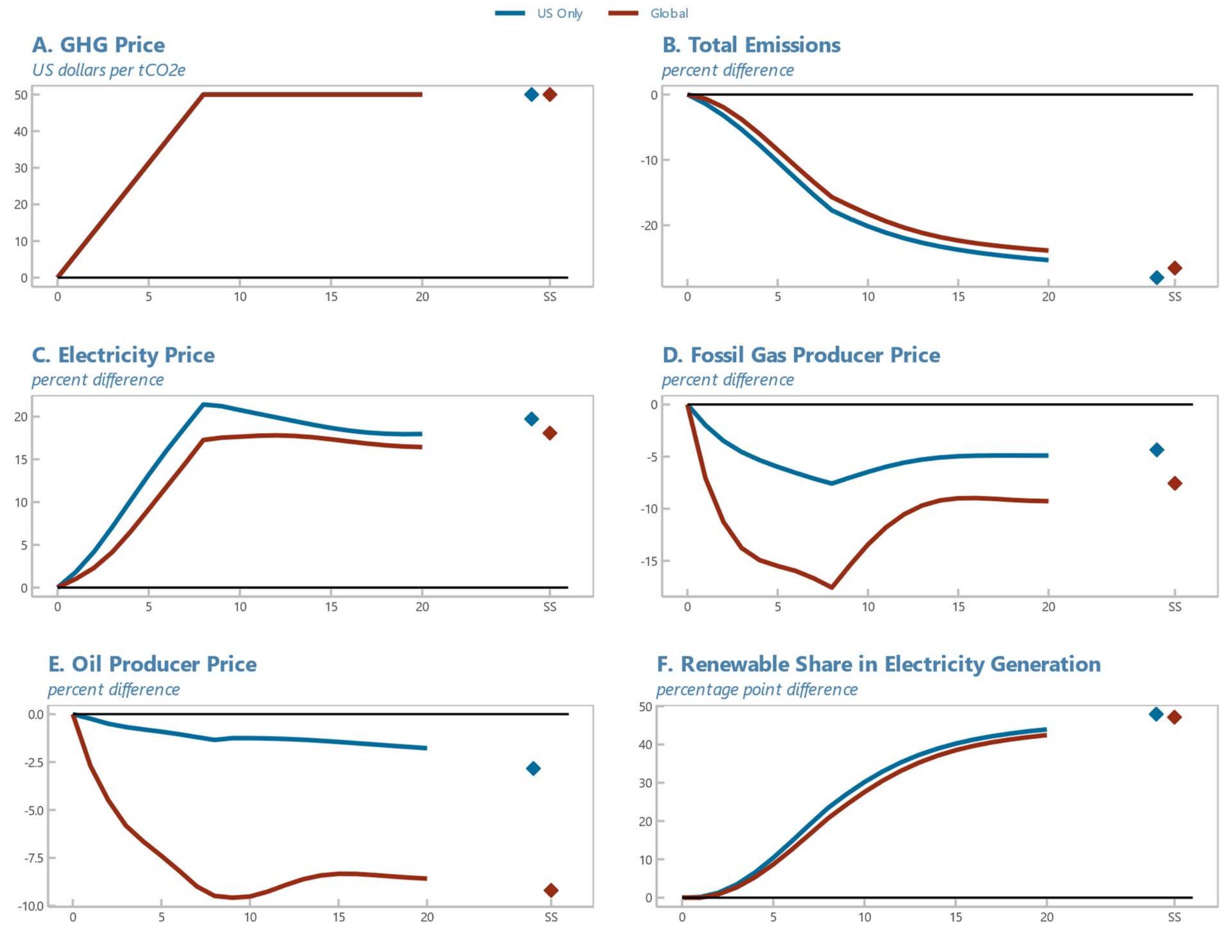
Figure 11 compares the adjustment of key GHG-emitting sectors in both scenarios. If the United States acts alone, producer prices of oil and fossil gas fall by less, as demand in other regions that did not implement a GHG price does not decline (Figure 11, Panels D and E). This effect is stronger for oil than for gas as the oil market is fully integrated. In addition, the decline in high-emission fossil fuel prices in the global scenario reduces incentives for the energy transition. This is reflected in a slightly smaller increase in the share of renewable electricity generation in the global scenario (Panel F). As a result, the decline in US total emissions is slightly larger when the United States acts alone (Panel B), though the global reduction in emissions is of course smaller in the absence of a global response.

Figure 10. Gradual Introduction of the GHG Price, US Only vs. Global — Macroeconomic Impact in the United States



Note: GHG tax revenues are recycled through a cut in the labor income tax rate. 'RoW' is all other blocs in the model aggregated as 'Rest of the World.'
Source: Authors' calculations

Figure 11. Gradual Introduction of the GHG Price, US Only vs. Global — GHG-Emitting Sectors in the United States



Note: GHG tax revenues are recycled through a cut in the labor income tax rate.
Source: Authors' calculations

Long-Term Impacts of GHG Prices

Figures 12 and 13 show the long-term adjustment of selected variables to different GHG prices depicted along the horizontal axis, for the case where the policy is adopted in the United States only and revenues are recycled through lowering labor income taxes. The figures highlight the model's nonlinearities, as the marginal long-term impact (the vertical axis) decreases with the level of GHG price (the horizontal axis).

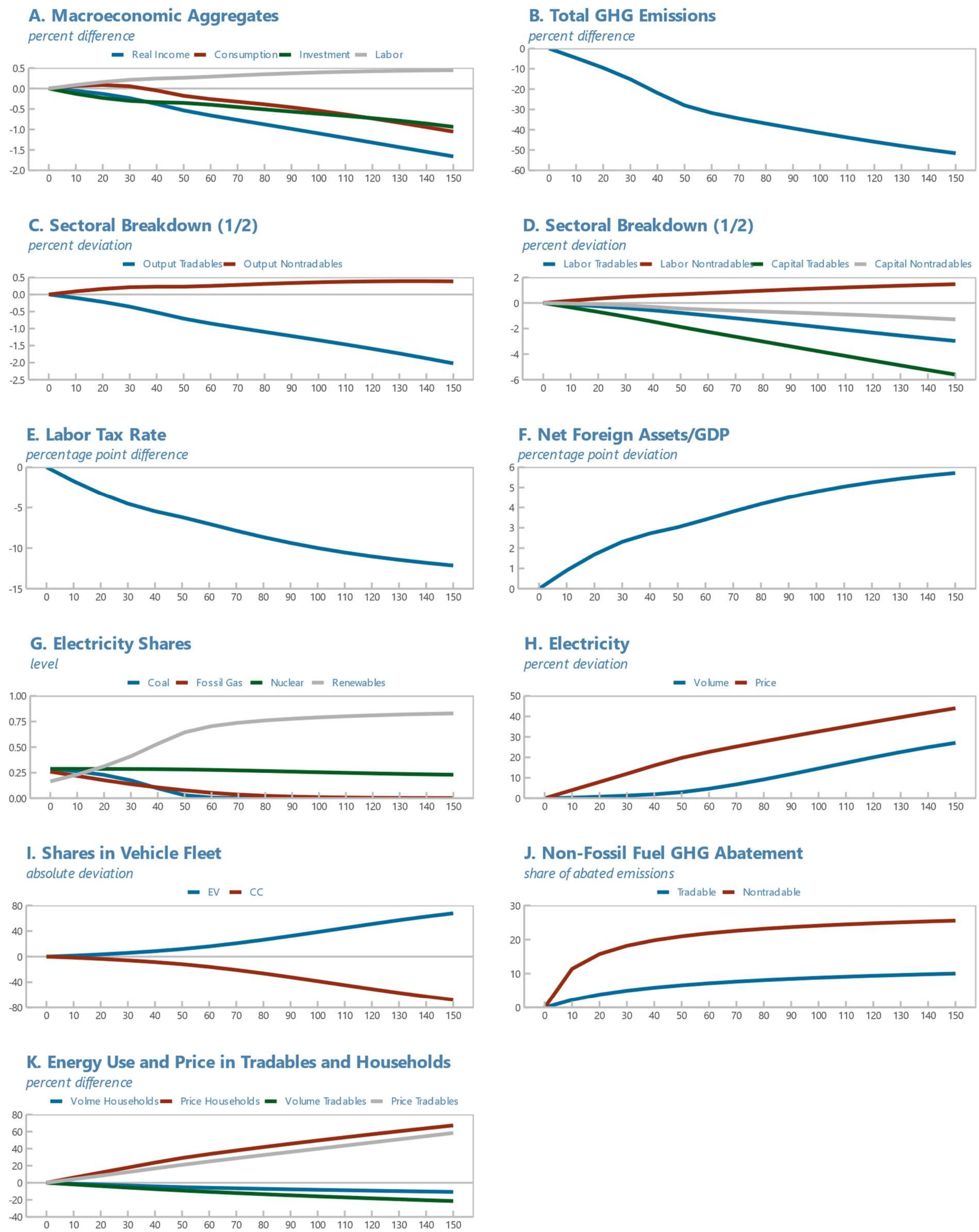
Total GHG emissions fall rapidly as the GHG price goes from US$0/tCO2e to US$50/tCO2e (Figure 12, Panel B), due to the reduction in the use of high-emitting coal in electricity generation (Figure 12, Panel G and Figure 13). Once the reduction in coal has been exhausted—beyond a GHG price of about US$50/t$CO_2$e—the marginal impact of raising the GHG price becomes smaller. The main driver or emission reductions beyond this point is the electronification of the transport sector, in which the long-term adjustment of the charging network play a key role (Figure 12, Panel I and Figure 13). The non-linearity in the abatement of non-fossil fuel related emissions (Panel J) reflects that the lower-cost mitigation options are implemented first, which renders additional abatement more expensive. Since the model abstracts from emission externalities and the resulting damages, bringing down emissions by disincentivizing the use of fossil fuels dampens the economy's productive capacity.

The price of electricity rises with the GHG price, while the generated volume starts to increase at about US$40/t$CO_2$e (Figure 12, Panel H). Since the hike in the electricity price falls short of the increase in the price of fossil fuels themselves (compare Panels H and K), this leads to electrification—the substitution of fossil fuels by electricity—of production and household energy use for both residential and transportation needs. This is reinforced by a higher EV share.

The degree of non-linearity in the long-term effects differs across macroeconomic aggregates (Figure 12, Panel A).[8] Emissions are the tax base for GHG prices. As emissions diminish, so does the marginal increase in tax revenues, which leads to smaller reductions in the labor income tax rate (Panel E). A further key non-linearity is the impact on the economy's long-term production potential. For tradables, the lesser usage of the energy input (Panel K) lowers demand for capital services and labor and leads to lower production (Panel C). The nontradables sector, in contrast, is less reliant on fossil fuels (see Table 4), and thus sees a shallower decline in the capital stock. This relatively smaller decline in capital implies a milder reduction of labor productivity, which allows for an increase in nontradables employment that absorbs the decline in employment from the tradables sector (Panel D). Nontradables output increases as a result (Panel C). The increase in the net foreign asset position (Panel F) results from the combination of a mild adjustment on overall wealth combined with a significant fall in the domestic capital stock.

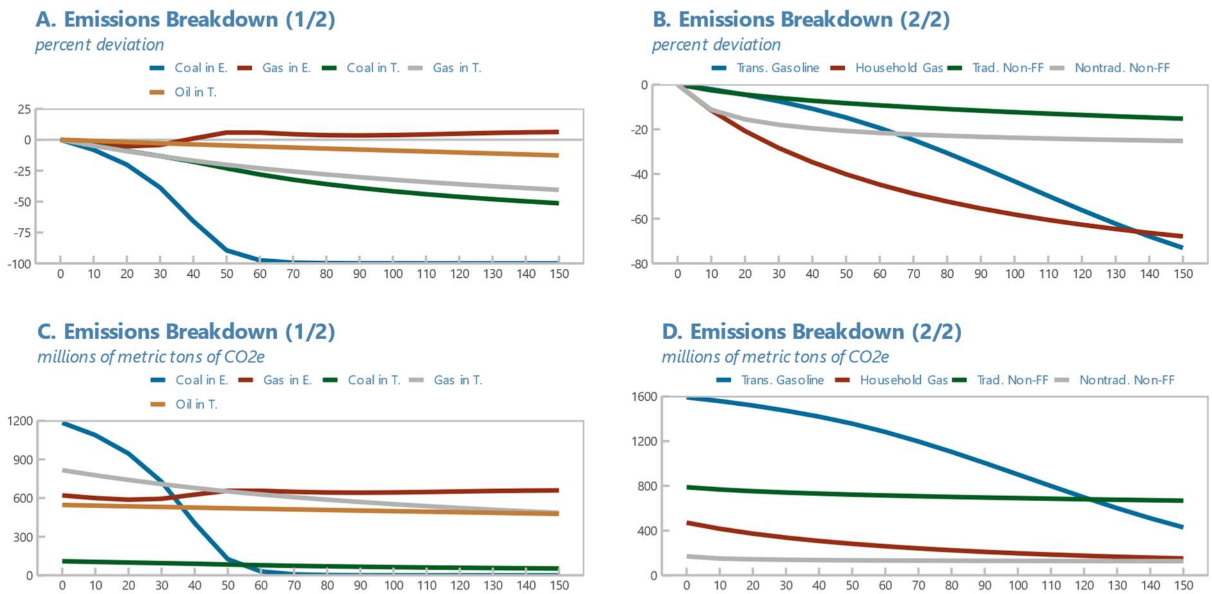
[8] Real GDP cannot be reported in the steady state, so real income (nominal GDP relative to the price of consumption) is shown instead. Real GDP is calculated by cumulating over time the chain-weighted relative prices and real volumes of its components (consumption, investment, government absorption, exports, and imports). When the steady state is presented alone (without any knowledge of the path from today's equilibrium), the time-dependent paths of those variables are not known, so real GDP cannot be calculated.

Figure 12. Long-Term Impacts of GHG Prices (1/2)



Source: Authors' calculations

Figure 13. Long-Term Impacts of GHG Prices (2/2)



Note: ‘Non-FF’ is ‘non-fossil fuels’, ‘Elec’ is electricity.
Source: Authors’ calculations

Sectoral Mitigation Policies

This section concludes the discussion the macroeconomic impact of different GHG emission mitigation policies, again using the United States as an illustrative example, but focusing instead on sectoral policies. This results in the introduction of two further sets of instruments besides GHG prices, which can also be configured on a sectoral basis.

The second set of mitigation policy instruments are sector-specific subsidies for green investment: low-emission technologies or activities that are close substitutes to high-emission ones. In GMMET, electricity generation from renewables, nuclear and hydro power plants, as well as EVs are the three main green investment opportunities. Green subsidies lower the relative price of low-emission substitutes and thereby induce expenditure shifting that ultimately reduces emissions. However, the resulting disincentives for emitting activities are not proportional to their emission intensities. Controlling for the size of the fiscal envelope (that is, subsidy payments are of the same magnitude as GHG tax revenues), the induced emission reduction is usually lower under subsidies than under direct GHG taxation.

The third set of mitigation policy instruments contains regulatory measures, or rules that apply to a given sector, limiting its emission intensity or the share of a specific high-emission good or activity in a bundle of related goods (such as coal-based electricity in overall electricity generation, or the share of CCs in the total of newly purchased vehicles). A regulation induces expenditure shifting without using a market instrument or an explicit price. This is the case with portfolio standards, where the composition of the portfolio of the amounts of electricity generation is shifted by government regulation rather than price signals from GHG taxation. This is captured technically in GMMET as a shadow price which measures the intensity of the regulation-induced constraint faced by the agent.

The section starts with an analysis focused on the electricity sector, leaving aside the transportation, tradable or nontradable sectors. This first analysis compares and contrasts within the electricity sector GHG prices, feebates and portfolio standards. It is followed by two analyses on the transportation sector – subsidization of the purchase of EVs and encouraging the expansion of EV use by increasing the network of charging stations available. It concludes with the analysis of two policies aimed at electricity generation, a subsidy on renewables generation capital and an expansion of nuclear power.

Comparison of GHG Prices, Feebates, and Portfolio Standards in Electricity Generation

Figure 14 compares three alternative policies to promote emissions reduction in electricity generation, for the case where policies are only implemented in the United States. First, the blue lines represent a gradual introduction over 8 years of a US$50/tCO2e tax on fossil fuels used in electricity generation, with revenues recycled by lowering the labor income tax. Second, the red lines show the gradual introduction of a feebate structure in the electricity sector that mimics the impact on relative prices from the GHG tax. The resulting tax revenues are used to subsidize the final electricity price instead. Third, the green lines show the effects of the gradual introduction of a portfolio regulatory standard in the electricity sector that increases the share of renewables. The regulation can be interpreted as a subsidy on renewable generation that is financed by equal taxes on all other generation technologies.

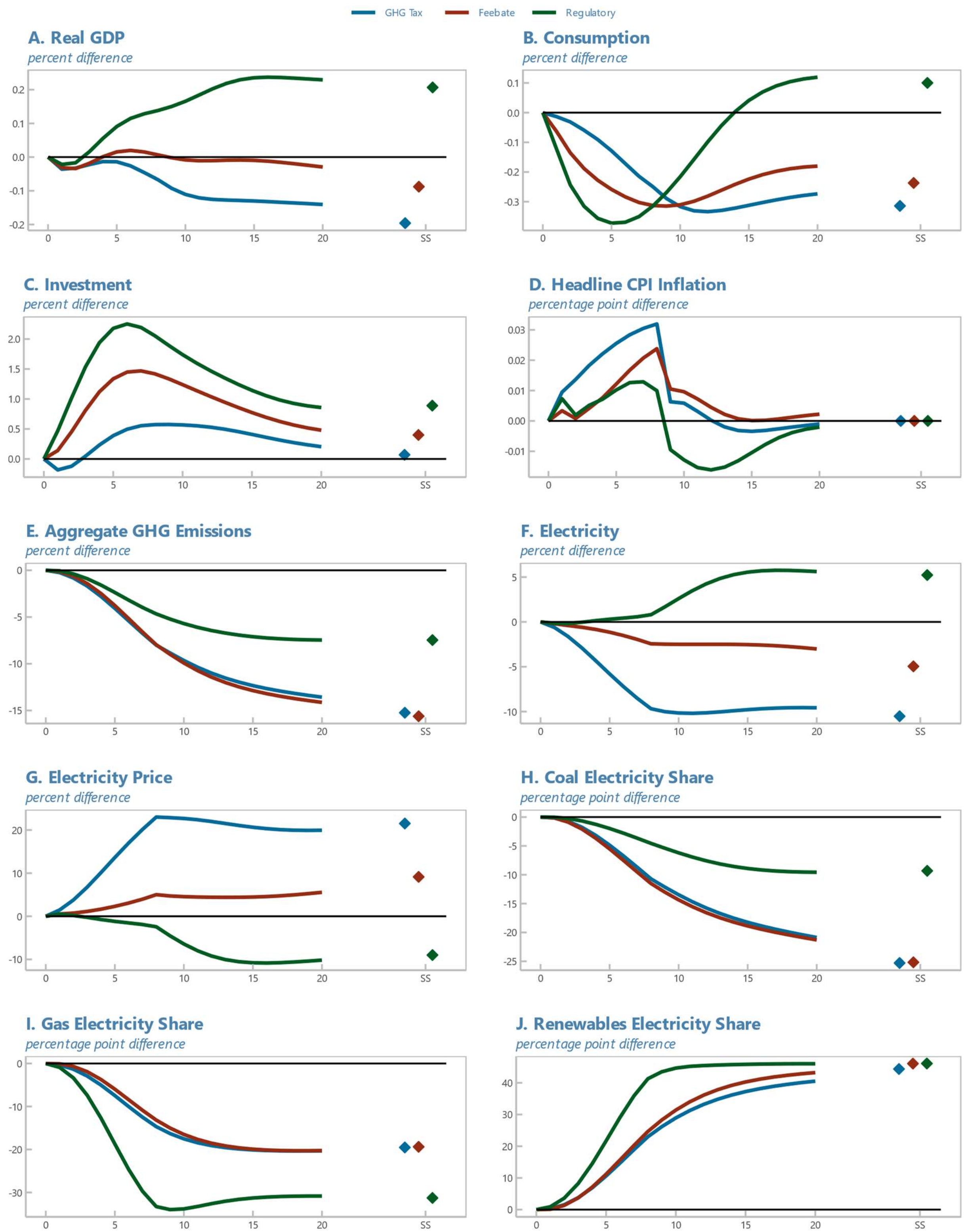
The three policies are comparable in that they bring about the same increase in the share of renewables in the electricity mix in the long term. However, there are differences in the decline in emissions. Under GHG tax and feebates, the decline in emission is roughly identical at about 15 percent in the long term (Panel E), reflecting a roughly similar impact on the electricity mix (Panels H, I and J). Both GHG taxes and feebates impose tax burdens on the different fossil fuels in proportion to their emission content—the per-unit tax on coal is twice as large on gas, for example. As a result, both policies have a similar effect on relative fuel prices and hence on emissions. In contrast, the relative price between fossil gas and coal is not affected when the share of renewables is raised via regulation. As a result, the increase in non-renewable generation comes at the expense of gas, which is more expensive, instead of coal, which is cheaper (see Panels H, I and J). The price of electricity declines due to the adjustment in the electricity mix (Panel G). The result is a smaller decline in emissions than under the other two policies.

The macroeconomic impact of the three policies is also different. Under feebates, the rise in the electricity price is mitigated by the implicit subsidies (Panel G). Investment rises under both GHG tax and feebates, in part due to the ramping-up of renewable generation capacity (Panel C). However, the increase is greater under feebates, due to the complementarity of electricity and capital in production. While a higher electricity price lowers the use of electricity (Panel F) and the desired capital stock, this effect is weaker under feebates as the increase in electricity prices is muted. Relative to feebates, the GHG tax supports household consumption during the transition period (Panel B). Due to the offsetting effects on private investment and household consumption, differences in the GDP and inflation responses are negligible over the transition period (Panels A and D). In the long term, the impact on both household consumption and output is determined by the policies' implications for the productive capacity of the economy. The result hinges on the assumed labor supply elasticity and the complementarity of capital and electricity in production. Fostering investment in the context of feebates is more productive than reducing distortionary labor income taxes under the GHG price.

The macroeconomic impact of the regulation follows instead from the lower electricity price and the associated increase in electricity use (Panel F), which in turn leads to higher private investment (Panel C). The induced rise the economy's production potential raises output (Panel A) and household consumption (Panel B) but at the cost of a smaller reduction in emissions. Headline inflation remains practically constant (Panel D).

When the share of renewables is raised via regulation, the relative price between fossil gas and coal is not affected, which contrasts with the GHG price and feebates (where the per-unit tax on coal is roughly twice as

Figure 14. Gradual Implementation of GHG Price, Feebate and Regulation in the Electricity Sector



Source: Authors' calculations

large as on gas). As a result, the crowding-out of non-renewable generation weights heavier on fossil gas than on coal (see Panels H, I and J). The overall adjustment in the electricity mix lowers the electricity price (Panel G) because the cheapest generation method, coal, only declines mildly, while expensive gas generation is to a significant extent replaced by cheaper renewable generation.

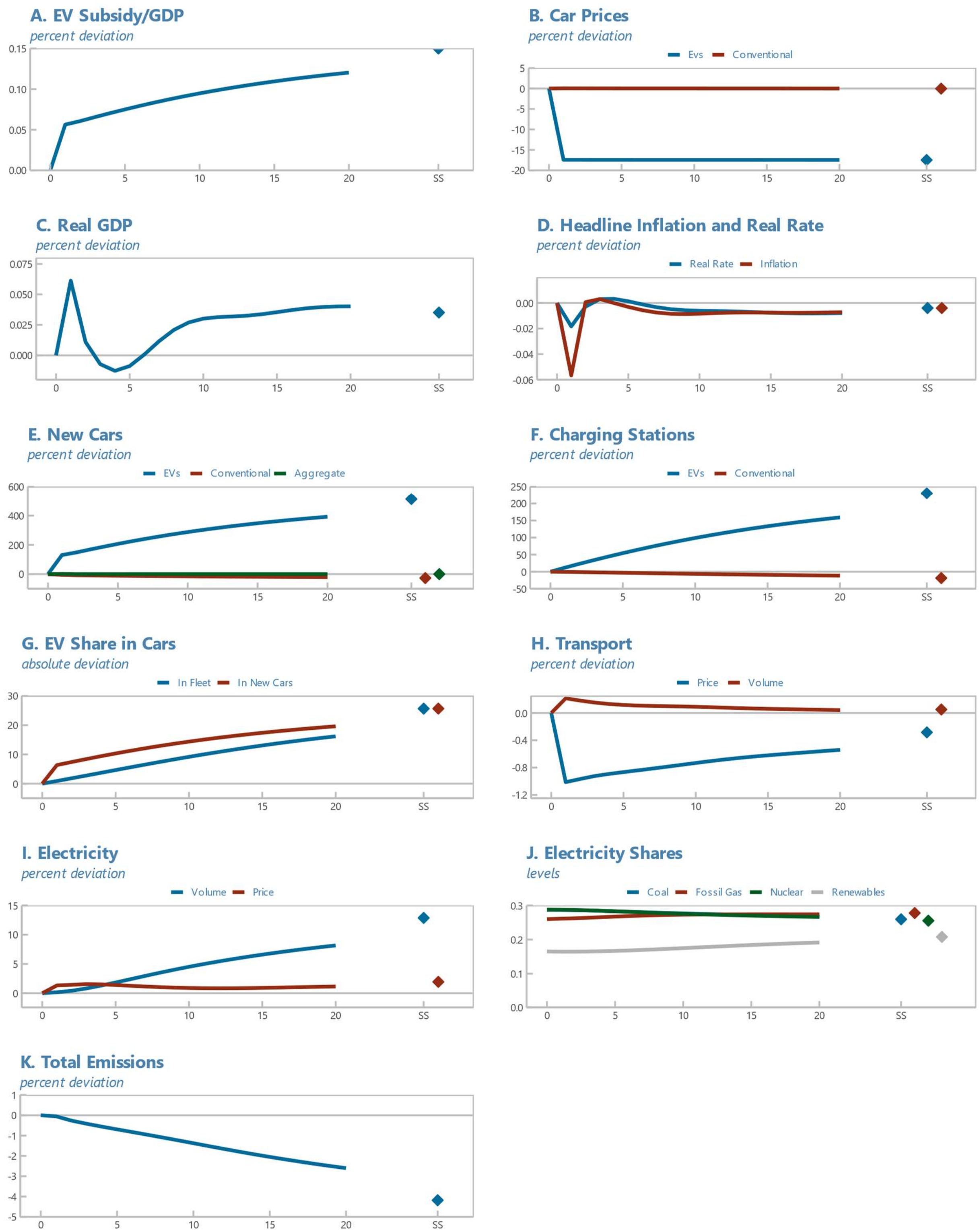
Subsidy for the Purchase of Electric Vehicles

Figure 15 illustrates the impact of a 17 percent subsidy on EV purchases in the United States, which is financed by a reduction in general lumpsum transfers to households (Panel B). With the purchase price dominating the vehicle's life-cycle costs, the subsidy greatly incentivizes EV purchases and leads to an immediate uptick in new purchases (Panel E). More EVs on the street incentivize the deployment of charging stations (Panel F), which in turn boosts EV purchases by mitigating so-called "range anxiety." This can be seen in the gradual rise in EV purchases (after the initial uptick) and in subsidy costs which converge to 0.15 percent of output in the long term (Panel A). The rising EV share in newly purchased cars gradually affects the composition of the car fleet, with the EV share gradually increasing to about a quarter of all vehicles in the long term (Panel G).

While the general macroeconomic implications of the policy are very small (real GDP and inflation, Panels C and D), the rising EV share boosts electricity demand and its price (Panel I). Depending on the electricity mix, additional emission from higher electricity generation can offset the emission decline from reducing gasoline consumption by CCs. Here, overall emissions decline by about 4 percent (Panel K), as fossil fuel-based technologies play the largest role in electricity generation (Panel J).

The electricity mix also adjusts in response to higher demand, which Is a general feature and not specific to this policy (Panel J). The fixed volume of nuclear generation declines as a share of rising overall production, while the expansion of renewables is the greatest as it is only constrained by climbing fossil fuel prices to the extent that gas is used as a backup. The difference between coal and fossil gas is again related to fossil gas being used as backup for renewables and to the scope for trade in fossil gas, which raises the price elasticity of supply.

Figure 15. Subsidy for the Purchase of Electric Vehicles



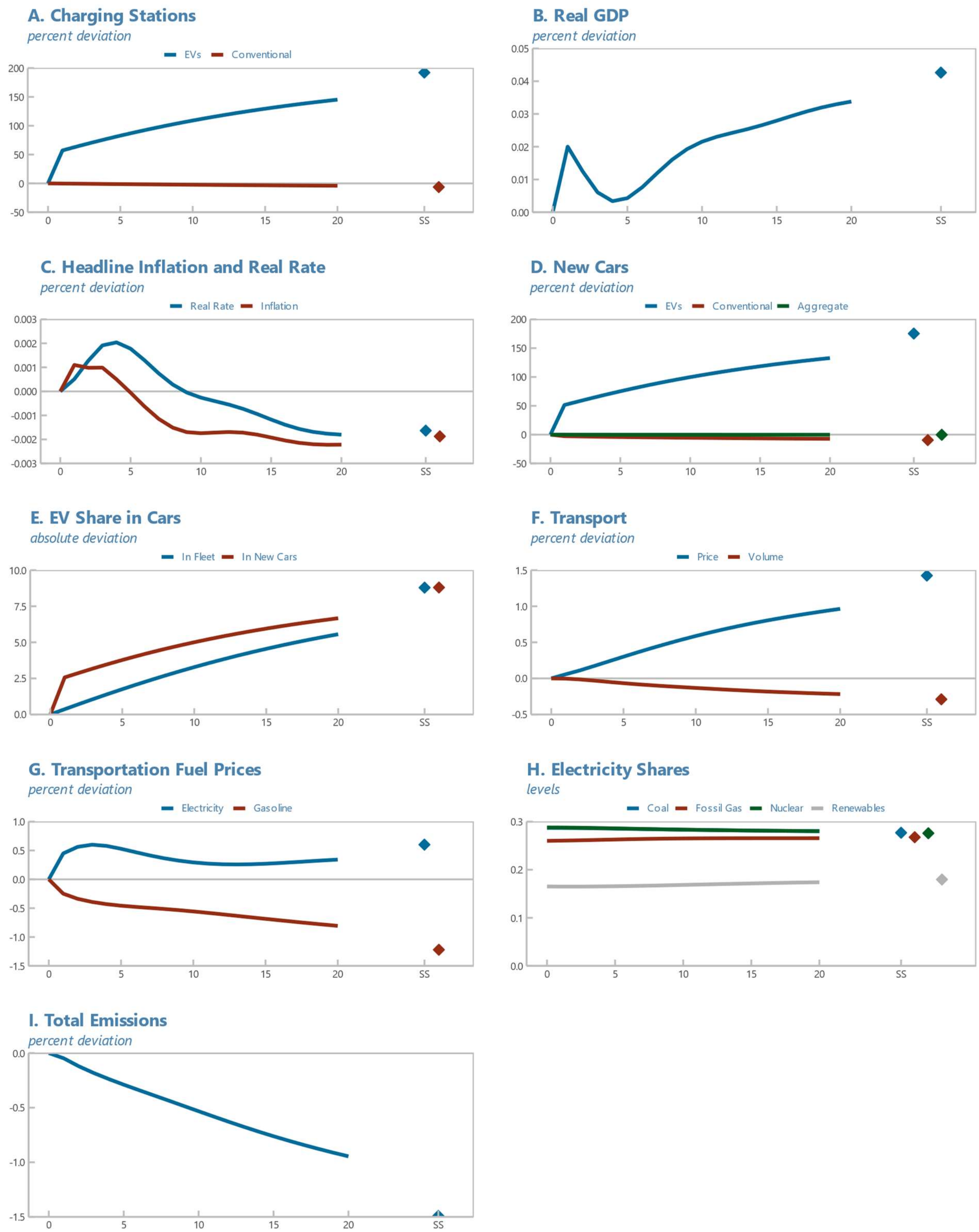
Source: Authors' calculations

Increase in the Number of EV Charging Stations

While the number of EV chargers adjusts endogenously to the EV share in the transportation fleet, there is an exogenous component that can be interpreted as a government-financed deployment. Figure 16 presents the impact of an exogenous increase in the number of EV chargers by 50 percent. The model does not track the associated fiscal costs as they are a negligible share of GDP. The policy-induced rise in EV charging stations makes EVs more attractive to households and endogenously increases the share of EVs in newly purchased cars (Panel D). This in turn incentivizes the deployment of new EV chargers and triggers a positive feedback loop that leads to a gradual increase in both the EV share and the number of charging stations beyond the initial, policy-induced uptick (Panels E and A).

A growing EV share in the transportation fleet boosts the demand for electricity and elevates its price, but also reduces gasoline demand and thus fuel costs of CCs (Panel G). Aggregate transportation costs increase mildly, which reduces the volume of aggregate transportation services (Panel F). This results from the assumption that the purchase price of EVs remains above that of CCs. Overall GHG emissions are reduced by about 1.5 percent in the long term (Panel I), which again highlights the relevance of the electricity mix (Panel H) in determining the impact of electrifying transportation on GHG emissions. Here, surging emissions due to higher electricity demand offset to a substantial degree the emission reductions from reduced gasoline consumption. The overall effect on real GDP and inflation is negligible as the policy only affects a small sector of the economy (Panels B and C).

Figure 16. United States: Permanent Increase in the Number of EV Charging Stations



Source: Authors' calculations

Subsidy on Investment in Renewable Electricity Generation

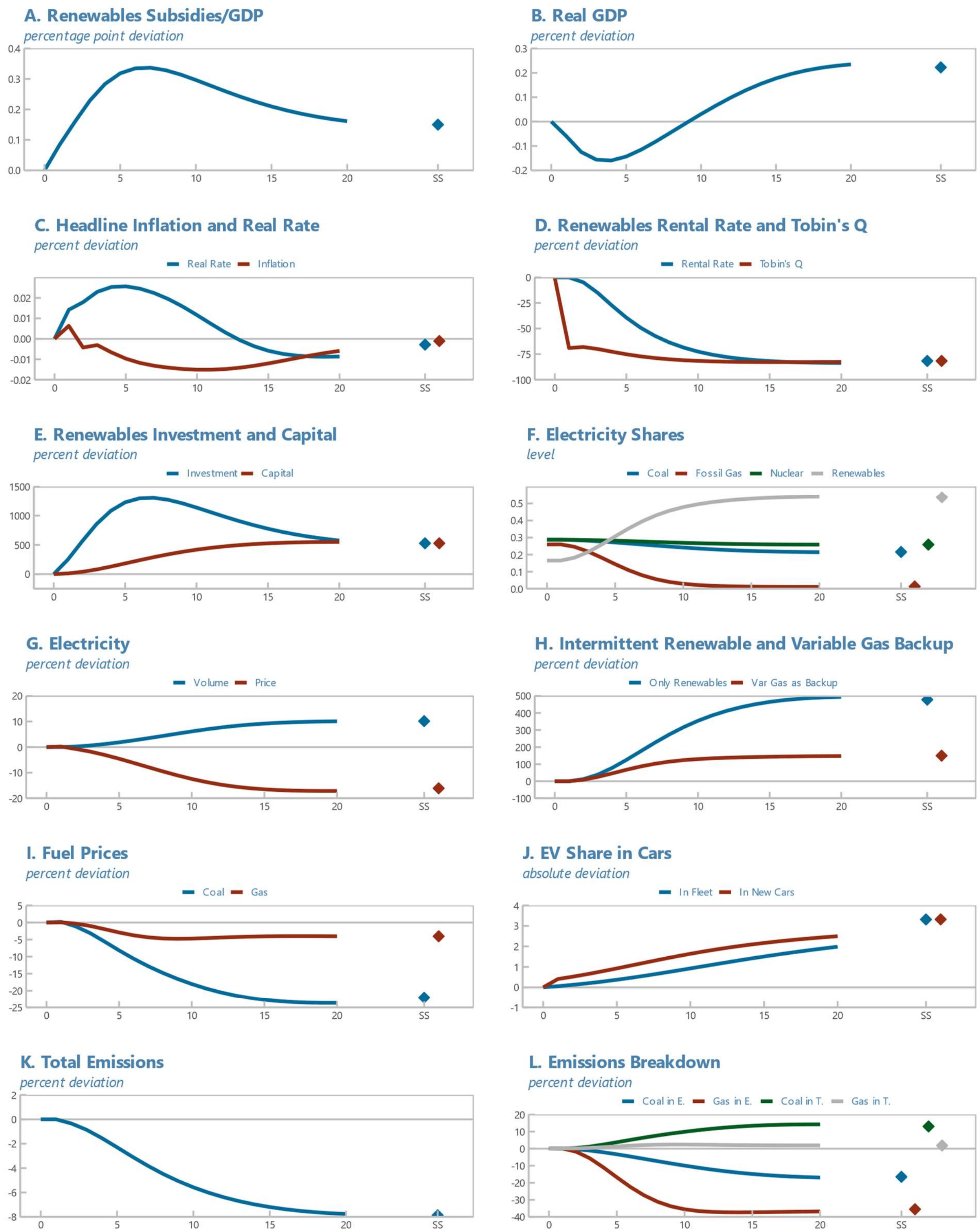
Figure 17 depicts the impact of a subsidy that reduces the price of renewable electricity generation capital by 80 percent in the United States. The volume of the subsidy remains modest, peaking at more than 0.3 percent of GDP when the speed of renewables capacity deployment is the highest, and converging to 0.15 percent of GDP in the long term (Panel A). The subsidy is financed by a reduction in general lumpsum transfers to both LIQ and OLG households. The policy leads to an expansion of investment in renewable electricity, and the resulting increase in the capital stock drives down the technology-specific rental rate (Panels E and D). This surge in investment comes to an end when Tobin's Q (the value of the marginal unit of capital) has declined by about 80 percent, to match the lower cost of the investment good resulting from the subsidy (Panel D).

The additional renewable generation crowds out other sources of electricity and leads to a rebalancing of the electricity mix (Panel F). Since nuclear electricity investment is exogenous, its share only drops by a negligible extent as aggregate generation expands. The share of fossil gas declines more than the share of coal, despite fossil gas being used as a backup for expanding renewables (Panel F). The reason lies in the trade structure of fossil fuels, which makes the supply of fossil gas more price elastic than the supply of coal. In contrast to the domestic coal price, the price of fossil gas is cushioned by the presence of foreign trading partners (Panel I) that increase their imports in response to a lower price.

The reduction in transfers depresses household consumption, either directly in the case of LIQ households or indirectly via the reduction of OLG households' wealth. Therefore, real GDP declines in the short term (Panel B). However, the impact on real GDP turns positive in the medium- and long-term, due to the surge in investment from the expansion in electricity generation capacity and lower electricity prices (Panel G). The induced gain in real GDP compensates for the reduced transfers in the long term, leaving both output and household consumption permanently elevated. Intuitively, saving from cutting back non-distortionary transfers are used to increase the economy's potential. The policy does not appreciably affect inflation or the interest rate (Panel C).

The reduction in the electricity price pushes down fuel costs for EVs and increases their share in the transportation fleet (Panel J). However, the EV share only rises mildly since the life-cycle costs are dominated by the price of the vehicle itself. The policy reduces overall GHG emissions by about 8 percent (Panel K). This is predominantly driven by the reduction in the use of fossil gas for electricity generation, and to a lower extent by the reduction in the use of coal (Panel L). At the same time, the expansion of output causes tradable sector GHG emissions to rise, which limits the total emission decline from the policy (Panel L). This mitigating impact is reinforced by the lower price of electricity resulting from greater use of renewables relative to more expensive coal and fossil gas.

Figure 17. Subsidy on Investment in Renewable Electricity Generation



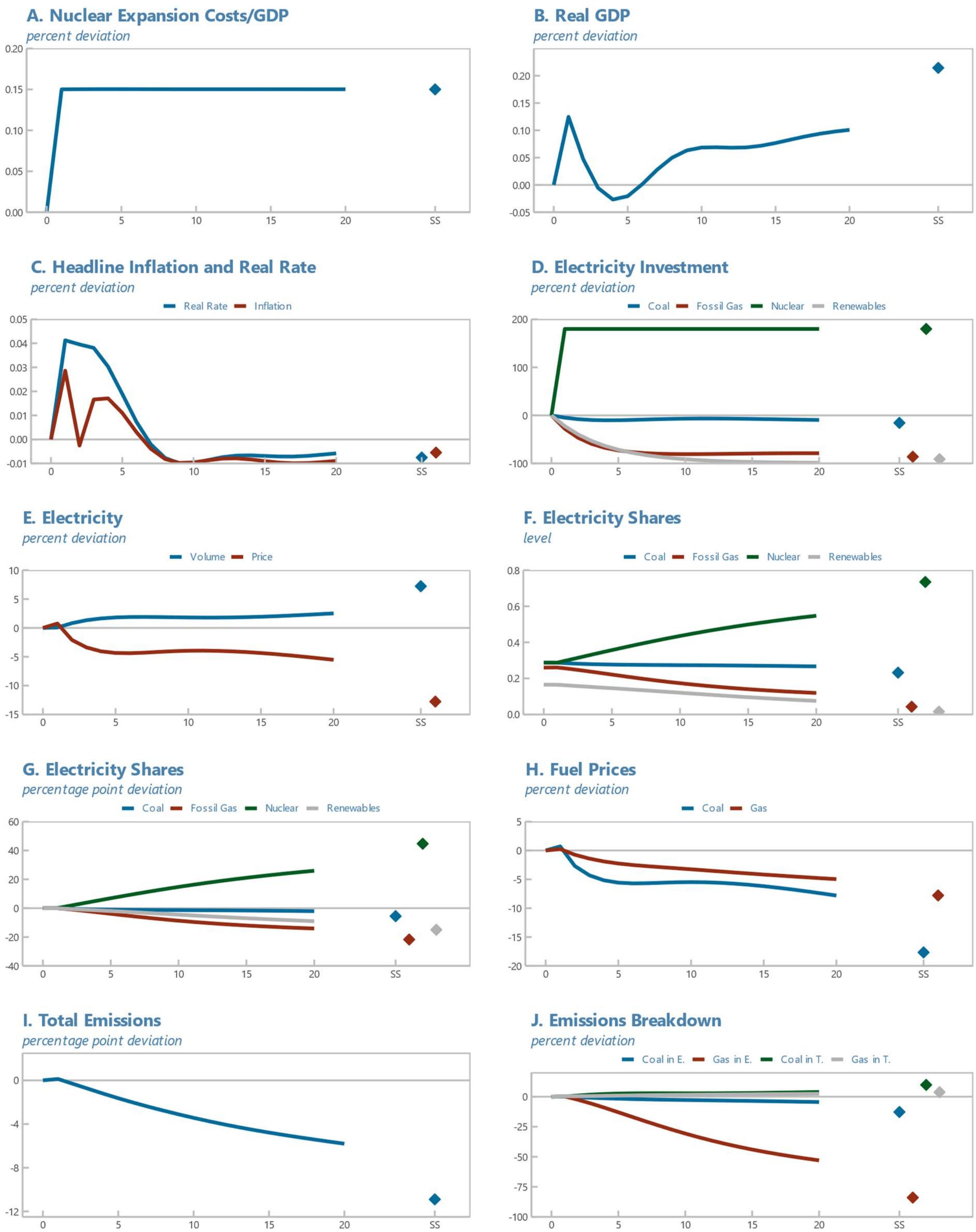
Source: Authors' calculations

Increase in Public Investment in Nuclear Electricity Generation

Figure 18 examines an exogenous increase in US nuclear power investment by the government of 180 percent. The associated fiscal costs amount to 0.15 percent of output and are funded by a decline in household transfers (Panel A). The surge in investment gradually increases nuclear electricity generation and crowds out other sources of electricity, with generation from coal declining substantially less than renewables and fossil gas (Panel F). The range of effects is explained by relative price-elasticity of supply. Supply of renewables has the highest long-term elasticity: its marginal costs (the rental rate of the capital stock) is constant. Generation from gas power plants has intermediate elasticity: the bulk part of its marginal cost, the price of fossil gas itself, is stabilized by other uses, in particular net exports (Panel H). Generation from coal has the lowest elasticity: domestic electricity generation represents most of its use, and the commodity is not traded internationally.

The impact on the wider economy resembles the impact of subsidizing renewables analyzed in the previous exercise. Additional electricity generation capacity lowers the electricity price and boosts output in the long term (Panel E). As in the previous scenario, cutting general lumpsum transfers to finance the increase in nuclear energy investment is akin to raising non-distortionary taxes to expand economy’s potential. The short-term adjustment differs from the case of the renewables investment subsidy in that real GDP initially rises (Panel B). While the government’s subsidization of investment in nuclear energy constitutes an immediate increase in investment, the expansion of renewables investment due to its subsidy is more gradual, owing to adjustment costs weighing on the investment decisions of private agents. Like the renewable subsidy, expanding nuclear power generation only mildly impacts the share of EVs and the impact on inflation is negligible (Panel C). Total emissions decline by about 10 percent, mainly driven by the reduced use of fossil gas in electricity generation (Panels I and J).

Figure 18. Increase in Public Investment in Nuclear Electricity Generation



Source: Authors' calculations

Model Properties for Global Energy Price Shocks

This section discusses supply shocks for oil and fossil gas. It is assumed that the shocks emanate from the rest-of-the-world bloc, as the latter includes OPEC and other major oil and fossil gas producers such as Canada, Mexico, Norway, and Russia. Both temporary and permanent supply shocks are considered.

Temporary Increase in the Oil Price

Figures 19 and 20 show the macroeconomic effects from a temporary increase in the global price of oil. It is assumed oil production in the rest-of-the-world bloc is cut by 25 percent in the first year of the simulation, with production returning to its initial level over a four-year period (Figure 19, Panel B). As a result, the global price of oil increases by 100 percent in the first year (Panel A) and returns to its initial level by year 3.

Higher oil prices have a direct effect on headline inflation, through household consumption of gasoline, and an indirect effect through higher energy costs in the tradable sector. The increase in headline inflation is large in the first year (Figure 20, Panel E), ranging from around one percent in China to close to 2 percent in the rest-of-the-world bloc, but then falls below target as the oil price returns to its initial level. Core inflation increases by around 0.1 percent since temporary higher energy costs are absorbed in part by lower firms' margins (Panel F). The inflation response differs by sector. Inflation in the tradeable sector rises by around 0.5 percentage points in the first two years, due to the impact on energy costs, whereas nontradable inflation slows down initially. Monetary policy reacts to core inflation and tightens slightly (Panel G), which, together with headline inflation falling in the second year, causes the real interest rate to rise (Panel H).

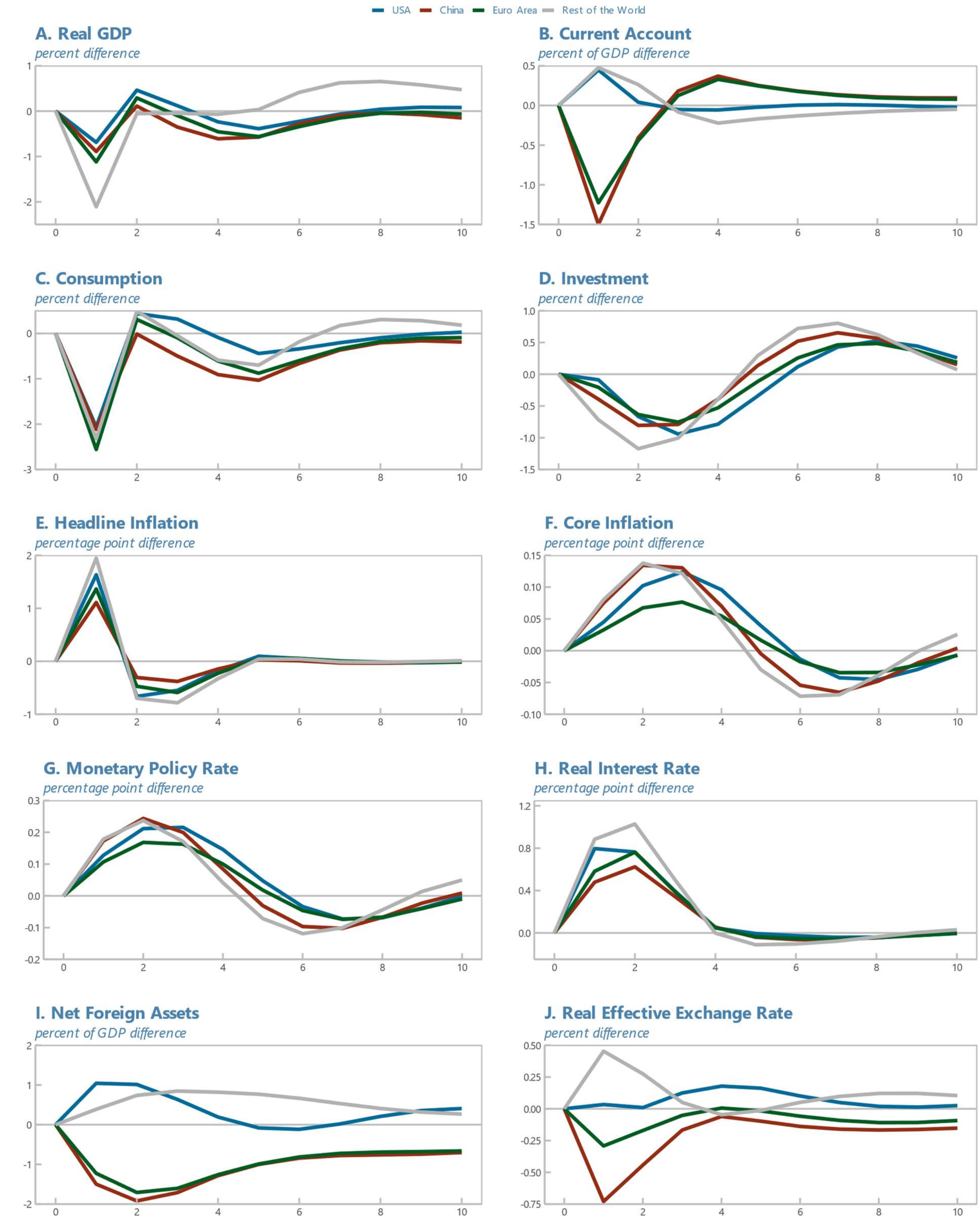
Lower real income and higher real rates result in a global decline in household consumption (Figure 20, Panel C). The impact is most visible for LIQ households (Panel D). There is also a relatively small decline in private investment across regions. Real GDP declines by less than or close to one percent in the United States, China, and the euro area (Panel A). The United States experiences the smallest GDP decline since its oil sector expands with higher oil prices (Figure 19, Panel B). China comes second: a lower share of oil in energy reduces the impact on household consumption (Figure 20, Panel C). The decline in household consumption and real GDP is larger in the euro area (Panels C and A). Finally, the rest-of-the-world bloc suffers the largest real GDP decrease (Panel A), reflecting a higher share of oil in energy use and the direct impact from the decline in oil production.

The evolution of energy prices balances supply and demand effects. In the first year, lower aggregate demand dominates, and the price of coal, fossil gas, and electricity all drop (Figure 19, Panel C). In the second year, substitution effects dominate instead: firms and households reduce their demand for oil and increase demand for other energy commodities, pushing up their prices. Finally, the divergent evolution of gasoline and electricity prices increases the share of EVs, with a modest but lasting effect on demand for electricity for transportation (Panel H).

Figure 19. Temporary Increase in Global Oil Prices – United States and Energy Sectors

Source: Authors calculations

Figure 20. Temporary Increase in Global Oil Prices – All Regions



Source: Authors calculations

Permanent Increase in the Oil Price

Figures 21 and 22 consider a permanent increase in the oil price. Oil production falls by 6 percent in the rest-of-the-world bloc (Figure 21, Panel B) leading to an increase in the price of oil of 10 percent (Panel A).

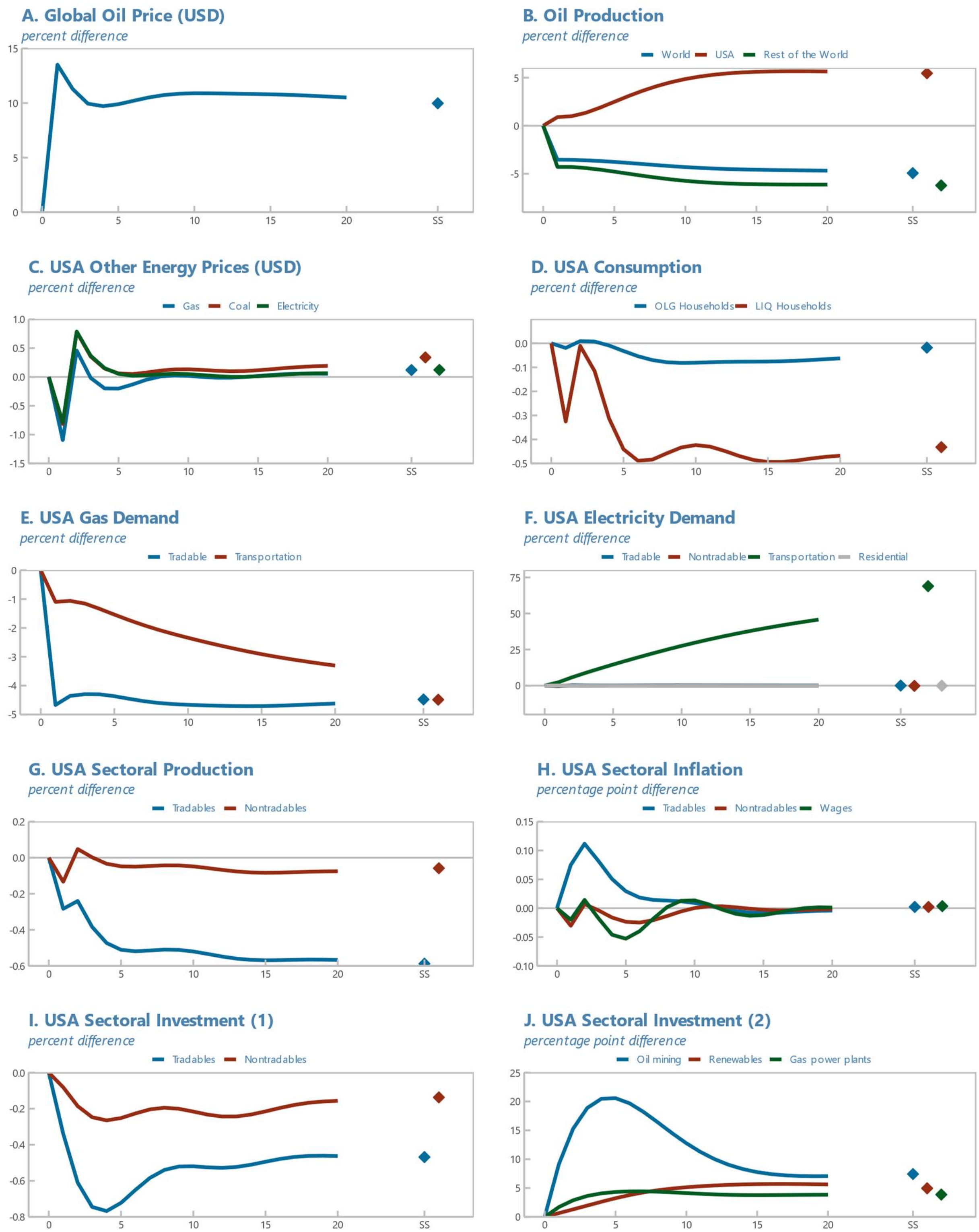
The permanently higher oil price modifies the structure of the economy in the long term. More expensive energy inputs reduce production capacity in the non-energy sectors, leading to a permanent drop in non-energy investment (Panel I). Aggregate investment declines in all regions but the United States, which benefits from a sizable increase in investment in oil production (Panel J). The decline in aggregate investment is largest in the rest-of-the-world block as it also experiences a large decline in oil investment.

Permanently more expensive energy inputs also reduce households' real GDP and consumption (Figure 22, Panels A and C). The impact is again larger for LIQ households (Figure 21, Panel D). Households also shift away from gasoline cars and demand for electricity for transportation increases (Panel F). In the short term, both consumption and investment weigh on aggregate demand. The decline in GDP is about twice as large as for a comparable temporary decrease in oil supply (Figure 22, Panel A).

The increase in the price of oil feeds into headline CPI inflation, which increases by roughly 0.2 percentage points in the euro area and the United States in the first year, and by a lesser extent in China and the rest-of-the-world block (Figure 22, Panel E). Core inflation does not increase noticeably (Panel F): while energy costs are permanently higher, real wages decline as demand for labor is lower. As core inflation does not increase and inflation expectations remain anchored, headline inflation is back to target in the second year. Monetary policy does not react (Panel G), and the real interest rate broadly remains at its initial level (Panel H).

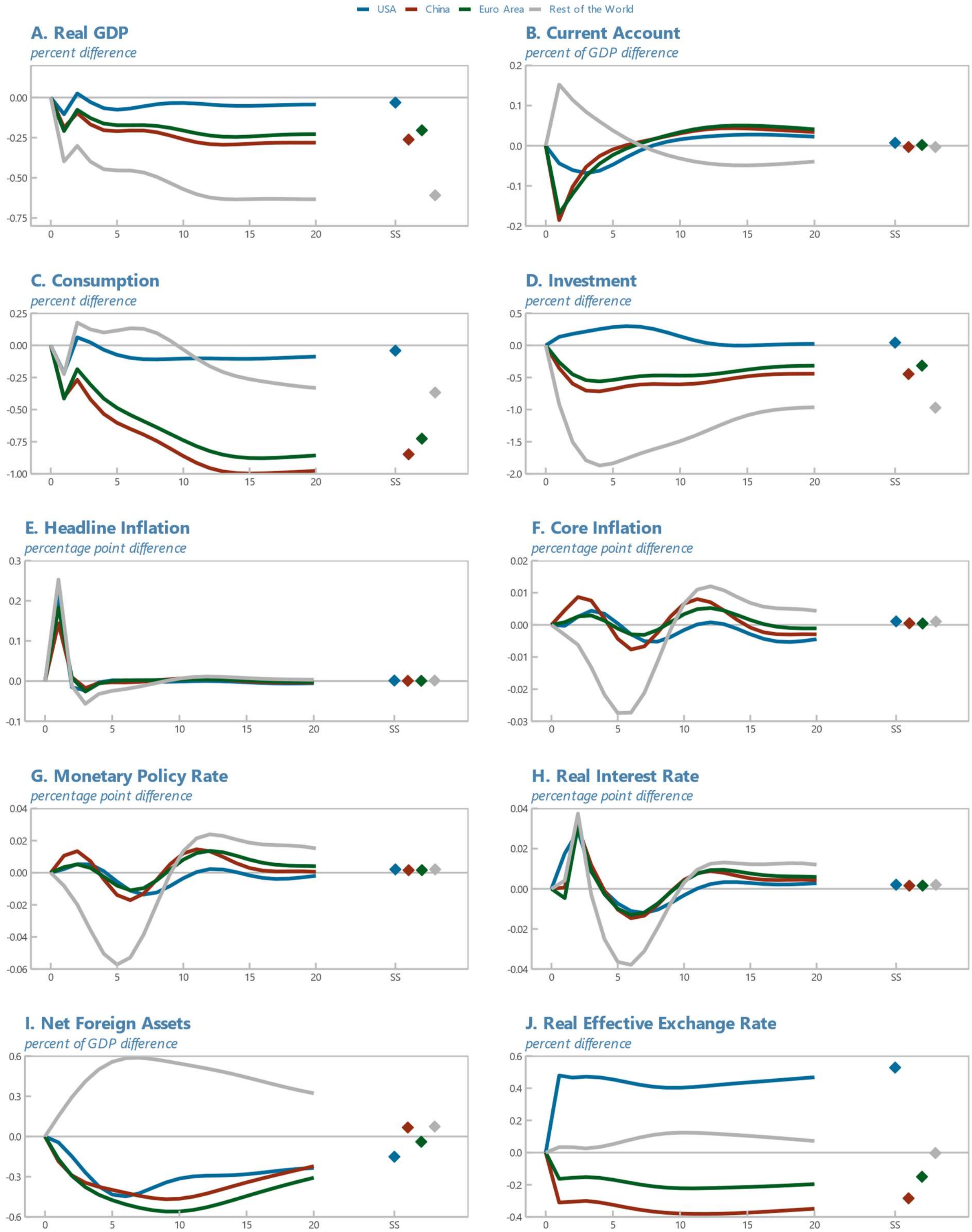
Differences in the macro effects across regions reflect differences in the oil balance, which also have implications for external accounts and real exchange rate dynamics. China and the euro area see a worsening of their terms of trade, which amplifies the negative effect on activity and requires a real depreciation of their REERs (Figure 22, Panel J). The real depreciation helps support exports and leads to an increase in the trade balance, but both regions see a decrease in their current account balance (Panel B) due to the worsening in their terms of trade, and net foreign assets decrease (Panel I). Given that the United States is both a large consumer and producer of oil, the impact on the US terms of trade is negligible, which helps cushion the impact on consumption and GDP (Panels C and A), and the US REER experiences a real appreciation (Panel J). The US current account decreases as it is the only region to experience an increase in private investment (Panel D), and its net foreign assets consequently decrease (Panel I). Finally, the rest-of-the-world bloc experiences a larger negative shock to GDP and investment (Panels A and D), which results in an increase in the current account and a real exchange rate appreciation (Panels B and J). The rest-of-the-world bloc's net foreign assets increase (Panel I).

Figure 21. Permanent Increase in the Global Oil Price – United States and Energy Sectors



Source: Authors' calculations

Figure 22. Permanent Increase in the Global Oil Price – All Regions



Source: Authors' calculations

Temporary Increase in Fossil Gas Prices

Figures 23 and 24 show the effects of a temporary increase in fossil gas prices. Gas production in the rest-of-the-world bloc is cut by 30 percent in the first year, with production returning to pre-cut levels by the fourth year. Unlike the market for oil, fossil gas markets are not fully integrated; the impact on prices therefore depends on the producing region (**Error! Not a valid bookmark self-reference.**Figure 23, Panel A). Euro area and the rest-of-the-world bloc depend primarily on the latter region's fossil gas production and experience the largest increase in prices (close to 80 percent). In China and the United States, fossil gas prices increase around 60 and 40 percent, respectively. In addition, since the United States and to a lesser extend China also produce gas, they react to the shock by increasing their domestic fossil gas production (Panel B).

Higher fossil gas prices raise headline inflation directly through households' consumption of gas and indirectly via higher electricity prices and energy costs in the tradable and nontradable sectors. Headline inflation increases in the first year (Figure 24, Panel E), ranging from around 0.3 percent in China to 1 percent in the rest-of-the-world bloc, but then falls below target as fossil gas prices fall back to initial levels. Core inflation increases by less than 0.1 percent as temporary higher energy costs are absorbed by lower firms' margins (Panel F). Monetary policy tightens (Panel G) such that the real interest rate increases by about 0.1 percentage point higher for several years (Panel H), but the magnitude of the tightening is small.

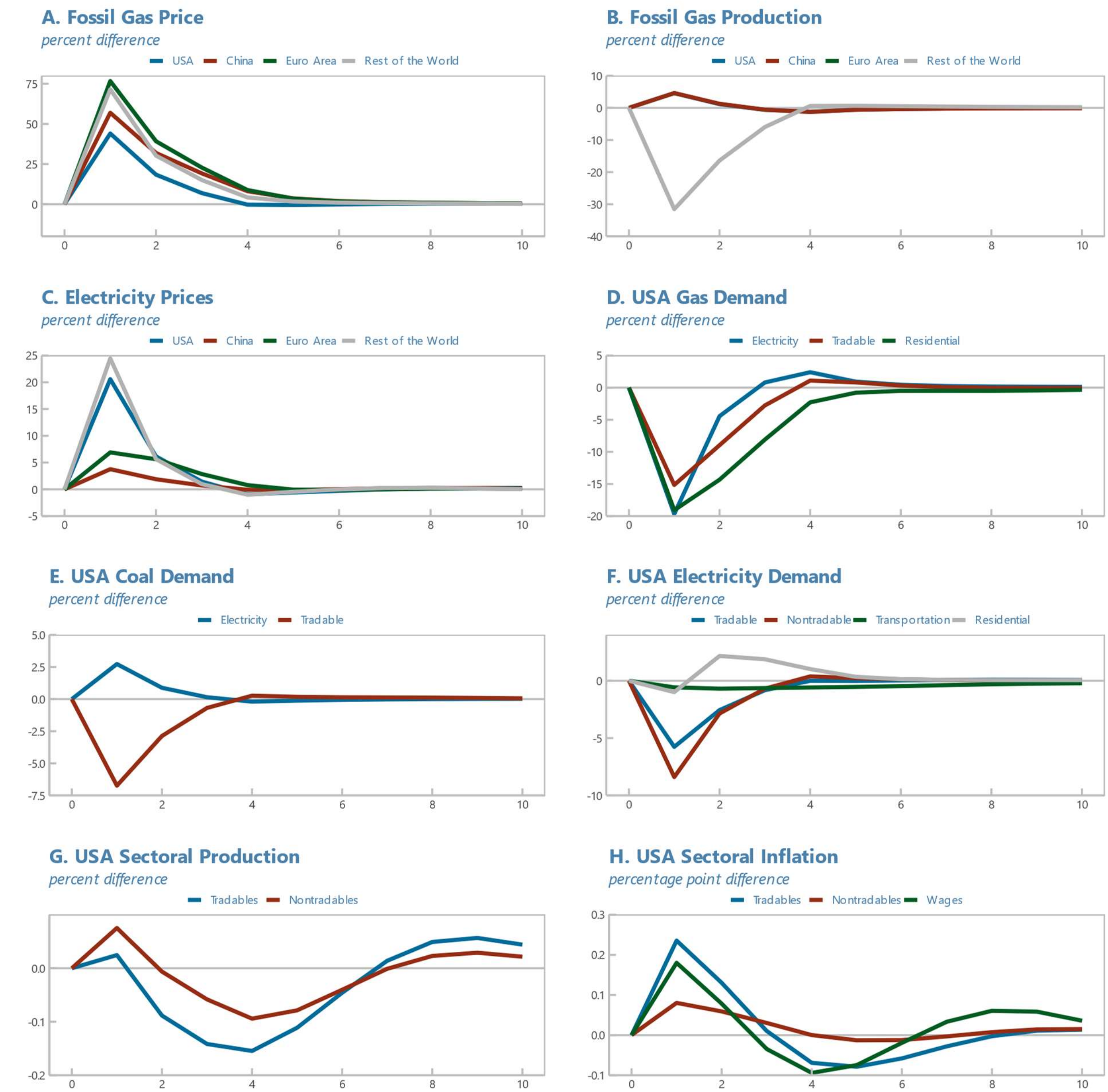
Electricity prices increase temporarily, with considerable variation across regions. Prices increase by 20 percent or more in regions that use fossil gas more heavily, the United States and rest-of-the-world bloc, and by 6 percent or less in regions that rely more on renewables (euro area) or coal (China) (Figure 24, Panel C). Coal demand in electricity generation increases as it is a close substitute for fossil gas (Panel E), pushing up its price. Contrary to the oil supply shocks considered, where the price of other forms of energy are barely affected, fossil gas and other sources of electricity generation are highly substitutable, causing their prices to comove to a large extent.

The higher cost of energy results in lower demand for labor and capital services, with the latter depressing investment (Figure 24, Panel D). Lower labor demand leads to lower labor income in the short term, depressing consumption, especially for LIQ households (Panel C). The impact on household consumption is smaller in the United States, due to the smaller increase in fossil gas prices, and larger in the euro area.

As in the case of oil, differences in the relative importance of fossil gas across regions affect the response of current accounts and real exchange rates (Figure 24, Panels B and J). The euro area sees a worsening in its terms of trade, leading to a decrease in its current account balance and a temporary real depreciation of its currency. China and the United States also experience real depreciations, while the rest-of-the-world bloc experiences a real appreciation.

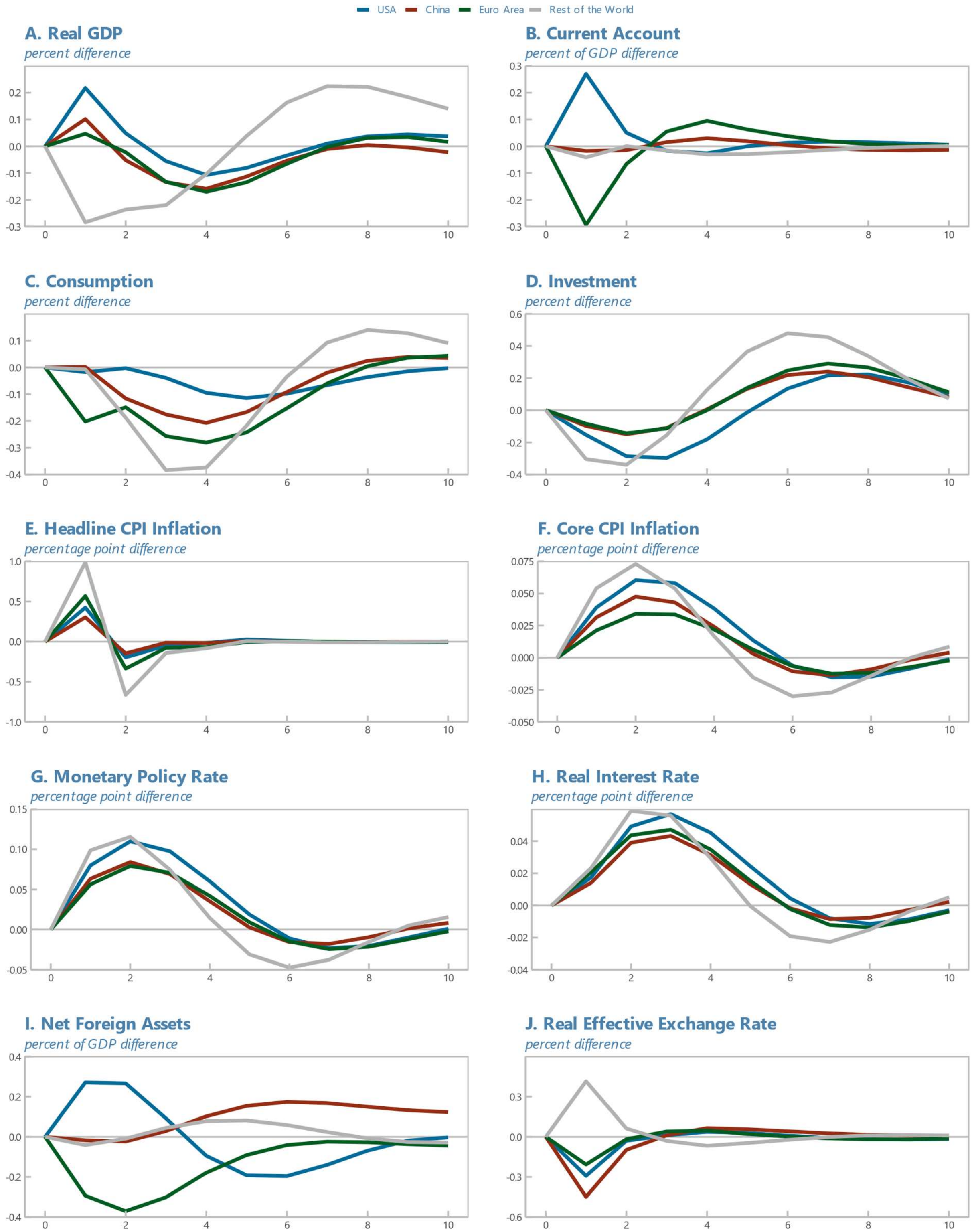
Finally, the cut in fossil gas production in the rest-of-the-world bloc results in a fall in real GDP in that region of around 0.3 percent (Figure 24, Panel A). Other regions experience a mild increase in real GDP, reflecting a shift in external demand due to the temporary depreciations in REERs mentioned above (Panel J).

Figure 23. Temporary Increase in Fossil Gas Prices – United States and Energy Sectors



Source: Authors' calculations

Figure 24. Temporary Increase in Fossil Gas Prices – All Regions



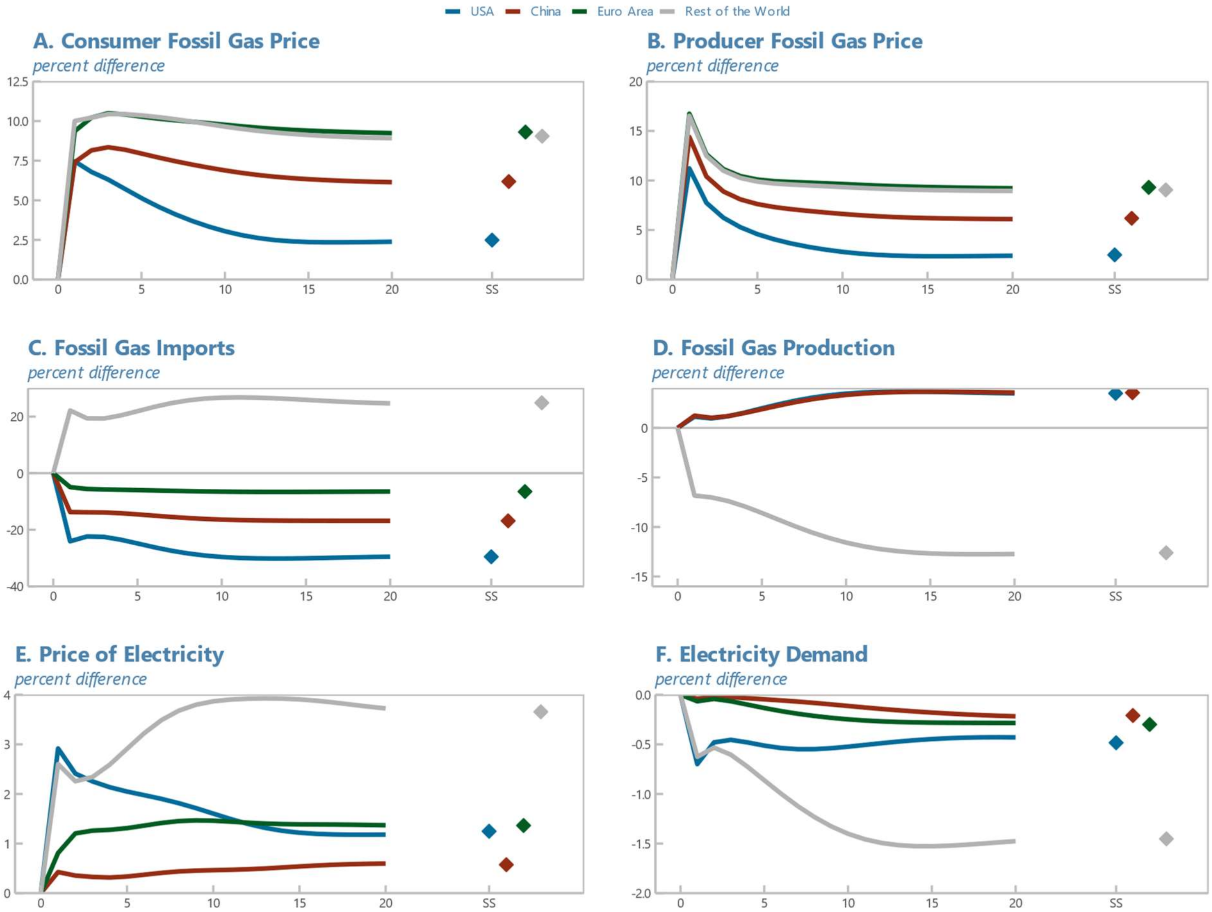
Source: Authors' calculations

Permanent Increase in Fossil Gas Prices

Figures 25 and 26 consider a permanent increase in fossil gas prices. A permanent decrease in fossil gas supply in the rest-of-the-world bloc (Figure 25, Panel D) leads to an immediate, permanent 10 percent rise in the fossil gas price for consumers in that region (Panel A). As in the previous simulation, less than complete integration of fossil gas markets worldwide leads to different price increases across regions. The euro area experiences a similar price increase, as they import their fossil gas from the rest-of-the-world bloc. China and the United States experience an immediate increase of around 8 percent. Over time, fossil gas production in these two regions increases in response to the higher price, while imports decrease (Panel C), which helps stabilize their fossil gas prices in the long term. This is more pronounced for the United States, which sees a lower increase in prices in the long term due to higher fossil gas production capacity. Higher fossil gas prices also have a negative impact on the electricity sector in all regions, increasing the price and decreasing the amount used (Panels E and F). The effects are most pronounced in the rest-of-the-world bloc.

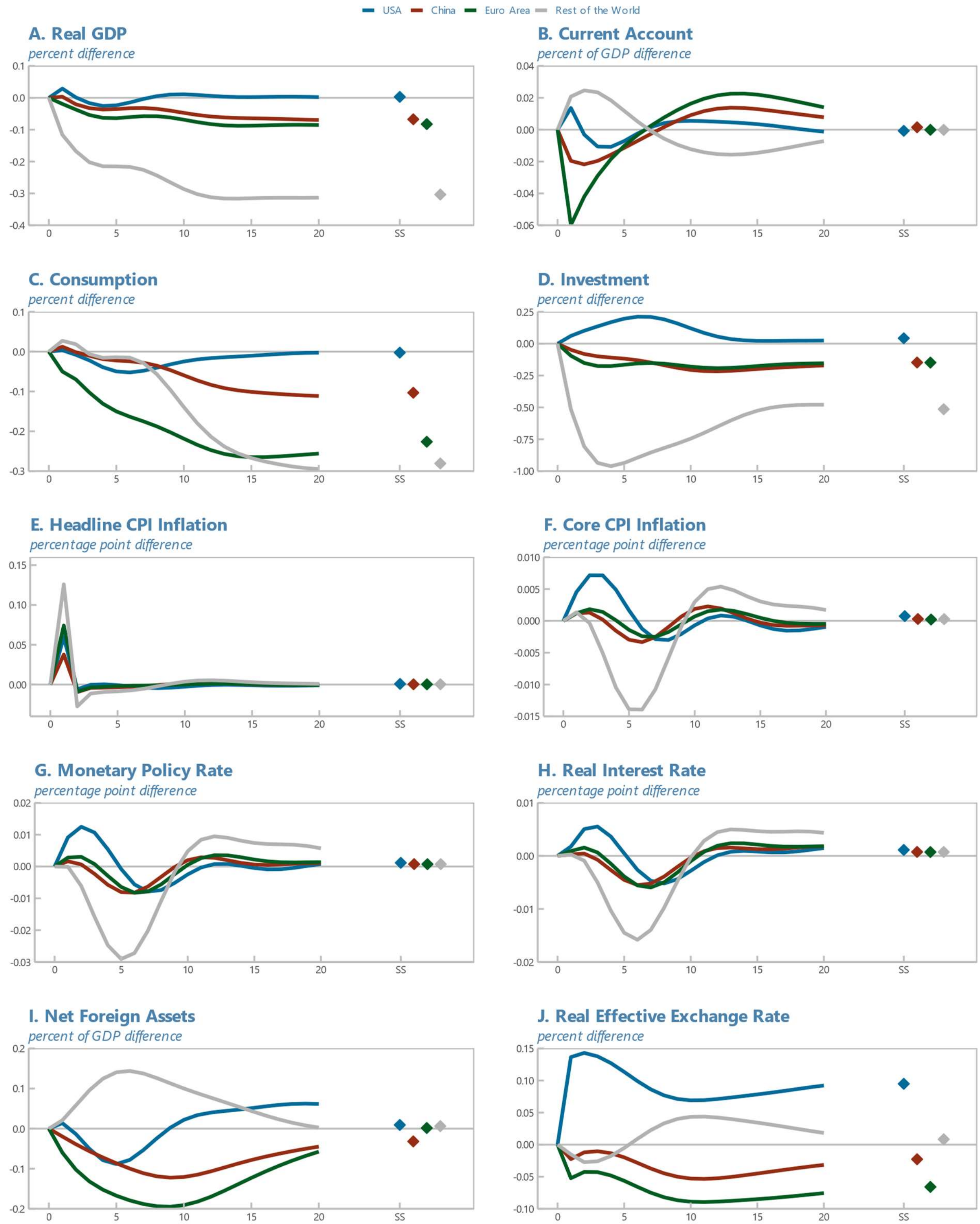
There is a permanent reduction in most regions' real GDP (Figure 26, Panel A), reflecting permanently lower household consumption and private investment (Panels C and D). The euro area and China experience a permanent decrease of about 0.1 percent. The rest-of-the-world bloc loses the most at 0.3 percent as the shock originates there. The United States is the exception: the impact from higher energy costs on household consumption is smaller and is offset by greater investment in fossil gas production. Finally, there is an initial spike in headline CPI inflation in all regions (Panel E), but no material difference in core inflation along the adjustment path (Panel F). The supply shock is immediate which means that its price impacts resolve quickly, requiring no role for monetary policy (Panels G and H).

Figure 25. All Regions: Permanent Increase in Fossil Gas Prices – Energy Sectors



Source: Authors' calculations

Figure 26. All Regions: Permanent Increase in Fossil Gas Prices – Macroeconomic Impacts



Source: Authors' calculations

Conclusion

This paper presented the Global Macroeconomic Model for the Energy Transition, GMMET, a large-scale, dynamic, nonlinear, microfounded, multiregion, general equilibrium model, whose purpose is to analyze the short- and medium-term macroeconomic impact of climate policies. This paper documents the model structure, data sources and model properties generated by an extensive set of simulations to form a reference guide of the model. To better capture real world obstacles for the energy transition, GMMET features granular, sector-specific modeling of electricity generation (capturing the intermittency of renewables), transportation (capturing network externalities between EV charging stations and EV adoption), and fossil fuel mining (replicating estimated supply elasticities at various time horizons). The model also features a rich set of policy tools for the energy transition, including taxation of GHG emissions, various subsidies, and regulations.

Due to the model's structure, a few key insights emerge. Firstly, the micro and macro effects of climate policies, such as the gradual implementation of a GHG tax (a source of revenue for the government) is conditioned on how revenues are spent (for example through lump-sum transfers or a reduction in the labor income tax). Secondly, there are important nonlinearities in the impact of climate policies. In the initial stages of a GHG price rise total GHG emissions fall rapidly as the use of high-emitting coal in electricity generation is phased out. However, once this reduction has been exhausted, emission reductions slow and the marginal impact of a GHG price rise lessens. Lastly, a further insight comes from the global dimension of the model. The macro and micro effects of climate policies depend crucially on whether a region implements policies unilaterally or many regions act simultaneously.

GMMET will be a living model, used for analysis for years to come to understand the macroeconomic implication of mitigating GHG emissions in the global economy. New developments have been documented in IMF (2023), for example the introduction of a metal sector to explore the impacts of metals mining and use on renewable energy and EVs and their role in the energy transition. Further development will investigate (i) the role of Emissions Intensive Trade Exposed Industries (EITEs) allowing for a more granular account of sector-specific abatement options and the trade implication of unilateral policies; (ii) model abatement costs as sector-specific capital accumulation (industrial retrofit); (iii) introduce endogenous sector-specific productivity (learning-by-doing) to capture technological progress and economies of scale for new technologies; and (iv) expand the transportation sector to include the transport of goods. Different versions of the model including more regions are also under development, allowing for greater insights into the cross-country interactions of climate policies and country-specific outcomes.

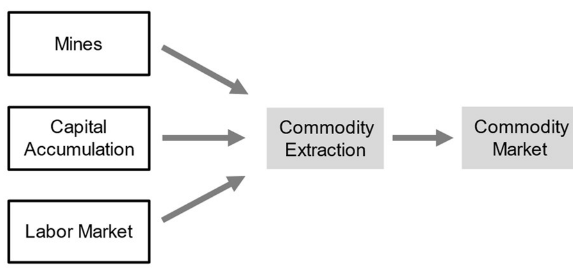
Annex I. Mathematical Derivations for Specific Sectors

The following annex provides additional details for sectors that are novel to GMMET relative to GIMF.

Mining Sectors

The production of fossil fuel commodities (oil, fossil gas, coal) is done through mining sectors indexed by f. Extraction of these commodities requires three factors: mines, labor, and specific capital stock. These factors enter a CES production function with an elasticity of substitution σ. The structure of the mining sector is shown below.

Annex Figure I.1. Structure of the Mining Sector



Since labor and capital service inputs are standard, the focus will be on the role of mines. To determine the volume of mining input $m_{f,t}$, an initial volume $\bar{m}_f$, which can be thought of as land, is multiplied by a time-varying scaling factor $\psi_{f,t}$:

$$m_{f,t} = \bar{m}_f \, \psi_{f,t}^{\phi_f}$$

Here, ϕ_f dictates the sensitivity of the volume to changes in the scaling factor, which itself is assumed to follow a moving average (MA) process of order 1:

$$\psi_{f,t} = \rho_f \, \psi_{f,t-1} + (1 - \rho_f) \frac{P_{f,t}^{m}}{P_{f,t}^{ff}}$$

where $P_{f,t}^{m}$ and $P_{f,t}^{ff}$ denote the prices of the mining input and the fossil fuel commodity output respectively, and ρ_f governs the persistence of the process. $\psi_{f,t}$ can be loosely interpreted as the relative price of opening or closing a mine to that of commodity extraction. With this ad-hoc formulation, the adjustment dynamics of $\psi_{f,t}$, which are governed by parameters ϕ_f and ρ_f, influence the supply elasticity of the fossil fuel output. Thus, the two parameters can be chosen such that the fuel output's supply elasticity matches empirical estimates at various time horizons (calibration targets are shown above in Table 7).

To see this link more clearly, define the fuel-specific supply elasticity for each production factor as η_i where $i \in [m, \; k, \; l]$, which enters the overall price-elasticity of commodity supply with weight α_m. The price-elasticity of commodity supply can be shown to be:

$$\epsilon = \frac{\sum_i \frac{\eta_i}{\sigma + \eta_i} \alpha_i}{\sum_i \frac{\sigma}{\sigma + \eta_i} \alpha_i} \sigma$$

This price elasticity varies between the short and long term. The price elasticity of supply for mines η_m is derived from the parameters ϕ_f and ρ_f presented above. Since the share of mining is negligible as a share of the economy-wide labor market, labor supply from the perspective of this sector is approximately perfectly elastic, $\eta_l = \infty$, in the short and long term. In the short term, capital accumulation is inelastic ($\eta_k = 0$). Under these assumptions the short-term price elasticity of commodity supply can be shown to be:

$$\epsilon = \frac{\frac{\eta_m}{\sigma + \eta_m} \alpha_m + \alpha_l}{\frac{\sigma}{\sigma + \eta_m} \alpha_m + \alpha_k} \sigma$$

In the long term, capital accumulation is assumed to be perfectly elastic as there is ample time for investment in new capital stock. The price elasticity of supply of mines is also higher in the long term as new mines can be explored. Therefore, the long-term price-elasticity of commodity supply is:

$$\epsilon = \frac{\frac{\eta_m}{\sigma + \eta_m} \alpha_m + \alpha_k + \alpha_l}{\frac{\sigma}{\sigma + \eta_m} \alpha_m} \sigma$$

An example for expositional purposes should help in understanding the mining sector. If the share of fuel-specific input in commodity extraction α_i is large and the elasticity of substitution between the factors σ is low, then the price elasticity of commodity supply will be low. Assume that the short-term price elasticity of substitution in mines $\eta_m = 0.1$, the functional form of the production function is Cobb-Douglas, $\sigma = 1$, and mines form 50 percent of the weight of production, α_m= 0.5, with labor and capital at 25 percent each, α_k= α_l= 0.25. In this case the short-term elasticity of supply to a change in commodity prices would be 0.42. In the long term, assuming the same production function but a higher long-term price elasticity for mines $\eta_m = 0.6$, the supply elasticity would be instead 2.2.

Renewables-Plus-Backup Utilities

Electricity generation from different technologies (depicted above in Figure 2) are treated as close to perfect substitutes. This reflects GMMET's modelling approach in which all technologies are all equally stable because intermittency from renewables is compensated within the renewables-plus-backup utility. This section provides derivations for the cost-efficient structure of the utility, complementing the explanation provided in the model description section and the discussion of Figure 3 above. In the following, L denotes the utility's constant generation volume, which is determined within the broader context of the model.

From the generation duration curve to the production frontier

Let M be renewable generation capacity, i.e., the maximum generation volume attained during the best weather regime (e.g., when wind is the strongest). The weather regime is denoted by x, and γ is the so-called intermittency parameter governing the shape of the generation duration curve for renewables, given by

$$G(x) = Mx^{\gamma}$$

The green curve in Panel B of Figure 3 above illustrates a generation duration curve, with generation being zero in the worst regime and M^2 in the best regime. Maintaining a constant generation level L requires the backup to fill any gaps between L and renewables generation $G(x)$ when the weather regime causes $G(x)$ to fall short. In contrast, when $G(x)$ exceeds L, excess generation is curtailed. The fraction of regimes where backup generation is required, $p = (L/M)^{1/\gamma}$, is determined by the condition $G(x) = L$, i.e., that renewables generation exactly covers L. Under GMMET's calibration of costs after taxes and subsidies, it is always cost-efficient to deploy a renewable generation capacity above L, so that $p < 1$ (as it is the case in Panel B).

On average over weather regimes, the expected generation volume from the gas backup B (corresponding to area B in the panel) is the residual generation that does not come from renewables,

$$B = pL - \int_0^p G(x)dx = pL - \frac{p^{\gamma+1}}{\gamma+1}M = \gamma p \frac{L}{\gamma+1}$$

It proves useful to introduce $\bar{R}$, renewables generation gross of curtailment, as an alternative to M, to express installed capacities. It is the sum of the average renewables generation volume, denoted by R, and the volume of curtailed generation, denoted by C (corresponding to areas R and C in the illustrative Panel B of Figure 3). $\bar{R}$ can be expressed by the fraction of weather regimes p during which the backup is required:

$$\bar{R} = R + C = \int_0^1 G(x)dx = \frac{M}{\gamma+1} = p^{-\gamma}\frac{L}{\gamma+1}$$

With these two expressions, varying p yields the set of possible tuples of intermittent gross generation $\bar{R}$ and backup generation B that generate a constant power of L (the production frontier).

From production frontier to production function

Eliminating p between the relations describing the production frontier (the last two equations) allows to write output L as a Cobb-Douglas function of backup generation B with share $\gamma/(\gamma+1)$ and intermittent gross generation $\bar{R}$ with share $1/(\gamma+1)$.

$$L = (\gamma+1)\left(\frac{B}{\gamma}\right)^{\gamma/(\gamma+1)}\left(\frac{\bar{R}}{1}\right)^{1/(\gamma+1)}$$

From production function to optimal structure of the utility

The utility's costs for producing one unit of electricity are given by $C^{R\ total}\bar{R} + C^{B\ var}B + C^{B\ fix}L$. Here, $C^{R\ total}$ denotes the average generation costs from renewables (fixed costs for generation capital plus variable maintenance costs), $C^{B\ var}$ the variable costs of backup generation (fuel plus maintenance costs), and $C^{B\ fix}$ fixed costs for backup generation capital. Costs for backup generation are split into the two components because backup capacity must equal L (to cover weather regimes when generation from renewables is zero), while variable costs depend on the actual use of backup generation B. Cost minimization subject to the Cobb-Douglas production function yields demand schedules for intermittent gross generation, as well as for the variable component of backup generation:[9]

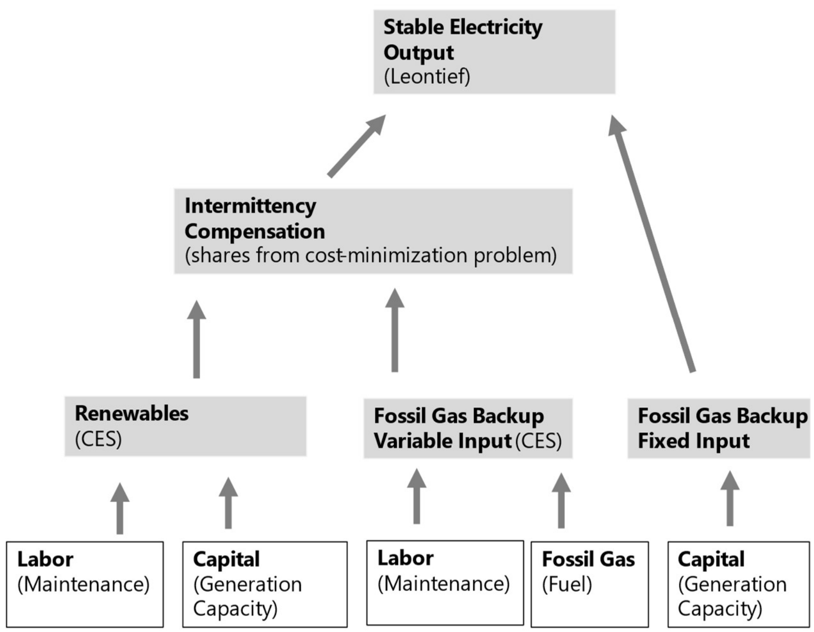
$$\bar{R} = \frac{1}{\gamma+1}\left(\frac{C^{R\ total}}{C^m}\right)^{-1}L \qquad B = \frac{\gamma}{\gamma+1}\left(\frac{C^{B\ var}}{C^m}\right)^{-1}L$$

[9] It is assumed that $C^{R\ total} < C^{B\ var}$ holds after taxes and subsidies. This corresponds to $p < 1$ and implies that M < L is not cost minimizing.

Where $C^m = (C^{R\,total})^{1/(\gamma+1)}(C^{B\,var})^{\gamma/(\gamma+1)}$. With the cost-efficient mix between intermittent and backup capacity, average cost of electricity generation C is given by:

$$C = (C^{R\,total})^{1/(\gamma+1)}(C^{B\,var})^{\gamma/(\gamma+1)} + C^{B\,fix}$$

Annex Figure I.2. Implementation of Renewables-Plus-Backup Utility



The implementation of the renewables-plus-backup utility in the model is illustrated in Annex Figure I.2, where "Stable Electricity Output" on the top corresponds to the respective electricity output in Figure 2 above. The row at the bottom of the figure depicts input factors. In the case of renewable generation (labeled "Renewables") generation capital (interpreted as windmills or solar panels) and labor (interpreted mostly as maintenance) are combined with a standard CES production function to generate intermittent electricity output. The second step (labelled "Intermittency Compensation") is the use of the backup to compensate variations in intermittent renewables output. This is done by combining the latter with the variable input factor from gas (labeled "Gas Backup Variable Input"), which in turn consists of a CES bundle of labor and gas fuel. The shares are endogenously determined as solution to the cost minimization outlined above, and thus adjust to changes in the relative costs of renewables and gas generation. The third step accounts for backup generation capacity. The Leontief production function (labeled "Stable Electricity Output") combines fossil gas capacity one-to-one with the combined "Intermittency Compensation" output from renewables and the backup (the one-to-one ratio allows the backup to cover wind regimes of zero renewable generation).

Tradables and Nontradables Production and the Abatement of Non-Fossil-Fuel GHG Emissions

Since fossil fuels are explicitly modelled as inputs to the production process respectively to consumption, the associated emissions can be tracked by linking them to the volume of the fossil fuel. Emission abatement then occurs when fewer fossil fuels are used because of policy. Non fossil fuel-related emissions are instead linked to the output of tradable and nontradable production and can be abated at a sectoral productivity cost as described below.

Firms in the tradables and nontradables sectors produce output Q with factor input F, which emits a volume E of greenhouse gases measured in metric tons of CO_2 equivalent. $A(\phi)$ is the inverse of productivity and depends on the share of abated emissions ϕ. It is normalized such that $A(0) = 1$. GHG emissions E are a proportion $(1 - \phi)\kappa$ of output, where κ is the sectoral (no-abatement) emission intensity.

$$F = A(\phi)Q \qquad E = (1-\phi)\kappa Q$$

Firm profits are given by:

$$\Pi(Q,\phi) = [P - \tau\kappa(1-\phi) - \lambda A(\phi)]Q$$

where λ and P denote the price of the factor and the output, respectively and τ indicates the tax burden per metric ton of CO_2 equivalent. Firms chose the optimal abatement share ϕ^* that equates the marginal costs from having to use more inputs $A'(\phi^*)\lambda$ with the marginal tax savings from lower emissions $\tau\kappa$.

$$A'(\phi^*) = \frac{\tau\kappa}{\lambda}$$

$A'(\phi)$ is the marginal abatement cost curve (MACC), whose functional form is informed by sector and region-specific empirical estimates provided by the US Environmental Protection Agency (US EPA 2019). Estimated MACCs report US dollar costs for abating an additional metric ton of CO_2 equivalent as a function of the abated emission volume in metric tons of CO_2 equivalent, which is converted into the share of current (no-abatement) emissions (corresponding to ϕ). This can be used to inform $A'(\phi)$ by exploiting that marginal abatement costs equal τ (the tax per metric ton of CO_2 equivalent GHG emissions) under optimality. That is, a (converted) MACC estimate is interpreted as showing τ as a function of the associated optimal abatement share ϕ^*. The following functional form is chosen:

$$A'(\phi) = \bar{\sigma}\phi + \frac{\gamma\bar{\phi}}{(\bar{\phi}-\phi)^2} - \frac{\gamma}{\bar{\phi}}$$

and calibrated such that, for a given ratio of κ/λ, the implicit function $\phi^*(\tau)$ is in line with the converted MACC estimate. This determines the parameters $\bar{\sigma}$ (which strongly influences the cost of initial emissions abatement), γ (governing to a great extent the productivity costs associated with larger abatement shares) and $\bar{\phi}$ (determining the maximum abatement share feasible for very high GHG prices).

The cost function then follows as $c + \int_0^{\phi} A'(\phi)$, where the constant follows from $A(0) = 1$, i.e., the absence of productivity costs when there is no abatement:

$$A(\phi) = 1 + \frac{\bar{\sigma}}{2}\phi^2 + \gamma\left[\frac{\bar{\phi}}{\bar{\phi}-\phi} - \frac{\phi}{\bar{\phi}} - 1\right]$$

Transportation Sector

Individual transportation is modelled as a service consumed by households and provided by a combination of fuels and a capital stock that is interpreted as the vehicle fleet.[10] Since the entire fleet is assumed to be always used in full and a car's milage is assumed constant, the quantity of transportation services corresponds to the number of vehicles. Two types of vehicles compete on the market, electric vehicles (EVs) and combustion engine cars (CCs). They are indexed by $i \in (\mathrm{EV}, \mathrm{CC})$ and differ in their purchase price P_t^i, their fuel intensity κ_t^i, and their fuel cost PF_t^i, which corresponds either to the electricity price or the price of oil. When a household purchases a new car, be it to increase the volume of transportation or to replace a scrapped vehicle, its decision between the two types is not just influenced by the vehicle price, but by the expected real cost over its life cycle:

[10] GMMET abstracts from the role of transportation as an input to the production of goods and services.

$$C_t^i = P_t^i + \kappa_t^i \mathbb{E}_t \left\{ \sum_{s\geq 0} (1-\delta)^s \mathcal{F}_t^{t+s} PF_{t+s}^i \right\}$$

where δ is the scrappage rate of both types and $\mathcal{F}$ the real discount factor. Incorporating expectations of future fuel prices allows for a more realistic role for the credibility of mitigation polices. The average cost (including fuel) of a new car C_t corresponds to type-specific costs weighted by their shares in newly purchased cars N_t^{i}/N_t (where N_t^{i} and $N_t = N_t^{\mathrm{CC}} + N_t^{\mathrm{EV}}$ depict the volume of type-*i* (combustion engine or electric) vehicles and total vehicles respectively):

$$C_t = \frac{N_t^{\mathrm{EV}}}{N_t} C_t^{\mathrm{EV}} + \frac{N_t^{\mathrm{CC}}}{N_t} C_t^{\mathrm{CC}}$$

The associated rental rate of the fleet RT_t then covers new car purchases and fuel costs:

$$RT_t = C_t - (1-\delta)\mathbb{E}_t\{\mathcal{F}_{t+1} C_{t+1}\}$$

Type-specific fleet accumulation is governed by $M_t^i = N_t^i + (1-\delta)M_{t-1}^i$, and the total transportation capital stock $M_t = M_t^{\mathrm{CC}} + M_t^{\mathrm{EV}}$ evolves accordingly, $M_t = (1-\delta)M_{t-1} + N_t$. The demand for M_t corresponds to the volume of the demanded transportation service, which is part of the household consumption bundle and therefore determined by total consumption and rental rate RT_t. The adjustment of the volume is slowed down by the presence of consumption of transportation habits to capture that households already owning a vehicle are not influenced in their behavior by changes in the price of newly purchased cars.

With M_t determined in the context of household consumption, demand for new vehicles N_t results from the capital accumulation equation, and the breakdown of newly purchased cars into both types is governed by:

$$N_t^{\mathrm{i}} = \frac{\alpha_t^{\mathrm{i}} C_t^{\mathrm{i}^{-\sigma}}}{\alpha_t^{\mathrm{EV}} C_t^{\mathrm{EV}^{-\sigma}} + \alpha_t^{\mathrm{CC}} C_t^{\mathrm{CC}^{-\sigma}}} N_t \quad , \qquad i \in (\mathrm{EV}, \mathrm{CC})$$

where α_t^{i} summarize preferences that are given by:

$$\alpha_t^{\mathrm{i}} = \frac{\nu^i CH_t^{i^{\epsilon_{fl}}}}{\nu^{EV} CH_t^{EV^{\epsilon_{fl}}} + \nu^{CC} CH_t^{CC^{\epsilon_{fl}}}}, \qquad i \in (\mathrm{EV}, \mathrm{CC})\,.$$

where CH_t^i , $i \in (\mathrm{EV}, \mathrm{CC})$ denote the number of charging stations for EVs and CCs and ν^i , $i \in (\mathrm{EV}, \mathrm{CC})$ are constant preference shifters discussed below. For simplicity, symmetric network effects are assumed between both types of vehicles, so that CH_t^{CC} can be interpreted as gas stations. Since the costs of charger deployment are only a very small share of GDP, they are ignored, and the number of charging or fueling stations for EVs and CCs are determined by $CH_t^i = M_t^{i^{\epsilon_{ch}}} + \varepsilon_t^{i\,charger}$, where $\varepsilon_t^{i\,charge}$ is an exogenous shock related to either EVs or CCs.

This modeling strategy bears resemblance to Li and others (2017) and allows GMMET to capture network externalities between EV market penetration and the deployment of EV chargers. The number of EV chargers adjusts to the size of the EV fleet with an elasticity of ϵ_{ch}, while at the same time the proportion of EVs to CCs in newly purchased cars, which can be written as $N_t^{\mathrm{EV}}/N_t^{\mathrm{CC}} = (\nu^{EV}/\nu^{CC})(CH_t^{EV}/CH_t^{CC})^{\epsilon_{fl}}(C_t^{\mathrm{EV}}/C_t^{\mathrm{CC}})^{-\sigma}$, reacts to the proportion of charger availability with an elasticity of ϵ_{fl}. The resulting network effects amplify the impact of policies aimed at altering relative prices of both types. This becomes apparent in the following long-term ratio of the fleet sizes of both types:

$$\frac{M^{\mathrm{EV}}}{M^{\mathrm{CC}}} = \left(\frac{\nu^{\mathrm{EV}}}{\nu^{\mathrm{CC}}}\right)^{\frac{1}{1-\epsilon_{fl}\epsilon_{ch}}} \left(\frac{C^{\mathrm{EV}}}{C^{\mathrm{CC}}}\right)^{\frac{-\sigma}{1-\epsilon_{fl}\epsilon_{ch}}}$$

where the elasticity with respect to relative life cycle-costs rises in a greater responsiveness of the charging network to the fleet composition (ϵ_{ch}) and greater role for the charging network in the purchase decision between both types (ϵ_{ch}). The constant preference shifters in the first term are chosen such that the model replicates currently observed EVs shares.

Sectoral emissions are tracked as the consumption of oil as gasoline for CCs and by the consumption of electricity as fuel for EVs. Depending on the GHG intensity of electricity generation, a shift from CCs towards EVs can reduce transportation emissions.

Annex II. Standard Model Properties

GMMET is not confined merely to understanding the impact of mitigation policies on the macroeconomy but can also be used to explore standard macroeconomic shocks. This annex considers the model's standard properties for the following shocks: a temporary increase in the monetary policy rate; a temporary increase in aggregate demand; permanent increases in productivity in the non-energy tradable sector or the non-energy economy as a whole; and an increase in the corporate risk premium. Second, properties related to the fiscal sector are presented, both fiscal multipliers for temporary fiscal stimulus for GMMET's non-mitigation-related fiscal instruments, and outcomes for a select few instruments when undertaking a fiscal consolidation.

Temporary Increase in the Monetary Policy Rate

Annex Figure II.1 shows the effects of a one-year 100 basis point increase in the monetary policy rate in the United States that comes as a surprise to firms and households (Panel I). On impact, real GDP decreases by 0.6 percent, due to fall in domestic absorption and export demand (Panel A). Inflation decreases by less than 0.2 percentage point at its trough in the first year (Panel H).

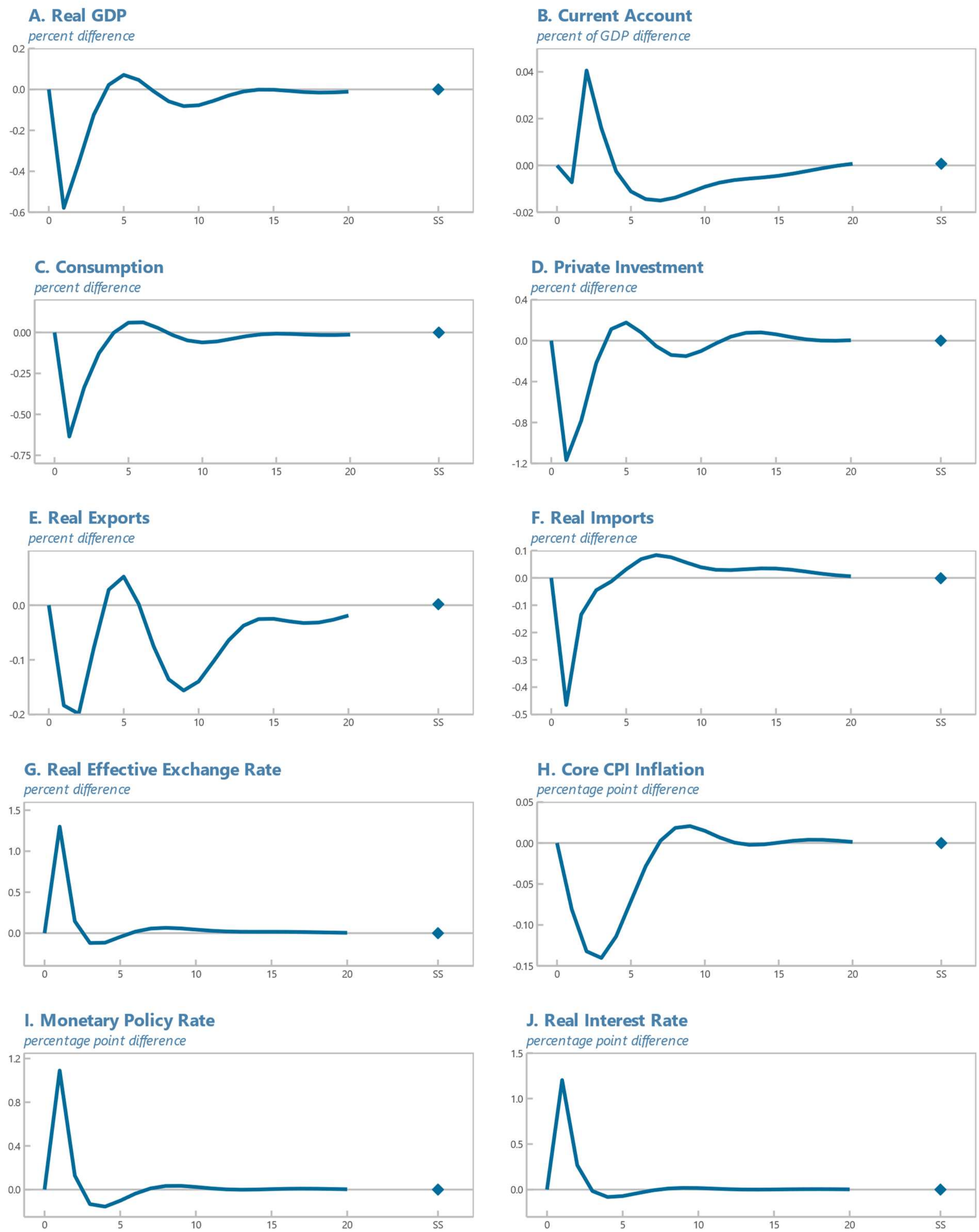
Higher real interest rates reduce both private investment and household consumption expenditure (Panels D and C). Business investment falls due to the higher cost of capital. Therefore, the profitability of firms decreases. This reduces household wealth. The fall in demand leads to temporarily lower production, and therefore a contraction in the demand for factor inputs, reinforcing the fall in capital services and leading to lower labor income. The fall in wealth, the decline in labor income, and the increase in the cost of current consumption relative to future consumption arising from the increase in interest rates all lead households to reduce consumption expenditure.

With real interest rates higher than foreign interest rates the US dollar appreciates (Panel G), weakening foreign demand for US goods (Panel E), while also reducing import prices facing US households. Although US households substitute toward foreign goods and away from domestic goods, the weaker level of domestic demand still results in a decline in imports that is larger than the fall in exports (Panel F). The net impact is a small increase in the current account surplus in the short term (Panel B).

Fiscal policy strives to stabilize activity through increasing transfers to households. This, and the higher debt servicing costs because of higher interest rates, increases the fiscal deficit in the short term. Eventually, the government reduces transfers to households to return the public debt-to-GDP ratio back to its long-term target level.

Overall, there is downward pressure on CPI inflation that is exacerbated by declining import prices owing to the currency appreciation. Therefore, following the exogenously induced tightening in the monetary policy rate, monetary policy must ease to return inflation to target (Panel I). The monetary authority reduces the monetary policy rate to achieve a period with real interest rates below their long-term level (Panel J), temporarily stimulating aggregate demand and re-anchoring inflation at the target.

Annex Figure II.1. Temporary Increase in Monetary Policy Rate



Source: Authors' calculations

Permanent Increase in the Level of Non-Energy Productivity

In Annex Figure II.2, two types of productivity increases are considered for the US economy, for either the entire non-energy economy (blue lines), or only in non-energy tradable goods (red lines). Each raises the level of real GDP by 1 percent in the long term (Panel A). The non-energy economy includes the non-energy tradable and nontradable goods sectors, but excludes the electricity sector, the transportation sector and the mining sectors.

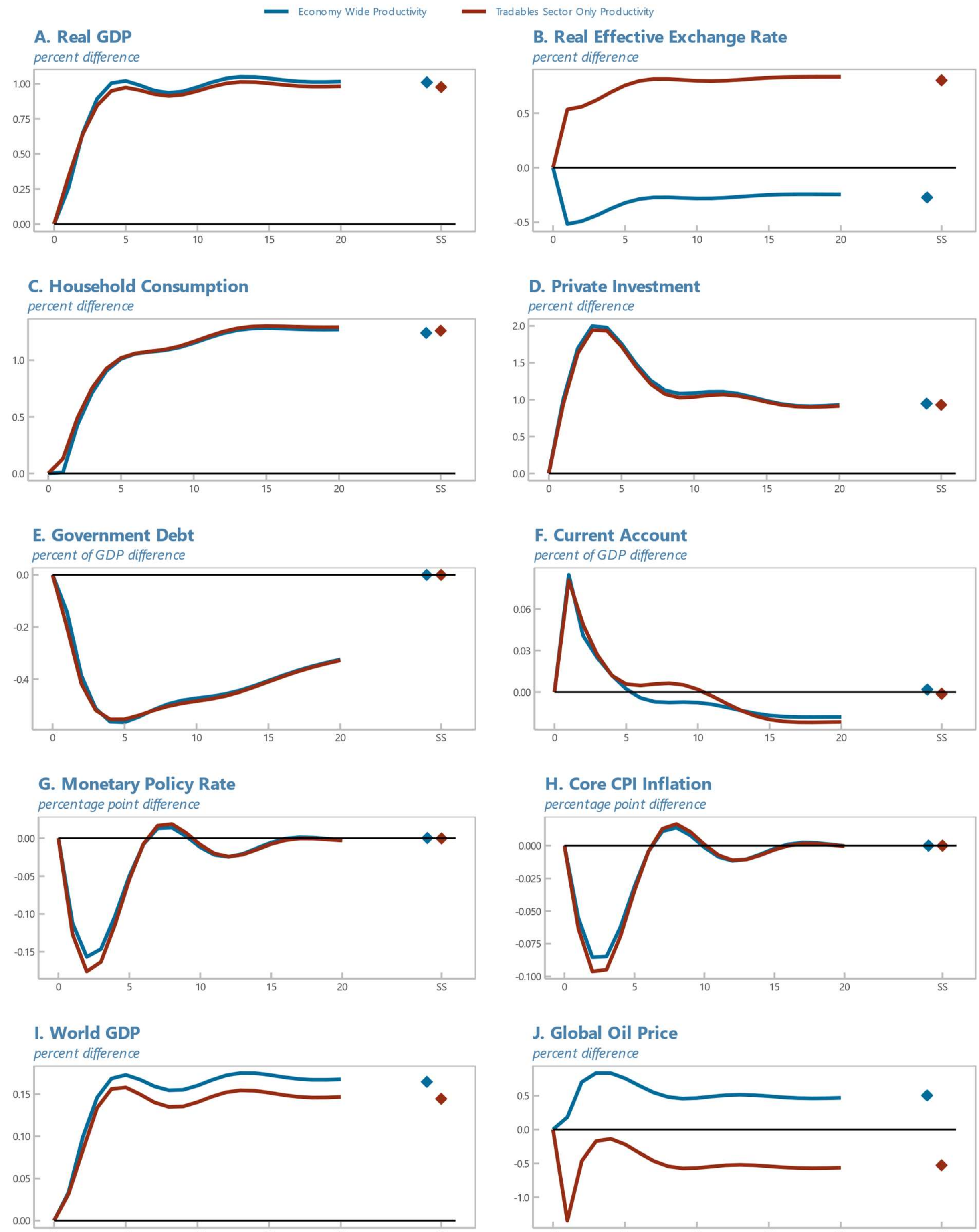
In the long term, the increase in productivity leads to more investment and a higher capital stock in both cases as higher productivity increases the return to capital (Panel D). There is also increased labor demand, increasing household labor income and wealth, which along with capital-stock-related wealth, allows households to consume more permanently (Panel C). Consumption can increase rapidly in the short term as OLG households partially anticipate their higher future wealth.

The interesting difference is in the behavior of the real effective exchange rate (REER; Panel B). When the productivity increase is located only in the tradable goods sector, the REER appreciates in the long term. This is the standard Balassa-Samuelson result given the increase in competitiveness of US tradable goods. When US tradable sector productivity rises relative to its trading partners, meaning those goods are cheaper relative to their competitors, the demand for US intermediate goods increases abroad. When the increase in productivity is across both the tradables and nontradables sectors, the REER depreciates in the long term, as the relative price of US tradable goods to nontradable goods does not fall. However, higher productivity leads to increased demand for goods and services by US households and firms, some of which they want to import. To maintain its external balance, the United States also needs to export more to pay for those imports and the only way to increase foreign demand is its currency to depreciate.

Along the dynamic adjustment path, most key components of real GDP reach their new steady-state levels within ten years. Since the increase in productivity is rapid, and fully anticipated by households, aggregate demand adjusts upwards more quickly than aggregate supply, which is a product largely of the slower accumulation of capital from higher investment. With higher productivity, goods are more cheaply produced and sold, so inflation falls (Panel H) and the monetary authority eases interest rates (Panel G).

The US shock has the effect of raising real global GDP by about 0.3 percent permanently (Panel I), which reflects the direct impact of higher real GDP in the United States, as well as the spillover effects. It also increases global demand for oil and fossil gas, permanently increasing both prices by about 0.2 percent (Panel J). The higher fuel prices act as automatic global stabilizers, dampening global demand slightly by increasing all regions' production costs.

Annex Figure II.2. Permanent Increase in Non-Energy Productivity



Source: Authors' calculations

Temporary Increase in Aggregate Demand

Annex Figure II.3 presents the impact of a one-year shock to US private domestic demand that is calibrated to raise real GDP by almost one percent relative to baseline (Panel A), such that an increase in private investment is roughly three times larger than the increase in household consumption.

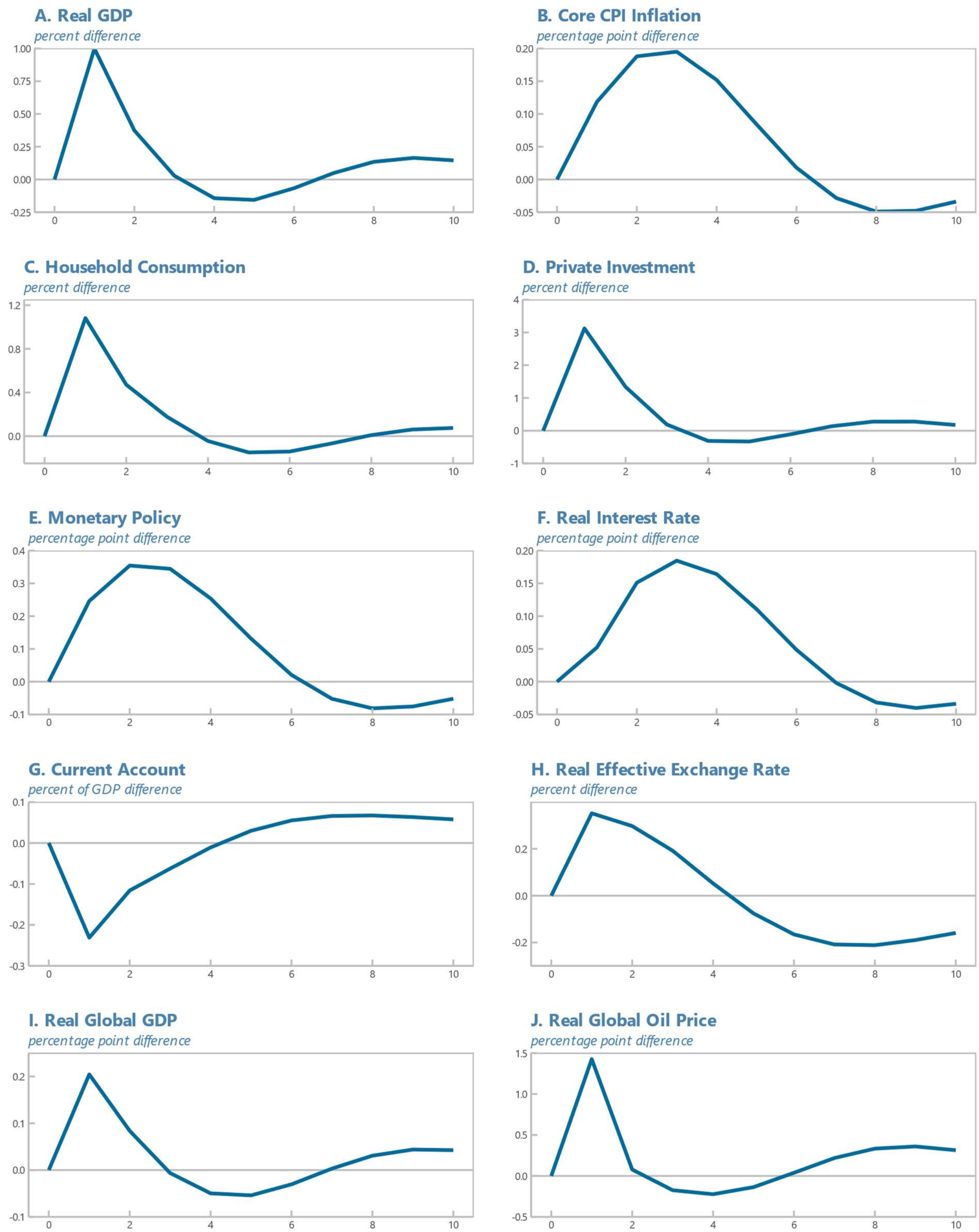
The increase in private investment accumulates into a higher stock of private capital and hence higher capital services, which contributes to a persistent increase in production (Panel D). In the short term, upward pressure on demand leads to increased inflation pressures, so that inflation rises above its target level, about 0.2 percentage point (Panel B). This leads to an increase in the monetary policy rate by the monetary authority (Panel E). This increase flows through into real interest rates (Panel F), which raises the cost of capital, thereby exerting downward pressure on private investment demand. In addition, higher real interest rates have an impact on the intertemporal consumption decision of OLG households, enticing them to increase private saving to the detriment of consumption after year 4 (Panel C).

As a result of the higher real interest rates relative to foreign real interest rates, the REER appreciates in the short term (Panel H). This appreciation reduces the price of imports, boosting import demand (which is complemented by the increase in domestic activity), while raising the cost of US exports in foreign markets, weakening the net export position and thereby the current account (Panel G).

On the fiscal side, the increase in domestic activity raises tax revenues and thus improves the fiscal balance (Panel B). The government responds in the short term to close the measured output gap by decreasing general lumpsum transfers (the “automatic stabilizer”), thereby acting as a dampening influence on private consumption. However, in the medium term it must stabilize the deficit and gradually restore the debt-to-GDP ratio to its target level by increasing general lumpsum transfers, which puts upward pressure on private consumption.

This shock has the effect of raising real global GDP by more than 0.2 percent, which reflects the direct impact of higher real GDP in the United States, as well as the spillover effects associated with this increase in demand (Panel I). Higher global demand boosts the global price of oil temporarily, by about 1.4 percent, respectively (Panel J). In this case, the higher fuel prices also act as automatic global stabilizers, dampening global demand slightly by temporarily increasing production costs in all regions.

Annex Figure II.3. Temporary Increase in Aggregate Demand



Source: Authors' calculations

Temporary But Persistent Increase in the Corporate Risk Premium

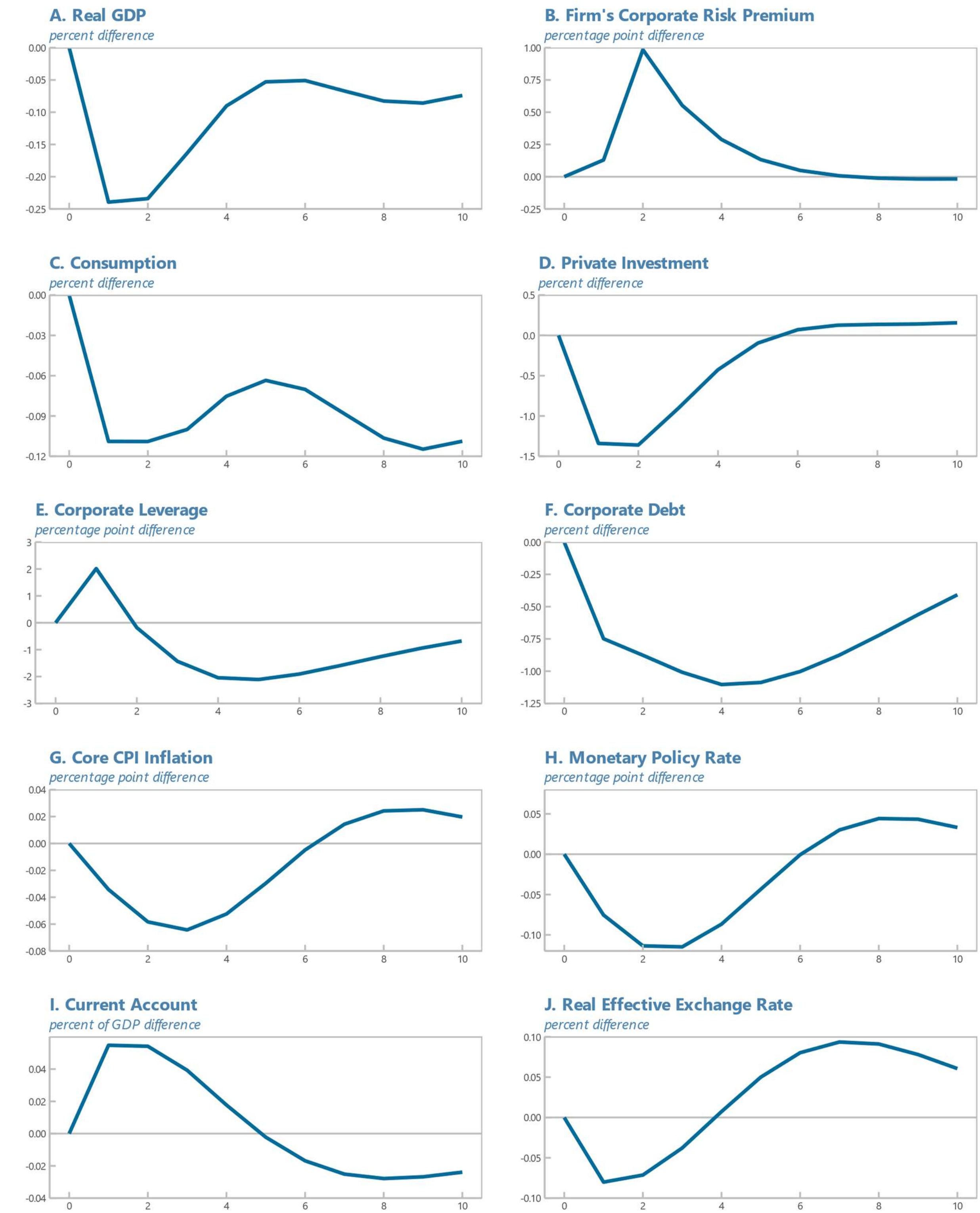
Annex Figure II.4 shows the effects of a temporary but persistent increase in the riskiness of US corporate borrowers that raises the corporate risk premium by 1 percentage point on impact and then declining by 40 percent each year thereafter (Panel B). Real GDP declines by approximately 0.25 percent on impact because of the fall in domestic demand (Panel A), particularly investment, while inflation falls by less than 0.1 percentage point (Panel G).

In GMMET, only tradable and nontradable goods firms borrow to finance their expansion while the energy-related firms all follow the simpler Tobin's Q model for investment. Therefore, the perceived increase in corporate riskiness raises only the borrowing costs faced by tradable and nontradable firms. There is an immediate increase in the cost of capital, leading to an immediate rise in leverage (Panel E), which unwinds as corporate debt falls (Panel F) in response to the higher borrowing costs. With less borrowing, firms are unable to invest as much and private investment is significantly lower for a several years (Panel D).

Household consumption declines from two sources (Panel C). First, the higher cost of capital reduces firms' profitability, leading to lower dividends paid to OLG households and a fall in their wealth. Second, higher costs lead firms to decrease production and demand less labor, driving down wages and labor income, with an immediate negative impact on LIQ households' consumption. Nevertheless, the decline in consumption expenditure is much less than that of investment spending.

Weaker economic activity reduces inflation slightly (Panel G). In response to lower inflation, the monetary authority decreases the policy interest rate (Panel H) in an effort to stimulate demand and return inflation to target. As a result, there is a slight fall in the short-term real interest rate, which yields a small real depreciation in the short term (Panel J). Consequently, exports increase slightly, while imports fall (reinforced by the fall in domestic demand). Overall, the current account improves modestly in the short term (Panel I).

Annex Figure II.4. Temporary Increase in Corporate Risk Premium



Source: Authors' calculations

Temporary Fiscal Stimulus

GMMET can also handle temporary fiscal stimulus, in much the same manner as GIMF. The impact of temporary fiscal stimulus is measured by the fiscal multiplier, where here the multiplier is defined as the average deviation of real GDP from the steady state during two years of fiscal stimulus. The fiscal stimulus measures are either a 1 percent of GDP increase in one of GMMET's four fiscal spending instruments, or a cut in one of its tax rates, financed by a concurrent increase in the government deficit.

The magnitude of the fiscal multipliers is in line with the broader literature (Coenen and others 2010). The largest multipliers attributable to fiscal spending multipliers for public consumption and investment that enter directly into real GDP (which a higher value for public investment, due to its productivity-enhancing properties as quantified in Bom and Ligthart 2014). The next largest have direct impacts through LIQ households' consumption (cuts in consumption and labor income taxes and increases in transfers targeted to LIQ households). The smallest impact comes from lumpsum transfers distributed to all households, where OLG households do not respond with higher consumption spending, as their transfers are subsumed in their wealth stock.

During periods of fiscal stimulus when there is significant slack in the economy, the monetary authority may not need to respond, as the stimulus would be unlikely to drive inflation above its target rate. Annex Table II.1 illustrates the magnifying effects of monetary accommodation. By holding interest rates unchanged, real interest rates which be lower than expected, and stimulate the economy. This extra stimulus will drive up inflation and lead to an even lower real interest rate. With the real interest rate notably below that which prevails if monetary policy responds ensures the impact of the fiscal stimulus on real activity is larger. Moreover, the longer the period of monetary accommodation, the greater the increase in the multiplier, as households expect inflation to respond more, thereby reducing the real interest rate even further. For example, when there is two years of monetary accommodation for fiscal stimulus through higher public consumption, real GDP is over 0.8 percentage points higher on average. However, if there was only one year of monetary accommodation the additional impact on real GDP would only be about 0.3 percentage points.

Annex Table II.1. Fiscal Multipliers with Monetary Accommodation, Average GDP Impact After the First Two Years

(percent deviation from the steady state)

Instrument	Normal Conduct of Policy	Two Years of Accomodation
Public Consumption	0.86	1.65
Public Investment	0.97	2.05
General Transfers	0.25	0.30
Targeted Transfers to LIQ Households	0.96	1.87
Consumption Tax	0.41	0.57
Labor Income Tax	0.31	2.00

Sources: Global Macroeconomic Model for the Energy Transition; and authors' calculations.
Note: Each elasticity is the outcome of several parameters in the model.

Permanent Fiscal Consolidation

Annex Figure II.5 illustrated three fiscal consolidation experiments, each of which reduces the United States' fiscal deficit permanently by 1 percent of GDP (Panel A), which in turn results in a permanent reduction in the ratio of public debt to GDP of roughly 20 percentage points (Panel G). The three different instruments under consideration are a reduction in public consumption (blue lines), an increase in the effective labor income tax rate (red lines), and a reduction in general lumpsum transfers (green lines). In each experiment, as the reduction in government debt leads to lower debt service costs, the same instrument that was initially changed is allowed to revert towards its original value, in order to confine the improvement in the fiscal deficit to 1 percent of GDP.

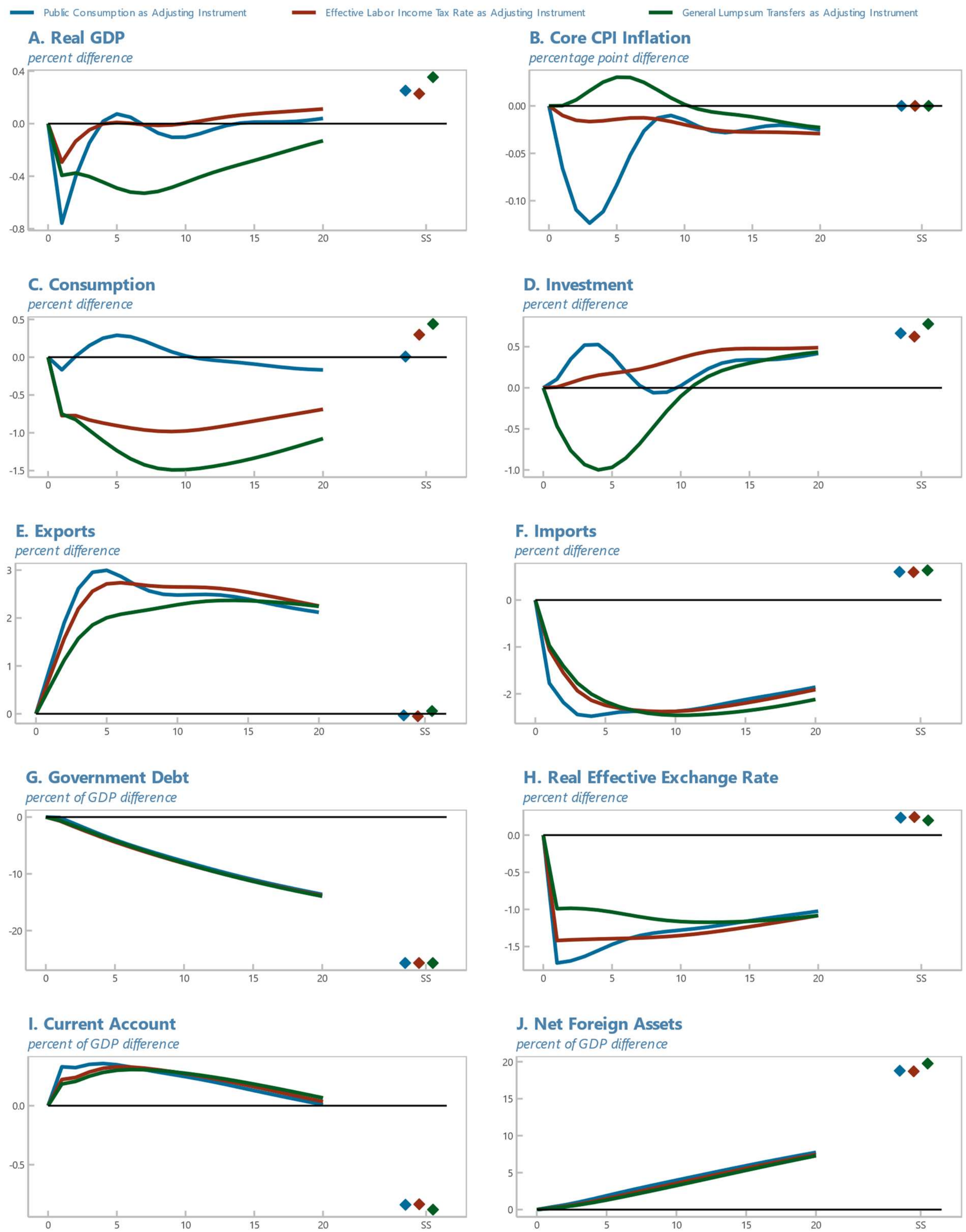
To first think about the new steady state that results from the reduced fiscal deficit is useful. Under all consolidations, real GDP is higher relative to baseline in the new steady state. This comes from two sources. One source is the gradual reduction in the debt burden over time, which results in permanently lower debt service costs. Therefore, the tightened fiscal policy can be more than unwound over the long term. The second feature is an outcome of the households' overlapping generations model. With higher public saving in the United States, the global supply of savings is higher, and the global real interest rate falls to equilibrate demand for and supply of savings. Because the United States is a large region in the world (nearly a quarter of global GDP), the impact on the global real interest rate is significant – about a 3-basis-point decline relative to a 10 percent of GDP public debt consolidation. The lower global real interest rate raises the desired level of capital and production is higher, pushing GDP higher and speeding up the consolidation. This feature does not occur in consolidations in individual small open economies (and even many medium-sized economies), since their fiscal debt burden are an insignificant share of the global saving-investment pool, having almost no influence on the level of the global real interest rate.

In the US cases explored here, as the government permanently increases its saving, the stock of domestic public bonds that households can hold among their assets declines. With households' desired wealth positions largely unchanged, they need to substitute foreign assets for government bonds and the net foreign asset position improves markedly in the new steady state (Panel J). The higher net foreign asset position implies that the net export position can deteriorate (given the improvement in the income balance), and the REER appreciates slightly in the long term (Panel H).

Along the transition path to the new steady state, real GDP initially falls in all cases (Panel A). The largest decline occurs when public consumption is reduced to improve the deficit, followed by the cases where labor income taxes rise or general lumpsum transfers fall. In all cases, private investment (Panel D) and net exports are driving the bounce back as firms respond to permanently lower real interest rates and net exports respond to the REER depreciation. Household consumption responds differently depending on the instrument in use – it falls most in the short term with general transfer cuts, closely followed by labor income tax increases (Panel C).

In all three cases, to facilitate the accumulation of net foreign assets, the REER initially depreciates (Panel J), thereby reducing imports and raising exports. The stronger is the negative effect of the consolidation on domestic demand, the greater the depreciation needs to be to achieve the required accumulation of net foreign assets (Panel I). The most depreciation occurs when government consumption falls, while the least depreciation occurs when general lumpsum taxes rise. The resulting paths for the current account and net foreign assets are similar in all three cases.

Annex Figure II.5. Permanent Fiscal Consolidation Using Different Fiscal Instruments



Source: Authors' calculations

Annex III. Simulation Techniques for GMMET

GMMET has many nonlinearities, including those related to its energy sectors, 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 price, the output of a region's coal mining sector can fall to almost zero long before other energy sectors 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 it is often not possible for the model simulation algorithm to produce solutions in face of those nonlinearities. To preserve as much of the impact of the model nonlinearities as possible, the model simulation toolbox needs an additional method that provides a solution closer to the full nonlinear answer than a first-order linear approximation. GMMET therefore employs an algorithm dubbed the "marginal numeric linearization method."

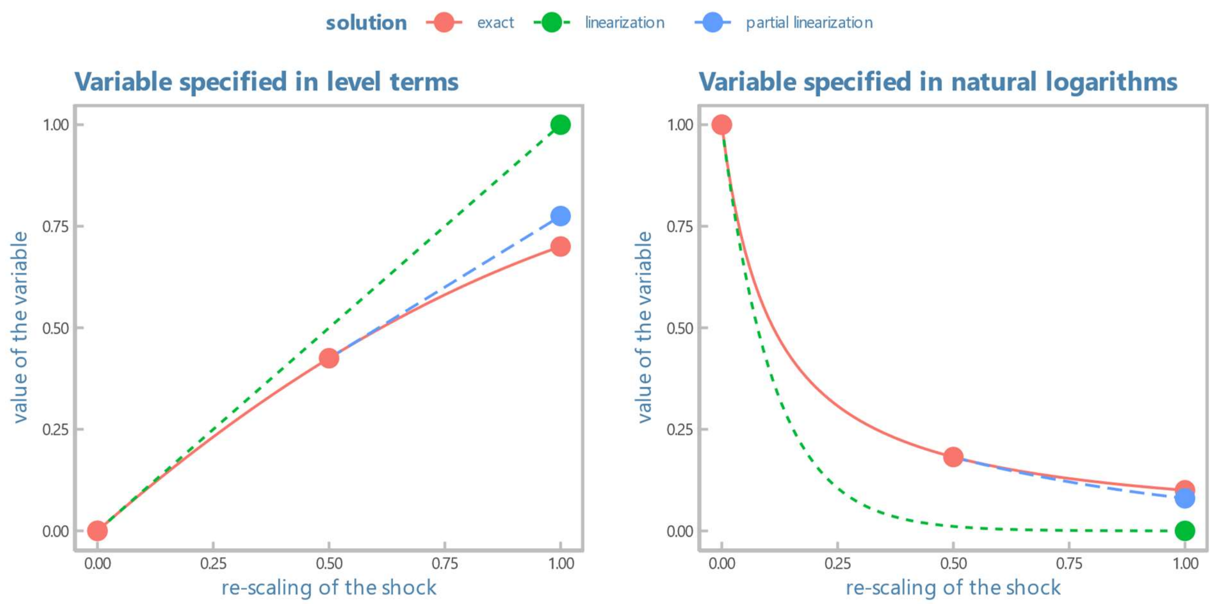
A global GHG price is a good example of a highly nonlinear shock that often cannot solve with the standard nonlinear solvers when the shock is very large, such as US$80/tCO2e. In order to compare the correct solution with a solution using the marginal linearization technique, consider the example of an immediate and permanent increase in the global GHG price to US$50/tCO2e. Presume, as an example, that the solution algorithm can only solve up to US$25/tCO2e – 50 percent of the shock. With the given information from the solution of 50 percent of the shock, it is possible to approximate the solution in its entirety.

As noted above, one method would be to use a first-order linear approximation. That is, the value for a variable v is computed based on the variable $\check{v}$ which for which there is a solution from 50 percent (ω) of the shock. Then the difference between $\check{v}$ and its steady-state value $\bar{v}$ would be multiplied by a factor of $\frac{1}{\omega} = 2$. The full numeric linearization method solves for the variable v as follows:

$$v = \frac{1}{\omega}(\check{v} - \bar{v}) + \bar{v}$$

Annex Figure III.1 presents the solution of two types of variables v in the model, either specified in level terms, or in natural logarithms (logs). Instead of the fully solved answer (if 100 percent of the shock was solved) represented by the red lines, the full numeric linearization method using the solution from 50 percent of the shock produces the green lines. However, there is an alternative method that can give a more accurate approximation, represented by the blue lines, the aforementioned "marginal numeric linearization."

Annex Figure III.1. Linearization Methods



Note: Marginal linearization uses the exact solution (fully nonlinear) for a rescaled shock (50 percent of the full shock in this example) and the first derivative of the exact solution at the same point. The left panel illustrates a variable in terms of its level, like GHG tax revenue, whereas the right panel illustrates a variable in terms of natural logarithms, like coal extraction.
Source: Authors' calculations

Marginal numeric linearization relies on an approximation more closely related to the first simulation, instead of the model's steady-state solution. In addition to obtaining $\breve{v}$ from the first simulation of the model, a second simulation is conducted for 1 percentage point less of the solution than in the first simulation. In this example, the second simulation solves for 49 percent of the GHG price increase, producing the variable $\tilde{v}$. Then in the final solution of v, 50 percent ($\breve{v}$) will be provided by the first simulation, while the remaining 50 percent (the remaining portion of the shock) will be the difference between the second and first simulations multiplied by the remaining portion of the shock – in this case, 50 percent. Therefore, the marginal numeric linearization method solves for the variable v as follows:

$$v = \breve{v} + (1 - \omega)100(\breve{v} - \tilde{v})$$

In Annex Figure III.1, the marginal linearization method would produce the blue lines, as noted above, which is a more accurate solution of the model. This is quantified below in Annex Figure III.2, which shows ten variables in the United States from the permanent and immediate increase in the global GHG price to US$50/tCO2e, where the red lines are the exact solution, the green lines employ the full numeric linearization method, and the blue lines the marginal linearization at 50 percent of the shock. The marginal numeric linearization method is closer to the correct solution for some variables. This is true of macro aggregates (Panels A, B, and C), and important components such as the marginal propensity to consume (Panel D). It is especially true for measures related to climate policy (at least in the short term): measures of emissions (Panels E and F); the emissions related to the marginal abatement curves in tradables (Panel G) and nontradables; GHG tax revenues (Panel H); and the price and volume of electricity (Panels I and J).

Annex Figure III.2. United States: Immediate and Permanent Increase in the Global GHG Price to US$50/tCO2e

Source: Authors' calculations

References

American Automobile Association. 2021. *Your Driving Costs: 2021*.

Anderson, Derek, Ben Hunt, Mika Kortelainen, Michael Kumhof, Douglas Laxton, Dirk Muir, Susanna Mursula, and Stephen Snudden. 2013. "Getting to Know GIMF: The Simulation Properties of the Global Integrated Monetary and Fiscal Model." International Monetary Fund, IMF Working Paper 2013/055, Washington, DC.

Bernanke, Ben, Mark Gertler, and Simon Gilchrist. 1999. "The Financial Accelerator in a Quantitative Business Cycle Framework." In John Taylor and Michael Woodford, eds., *Handbook of Macroeconomics*, Volume 1c, Amsterdam: Elsevier.

Bistline, John, Geoffrey Blanford, Trieu Mai, and James Merrick. 2021. "Modeling Variable Renewable Energy and Storage in the Power Sector." *Energy Policy* 156: 112424.

Blanchard, Olivier. 1985. "Debts, Deficits and Finite Horizons." *Journal of Political Economy* 93(21): 223-47.

Boer, Lukas, Andrea Pescatori, and Martin Stuermer. 2021. "Energy Transition Metals". International Monetary Fund, IMF Working Paper 21/243. Washington, DC.

Bom, Pedro, and Jenny Ligthart. 2014. "What Have We Learned from Three Decades of Research on the Productivity of Public Capital?" *Journal of Economic Surveys* 28(5): 889–916.

Bosetti, Valentina, Enrica De Cian, Alessandra Sgobbi, and Massimo Tavoni. 2009. "The 2008 WITCH Model: New Model Features and Baseline." Fondazione Eni Enrico Mattei, Nota di Lavoro No. 85.2009. Milan.

Buiter, Willem. 1988. "Death, Birth, Productivity Growth and Debt Neutrality." *Economic Journal* 98(391): 279-93.

Coenen, Günter, Christopher Erceg, Charles Freedman, Davide Furceri, Michael Kumhof, René Lalonde, Douglas Laxton, Jesper Lindé, Anna Mourougane, Dirk Muir, Susanna Mursula, John Roberts, Werner Roeger, Carlos de Resende, Stephen Snudden, Matthias Trabandt, Jan in't Veld. 2010. "Effects of Fiscal Stimulus in Structural Models." International Monetary Fund, IMF Working Paper 10/73. Washington, DC.

Corong, Erwin, Thomas Hertel, Robert McDougall, Marinos Tsigas, and Dominique van der Mensbrugghe. 2017. "The Standard GTAP Model, Version 8." *Journal of Global Economic Analysis* 2(1): 1-119.

de Saint Vaulry, Alix. 2008. "*Base de données CHELEM - Commerce international du CEPII*." Centre d'études prospectives et d'information international, Document de travail du CEPII 2008-09. Paris.

Eboli, Fabio, Ramiro Parrado and Roberto Roson. 2010. "Climate Change Feedback on Economic Growth: Explorations with a Dynamic General Equilibrium Model." *Environment and Development Economics* 15(5): 515-533.

European Commission Joint Research Centre. 2022. “EDGAR - Emissions Database for Global Atmospheric Research.” European Commission Joint Research Centre. Brussels, Belgium. https://edgar.jrc.ec.europa.eu/

Fally, Thibault, and James Sayre. 2019. “Commodity Trade Matters.” CEPR Discussion Paper DP13132, Centre for Economic Policy Research, London, United Kingdom.

Holland, Stephen, Erin Mansur, and Andrew Yates. 2021. “The Electric Vehicle Transition and the Economics of Banning Gasoline Vehicles.” *American Economic Journal: Economic Policy* 13(3): 316-44.

Intergovernmental Panel on Climate Change (IPCC). 2022. *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, and others. Geneva, Switzerland.

International Energy Agency (IEA). 2021. *Greenhouse Gas Emissions from Energy Data Explorer.* International Energy Agency. Paris. https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer

__________. 2022a. *World Energy Balances: Overview*. International Energy Agency. Paris. https://www.iea.org/reports/world-energy-balances-overview.

__________. 2022b. *Transport. I*nternational Energy Agency. Paris. *https://www.iea.org/reports/transport.*

International Monetary Fund (IMF). 2022. “Near-Term Macroeconomic Impact of Decarbonization Policies” in International Monetary Fund, *World Economic Outlook: Inflation and Uncertainty, October 2022,* Washington, DC.

__________. 2023. “Fragmentation and Commodity Markets: Vulnerabilities and Risks” in International Monetary Fund, *World Economic Outlook: Navigating Global Divergences, October 2023,* Washington, DC.

Ireland, Peter. 2001. “Sticky-Price Models of the Business Cycle: Specification and Stability." *Journal of Monetary Economics* 47(1): 3-18.

Kumhof, Michael, Douglas Laxton, Dirk Muir, and Susanna Mursula. 2010. “The Global Integrated Monetary and Fiscal Model (GIMF) – Theoretical Structure.” International Monetary Fund, IMF Working Paper 10/34. Washington, DC.

Leimbach, Marian, Nico Bauer, Lavinia Baumstark, and Ottmar Edenhofer. 2010. “Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R.“ *Environmental Modeling and Assessment* 15: 155-173.

Li, Shanjun, Lang Tong, Jianwei Xing, and Yiyi Zhou. 2017. “The Market for Electric Vehicles: Indirect Network Effects and Policy Design.” *Journal of the Association of Environmental and Resource Economists* 4(1): 89-133.

McKibbin, Warwick, and Peter Wilcoxen. 1999. “The Theoretical and Empirical Structure of the G-Cubed Model.” *Economic Modelling* 16(1): 123-48.

__________. 2013. “A Global Approach to Energy and the Environment: The G-Cubed Model.” *Handbook of Computable General Equilibrium Modeling, Volume 1*. Amsterdam: Elsevier.

Nordhaus, William. 2014. "Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches." *Journal of the Association of Environmental and Resource Economists* 1(1/2): 273-312.

Organization for Economic Cooperation and Development (OECD). 2021. "OECD Inter-Country Input-Output Database." Organization for Economic Cooperation and Development. Paris. http://oe.cd/icio

Price, Robert, Thai-Thanh Dang, and Jarmila Botev. 2015. "Adjusting Fiscal Balances for the Business Cycle: New Tax and Expenditure Estimates for OECD Countries." Organization for Economic Cooperation and Development, OECD Working Paper 2015-93 and Economics Department Working Paper No. 1275. Paris.

Ramos, Luma, Kevin Gallagher, Corinne Stephenson, and Irene Monasterolo. 2022. "Climate Risk and IMF Surveillance Policy: A Baseline Analysis." *Climate Policy* 22(3): 371-388.

Rotemberg, Julio. 1982. "Sticky Prices in the United States." *Journal of Political Economy* 90(6): 1187-1211.

Ueckerdt, Falko, Robert Pietzcker, Yvonne Scholz, Daniel Stetter, Anastasis Giannousakis, and Gunnar Luderer. 2017. "Decarbonizing Global Power Supply Under Region-Specific Consideration of Challenges and Options of Integrating Variable Renewables in the REMIND Model." *Energy Economics* 64(C): 665-684.

United States Environmental Protection Agency (US EPA). 2019. "Global Non-CO2 Greenhouse Gas Emission Projections and Mitigation 2015–2050." Office of Atmospheric Programs, Climate Change Division, EPA-430-R-19-010, Washington, DC.

Varga, Janos, Werner Roeger, and Jan in 't Veld. 2022. "E-QUEST: A Multisector Dynamic General Equilibrium Model with Energy and a Model-Based Assessment to Reach EU Climate Targets." *Economic Modelling* 114: 105911.

Weil, Philippe. 1987. "Permanent Budget Deficits and Inflation." *Journal of Monetary Economics* 20(2): 393-410.

Weitzel, Matthias, Bert Saveyn, and Toon Vandyck. 2019. "Including Bottom-up Emission Abatement Technologies in a Large-Scale Global Economic Model for Policy Assessments." *Energy Economics* 83(C): 254-263.

Yaari, Menahem. 1965. "Uncertain Lifetime, Life Insurance, and the Theory of the Consumer." *Review of Economic Studies* 32 (2): 137-50.

PUBLICATIONS

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