Online Annex 1.1. Baseline CO_2 Emission Projections by Country

The *Fiscal Monitor* uses a spreadsheet tool providing standardized analyses, on a country-by-country basis, of carbon pricing and other mitigation instruments.[1] The model uses recent data on the use of fossil and other fuels for the power generation, transportation, household, and industrial sectors and projects fuel use forward in a baseline scenario of CO_2 emissions. No mitigation measures beyond those previously enacted and reflected in historical fuel consumption data are assumed.

These projections are based on assumptions regarding (1) future GDP growth; (2) how higher GDP affects the demand for energy products; (3) rates of technological change (for example, changes that improve energy efficiency); and (4) future international energy prices. The change in fossil fuel use and CO_2 emissions from mitigation policies, relative to the baseline, depends on (1) the change in fuel and electricity prices; (2) switching among fuels in power generation (coal, natural gas, oil, renewables, nuclear); and (3) the price responsiveness of demand for electricity and fuel in other sectors (capturing changes in both energy efficiency and product use). Electricity and fuel price elasticities are assumed to be between –0.5 and –0.8, based on cross-country empirical evidence and results from more detailed energy models. The model is applied here to the Group of Twenty (G20) countries, which collectively are projected to account for 80 percent of baseline CO_2 emissions in 2030.[2]

Fossil fuel CO_2 emissions are projected to increase significantly between 2017 and 2030 in the baseline case (Figure 1.1.1). For G20 countries combined, (emission weighted) GDP expands 78 percent over the period (by more than 100 percent in China and more than 150 percent in India). However, the energy intensity of GDP falls by 20–40 percent over the period[3] with generally modest changes in the CO_2 intensity of energy.[4] The net result is that CO_2 emissions (shown by the black squares in Figure 1.1.1) for the G20 countries combined increase by 28 percent, though emission growth is much larger in, for example, India, at 73 percent. The levels of projected emissions per capita in 2030, however, are largest in Australia, Canada, and the United States (about 14 tons per capita) and lowest in Brazil, India, and Indonesia (about 2 tons per capita). In absolute terms, projected 2030 emissions are highest in China (13.3 billion tons), the United States (5.0 billion tons), and India (3.6 billion tons).

[1] The tool has been applied to 135 countries. See IMF (2019c).

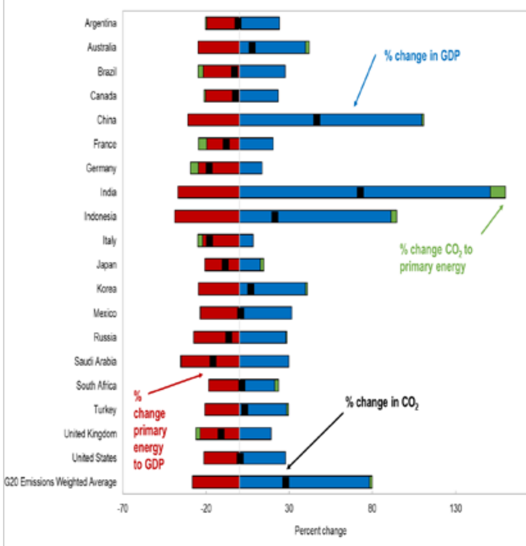
[2] See IMF (2019) for more extensive country results and details on data and methodology. (The current analysis updates GDP and international energy price data). The model is streamlined in various ways. For example, it does not account for trade linkages nor for the dampening effect on fuel price responsiveness in the nearer term stemming from gradual turnover of capital stocks. Moreover, the impact of higher energy prices on the deployment of emerging, low-carbon technologies remains uncertain.

[3] This reflects improving energy efficiency, an assumption that the proportionate increase in demand for energy products is less than the proportionate increase in GDP, and the dampening effect on energy demand from gradually rising international energy prices.

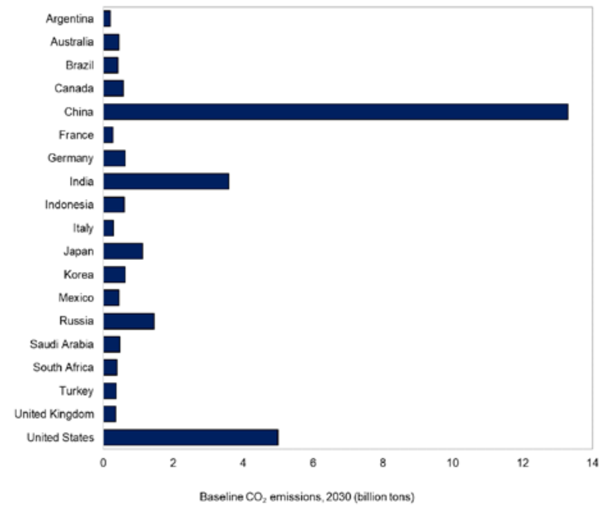
[4] CO_2 intensities would fall more in the longer term with greater substitution of renewables for (long-lived) fossil fuel capital.

Online Annex Figure 1.1.1. Baseline Projections of Fossil Fuel CO_2 Emissions

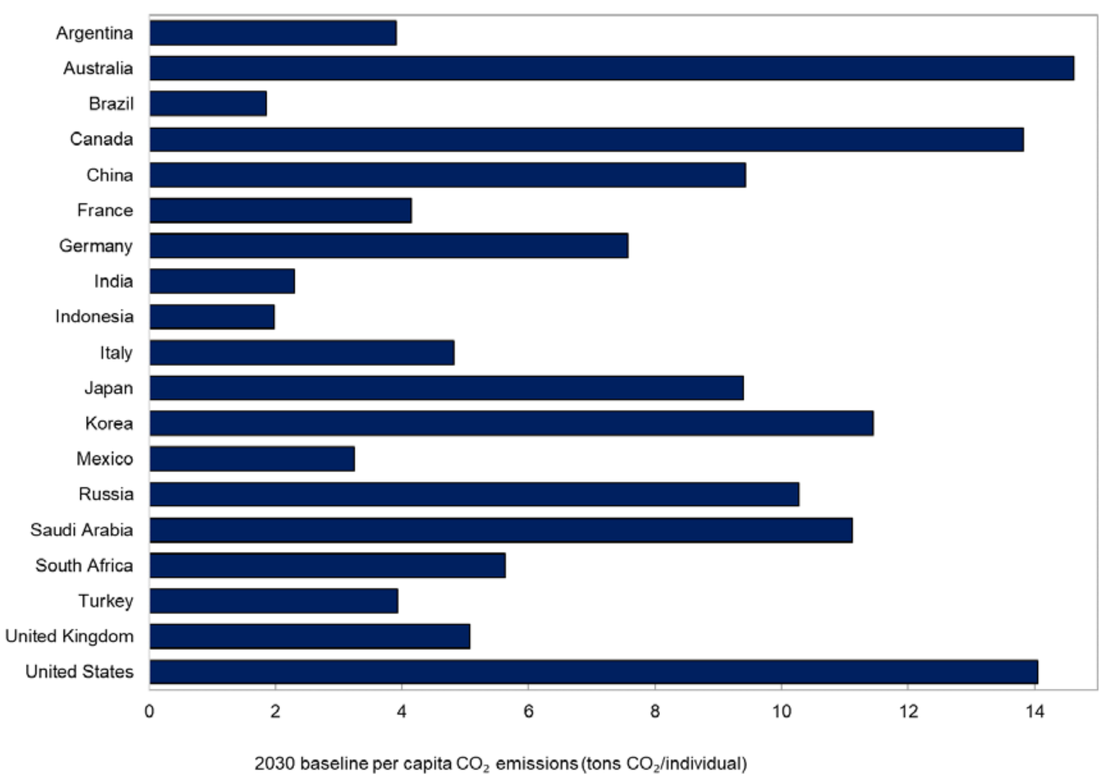
1. Change in Emissions, 2017–30



2. Total Emissions, 2030



3. Emissions Per Capita, 2030



Online Annex 1.2. Mitigation Aspects of the Paris Agreement

One hundred and ninety-seven parties are members of the UN Framework Convention on Climate Change (UNFCCC), an international environmental treaty adopted in 1992. The framework outlines how international agreements or protocols may be negotiated to specify action to progress on the objective of stabilizing atmospheric greenhouse gas concentrations to prevent dangerous climate change. The parties to the convention have met annually since 1995 in Conferences of the Parties (COPs) to assess progress in dealing with climate change. At COP 21, in 2015, the Paris Agreement was adopted and signed by 195 parties and went into effect in 2016 following ratification by a sufficient number of countries (to date 185 parties have ratified the agreement). The central goal of the Paris Agreement is to limit future global warming to 2°C above preindustrial levels, with an aspirational target of 1.5°C.[1]

One hundred and ninety parties submitted climate strategies, now referred to as "Nationally Determined Contributions" (NDCs), for the Paris Agreement. NDCs contain mitigation objectives and (in 140 cases) adaptation goals.[2] Mitigation pledges are difficult to compare because they vary in terms of (1) target variables (for example, emissions, emission intensity, clean energy shares); (2) nominal stringency (for example, percent emission reductions); (3) baseline years against which reduction targets apply (for example, historical versus projected baseline emissions); and (4) whether pledges are contingent on external finance and other (for example, technical) support.

Parties are required to submit revised NDCs every five years starting in 2020, with mitigation pledges that are expected to be progressively more stringent. Parties are required to report their emissions, and their progress in reducing them, to the UNFCCC every two years starting in 2024, based on the latest emission accounting guidelines from the Intergovernmental Panel on Climate Change (IPCC 2019).

[1] See IPCC (2018) comparing the climate impacts of warming of 1.5°C and 2°C. The United States has announced its intention to withdraw from the agreement in 2020.

[2] Mitigation pledges are summarized in IMF (2019), WBG (2019), and at http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

Online Annex 1.3. The Effects of Carbon Mitigation Policies: A Diagrammatic Treatment

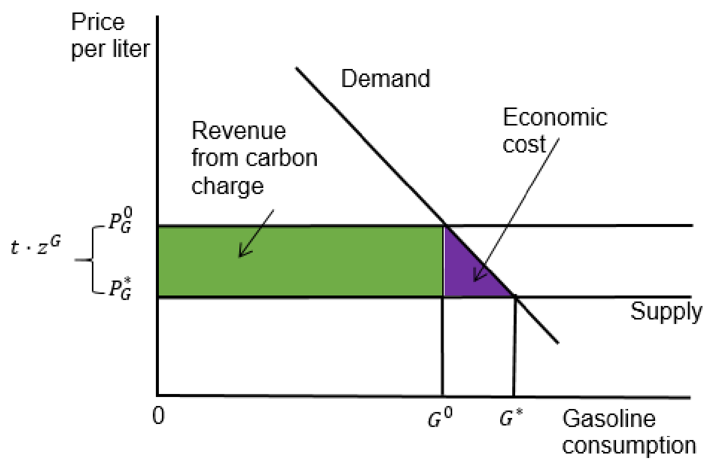
This annex uses a series of diagrams to explain the approach underpinning estimates of the emission, cost, price, and revenue impacts of carbon pricing presented in the *Fiscal Monitor*. The subsections below discuss the impacts of carbon pricing in energy markets, the impacts of alternative mitigation instruments, and the broader costs of carbon mitigation policies arising from their impacts on factor markets.

Impacts of Carbon Pricing on Energy Markets

Consider first, a tax on the supply of fossil fuels in proportion to their carbon content.

Gasoline Market: Figure 1.3.1 indicates the impact on the gasoline market: the height of the demand curve reflects the value to fuel users of an extra unit of consumption; the height of the supply curve reflects the cost of producing and distributing an extra unit of gasoline. The supply curve is drawn as flat, which is usually a reasonable longer-term approximation given that countries can purchase fuel from, or sell fuel to, global markets at a fixed price. Initially, the consumer and producer fuel price is P_G^* and consumption is at the economically efficient level G^*, in which the benefit to consumers from an extra unit of gasoline is equal to the cost of supplying that unit (the implications of preexisting fuel taxes are noted later).

Online Annex Figure 1.3.1. Gasoline Market

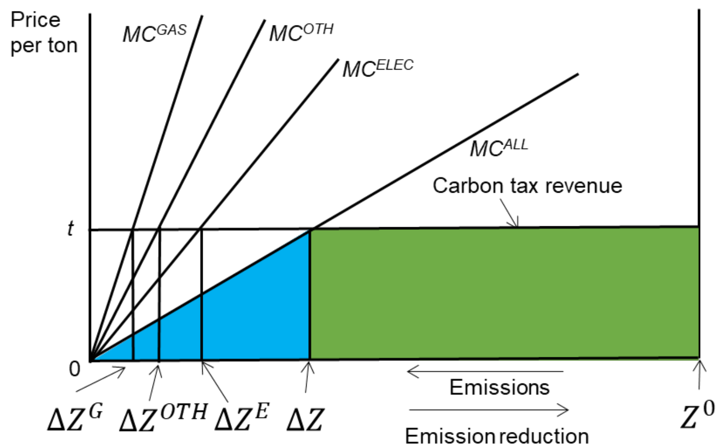


Source: IMF staff.

Suppose a per unit carbon charge of $t \cdot z^G$ is introduced on gasoline, in which t is a tax per ton on CO_2 emissions and z^G is the emission factor for gasoline (tons of CO_2 generated per unit of fuel use). The tax drives a wedge of $t \cdot z^G$ between the price paid by the consumer (now equal to P_G^0) and the price received by the producer (which remains at P_G^*) and reduces gasoline consumption to G^0. The tax causes an economic welfare loss indicated by the purple triangle, which can be interpreted as the loss of benefits to fuel users (the area under the demand curve between G^0 and G^*) minus saved supply costs (the area under the supply curve between G^0 and G^*). The former reflects losses to motorists from driving less, and using less-emission-intensive vehicles, than they would prefer. Revenues raised by the tax equal the tax rate times the new level of gasoline consumption G^0.

In Figure 1.3.2, MC^{GAS} is the marginal abatement cost schedule for reducing emissions from gasoline use—the height of this curve is the economic cost of reducing CO_2 emissions from gasoline consumption by an extra ton. The carbon tax t reduces CO_2 emissions from gasoline consumption by $\Delta Z^G = z^G(G^* - G^0)$; that is, CO_2 per gallon of fuel times the reduction in gasoline use and the area under the MC^{GAS} integrated over this emission reduction corresponds to the shaded triangle in Figure 1.3.1.

Online Annex Figure 1.3.2. Marginal Abatement Cost Curves for Reducing CO_2

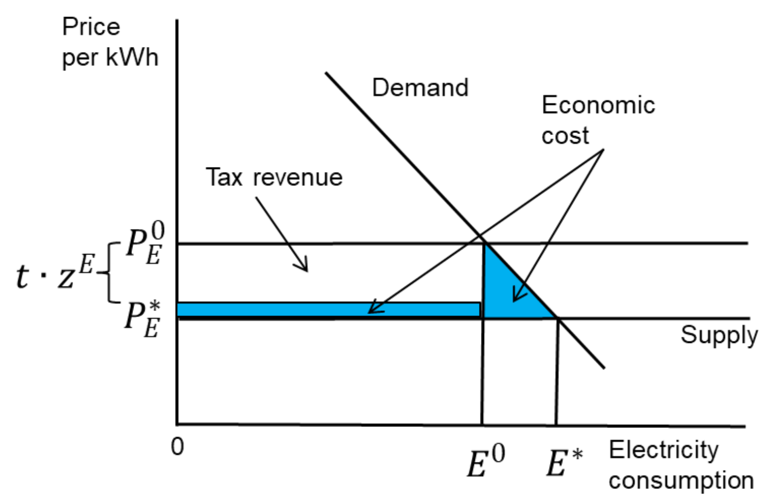


Source: IMF staff.

Next, consider the electricity market, as shown in Figure 1.3.3, in which the height of the demand curve is the value to firms or households of an extra unit of consumption, and the supply curve (drawn as flat for simplicity) is the cost of generating and distributing an extra unit of electricity from the marginal fuel source (for example, coal, natural gas, wind, solar). Initially, the consumer and producer price of electricity is P_E^* , and consumption is E^*, again the efficient level at which the benefit from incremental consumption to electricity users equals the incremental supply cost.

Suppose a tax on the carbon content of power generation fuels—or, equivalently, of power generation emissions—is introduced. The electricity price for consumers increases to P_E^0 , and this increase has two components. First, unit production costs increase to the extent generators react by switching from carbon-intensive fuels like coal to zero- or lower-carbon—but costlier—fuels to lower their average CO_2 emissions per unit of generation and these higher costs are passed on in higher electricity prices.[1] Second, generators must pay a tax on the remaining CO_2 emissions, causing a price increase equal to the (new) CO_2 emission rate per unit of generation z^E times the per ton CO_2 tax.

Online Annex Figure 1.3.3. Electricity Market



Source: IMF staff.
Note: kWh = kilowatt-hour.

The economic cost of the tax in Figure 1.3.3 has two components. One is the blue triangle, reflecting forgone benefits from the reduction in consumption to E^0 (the area under the demand curve between E^0

[1] It is assumed that, in the absence of a carbon tax, generators would choose their fuel mix to minimize generation costs.

and E^*) minus supply cost savings (the area under the supply curve between E^0 and E^*), in which the former reflects consumers' less intensive use of electricity-consuming products and increased reliance on more efficient (but costlier) products and technologies than they would prefer. The second cost is the blue rectangle, reflecting the higher average resource costs involved in producing the new level of output. Revenue from the tax is the carbon tax rate times CO_2 emissions per unit of output times the new output level E^0.

In Figure 1.3.2, MC^{ELEC} is the marginal abatement cost schedule for reductions in power sector emissions—the height of this curve is the economic cost of reducing CO_2 emissions from the power sector by an extra ton. The carbon tax t reduces CO_2 emissions from the power sector by ΔZ^E; that is, the product of the initial emission rate and initial output minus the product of the new emission rate and new output and the area under the MC^{ELEC} integrated over this emission reduction corresponds to the sum of the shaded blue areas in Figure 1.3.2.

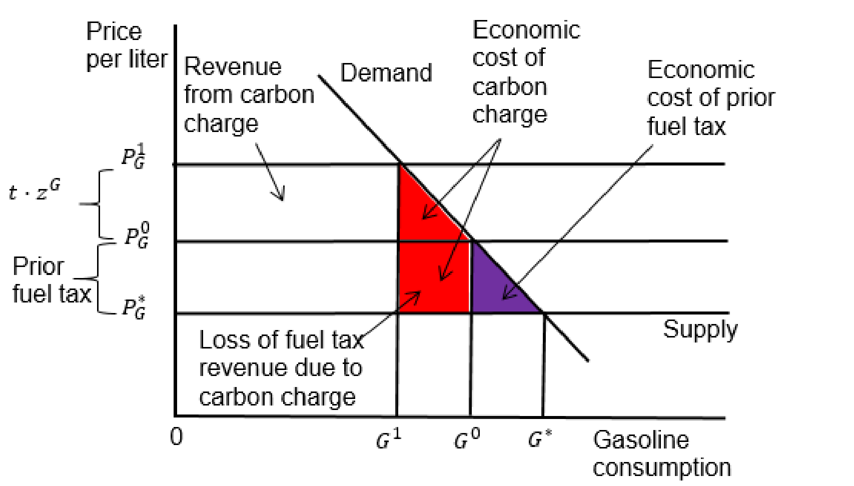
Also shown in Figure 1.3.2 is MC^{OTH}, which summarizes the marginal abatement cost schedule from reducing CO_2 from all other (energy-related) sources, such as direct industrial and household fossil fuel use, diesel vehicles, and other transportation—the emission reduction from these sources is denoted ΔZ^{OTH}. MC^{ALL} in Figure 1.3.2 is the envelope or horizontal summation of all the marginal cost curves, in which emissions fall by $\Delta Z = \Delta Z^G + \Delta Z^E + \Delta Z^{OTH}$ under the tax of t per ton of CO_2. The total economic welfare cost of the tax is the area under the MC^{ALL} curve, given by

$$\frac{t \cdot \Delta Z}{2}. \qquad (1.3.1)$$

Total revenues raised by the carbon tax (from all emission sources), indicated by the green rectangle in Figure 1.3.2, are $t \cdot (Z^0 - \Delta Z)$, in which Z^0 is emissions in the absence of mitigation.

Suppose now that in the gasoline market in Figure 1.3.4 there is a preexisting fuel tax that causes initial fuel consumption G^0 to be below the efficient level G^*, resulting in an initial economic cost indicated by the purple triangle. Imposing the carbon charge increases the gasoline price to P_G^1, which reduces consumption to G^1, resulting in an additional economic cost indicated by the red trapezoid—again this is the loss of consumer benefits (the area under the demand curve between G^1 and G^0) minus production costs saved (the area under the supply curve between G^1 and G^0). The carbon charge raises revenues equal to the tax per unit of fuel use times G^1, but it also reduces the amount of revenue that would have been collected from the preexisting fuel tax by the red box in Figure 1.3.4.

Online Annex Figure 1.3.4. Gasoline Market with Prior Fuel Tax



Source: IMF staff.

Impacts of Other Mitigation Instruments

Suppose instead that the same emission reduction ΔZ was obtained by an emission trading system applied to power generators in a downstream program that prices emissions at the point of fuel combustion. In this case, the cost of the policy is given by the relevant area under the MC^{ELEC} curve in Figure 1.3.2 (rather than the area under MC^{ALL}). By similar triangles, the slope of this curve is equal to $\Delta Z / \Delta Z^E$ times the slope of the MC^{ALL} curve.

Alternatively, consider an emission standard for the power sector under which all generators are subject to a maximum allowable rate of CO_2 per kilowatt-hour (kWh). This policy promotes fuel switching in the same way a carbon pricing policy does. However, it avoids a large transfer of tax revenue to the government or the introduction of allowance rent, the main cause of higher electricity prices and reduced electricity demand under a carbon tax or emission trading system. Firms lower their average emission rate without paying taxes on, or acquiring allowances to cover, their remaining emissions.[2] Assuming the policy has a minor impact on electricity demand, and following the same logic as above, the slope of the marginal cost curve for this policy would equal the slope of the MC^{ALL} curve divided by the share of economy-wide emission reductions (under economy-wide emission pricing) that comes from fuel switching in the power sector.

Links between Carbon Mitigation Policies and the Broader Fiscal System

Broader taxes in the fiscal system—primarily taxes on personal and corporate income, payrolls, and consumption—create two sorts of distortion to economic activity.

First, the tax system distorts factor markets, thereby reducing the overall *level* of economic activity. By lowering the net-of-tax return from working—and therefore discouraging labor force participation, effort on the job, investment in human capital, and so on—taxes on labor income reduce work effort below what would otherwise maximize economic efficiency. Similarly, by lowering the net-of-tax returns on capital investments, taxes on corporate income and personal savings reduce capital accumulation below economically efficient levels.

Taxes also distort the *composition* of economic activity. Taxes encourage more activity in the informal sector, where productivity tends to be lower than in the formal sector. They also generate a bias toward other tax-sheltered activities or goods—for example, tax preferences for owner-occupied housing cause people to spend more on housing and less on ordinary goods than they would prefer. Tax exemptions for fringe benefits such as employer-paid medical insurance imply that workers receive excessive compensation in the form of fringe benefits at the expense of ordinary wage income.

Public finance economists have emphasized the importance of considering the full range of behavioral responses—the composition as well as the level effect—when evaluating the economic costs of distortions caused by the tax system.[3]

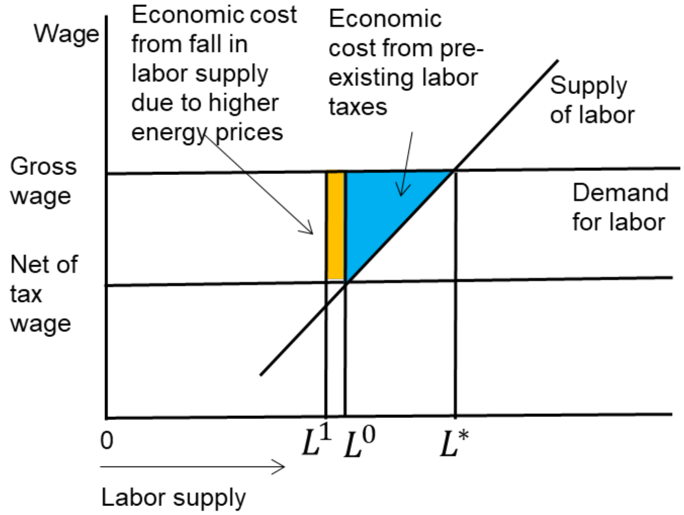
Figure 1.3.5 takes a closer look at tax distortions in the (economy-wide) labor market. Here the height of the demand-for-labor curve reflects the value of the output from extra work effort—this curve is drawn as flat, which is a reasonable approximation when returns to scale are constant (that is, doubling the

[2] Since there is no cap on total emissions, there is no creation of scarcity rents.

[3] For example, Saez and others (2010).

amount of labor and capital input doubles output). In a competitive market, the wage paid by firms tends to reflect the value of extra output from additional work effort.

Online Annex Figure 1.3.5. Tax Distortions in the Labor Market



Source: IMF staff.

The supply-of-labor curve is drawn as sloping upward as higher wages tend to cause responses that increase work effort (for example, people putting in more effort or hours on the job, taking a second job, or delaying retirement or secondary workers in the household joining the labor force). According to economic theory, households will tend to supply labor until the wage they receive compensates them for the value of time forgone (in leisure activities, child rearing, schooling, volunteering, and so on). In the absence of taxes (or other distortions, such as institutional wage setting) the employer and household wage would be the same, and with the market in equilibrium employment would be at L^* in Figure 1.3.5. This is the economically efficient employment level as it is where the value of the extra output from additional work effort equals the cost to households from supplying additional effort.

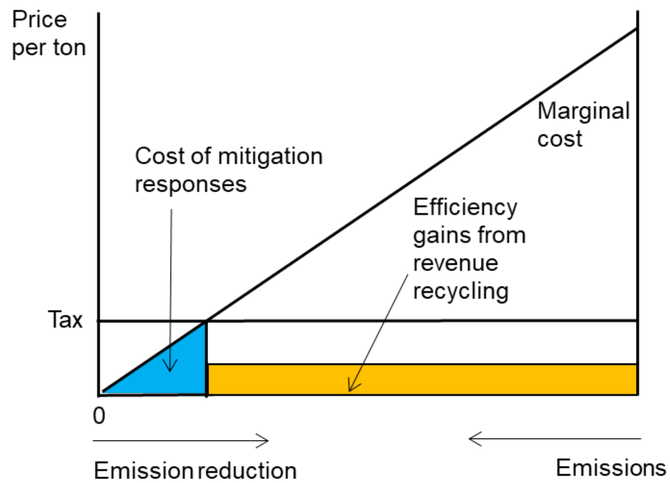
However, a variety of taxes—including payroll taxes paid by employers and employees, personal income taxes, and consumption taxes—combine to drive a large wedge between the wage paid by firms and the net-of-tax wage to households (in terms of how much consumption they can afford). As a result, the equilibrium level of employment is below the efficiency level at L^0, and there is an economic cost indicated by the blue triangle. This cost is the value of the output forgone (the area under the demand curve between L^0 and L^*) minus the value of the extra time for households as a result of supplying less labor (the area under the supply curve between L^0 and L^*). Cutting labor taxes therefore produces an economic efficiency gain as it reduces the tax wedge and pushes labor supply to move closer to its efficient level.

Carbon taxes or emission trading systems interact with the broader fiscal system in two important ways.

First, large gains in economic efficiency can be generated when revenues are used to lower other distortionary taxes. In terms of Figure 1.3.6, these gains are indicated by the yellow rectangle, or the amount of revenue raised—the carbon price times emissions—multiplied by the efficiency gain per dollar of revenue used to cut distortionary taxes. More generally, the revenue-recycling benefit is similar if instead revenues are used to fund investments (for example, for United Nations Sustainable Development Goals) that might benefit the economy significantly more than the investment costs.

Second, however, there is a counteracting economic cost. Higher energy prices tend to compound the distortions from taxes in factor markets by reducing (via a slight contraction in overall economic activity) work effort and capital accumulation. If higher energy prices lead to a reduction in labor supply to L^1 the resulting economic cost is measured by the yellow rectangle in Figure 1.3.5, with the base equal to the reduction in labor supply ($L^0 - L^1$) and the height equal to the tax wedge, or the difference between the value to firms per unit of work effort and the cost to households per unit of labor supply.

Online Annex Figure 1.3.6. Economic Efficiency Gains from Revenue Recycling



Source: IMF staff.

To a point, and leaving environmental benefits aside, there can be a net economic gain from shifting taxes from labor and capital to fossil fuels (that is, the first effect above can overshadow the second). This is because cutting broader taxes helps reduce distortions both to the level of economic activity (through more incentives for work effort and investment) and to the composition of economic activity (through fewer incentives to shift spending toward tax-favored goods and assets). Although higher energy prices can reduce economic activity, they do not necessarily increase distortions in the composition of economic activity.[4]

The more important point, however, is that if revenue opportunities are not exploited—for example, if allowances are freely allocated in an emission trading system rather than auctioned or if carbon tax revenues are returned as lump-sum transfers (which do not encourage work effort and investment)—fiscal linkages can considerably increase the overall costs of carbon pricing policies. This follows because such policies fail to offset the second source of economic cost (in Figure 1.3.6) with economic efficiency benefits from revenue recycling.

Feebate and regulatory approaches generally do not raise revenue and therefore do not reap the efficiency benefit shown in Figure 1.3.6. At the same time, however, they have a much weaker impact on energy prices (Figure 1.3.3) and therefore tend to cause much smaller reductions in labor supply, in Figure 1.3.5, compared with those under carbon pricing. As a result, feebates and regulations can be less costly overall (for a given economy-wide reduction in emissions) than carbon pricing approaches that do not exploit the efficiency benefits of revenue recycling.[5]

Details on Cost Calculations

The economic efficiency benefits from recycling carbon pricing revenues is given by the following equation:

$$t \cdot (Z^0 - \Delta Z) \cdot M^R, \qquad (1.3.2)$$

[4] For example, Parry and Bento (2000), Bento and others (2018).

[5] For example, Goulder and others (1999).

in which M^R is the efficiency gain per $1 of revenue; for example, from reducing taxes that distort the level and composition of economic activity or from funding productive investments. The calculation in The *Fiscal Monitor* uses an illustrative value of M^R = $0.35 for the United States based on estimates (albeit uncertain) of behavioral responses to taxes,[6] although the calculation assumes 75 percent of revenues are used for this purpose and 25 percent for transfer payments with no economic efficiency benefits (but necessary to address, for example, burdens on lower-income households).

The economic cost of the increased distortion in the labor market induced by higher energy prices under carbon taxes is given by[7]

$$t \cdot \left(Z^0 - \frac{\Delta Z}{2}\right) \cdot M^L \cdot \left(\frac{1+M^R}{1+M^L}\right), \qquad (1.3.3)$$

in which M^L is the efficiency cost of labor taxes per $1 of extra revenue, accounting for impacts in the labor market alone (that is, not including distortions to the composition of economic activity). M^L is taken to be 0.23.[8] Finally, the economic efficiency cost of a feebate policy in the labor market is given by

$$M^L \cdot \frac{t \cdot \Delta Z}{2}. \qquad (1.3.4)$$

Equations (1.3.1)–(1.3.4) are used to compute the costs in Figure 1.10 of the *Fiscal Monitor*, which focuses on a $50 carbon tax for the United States in 2030. According to calculations from the IMF spreadsheet model, this implies CO_2 emission reductions 22 percent below baseline levels.

A Closer Look at Some Underlying Assumptions

Comparing (1.3.2) and (1.3.3), if $M^R = M^L$; that is, if labor taxes cause distortions only in labor markets, there is a net cost from interactions with the tax system. However, to the extent that $M^R > M^L$, the efficiency benefit from cutting income taxes is larger because income taxes distort other margins of behavior rather than just labor markets and, in this case, there can be a net economic benefit from interactions with the tax system.

The environmental tax literature has explored various modifications to the basic analysis above. For example, suppose that, instead of using 75 percent of carbon tax revenues to cut income taxes, these revenues were used to fund (general or environmental) public investments. Then the efficiency gains from revenue use would be larger or smaller than in equation (1.3.2), depending on whether these investments generate larger or smaller economic efficiency gains than from cutting distortionary taxes.

In addition, some analyses have studied links between carbon taxes and the broader fiscal system in dynamic models that capture the distortive effects on investment from taxes on the return to capital. In these models the efficiency costs of taxes on capital tend to exceed those of taxes on labor; therefore using the revenues from carbon taxes to cut capital taxes yields larger efficiency gains and strengthens the prospect of a net efficiency gain from links with the tax system (though the benefits from cutting capital taxes are skewed toward the better-off).[9]

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[6] Parry and Williams (2010).

[7] The equations below are based on Parry and Williams (2010).

[8] Parry and Williams (2010).

[9] For example, Goulder and Hafstead (2018).

Online Annex 1.4. Rationale for Feebates and the Impact of Applying them to Key Energy Sectors

There are several rationales for feebates. Potentially they

Are *effective* at reducing energy use, if they are applied across major energy-using products—vehicles, washing machines, light bulbs, air conditioners, refrigerators, and so on—and set to provide continuous (rather than discrete) rewards for higher efficiency (see below), and are appropriately scaled;

Are *cost-effective*, if there is a uniform reward for reducing energy, or more precisely emissions, across different types of products;

Limit administrative burdens, to the extent they can be incorporated into existing procedures for collection of excises on imported or domestically produced goods, though their application to power generators likely involves new capacity for monitoring emission rates and administering fees and rebates; and

Limit burdens on vulnerable households and firms, as they do not involve a first-order pass-through of new tax revenues to higher fuel, electricity, or product prices.

Application to Transportation

Many excise tax systems for new or imported vehicles classify the vehicles according to engine size (a proxy for fuel consumption rates) and then apply higher tax rates to vehicle categories with larger engines. These tax systems do not reward other vehicle characteristics, such as smaller cabin size, lighter body materials, or better aerodynamics, that can also lower fuel consumption and emission rates. And they offer no reward for a shift to lower-emission-rate vehicles within a classification (all vehicles within a tax bracket are subject to the same tax rate). Moreover, as people shift toward smaller vehicles this reduces the amount of revenue collected from the tax system.

The above problems can be addressed by a shift toward a vehicle excise tax system with an ad valorem, and a feebate, component.[1] The proportional tax in the ad valorem component can be set to meet a revenue target and does so without distorting the choice among different vehicles (because it leaves the relative price of different vehicles unaffected).

A feebate levies a tax on fuel-inefficient vehicles in proportion to the difference between their fuel consumption rate (that is, the inverse of fuel economy) and a "pivot point" fuel consumption rate. Conversely it subsidizes efficient vehicles in proportion to the difference between the pivot point and their fuel consumption rate; equivalently, fees and rebates can be levied on CO_2 emission rates. That is, a vehicle receives a fee or rebate according to the formula $t \cdot (CO_2/mile - \overline{CO_2/mile})$, in which the bar denotes the pivot point emission rate per mile and *t* is a charge per ton of CO_2 per mile.

The feebate component can be made (approximately) revenue-neutral by setting the pivot point emission rate equal to the average emission rate of vehicles sold in the previous year and updating it over time as the average emission rate of the vehicle fleet progressively declines. The tax or subsidy rates in the feebate can be set as aggressively as needed to encourage shifting to more efficient vehicles without eroding the revenue base (which depends on vehicle prices). Implementing this tax system would require data on the fuel per mile (the inverse of fuel economy) for different models.[2] Emission rates per mile can be inferred from the emission factors and fuel consumption rates per mile. Alternatively, the tax or

[1] See for example Parry (2011).

[2] For example, from www.fueleconomy.gov.

subsidy rates can be levied on differences between a vehicle's CO_2 emissions per mile and a pivot point CO_2 per mile. Fuel economy can be converted to CO_2 per mile by inverting (from miles per gallon to gallons per mile) and multiplying by CO_2 per gallon—8,850 grams of CO_2 per gallon for gasoline and 10,250 grams per gallon for diesel.

A number of countries have recently introduced feebates, including Denmark, France, the Netherlands, and Norway (and many others have elements of feebates). The pivot points in these systems are typically equivalent to between 200 and 250 grams of CO_2 per mile, although the feebate prices differ significantly. For example, $10 per gram of CO_2 in France and up to $155 in Norway.[3] For illustration, a feebate with a pivot point of 250 grams of CO_2 per mile, and a price of $100 per gram of CO_2, would provide a subsidy of $5,000 to a vehicle with fuel economy of 45 miles per gallon and would impose a tax of $10,000 on a vehicle with fuel economy of 25 miles per gallon.

Electricity Sector

An excise analogous to the one described above for vehicles, with both ad valorem and feebate components, could be applied to sales of appliances and other electricity-using capital. Again, the ad valorem component could remain at any existing excise tax rate to maintain revenue. The feebate would involve taxes on products with relatively low energy efficiency in proportion to the difference between their electricity consumption rate and a pivot point consumption rate and conversely provide a subsidy to relatively efficient models in proportion to the difference between the pivot point and their consumption rate. For example, refrigerators might receive a fee or rebate according to the formula $t \cdot (kWh/(cubic\ foot\ cooled) - \overline{kWh/(cubic\ foot\ cooled)})$, in which kWh/(cubic foot cooled) is the electricity consumption rate, a bar denotes the pivot point consumption rate, and *t* is the charge per kWh/(cubic foot cooled).

To illustrate, if the pivot point consumption rate is 5 kWh/month and the feebate price is $30 per kWh/month, then a refrigerator with an energy consumption rate of 8 kWh/month would be subject to a tax of $90; a refrigerator with an energy consumption rate of 2 kWh/month would receive a $90 subsidy.[4] And again the feebate component can be made (approximately) revenue-neutral by setting the pivot point equal to the average electricity consumption rate of models within a product class sold in the previous year, with updates as the consumption rate progressively declines. To minimize the cost of reducing electricity use across a range of different product classes, the same incremental reward on kWh (that is, the tax rate *t*) should be uniform across electricity-using products.

Feebates could be applied to power generators. Generators would pay a fee (or receive a rebate) in proportion to their output times the difference between their emission rate per kilowatt-hour (averaged across their plants) and the industry average emission rate.

[3] Bunch and others (2011), 59–61. In some cases, however (for example, Denmark), the implicit price of CO_2 is substantially higher for vehicles receiving rebates than for vehicles subject to fees, which results in net revenue losses from the feebate and violates the principle of providing the same reward for reducing emissions across all vehicle classes.

[4] As another example, the fee or rebate for air conditioners would be $t \cdot (kWh/(BTU\ of\ heat\ removed) - \overline{kWh/(BTU\ of\ heat\ removed)})$, where BTU is British Thermal Unit.

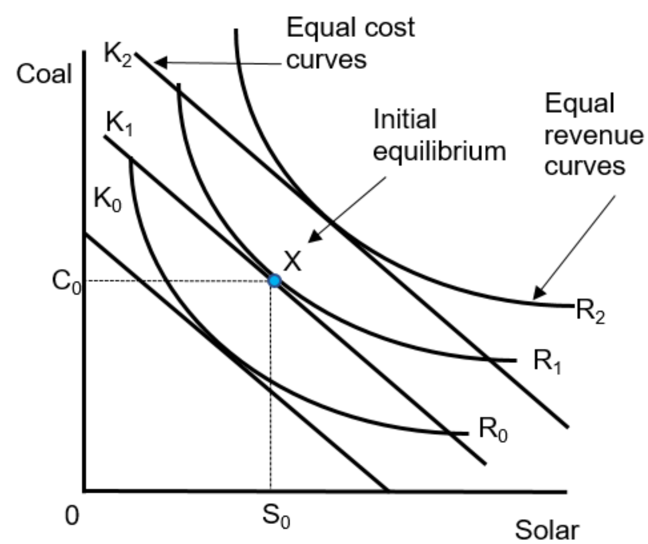
Online Annex 1.5. Carbon Taxes versus Feebates: A Closer Look

This annex offers further explanation of the difference between carbon taxes and feebates, as applied to the power generation sector, using a diagrammatic approach. The different impacts on firm-level choices, economic efficiency costs, revenue, and distributional burdens are discussed in turn.

Impact on Firm Choices

Consider Figure 1.5.1, which depicts the choice of output level, and input mix, for a power generation firm. The firm can choose between coal generation, which produces CO_2 emissions, and solar generation, which does not.

Figure 1.5.1. Firm Optimization over Input Mix and Output Level



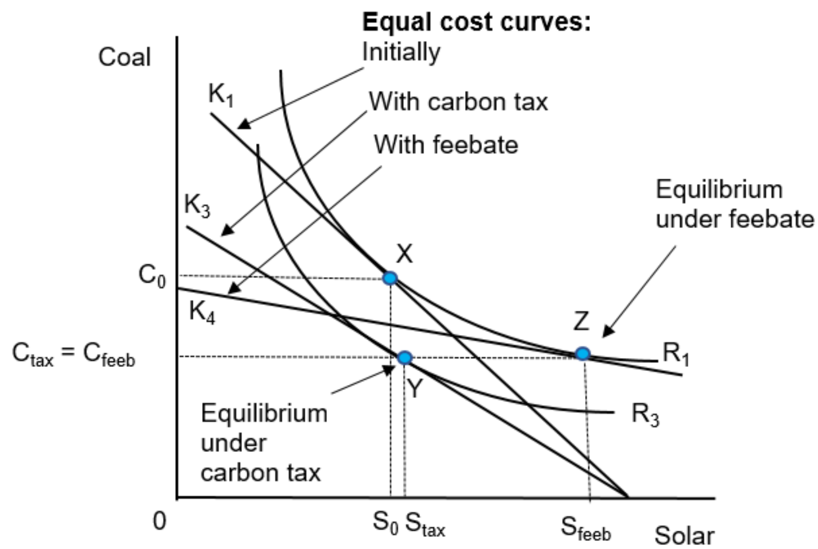
Source: IMF staff.

The downward sloping lines labeled K_0, in this figure are equal cost curves; that is, a given curve shows different combinations of coal and solar power inputs that would result in the same total production cost to the firm. The slope of these curves is the ratio of the cost per unit of solar generation to the firm to the cost per unit for coal generation.

The curves labeled R_0, in Figure 1.5.1 are equal revenue curves; that is, a given curve shows different combinations of coal and solar power inputs that would result in the same revenue to the firm. These curves are convex to the origin, because it is increasingly difficult to substitute one input for the other—for example, as the most productive sites for solar generation are used up, a progressively larger investment in solar is needed to progressively increase output by an extra unit. Increasing the quantity of both inputs by 10 percent boosts revenue by less than 10 percent—this could reflect the impact of greater supply at the industry level on reducing the market price of electricity and/or diminishing returns to scale (that is, the declining addition to output from progressive increases in coal and solar investments as the most productive sites are used up). In contrast, increasing the quantity of both inputs by 10 percent leads to a 10 percent increase in total production costs.

The firm chooses point X, where the equal revenue curve R_1 is tangential to the equal cost curve K_1. At this point, the level of output is optimized by the firm—expanding output by an extra unit beyond X would bring in less additional revenue than the extra cost; conversely, reducing output by a unit below X would lose more revenue than it would save in costs. In addition, the mix of inputs at point X, C_0 level of coal and S_0 level of solar, minimizes costs to the firm. A revenue-preserving increase in solar generation, and a reduction in coal generation, would move the firm along the R_1 curve to the right of point X. This would shift the firm to a higher cost curve. (Similarly, increasing coal input and reducing solar input to preserve revenue would move the firm along the R_1 curve to the left of point X, again shifting the firm to a higher cost curve.)

Figure 1.5.2. Firm Optimization under Carbon Tax and Feebate



Source: IMF staff.

Now consider Figure 1.5.2, which compares the outcome just described with outcomes under either a carbon tax or a feebate. A carbon tax increases the unit cost of coal generation to the firm, thereby flattening the equal cost curves—specifically, the total production cost from a given quantity of inputs will increase in proportion to the increase in the cost of coal generation times the share of coal generation in total production costs. The new equilibrium is depicted by point Y, where the equal revenue curve denoted R_3 is tangential to the equal cost curve K_3, and the new quantities of coal and solar generation are C_{tax} and S_{tax}, respectively. Coal use falls for two reasons. First, the increase in the cost of coal generation relative to solar generation will cause a shift away from coal toward solar for any given level of output—a movement along the equal revenue curve R_1 to the right of point X. Second, at the market level consumer demand for electricity will fall as coal tax revenue is passed forward in higher electricity prices, and the representative generator will respond by reducing output, as represented by the shift to the lower equal revenue curve R_3, which in turn implies less use of both coal and solar inputs. Coal use falls while net carbon-free generation could increase or decrease.

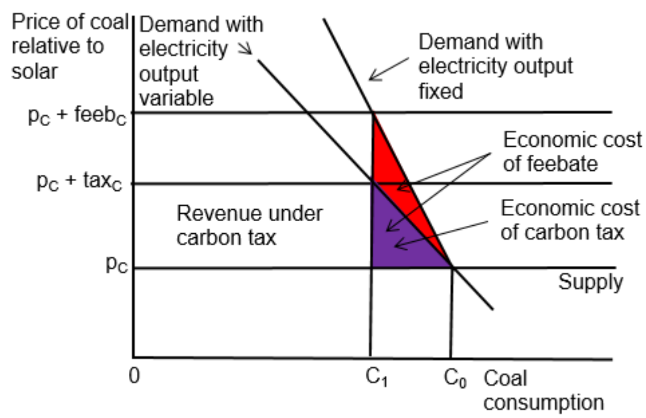
The feebate policy is defined as revenue-neutral and is designed to deliver the same decline in coal use as under the carbon tax. The feebate increases the unit cost of coal generation to the firm and reduces the unit cost of solar, but without (approximately speaking) a reduction in industry output (there is no net tax payment passed forward in higher electricity prices). In terms of Figure 1.5.2, the policy induces a movement along the initial equal revenue curve to point Z at the point of tangency with the new equal cost curve K_4, which has a flatter slope than the initial equal cost curve. As drawn in Figure 1.5.2, coal generation is the same as under the carbon tax. Solar generation is greater, however, as all the reduction in coal use results from switching toward the zero-carbon fuel—none of it reflects a general reduction in use of all inputs in response to less total electricity generation.

To achieve the same emission reduction as under a carbon tax—that is, to induce the same reduction in coal generation—the feebate policy must bring about a greater increase in the cost of coal generation relative to solar generation. This can be seen from Figure 1.5.2, in which the equal cost curve K_4 has a flatter slope than K_3 to compensate for its failure to reduce output and shift the firm to a lower equal revenue curve.

Economic Efficiency Costs

To compare the economic efficiency costs (excluding environmental benefits) of carbon taxes and feebates applied to the power sector, consider Figure 1.5.3, which shows the industry-wide market for coal used as an input in power generation. The lower, downward sloping curve is the demand for coal, and the height of this curve at any point is the value to generators (or profit) from using an extra unit of coal. The height of the supply curve reflects the cost of producing an extra unit of coal and, for simplicity, this is taken to be constant and equal to p_C, the supply price for coal. In the absence of policy intervention, the coal market is taken to be in equilibrium with coal consumption, given by C_0.

Figure 1.5.3. Economic Costs of Carbon Tax and Feebate in the Coal Market



Source: IMF staff.

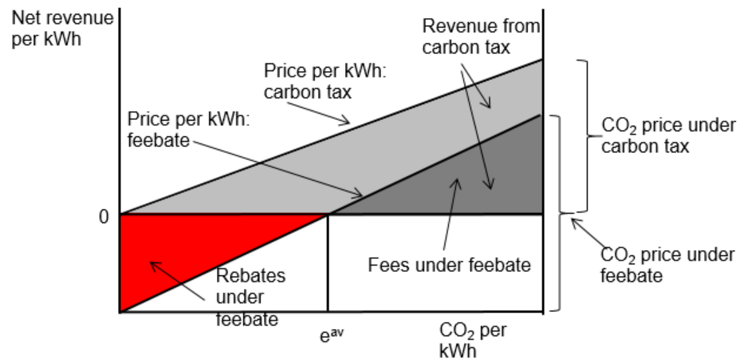
Now suppose a per unit tax of tax_C is imposed on coal use, corresponding to a carbon tax. The market price of coal will rise to $p_C + tax_C$ and coal use will fall to C_1, reflecting both shifting to the zero-carbon fuel and reductions in the overall level of electricity production. The resulting efficiency cost is given by the area under the demand curve between C_1 and C_0 (the benefits forgone from less coal use) minus the area under the supply curve between C_1 and C_0 (the supply cost savings).

Under a feebate policy, the demand for coal falls due to switching to solar, but (as an approximation) there is no reduction in overall electricity production. The relevant input demand curve for this policy therefore has a steeper slope than the corresponding demand curve under the carbon tax. Consequently, achieving the same reduction in coal use to C_1 (and therefore the same reduction in emissions) involves a higher efficiency cost as indicated by the red triangle in Figure 1.5.3—this extra cost arises because the feebate policy pushes excessively on fuel switching to compensate for not reducing electricity production.

Revenue Impacts

Finally, Figure 1.5.4 compares the revenue implications of carbon taxes and feebates applied to the power sector and allowing now for the possibility that firms have different mixes of fuels in their portfolio of generation plants. The industry-wide average CO_2 emission per kilowatt-hour (kWh); that is, total CO_2 emissions produced by the industry divided by total generation from the industry, is denoted as e^{av}.

Figure 1.5.4. Revenue Impacts of Carbon Tax and Feebate Applied to Power Generation



Source: IMF staff.
Note: kWh = kilowatt-hour.

Under the feebate policy, e^{av} is taken to be the pivot point emission rate, below or above which rebates or fees apply. Generators with emission rates below e^{av} (for example, those with relatively high shares of renewables and nuclear in their portfolios) will receive rebates per unit of generation equal to the CO_2 price times the difference between e^{av} and the average emission rate for their portfolio. Generators with emission rates above e^{av} (for example, those with relatively high shares of coal or diesel plants in their portfolios) will pay taxes per unit of generation equal to the CO_2 price times the difference between the average emission rate for their portfolio and e^{av}. The lower curve in Figure 1.5.4 shows the net revenue paid per unit of generation under the feebate—this curve has a negative intercept equal to e^{av} times the emission price in the feebate and slope equal to the emission price. Total rebates paid to firms with below average emission rates are indicated by the red triangle, while total taxes paid by firms with above average emission rates are indicated by the darker gray triangle. Total fees equal total rebates because the feebate is designed to be self-financing. And (as in Figure 1.5.3) the emission price under the feebate is larger than under the tax, because the feebate is designed to promote more switching between coal and solar.

Under a carbon tax all generators (aside from those with exclusively zero-emission portfolios) will pay taxes per unit of generation equal to the CO_2 price under this policy times their average emission rate. The upper curve in Figure 1.5.4 shows the revenue paid per unit of generation—this curve has a zero intercept and slope equal to the emission tax. Total taxes paid are indicated by the sum of the lighter and darker gray shaded areas.

Distributional Burdens

Under a carbon tax, most of the tax payments are likely passed forward in higher electricity prices to households and other electricity consumers, though a minor portion might come at the expense of rents for coal and electricity producers. Clean energy can benefit under both policies, but more so under the feebate. In this regard the feebate may garner more support from clean energy producers, and face less opposition from electricity and coal producers, though carbon taxes also raise revenues that can be used in ways to garner political support.

Online Annex 1.6. The Concentration of Coal-Related Employment within Countries

Reducing carbon emissions from coal is key if countries are to scale up efforts to tackle climate change. Yet in many countries, including some of the world's largest producers, coal activity is concentrated in a few regions, making it politically difficult to reduce the role of coal because that would generate sizable job losses in those regions. The regional implications of climate change mitigation policies thus need to be considered.

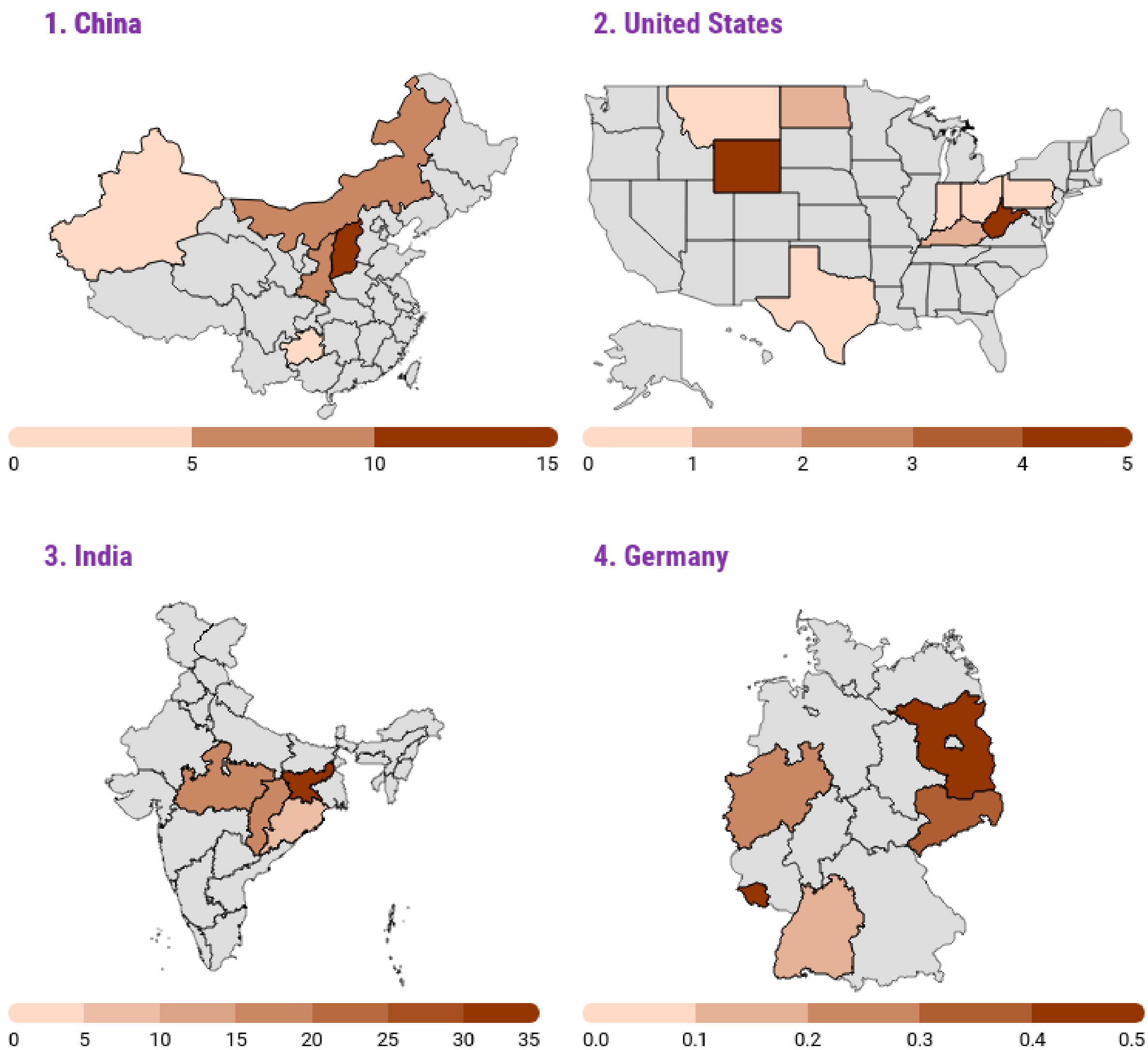
The top five regions on average account for about three-quarters of nationwide coal production for a sample of eight countries including China, the Czech Republic, India, Germany, Poland, and the United States (Table 1.6.1). Moreover, these coal-intensive regions often have lower per capita GDP (at about 60–90 percent the national average). Those regions also may have fewer alternative jobs and less diversified economies, as shown in the greater shares of the energy sector in regional GDP and coal-related jobs in total employment (Table 1.6.1; Figure 1.6.1). Coal workers often face longer spells of unemployment after layoffs and a permanent wage cut by as much as 30 percent in new jobs that often require relocation (Bollinger and others 2018; Johnson and Gosselin 2018). Communities that shut down coal mines also tend to face a sharp drop in labor force participation rates.

Online Annex Table 1.6.1. Regional Coal-Related Production and Employment (2015–17)
(Percent, unless otherwise stated)

Country/Region [2/]	Regional Share of National Coal Production (percent)	Coal to Total Regional Employment[1/] (percent)	Coal Production Per Capita (tons)	Regional Share of National Capacity of Coal-Fuel Power Plants (percent)	Energy Share of Regional GDP (percent)	Regional Per Capita GDP (percent of nationwide level)	Regional Population (percent of national population)
United States Coal Intensive Regions	85	1.6	46	46	7	92	25
Illinois	6	0.2	4	5	2	109	4
Indiana	4	0.5	5	6	2	91	2
Kentucky	5	1.1	9	5	3	77	1
Montana	5	0.8	34	1	4	77	0
Ohio	1	0.8	1	6	3	94	4
Pennsylvania	6	0.3	4	4	4	98	4
Texas	5	0.1	1	11	9	100	9
West Virginia	12	5.1	51	6	14	69	1
Wyoming	41	5.9	540	3	21	114	0
China Coal Iintensive Regions	76	6.7	17	n.a.	n.a.	83	12
Guizhou	5	2.1	5			64	3
Inner Mongolia	26	5.8	36			108	2
Shanxi	25	18.2	24			71	3
Shaanxi	16	5.1	15			97	3
Xinjiang	5	2.2	7			76	2
Germany Coal Intensive Regions	53	0.3	7	39	5	85	31
Brandenburg	19	0.4	14	10	6	72	3
North Rhine Westphalia	19	0.2	2	18	4	98	22
Saarland	0	0.5		5	4	92	1
Saxony	15	0.3	7	6	5	76	5
India Coal Intensive Regions	71	19.7	3	n.a.	n.a.	62	14
Chhattisgarh	20	19.4	5			73	2
Jharkhand	19	36.3	4			52	3
Madhya Pradesh	13	15.4	1			64	6
Odisha	19	7.8	3			62	3

Sources: Alves Dias and others (2018); CEIC; India's statistics office; US Bureau of Economics Analysis; and IMF staff estimates.
Note: Regions within countries are listed in alphabetical order. Coal-intensive regions are selected based on the shares of regional coal mines, the capacity of regional coal-fueled power plants, and regional coal-related jobs at the national level. The estimates include coal and lignite production capacity.
1/ Coal-related employment includes direct jobs in coal mines and coal-fueled power plants and estimated indirect jobs linked to the coal sector.
2/ For India, coal employment is expressed as a share of industrial (mining and factory workers) employment because of data limitations. For China, total employment in the region refers to total urban employment. n.a. = not available.

Online Annex Figure 1.6.1. Coal-Related Employment to Total Regional Employment in Coal-Intensive Regions (2015–17)
(Percent)



Sources: Alves Dias and others (2018); CEIC; India's statistics office, US Department of Energy; and IMF staff estimates.
Notes: Coal-related employment includes direct jobs in coal mines and coal-fueled power plants and estimated indirect jobs linked to the coal sector. For China, total employment in the region refers to total urban employment. In India, coal employment is expressed as a share of industrial (mining and factory workers) employment because of data limitations. Coal-intensive regions are selected based on the shares of (1) regional capacity of coal mines and coal-fueled power plants and (2) the regional coal-related jobs at the national level. The boundaries, colors, denominations, and any other information shown on the maps do not imply, on the part of the International Monetary Fund, any judgment on the legal status of any territory or any endorsement or acceptance of such boundaries.

Online Annex 1.7. Prior Experiences with Carbon Taxation

More than 20 national and subnational governments have introduced carbon taxes (WBG 2019). The table below summarizes recent experiences in Colombia, France, and Singapore and long-standing experience in Sweden. The World Bank publishes an annual report (for example, WBG 2019) with details on carbon pricng systems worldwide.

Online Annex Table 1.7.1. Experiences to date in Colombia, France, Singapore, and Sweden

Country	Year of Reform	Carbon Tax Reform [1]	Success of Reform	Speed of Phase in	Stakeholder/Communications Program	Low-Income Households	Vulnerable Firms	Revenue Use
Colombia	2017	Tax of $5 per ton on oil and natural gas products with planned gradual increase to $11 per ton.	Successfully introduced	Gradual	Tax was adopted as part of a structural tax reform.	No information available	Exemptions for natural gas consumers that are not in the petrochemical and refinery sectors and fossil fuel consumers that are certified carbon-neutral.	Revenues earmarked for the Colombia Peace Fund, which supports activities like watershed conservation, ecosystem protection, and coastal erosion management.
France	2014	Tax on emissions not covered by the EU ETS. Rates were initally set at $8 per ton and were on a trajectory to reach $97 per ton in 2022.	Ramping up of tax suspended at $50 per ton in 2018	Rapid	Lack of public communication, especially on the use of carbon tax revenues.	Compensation system introduced in 2015 providing financial assistance to low-income households for their energy bills.	Agriculture, taxis, and trucks exempt to protect their competitiveness.	While France does not generally earmark revenues, the reform was accompanied by some support for the energy transition, financial assistance to low-income households, and broad tax reductions.
Singapore	2019	Tax, applying downstream to large emitters is set at $4 per ton from 2019 to 2023, with plans to increase it to $8-$11 by 2030.	Successfully introduced	Gradual	Public consultations carried out by various government agencies with stakeholders.	No information available	Tax rate starts low to account for potential competitiveness impacts.	Support climate initiatives (e.g., energy efficiency improvements for industry).
Sweden	1991	Tax on motor and heating fuels starting at $28 per ton (industries covered by the EU ETS emissions are excluded) and increased to $127 per ton by 2019. Lower rate for industry (at $7 per ton in 1991) was phased out by 2018.	Successfully implented as planned	Gradual	Tax was part of a broader fiscal reform including the reductions in taxes on energy, labor and capital, elimination of various tax shelters, and base broadening of the value-added tax. Business and other stakeholders were involved in the decision making process through general public consultation of the reform proposal.	Social transfers and reductions in the basic rate of income tax helped low and middle-income households.	Much lower initial rate for industry, which was phased out gradually.	Revenues go to the general budget but may be used for specific purposes linked to the carbon tax (e.g., addressing distributional consequences through cuts in income and labor taxes, financing other climate-related measures and public transportation investment).

Sources: WBG (2018, 2019); NCCS (2019); and www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax.
Note: EU ETS = European Union Emissions Trading System.
[1] Tax rates are in 2017 US dollars.

Online Annex 1.8. Incidence Analysis

Input-output tables are used to estimate the impact of carbon pricing on industry costs. These costs are assumed to be passed into consumer prices, which are matched with household expenditure surveys to infer burdens across household groups, defined by per capita consumption. Incidence impacts are projected for 2030.[1]

The burden on household consumption groups from carbon pricing is measured by changes in "consumer surplus." Consumer surplus is defined as the benefit from consumption of a product minus what consumers pay for that product. In Figure 1.3.1, for example, the consumer surplus from the initial level of gasoline consumption is measured by the area between the demand curve and supply curve with height P_G^*, integrated between the origin and fuel consumption G^*. And with the new tax, consumer surplus falls to the area between the demand curve and supply curve with height P_G^0, integrated between the origin and fuel consumption G^0. That is, the reduction in consumer surplus, or the burden of the tax, is equivalent to $(P_G^0 - P_G^*) \cdot G^*$, the extra spending required to maintain the initial level of consumption, minus $(P_G^0 - P_G^*) \cdot (G^* - G^0)/2$, which is equivalent to the savings over spending at the higher price, minus the loss of consumer benefits, from the reduction in consumption. Dividing by total household consumption, and a little manipulation, gives

$$\rho^G \cdot \pi^G (1 - \alpha^G/2). \qquad (1.8.1)$$

In this expression, ρ^G is the proportionate increase in the price of gasoline from the tax, π^G is the share of the budget for the household group that is initially spent on gasoline, and α^G is the proportionate reduction in gasoline consumption caused by the tax. If the budget share for gasoline is, say, 10 percent, this formula implies that a 20 percent increase in its price, causing a 10 percent reduction in consumption, will cause a burden of 1.9 percent of income. The same approach, used for calculating the burden from the increase in prices for other consumer products and aggregating over products, gives the total household burden from the tax.

Budget shares are from the Survey of Household Spending[2] for Canada, the China Family Panel Studies[3] for China, the 68th Round of the National Sample Survey[4] for India, the 2015–16 Living Costs and Food Survey[5] for the United Kingdom, and the Consumer Expenditure Survey[6] for the United States. Households are first separated into quintiles by their total consumption expenditure, and budget shares are calculated by dividing spending on individual goods and services by total expenditure.

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[1] For other recent studies on the burden of carbon pricing see, for example, Vogt-Schilb and others (2019) and Dorband and others (2019).

[2] The survey, provided by Statistics Canada, distinguishes 20 aggregated categories of goods and interviewed 16,758 households in 2009.

[3] This includes data on household expenditures for 25 aggregated categories of goods and services. The latest year available for the survey is 2012 and includes information from a nationally representative sample of more than 13,000 households across 25 provinces in China. See www.isss.edu.cn/cfps/EN.

[4] The survey, which distinguishes 39 categories of goods, interviewed 101,724 households (59,700 rural and 42,024 urban) between July 2011 and June 2012.

[5] This survey contains 13 aggregated categories of expenditures, based on the Classification of Individual Consumption by Purpose (COICOP) standard, with an initial sample of 11,484 households (see https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/incomeandwealth/methodologies/livingcostsandfoodsurvey).

[6] The 2015 survey was used based on a nationally representative sample of 24,617 households (see www.bls.gov/cex/home.htm).

The spreadsheet tool mentioned in Annex 1.1 is used to calculate the impacts of carbon pricing on fuel and electricity prices and reductions in household demand for energy products. Indirect price increases for other consumer goods are calculated, assuming full pass-through of the burden from producers to consumers, using input-output tables (demand responses for these products are ignored but are likely of minor significance for overall incidence impacts). For Canada, the national input-output table is for 2013, for China 2012, for India 2007–08, for the United Kingdom 2015, and for the United States 2007.[7] Industries are mapped to the relevant product classification in the household data, and within that classification are weighted by their contribution to total household spending on that product.

In projecting to 2030, the shares of different industries in total output are assumed to be the same as in the years of the input-output data, while the energy intensity of the economy is assumed to decline based on estimates from Annex 1.1. The household budget shares for electricity and direct fuel consumption are scaled by the corresponding 2030 energy prices relative to prices in the year of the household survey. In addition, the weights of the household surveys are adjusted to reflect population projections in 2030, and household burdens are adjusted to fully reflect the impacts of fuel price increases on private consumption and investments.

When simulating the impact of various options on the use of carbon tax revenue, it is assumed that carbon tax revenue is first used to offset the impact on government consumption and investment (estimated from the input-output table) and to provide support for trade-affected firms and sectoral and place-based assistance. For the rest of carbon tax revenue, (1) under the universal lump-sum option, an equal amount is distributed among the entire population; (2) under the public investment option, the incidence is assumed to be the same as that of consumption; and (3) under the tax cut option, the incidence is assumed to be the same as that of existing payroll or income tax.

There are several caveats for the incidence analysis methodology:

(1) Not all the burden of carbon pricing may be passed forward in higher prices for households—some (likely a minor fraction) may be passed backward in lower prices for firms. As a result, some of the burden may be borne by owners of capital or workers in these firms, though it can be difficult to apportion these impacts to different household consumption groups.

(2) Not all the economic efficiency impacts of the carbon tax and the use of the carbon tax revenue are captured by the analysis—for example, the economic efficiency loss from the carbon tax on sectors beyond the energy sector and the economic efficiency gain from public investment and tax cuts of carbon tax revenue.

[7] For Canada, the table is the latest version published by Statistics Canada and disaggregates 230 industries. For China, the table is the latest version published by the National Bureau of Statistics, covering 139 industries. For India, the table is from the Central Statistics Office, Ministry of Statistics and Programme Implementation of India, covering 130 industries. See http://mospi.nic.in/publication/input-output-transactions-table-2007–08. For the United Kingdom, the 2015 table (which includes 129 industries) was obtained from the Office for National Statistics: https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed. For the United States, the table is from the US Bureau of Economic Analysis (see www.bea.gov/industry/io_annual.htm) and covers 389 industries. Although more recent input-output tables are available from other sources (for example, www.wiod.org/home), they cover only a (standardized) set of (56) industries, which does not provide the necessary level of disaggregation (that is, separate categories for energy products, such as coal, oil, natural gas, electricity, and road fuels) needed to analyze the direct and indirect effects of carbon taxation. In any case, for comparable categories, budget shares have not changed much in more recent tables.

(3) The distributional incidence of the domestic environmental co-benefits of carbon pricing—principally the air pollution benefits—is not considered. If the valuation of health risks is roughly proportional to income,[8] then these benefits may be skewed toward lower-income households if these households are more likely to reside in severely polluted areas. Again, the effects become complex, however, if for example property values increase in areas with improving air quality (which would hurt low-income renters).

[8] See for example Coady and others (2019), 12–13.

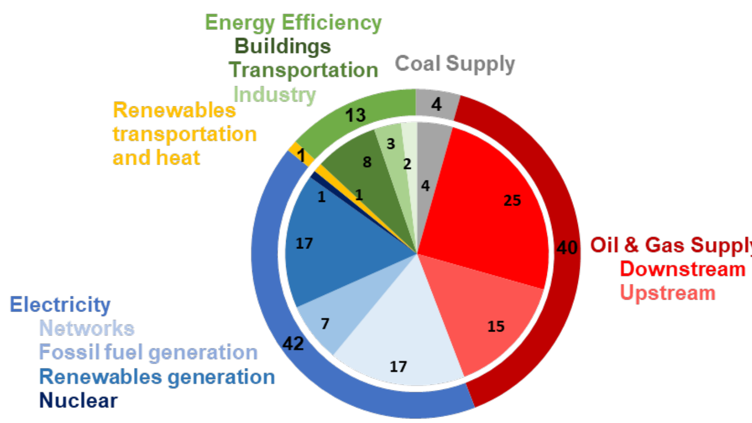
Online Annex 1.9. Energy Investment Needs, Methodology, and Case Studies

This annex takes a closer look at energy investment needs for climate change mitigation, discusses the methodology used to extrapolate model-based energy investment needs at the global level (obtained from existing studies[1]) to individual G20 countries, and provides examples of how supporting policies could improve investment incentives in China, India, and the United States.

Investment Needs for Mitigation

As of 2017, total investment in the global energy system was $1.8 trillion, or 1.9 percent of global GDP. Forty-two percent of the investment was in power generation (17 percent in new renewables capacity, 7 percent in fossil fuel generation, 17 percent in network upgrades, and a small fraction of a percent in nuclear); 40 percent was in oil and gas supply and distribution infrastructure; 13 percent was in energy efficiency in buildings, vehicles, and industry; and 4 percent was in new coal supply (Figure 1.9.1). Investment is more substantial in developing and emerging market economies, where energy use is expanding rapidly, averaging 3.5 percent of GDP compared with 1.3 percent of GDP in advanced economies. Much of the energy infrastructure (for example, power plants, refineries, power grids, buildings) has an expected lifetime of 30–60 years, underscoring the difficulty of rapidly transforming energy supply systems, but also the prolonged impact of investment choices made today.

Online Annex Figure 1.9.1. Global Energy Investment in 2017
(Percent)



Source: IEA (2018).

Achieving emission reduction targets under the 2°C scenario requires higher investment in China and India (by a third and a quarter, respectively),[2] though not necessarily in other G20 countries (Figure 1.9.2, estimated based on the methodology discussed below[3]). More important, model results from existing studies show that transforming the global energy system toward the 2°C scenario requires a significant reallocation of supply-side investment portfolios (Figure 1.9.3, panel 1). Investment must be shifted away

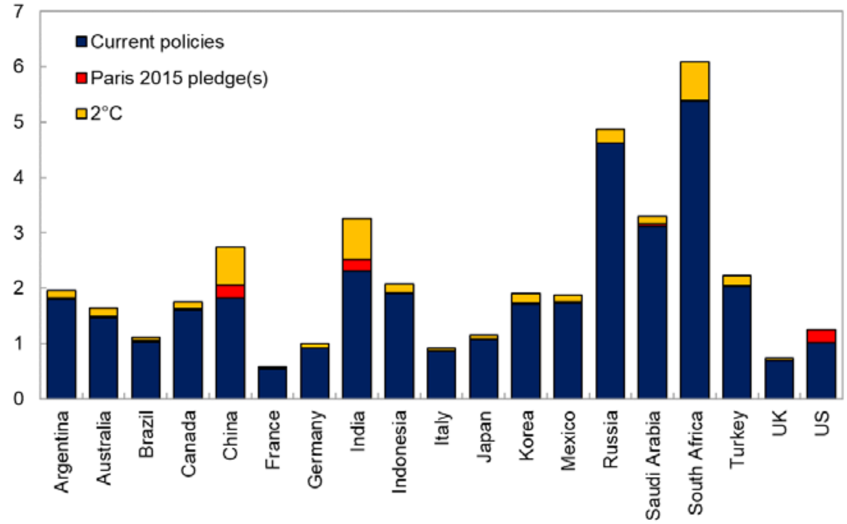
[1] McCollum and others (2018) and IEA/IRENA (2017).

[2] This is mainly because of China's and India's greater reliance on coal and the significantly higher investment costs of alternative technologies (for example, renewables).

[3] Numbers for China, India, and the United States are obtained directly from the multimodel averages of McCollum and others (2018). Investment needs for other G20 countries are those of the IMF staff based on estimates at the global level from existing studies. Note that these numbers are subject to significant variation across models. Moreover, future technological breakthroughs and costs and the speed and strategy of countries' adoption to achieve climate goals affect the size of investments.

from fossil fuel supply and conventional power generation to low-carbon sources, including renewables, nuclear, improved transmission and distribution networks, and carbon capture and storage.[4]

Online Annex Figure 1.9.2. Investment Needs (2030)
(Percent of GDP)

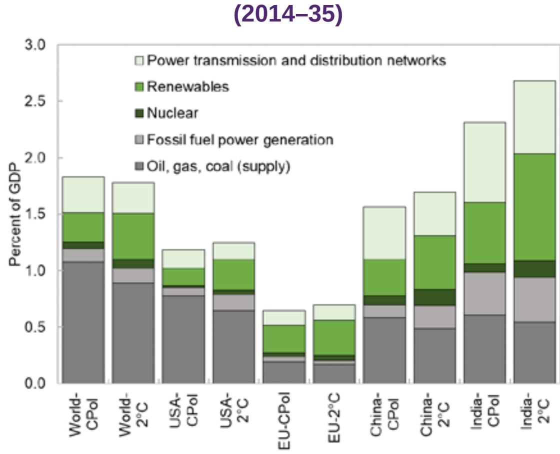


Source: IMF staff calculations based on IMF (2019) and McCollum and others (2018).
Note: NDC = Nationally Determined Contribution.

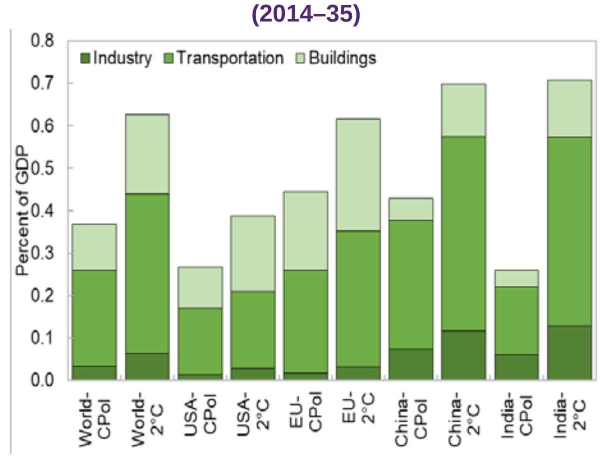
Moreover, sizable additional investment in energy efficiency is needed for buildings (for example, heating, cooling, appliances), transportation (for example, electric cars), and industry, amounting to 0.5 percent of global GDP (Figure 1.9.3, panel 2).[5] Such energy efficient investments can curb emissions more quickly because of their shorter life cycles compared with energy supply infrastructure.[6]

Online Annex Figure 1.9.3. Investment Needs under Current Policies and 2°C Scenario

1. Average Annual Supply-Side Investments (2014–35)



2. Average Annual Energy-Efficiency Investments (2014–35)



Source: IMF staff calculations based on WEIO (2014).
Note: CPol: current policies; 2°C: 2 degree Celsius scenario.

[4] Whether the costs associated with greater use of nuclear power outweigh the gains through lower carbon emissions is a hotly debated issue (for example, IPCC 2014). If nuclear is used, it would require adequate regulations and safeguards.

[5] IEA/IRENA (2017).

[6] IEA (2018).

Methodology for Extrapolating Investment Needs at the Country Level

Using the contribution of each G20 country to total CO_2 emission reduction at the global level under Nationally Determined Contributions (NDCs) and 2°C scenarios (obtained from IMF 2019 and model-based projections from the literature), we calculate the slope of the marginal abatement cost (MAC) curve for G20 countries individually and collectively (the MAC shows the marginal cost of reducing emissions). We follow previous studies[7] in postulating that the G20-wide total abatement cost (TAC) is a quadratic function of CO_2 emission reductions, or

$$\mathrm{TAC} = \theta(\Delta\mathrm{CO}_2)^2 \,,$$

in which ΔCO_2 is the reduction in total CO_2 emissions at the G20 level from the reference scenario and θ is a scaling parameter. The MAC can then be derived as follows:

$$\mathrm{MAC} = 2\theta(\Delta\mathrm{CO}_2).$$

The slope of the G20-wide MAC curve can be estimated from model-based energy investment cost projections as

$$\beta = \frac{MAC}{\Delta\mathrm{CO}_2} = 2\theta.$$

Given that the G20-wide MAC curve is the horizontal sum of the individual-country MAC curves,[8] we can use β to calculate the slope of the MAC curve of country *i*:

$$\beta_i = \frac{MAC}{(\Delta\mathrm{CO}_2)_i} = \frac{\beta * (\Delta\mathrm{CO}_2)}{(\Delta\mathrm{CO}_2)_i} = \frac{\beta}{\alpha_i} = \frac{2\theta}{\alpha_i},$$

in which α_i is the contribution of country *i* to total emission reductions, ensuring that emission abatement is achieved in the most cost-effective way.

The contribution of individual countries to total CO_2 emission reductions is known from the IMF spreadsheet tool (Annex 1.1), so individual MAC curves can be estimated after solving for the scaling parameter θ. With a quadratic TAC function, the average abatement cost (AAC) is as follows:

$$\mathrm{AAC} = \theta(\Delta\mathrm{CO}_2),$$

implying that

$$\theta = \frac{AAC}{\Delta\mathrm{CO}_2}.$$

Hence, the individual MAC curve slope can be computed as

$$\beta_i = \frac{2\theta}{\alpha_i} = \frac{2}{\alpha_i} * \frac{AAC}{\Delta\mathrm{CO}_2}.$$

Given that the total G20 investment needs under the Nationally Determined Contributions and 2°C scenarios are known from the literature, the average abatement cost per ton of emission reduction can be calculated and used to compute the slope of the individual G20 MAC curves (see Figure 1.9.4 on MAC curves under the 2°C scenario).Once the slopes of the individual MAC curves are known, the total investment needs for an individual country *i* is computed as follows (Figure 1.9.2):

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[7] See Cline (2011); Kesicki (2015); and Ibrahim and Kennedy (2016) for details.

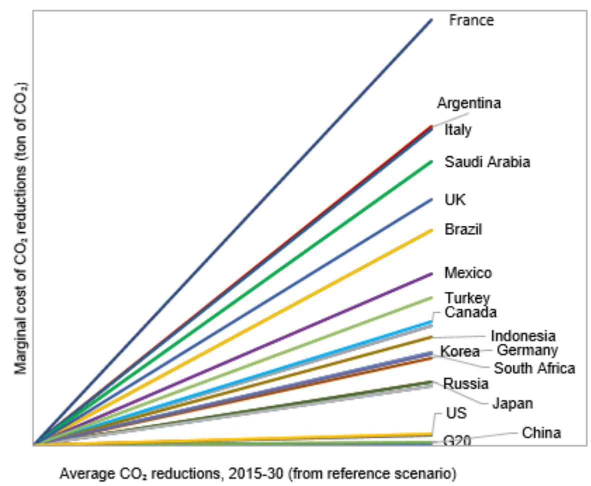
[8] The analogy is the following: the market supply curve is the horizontal sum of individual firm supply curves.

$$\mathrm{TAC}_i = \frac{\alpha_i\beta_i}{2}(\Delta\mathrm{CO}_2)_i{}^2.$$

Case Studies for Supportive Policies for Mitigation Investment (public and private)

Section V. (Supporting Policies for Clean Technology Investment) discusses how even with robust carbon pricing, investment in low-carbon technologies may be inadequate given various technology-related market failures and impediments. Here, case studies of China, India, and the United States highlight some of these impediments and how to address them.

Online Annex Figure 1.9.4. Marginal Abatement Cost Curves for G20 Countries under 2°C Scenario



Source: IMF staff calculations based on McCollum and others (2018).

China invested about $100 billion a year in clean energy during 2012–18. Progress was made to mitigate the curtailment rate—the loss of energy delivery from a generator to the electrical grid, typically because of transmission congestion or lack of transmission access—of wind and solar renewables, largely on par with other advanced countries. As some renewable technologies, such as solar photovoltaic cells, become more mature, fiscal incentives for their deployment are adjusted appropriately. For example, total subsidies for solar projects were targeted to be $0.4 billion in 2019, down from $18 billion in 2017. China also plans for subsidy-free solar and wind projects and aims to reach a grid parity target by 2020 so that electricity generated from solar and wind can be sold at the same price as coal-fired power (NDRC 2018). Tax exemptions on electronic vehicle purchases are extended in part to facilitate the adoption of tighter automobile emission standards (China VI) in key provinces ahead of schedule to contain pollution.

Nonetheless, changing the investment composition to meet emission reduction goals requires bolder action on market reforms of the energy sector. Specifically,

- *Less reliance on coal:* Coal accounts for two-thirds of the energy source in electricity generation capacity. The low cost of coal and a relatively stable grid purchasing price reinforce state-driven investment in fossil fuels (OECD 2017). A complex web of cross-subsidization of renewables and fossil fuels also tends to favor incumbent state-owned enterprises, hindering investment in renewables by new entrants. As a result, it is important to align fiscal incentives to avoid subsidizing both fossil fuels and renewables while enforcing restrictions on new coal investment to reduce reliance on coal. Greater investment in carbon capture and storage also mitigates emissions from the use of coal.

- *Reforming the electricity market:* Electricity generation from renewables is more volatile, and in many cases, costs more. For renewables to be competitive, electricity prices will need to be flexible to reflect supply and demand conditions. However, regulated electricity prices for power companies reduce incentives to switch to a more variable renewable energy supply and could contribute to the remaining curtailment (reduction of energy delivery from generation to electricity grid) of renewables generation

(OECD 2017).[9] Second, although state ownership of enterprises is found to increase renewables investment, it also raises market concentration that impedes new private entrants (Prag, Rottgers, and Scherrer 2018). At the same time, the recently proposed emission trading system contains multiple emission allowance benchmarks, which would likely not be cost-effective and would undermine the price signals for low-emission investment.[10] Finally, even the proposed system has the potential to take into account the disparity of regional development and economic cycles. Local governments may not be able to enforce compliance and distribute allowances effectively.

India has launched multiple policies and set up institutional mechanisms to support low-carbon investment (see India Economic Survey 2017–18 for details). The government is implementing the National Action Plan on Climate Change. Key measures include (1) expanding renewable energy capacity fivefold from 2014 to 2022, albeit from low levels; (2) introducing and increasing clean energy processes on coal; and (3) developing domestic carbon markets. In terms of instruments, India provides generation-based incentives, feed-in tariffs for power purchase agreements, capital and interest subsidies, grants, concessional finance, and priority lending. It introduced disclosure requirements for issuance and listing of green bonds. There are also regulations for mandatory installation of efficient appliances in all central government buildings. Nonetheless, implementation challenges and policy inconsistencies remain.

Despite tangible progress in expanding renewable energy capacity, market distortions may impede large-scale low-carbon investment in India. Specifically,

- *Reliance on coal:* About 60 percent of electricity is generated by burning coal, and there is substantial support for coal through subsidies (higher than for renewables; see Figure 1.9.5). The Goods and Services Tax (GST) rate on coal is 5 percent, and the clean energy excise (which later became the GST compensation cess on coal) is only 400 rupees (about $6) per ton of coal. Therefore, there is room for reconfiguration of subsidies, stricter environmental regulations on new coal plants, more efficient use of coal, and investment in carbon capture and storage technologies.

- *Financial weakness of power distribution companies:* Despite improvement in fuel supply and electricity generation, distribution remains problematic given the financial weaknesses of state-owned power distribution companies. These companies experience operational losses in part because electricity tariffs are low relative to the high cost of procuring power. The problem is worse for electricity generated from renewables given their higher production costs and low tariffs in power purchase agreements. Moreover, renewables in India are underused and have not reached economies of scale despite government subsidies (initially investment-based but more recently production-based, which is

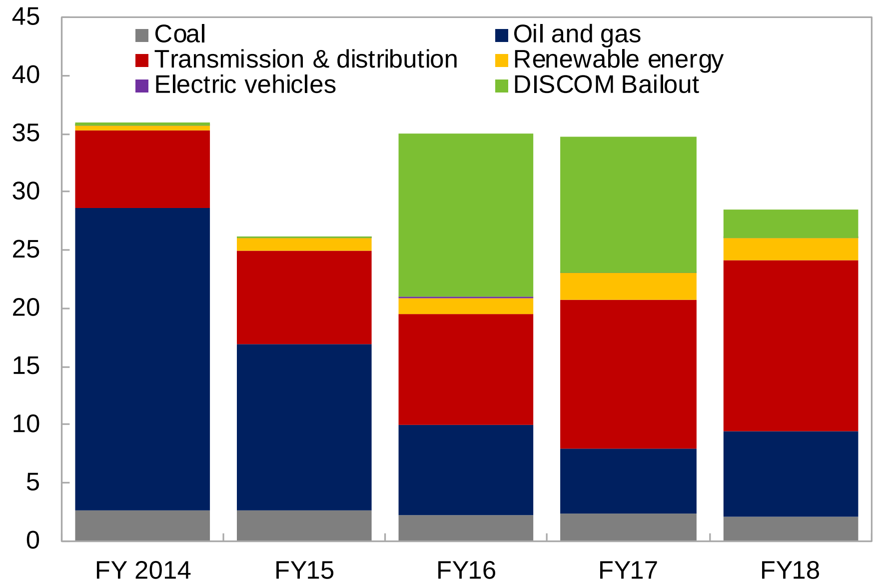
[9] Administered prices for electricity are generally set to cover average cost; public authorities require those generators to produce an annual quantity of electricity to equalize revenue and average cost. This reportedly led to heavy curtailment of renewables generation to maintain fossil fuel plants' hours of operation.

[10] China announced a rate-based emission trading system (ETS) in 2017 for carbon emissions from the fossil fuel power sector (with a plan to extend to six other industries later). The design of the ETS is a tradable performance standard, which includes an industry- and technology-specific allowance benchmark so that the size of allowances individual power plants receive depends on their end-of-period emission output ratios. This differs from a typical ETS in which the nationwide cap is not specified in advance by the regulatory authority. Detailed parameters have not been announced yet. The ETS in China can adapt to economic conditions to avoid high allowance prices and abatement costs during economic booms while mitigating the decline of allowance prices in downturns. It also allows for regional distribution disparity to accommodate the less-developed power plants in low-income areas under a carbon pricing system. However, the ETS is not expected to be fully cost-effective because differences in benchmarks imply sustained variation in power companies' marginal abatement costs if there are significant impediments to allowance trading. It also leads to higher output and emissions and lower electricity prices than under a typical cap-and-trade ETS (Goulder and Morgenstern 2018; Pizer and Zhang 2018).

less distortionary). Building on past efforts, measures need to be implemented to improve the operational efficiency of the state power distribution companies, including reducing transmission losses and raising power tariffs when needed.

- *Land acquisition challenges:* Streamlining and expediting land acquisition for renewables plants and simplification of procedures, at both the central and state levels, remains a priority. Recent initiatives include setting up special purpose vehicles to acquire land and obtain relevant permits and transferring procedural and administrative risks related to land acquisition to the government.

Figure 1.9.5. Subsidies for Fossil Fuels and Renewable Energy
(Billions of US dollars)



Source: Soman and others (2018).

In the **United States**, investments in low-CO_2 technologies have risen, particularly in the transportation and electricity sectors. Plug-in electric vehicles, including plug-in hybrids and all-electrics, first entered the US market in 2011. Sales have grown steadily, and by 2018 these vehicles accounted for 2 percent of new vehicle sales—roughly equaling sales of non-plug-in hybrids. However, the on-road vehicle fleet turns over gradually, and in 2018 plug-in vehicles accounted for less than 1 percent of total passenger vehicle travel.[11]

Likewise, in the electricity sector, wind and solar investments grew from negligible in the late 2000s to 11 gigawatts in 2018 (out of 31 gigawatts of utility-scale capacity additions during that year).[12] Because fossil-fuel-fired generators typically operate 40 years or more and the existing-generation stock includes roughly 1,000 gigawatts of capacity, the recent wind and solar investment levels will cause a gradual transition from fossil-fuel-fired to renewable sources of generation.[13]

Despite recent federal efforts to scale back national emission policies, such as carbon dioxide emission standards for electricity generators, several federal and state-level climate policies continue. Most supporting policies target the electricity and transportation sectors, which collectively account for roughly 60 percent of US greenhouse gas emissions.[14]

[11] The numbers on the share of mileage and average age were computed from the 2017 National Household Travel Survey, under the assumption that travel and age patterns during the 2017 survey year are similar to those in 2018.

[12] https://www.eia.gov/todayinenergy/detail.php?id=36092. The investment share excludes residential and commercial rooftop solar photovoltaic installations.

[13] https://www.eia.gov/todayinenergy/detail.php?id=1830.

[14] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

Research and development: Since 2009, Advanced Research Projects Agency–Energy (ARPA-E) has provided roughly $2 billion in grants to early-stage research projects. Collectively, the projects have a range of potential applications—such as grid-scale or vehicle electricity storage, low-carbon fuels, and energy efficiency—and have attracted more than $2 billion in follow-up private investment. ARPA-E is part of the U.S. Department of Energy, which also provides loan guarantees to reduce capital costs for commercial projects.

Renewables: The federal government supports renewables investment through tax credits equal to 30 percent of up-front investment costs. Historically, wind projects have received a production tax credit instead of the investment tax credit, but the production tax credit is being phased out. Many states provide additional investment subsidies for wind and solar, and some local governments provide feed-in tariffs. About 30 states have renewable portfolio standards, which require that renewables account for a specified share of total generation. For example, California has among the most aggressive policies, requiring that renewables account for 60 percent of generation in 2030.

Alternative fuel vehicles: Plug-in electric vehicle buyers are eligible for a federal tax credit of up to $7,500, depending on the vehicle's battery size. Currently, these tax credits are available for the first 200,000 vehicles sold by each manufacturer. California and 13 other states, which collectively account for 36 percent of the total passenger vehicle market, require manufacturers to sell a certain number of plug-ins and fuel cell vehicles each year.[15] Many states subsidize plug-in and fuel cell vehicles using policies such as tax credits for purchases, rebates for upgrading home charging systems, and access to high-occupancy-vehicle lanes.

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[15] https://ww2.arb.ca.gov/sites/default/files/2019-03/177-states.pdf.

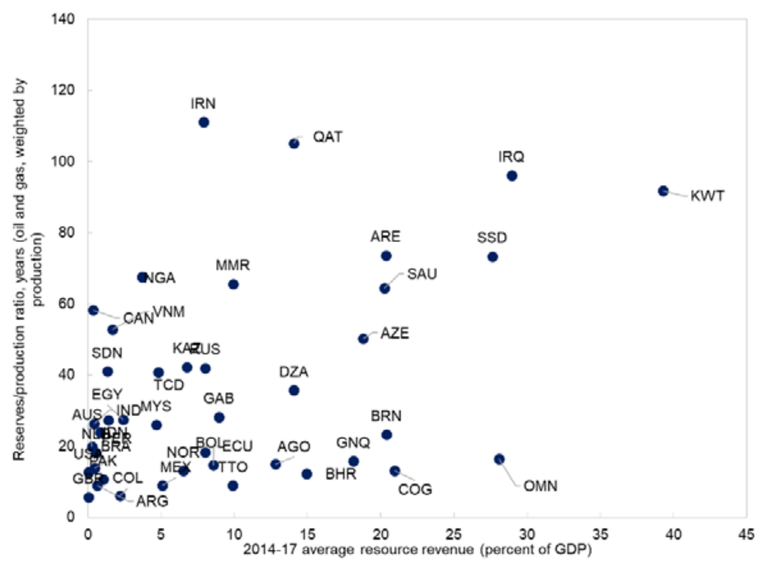
Online Annex 1.10. Fiscal Implications for Fossil-Fuel-Rich Countries

Considerable uncertainty surrounds the future baseline growth of fossil fuel use, the extent of future global mitigation, and the impacts of mitigation on fossil fuel production and prices. The general direction is clear; however, coal and oil production would fall the most, with the share of natural gas likely increasing in the energy mix given its somewhat lower carbon emissions, and carbon pricing would lead to a growing wedge between consumer and producer prices for all fossil fuels.

Revenue Risks for Producing Countries

Countries may be vulnerable if they are dependent on fossil fuel revenue or at risk of ending up with "stranded" fossil fuel assets that can no longer be extracted on a commercial basis. Figure 1.10.1 provides a snapshot of potentially vulnerable countries by reporting oil and gas revenues collected in recent years (as a share of GDP) and the remaining years of production from proven oil and gas reserves.[1] Several countries in the Middle East and Africa are dependent on fossil-fuel-based revenues and have large remaining reserves (for example, Iraq and Kuwait). Other large producers of fossil fuels are much less revenue-dependent, reflecting their more diversified economic structures (for example, China, India, United States). Some countries have large fossil fuel discoveries that have not yet been developed, which poses a risk of stranded assets (for example, Guyana, Mozambique, Timor-Leste).

Online Annex Figure 1.10.1. Revenue from Oil and Gas Compared with Remaining Years of Production



Sources: BP; IMF Fiscal Affairs Department Resource Revenue Database; and IMF, *World Economic Outlook.*
Note: Data labels in the figure use International Organization for Standardization (ISO) country codes.

The decline in fossil fuel demand will not impact producing countries uniformly, and countries with high extraction costs will likely face a greater proportional reduction in production with global climate change mitigation—as producer prices fall, production from fossil fuel assets with higher costs will be reduced or perhaps not developed at all. Fossil fuel producers may have an incentive to accelerate exploitation in the face of a credible climate mitigation scenario (especially small or emerging producers, whereas large producers may be more restrained to avoid further accelerating producer price declines). This is an example of the "green paradox," whereby announcement of future climate change mitigation measures leads to front-loading of fossil fuel production with a commensurate acceleration of CO_2 emissions.

Differences in countries' fiscal regimes (that is, tax and nontax instruments used to collect revenue from fossil fuel extraction) will also influence production decisions. Generally, a fiscal regime that depends

[1] BP defines proven or 'proved reserves of a field as those that geologic and engineering data show have a better than 90 percent chance of being produced over the life of the field, under current economic and operating conditions.

more on production-based taxes (for example, a royalty) will impose a heavier tax burden on less profitable projects, which will discourage production. In contrast, the tax burden associated with more-profit-based instruments is more responsive to changes in profitability.

Countries therefore face a trade-off between production and revenue objectives in the transition to a future with lower fossil fuel production and prices. A fiscal regime that adapts more flexibly to a range of profitability outcomes (that is, more emphasis on profit-based fiscal instruments) would adjust better to declining economic rents. However, a production-based tax (such as a royalty) would provide more certainty about revenue during the transition period.

Estimating the Impact on Fossil Fuel Revenues

A simple modeling framework is used to estimate the impact of production and price declines on annual fossil fuel revenue by 2040 based on International Energy Agency (IEA) forecasts, capturing the combined impact of country-level differences in extraction costs and fiscal regime design.[2]

The framework uses the IMF Fiscal Analysis for Resource Industries (FARI) methodology to estimate the revenue impact of the production and price projections associated with various climate mitigation scenarios on a representative oil, gas, and coal project, for a sample of resource-rich countries.

FARI is a project-level modeling methodology to estimate the government's share of a resource project's total pretax net cash flows. It is an Excel-based, discounted cash flow model set up to reflect tax accounting rules and specific tax payments to the government. The FARI methodology starts with the calculation of projected net cash flows before any fiscal impositions. It then calculates each fiscal payment according to fiscal regime parameters. These individual payments are added up to calculate the total government revenue from the project. The model captures the effect of interactions among the parameters constituting the entire fiscal regime.

For each country in the sample, using a tailored project example and country-specific fiscal regime, the model calculates the relative change in government revenue under the price and production assumptions associated with each climate mitigation scenario, compared with a baseline scenario at 2017 price levels. This relative change is then applied to 2017 fossil fuel revenue figures from the IMF Resource Revenue Database to generate an estimate of revenue in 2040 under different price and production scenarios. GDP projections to 2024 are drawn from the World Economic Outlook database; real GDP growth thereafter is based on growth in the working-age population (sourced from the United Nations) and projected productivity growth. As a simplifying assumption, GDP projections are kept constant across all scenarios.

In applying country fiscal regimes to a tailored project example, this methodology seeks to quantify the revenue impact on producing countries, taking into account differences in fiscal regimes and production costs. Country selection was based on current fossil fuel production levels, remaining reserves, and current dependence on fossil fuel revenues. The sample comprises 57 countries (Figure 1.10.2), accounting for 95 percent of current global petroleum production and 95 percent of coal production. Prospective fossil fuel producers with recent discoveries, such as Guyana and Mozambique, are not included in the analysis.

[2] The estimates focus on 2040 to assess the longer-term impact on fossil fuel production, prices, and government revenues over the next two decades.

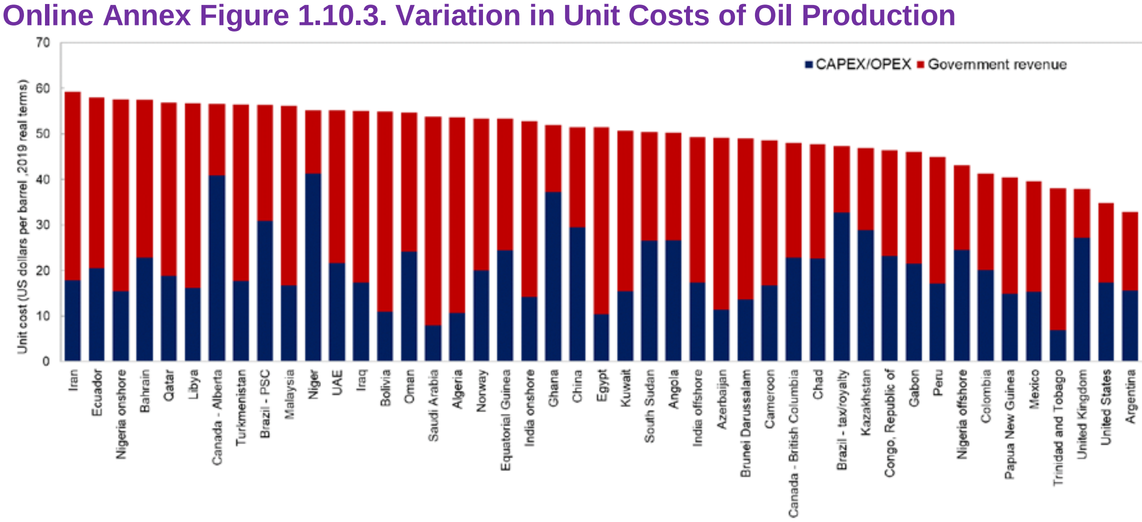
Online Annex Figure 1.10.2. Fossil Fuel Producers

Source: IMF staff.

Model Inputs

- **Project Costs:** The framework uses stylized oil, gas, and coal project examples with country-specific adjustments. In modeling the impact on each resource producer, a country-specific adjustment is made to the assumed cost parameters to reflect the variation in unit capital and operating costs across countries (Figure 1.10.3).

Online Annex Figure 1.10.3. Variation in Unit Costs of Oil Production

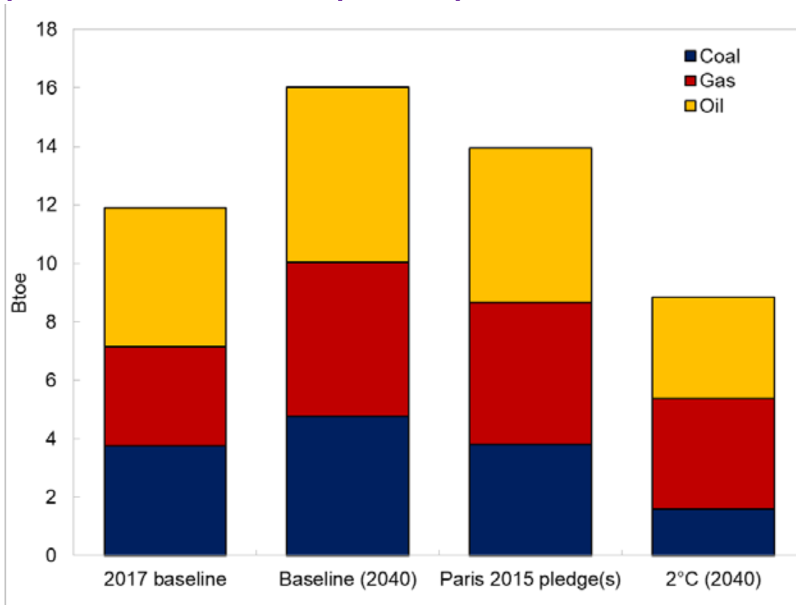


Sources: Rystad Energy; and IMF staff estimates.
Note: CAPEX = capital expenditure; OPEX = operational expenditure; PSC = production sharing contract; UAE = United Arab Emirates.

- **Fiscal Regime Parameters:** For each country, a representative fiscal regime was applied to the pretax cash flow of the stylized project example. The fiscal regime modeled constitutes the core tax and nontax charges on profit and production (for example, royalties, corporate income tax, additional rent taxes, payments to government under production sharing agreements, revenues from state participation in resource projects). In some countries (for example, Norway, United Kingdom), this reflects the statutory regime applicable to all projects operating in the country. In countries where the regime differs by type of operation (for example, onshore or offshore), both types of operations were modeled. In cases where fiscal regimes vary by contract, a representative regime was selected.

- **Production:** Oil, gas, and coal production forecasts under different climate change mitigation scenarios provide the basis for assessing the impact on fossil-fuel-producing countries (IEA 2018; Figure 1.10.4).[1] Under the business as usual (BAU) forecast, continued high demand for fossil fuels is expected to lead to increased production of coal and oil by 2040, together with a marked expansion of gas production. In an alternative scenario assuming implementation of the Paris pledges, fossil fuel production is lower than in the BAU forecast but still higher than today's production levels. A more ambitious climate change mitigation scenario, sufficient to keep global temperature increases below 2°C, envisages a reduction in oil and coal production in 2040 by 30 percent and 60 percent, respectively, relative to current levels.

Online Annex Figure 1.10.4. Global Fossil Fuel Production by Climate Mitigation Policy Scenario, 2017 and 2040
(Billions of tons of oil equivalent)



Source: IEA 2018 *World Energy Outlook*.
Note: BAU = business as usual.

Under the modeling framework, any change in global production associated with different climate mitigation scenarios is assumed to be distributed across countries weighted according to relative unit costs as well as current levels of production in each country. This reflects the premise that in a scenario of reduced fossil fuel demand and production, more costly operations will be curtailed, and if demand were to increase, the least costly production would increase, subject to production capacity and resource availability. The fiscal regime is assumed to remain constant; in practice, countries may adjust their fiscal regime as part of their adaptation strategy. Under the modeling framework, this country-specific relative

[1] (1) The BAU (IEA "current policies") scenario assumes no change in demand, which is expected to increase with GDP growth; (2) the Paris pledges (IEA "new policies") scenario assumes the implementation of all pledges; and (3) the (below) 2°C (IEA "sustainable development") scenario assumes a carbon price of \$75/ton CO_2 by 2030 and \$140/ton CO_2 in 2040. This scenario assumes technological innovation in both carbon capture and overall energy efficiency.

production increase or decrease associated with each climate scenario was applied to the stylized project example.

Prices: A constant oil, gas, or coal price from the IEA forecasts corresponding to the relevant climate change mitigation scenario is applied to the stylized project example. The IEA 2018 *World Energy Outlook* assumes an increase in real crude oil prices to $137/barrel by 2040 in the BAU scenario, with relatively lower prices of $112/barrel under the Paris pledges scenario and $64/barrel in the 2˚C scenario. Gas and coal prices follow a similar trajectory (Table 1.10.1). Given the uncertainty around these price paths, the analysis incorporates an alternative sensitivity scenario with lower commodity prices for the 2˚C scenario. The oil prices in the IEA scenario reflect a requirement that new fossil fuel investment compensate for declines in output from existing fields. The alternative price scenario is derived from a general equilibrium model developed by the IMF Research Department (Annex 1.11).

Results

The analysis shows that the revenue impact of the Paris pledges scenario is relatively benign for fossil fuel producer revenues, given the increase in prices and production relative to the current baseline. [2] However, under a 2˚C climate change scenario, revenues could decline between 7 and 9 percent of GDP by 2040, albeit with considerable variation between countries (Figure 1.10.5).

Online Annex Table 1.10.1. Mitigation Scenarios: Producer Price Assumptions

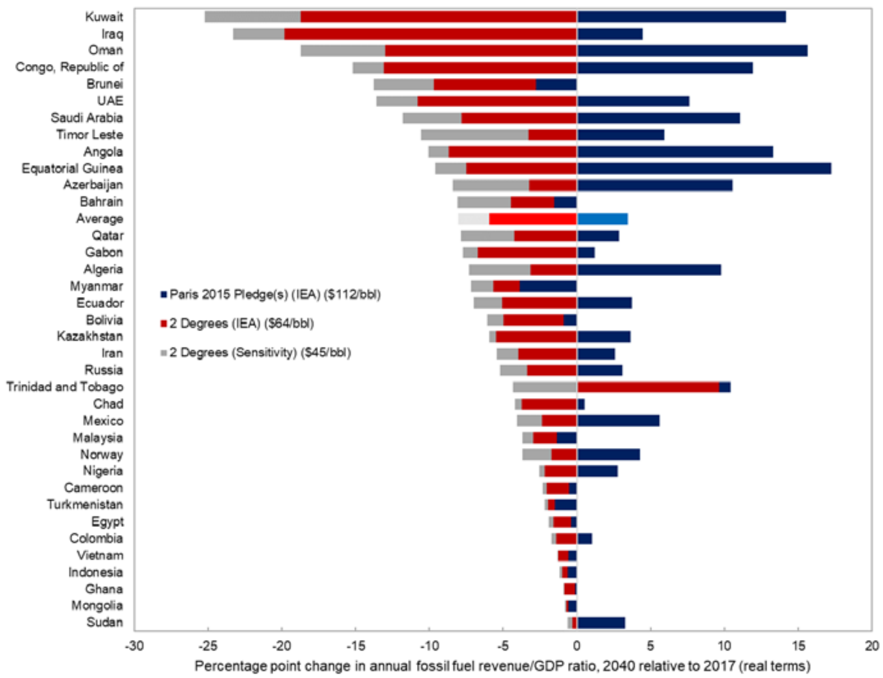
		2017	2040			
		Current	Baseline	NDC	2DC	2DC (sensitivity)
Crude Oil	*$/barrel*	52.05	137.00	112.00	64.40	45.00
Natural Gas						
United States	*$/MBTU*	2.99	5.30	4.90	3.60	2.52
European Union	*$/MBTU*	5.83	9.40	9.00	7.70	5.38
China	*$/MBTU*	6.48	10.20	9.80	8.50	5.94
Japan	*$/MBTU*	8.15	10.50	10.10	8.80	6.15
Steam coal ($/ton)						
United States	*$/ton*	60.40	68.83	63.72	56.43	39.43
European Union	*$/ton*	84.50	98.41	84.88	66.24	46.29
Japan	*$/ton*	94.76	104.54	90.22	70.40	49.19
Coastal China	*$/ton*	101.84	105.93	94.40	78.72	55.01

Source: IMF staff estimates.
Note: BAU = business as usual; MBTU = thousands of British thermal units.

The biggest economic impact will be felt in countries most dependent on fossil fuel revenue (for example, Kuwait, Saudi Arabia, Timor-Leste). Kuwait, for example, which currently collects about 40 percent of GDP in revenues from petroleum, would collect between 11 and 18 percent of GDP in 2040. The results are driven largely by movements in oil prices and production (Figure 1.10.6). While the impact of reduced coal production in affected regions may be significant, in macro-fiscal terms, coal revenues represent a small proportion of GDP in producing countries. The effect of changes in gas revenues is also modest under the IEA 2˚C price assumptions, generating significant effects only in a few predominantly gas producing countries. Other countries, while experiencing a large revenue decline relative to current levels, appear less vulnerable due to the relative diversification of their economies (for example, Colombia, Malaysia; Figures 1.10.7 and 1.10.8).

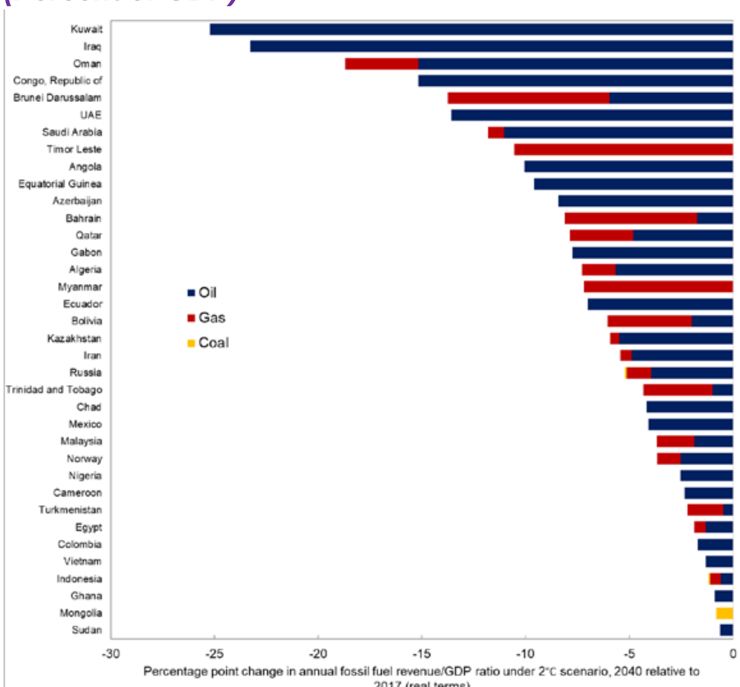
[2] Some countries (for example, Libya and South Sudan) see a decline in fossil fuel revenue relative to GDP even in the Paris pledges scenario (Figure 1.10.5). This is driven by GDP growth that is higher than the increase in fossil fuel revenues.

Online Annex Figure 1.10.5. Change in Fossil Fuel Revenue by Scenario
(Percent of GDP)



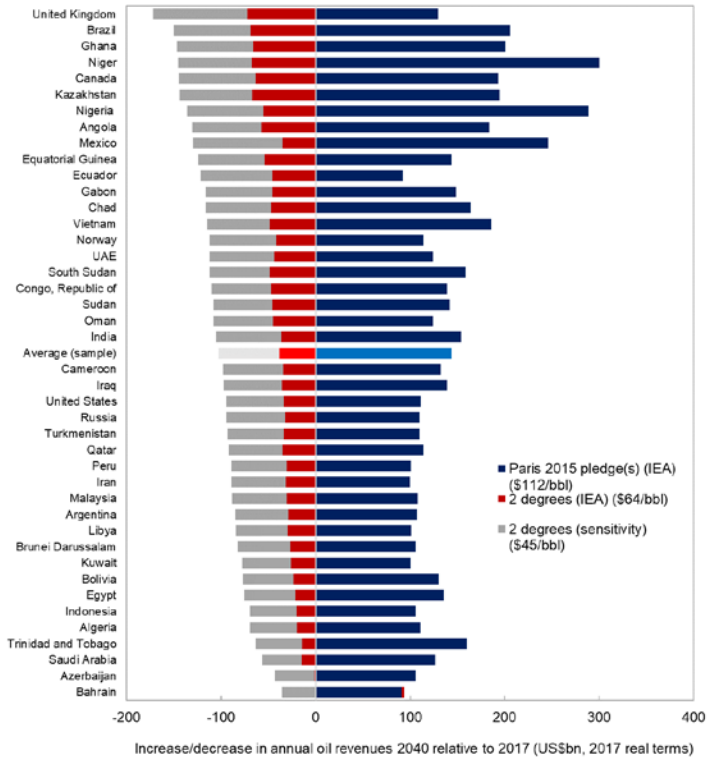
Source: IMF staff calculations.
Note: UAE = United Arab Emirates.

Online Annex Figure 1.10.6. Impact on Fossil Fuel Revenues by Commodity—2°C Scenario (Sensitivity)
(Percent of GDP)



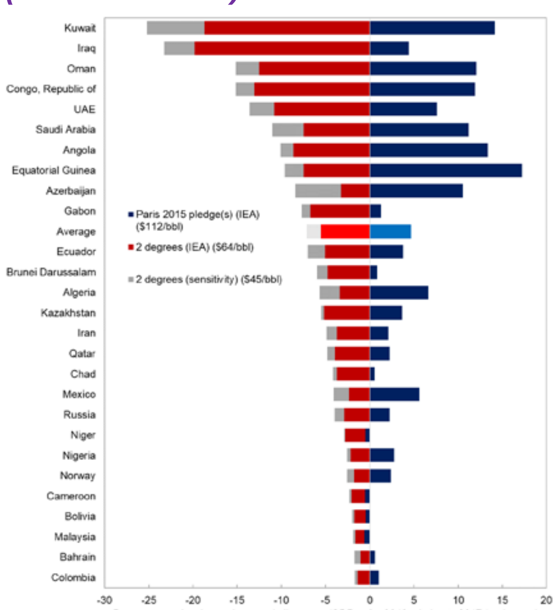
Source: IMF staff calculations.

Online Annex Figure 1.10.7. Percentage Change in Oil Revenues by Scenario



Source: IMF staff estimates.
Note: bbl = barrel; bn = billion; UAE = United Arab Emirates.

Figure 1.10.8. Change in Oil Revenues by Scenario *(Percent of GDP)*



Source: IMF staff estimates.
Note: bbl = barrel; bn = billion; UAE = United Arab Emirates.

For countries that depend on fossil fuel revenue, this potential revenue decline will require a significant fiscal adjustment. Beyond diversifying their economies, fiscal reforms that these countries should consider include scaling up financial savings from current hydrocarbon revenue and establishing a sound domestic revenue base outside the fossil fuel sector. The fiscal adjustment would also be supported by removing remaining fossil fuel subsidies.

A Carbon Royalty on Fossil Fuel Production

In the context of an internationally coordinated approach on a minimum carbon tax floor, one challenge in reaching consensus on a consumption-based carbon tax is the varied impact across countries—net importers of fossil fuel, which collect revenues on fuel consumption, and net exporters, which face revenue losses from reduced production and lower producer prices. In view of this adverse impact on revenues and economic activity for fossil-fuel-rich countries, it is important to explore innovative ways of making carbon taxation more acceptable for them.

In principle, a carbon tax could be imposed at any point in the fossil fuel production chain to achieve a particular production outcome. While a carbon tax imposed on consumption directly impacts consumer demand with a resulting effect on production and prices, a carbon tax on production would have a more direct impact on production decisions. Could a carbon tax imposed on production (combined with consumption-based measures) provide incentives for petroleum producing countries to support a carbon tax agreement and ease the transition to a low-carbon future?

Designing a Carbon Royalty

A royalty is commonly imposed as an ad valorem charge on fossil fuel production,[1] providing revenue to the government from the start of production.[2] Royalties are typically collected either by the tax authorities or a sector ministry or regulator. A carbon royalty could therefore be added to existing royalties in the petroleum fiscal regime,[3] and tax collection could utilize the existing institutional setup for administering production-based royalties. In some cases, it may also be politically preferable to collect a carbon tax directly on production rather than on final consumption.

However, the design of a carbon royalty would differ in some respects. A carbon royalty should be imposed as a specific levy based on the carbon content of fossil fuels (that is, per ton of CO_2). As an illustration, a carbon tax of $35 per ton of CO_2 would equal a production tax of $15 per barrel of oil and $11 per barrel of oil equivalent of gas, based on CO_2 emissions of 0.43 and 0.32 metric tons per barrel of oil equivalent, respectively. The taxes should be applied to all fossil fuels—oil, gas, and coal and to any refined fuel products derived from these commodities.

International Coordination

A carbon royalty could play an important role in reaching consensus for an internationally coordinated approach on a carbon price floor. A carefully calibrated combination of both a carbon royalty on fossil fuel production and a carbon tax on consumption would allow for a more even distribution of tax

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[1] Imposing a limit on cost oil recovery under a production sharing agreement also has a similar effect to a royalty.

[2] However, it also increases the risk of the production being shut down earlier as marginal costs increase.

[3] The "normal" royalty could alternatively be interpreted as a rent payment to the resource owner, an option price on extracting the resource, or a minimum tax payment to the government from the start of production.

revenue between net importers and exporters of fossil fuels while still achieving the same price and production outcomes.[4]

If a royalty were introduced among countries with sufficient collective market power, consumer and producer prices would indeed be unaffected by whether the carbon tax is imposed on consumption or production.

The carbon royalty could be part of a coordinated agreement on an international carbon price floor, with importing countries adjusting the carbon tax imposed on fossil fuel imports to provide a rebate for any carbon royalty paid on fossil fuel extraction in the exporting country.[5] The border adjustment is an important mechanism to ensure that the arrangement is not undermined in the event that a country reneges on the agreement. For example, if a producing country decided to reduce its carbon production tax, there would be an offsetting increase in the tax on consumption in the importing country to maintain the overall carbon tax burden. [6]

However, such international coordination would require careful design and consideration. Some countries may be driven to offset the introduction of a carbon royalty by reducing other royalty rates (or through other offsetting changes to the fiscal regime).[7] This is especially likely if their objective is to encourage continued investment and production of fossil fuels in a low-carbon environment. The issue may also be particularly pertinent for fossil fuel production by a national oil company in which case a higher royalty can be offset by lower transfers of after-tax profits to the national treasury. The scope for countries to impose additional taxes on fossil fuel extraction activities may also be limited by contractual stability clauses for existing projects.

The carbon royalty could also be introduced effectively by a group of countries (or a large producer) in the absence of a global agreement on carbon taxes. In this case, while other oil producers may have an incentive to increase production to meet the resulting unmet demand, doing so would still have an impact on final consumer prices, since the oil supply curve in individual countries is upward sloping, implying higher costs for any additional production.

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[4] While in theory, this would involve equalizing the posttax producer price by setting project-specific carbon royalties reflecting inter- and intracountry variations in cost and fiscal regime, this would be administratively complex, and therefore a more practical proposal involving a single specific carbon royalty rate is described here.

[5] In situations with more integrated supply chains—for example, crude oil refined in another country—this would require a monitoring system to track the origin of fuel products.

[6] An alternative revenue collection mechanism could collect the tax on final consumption but agree on a revenue sharing arrangement between net-importing and net-exporting countries (consumers and producers). However, this is likely to be less practical and politically more difficult as it would require continued revenue transfers from fossil fuel net importers to net exporters.

[7] This is not a unique problem but may also arise in the case of a domestic carbon tax and possibly offsetting adjustments to excise duties on fuel products.

Online Annex 1.11. The Oil Market Effect of a Carbon Tax Consistent with 2°C (Alternative Price Scenario)

A stylized oil market model is used to study the effect of a carbon tax consistent with a reduction in CO_2 emissions that would limit the rise in global temperature to 2 degrees Celsius—the upper limit proposed in the Paris 2015 agreement.

The Model

The model has two oil sectors, shale and conventional oil, oil-specific investment, and a demand side driven by population and income growth for a given oil price. A carbon tax is introduced as a wedge between the producer and consumer (that is, end-user) prices. Two price elasticities govern the demand substitution from petroleum products and oil-sector investment decisions. There is a substantial lag for conventional oil investment before oil production can come onstream, but this is much shorter for the tight oil sector. On the demand side, the price elasticity of demand is nonconstant and increases from zero, as the oil price deviates from its baseline value.[1] Both consumer and producer prices will be determined to clear the oil market and equilibrate demand and supply of oil.

The model is cast in deviations from a baseline assumed to be consistent with the approximate adoption of the Nationally Determined Contributions, in which oil consumption and emissions increase as in the International Energy Agency (IEA) "new policies" scenario. In contrast to the IEA's scenario, however, the model's baseline assumes a $60 (in 2018 US dollars) oil price prevailing over the long term as this is near its 1974–2018 historical average and the average of the five-year-ahead futures prices since the oil price collapse in 2015.[2]

The carbon tax required to meet the 2°C target is assumed to be $150 per ton of carbon, slightly higher than in the IEA sustainable development scenario (which, however, includes additional mitigation policies). We assume that the carbon tax is fully anticipated and introduced smoothly, rising from $0 to $150 by $6 a year with a five-year implementation lag.

Results

At the announcement, the carbon tax has a positive effect on energy prices as conventional oil producers cut investment in anticipation of reduced demand for petroleum products as a result of the future introduction of the carbon tax. Hence, initially, oil production declines, but only modestly since shale oil partially offsets that decline, gaining market share, attracted by short-term profits (see Figure 1.11.1). As the carbon tax wedge increases, however, both shale and conventional oil production decline since consumers become more sensitive to the higher prices of petroleum products and more willing to switch away from products with high carbon content. Under our reference scenario, the producer price of oil declines by 43 percent while global oil production declines by more than 30 percent. This means that the value of production has declined by more than 60 percent. The value of global oil production as a share

[1] The time-varying nature of the price elasticity captures the possibility of switching to alternative technologies with nonnegligible adoption costs. The stronger the change in the prospective oil prices the higher the price elasticity of demand. We calibrate the price elasticity of demand such that it is zero in a neighborhood of the baseline oil price, but it increases to –0.2 as the price increase reaches 20 percent and higher as the price increases further.

[2] An oil price at [$110] (2018 US dollars), as in the IEA new policy scenario, is the top 5th (3rd) percentile of the oil price distribution between 1974 and 2018 (1861 and 2018).

of global GDP initially increases slightly to 2.6 percent from 2.5 percent in the baseline and subsequently declines to 0.8 percent by 2040.[3]

Online Annex Table 1.11.1.

Assumptions		2016	2020	2025	2030	2035	2040	2045	2050-
Base Price (real)	(assumption)	$45	$60	$60	$60	$60	$60	$60	$60
Carbon Tax (wedge log difference)	(assumption)		0%	20%	40%	60%	80%	100%	100%
Carbon Tax (per barrel)			$0	$12	$24	$36	$48	$60	$60
Implied Carbon Tax per ton of CO_2			$0	$30	$60	$90	$120	$150	$150
Oil Production Base (MB/D)	(assumption)	96	101	105	108	109	111		
Energy Use (MB/D)		82	85	86	86	85	85		
Combustion (MTOE)		3,719	3,881	3,908	3,917	3,870	3,864		
TPED (MTOE)		4,364	4,559	4,754	4,830	4,842	4,894		
Petrochemical Use (MB/D)		9	9	10	11	12	13		
Global Oil Production over GDP	%	1.9%	2.5%	2.2%	1.9%	1.6%	1.4%		
Simulation Results									
Oil Production (MB/D)			101	103	99	91	83		
Producer Prices	USD (2018)		$62.3	$64.1	$59.5	$52.9	$44.9	$35.5	$36.5
Consumer Prices	USD (2018)		$62.3	$76.1	$83.5	$88.9	$92.9	$95.5	$96.5
Global Oil Carbon Tax Revenue	Billion USD (2018)		$0.0	$368.4	$693.3	$934.5	$1,113.7		
Global Oil Carbon Tax Revenue/GDP	%		0.0%	0.3%	0.6%	0.6%	0.6%		
Global oil production value/GDP	%		2.6%	2.3%	1.7%	1.2%	0.8%		

Source: International Energy Agency and IMF staff calculation.
Notes: Base oil production and global GDP projections are based on the International Energy Agency's, World Economic Outlook new policy scenario. MB/D = millions of barrels a day. USD = US dollars.

The burden of the carbon tax is initially borne by consumers who have difficulty switching to alternative oil sources in the initial transition phase after the tax is implemented. By 2030, indeed, almost 100 percent of the $60 carbon tax is borne by consumers. As the model converges to the new steady state the share of the carbon tax is rebalanced, with consumers paying 55 percent of the $150 carbon tax.

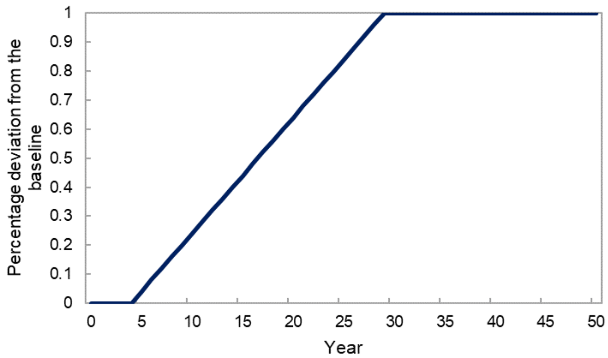
The carbon tax also raises fiscal revenues, which initially increase as the tax level rises but later stabilize thanks to the offsetting effect of lower oil production value.[4] The overall carbon tax revenues from oil rise to more than $1 trillion by 2035, representing 0.7 percent of global GDP.

[3] As in the IEA scenario we assume that global GDP grows 3.4 percent a year in 2018 US dollars, on average, between 2017 and 2040 (IEA 2018).

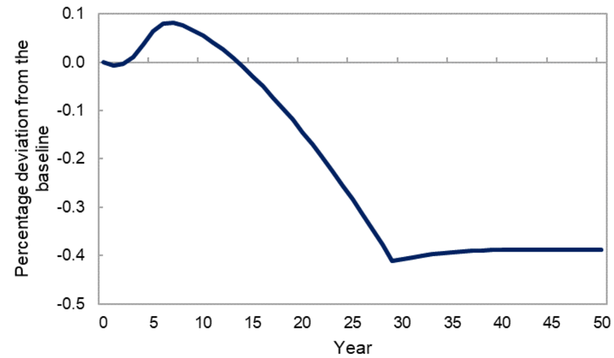
[4] For simplicity, in the model we posit that the use of fiscal revenues has no effect on demand for petroleum products or on CO_2 emissions.

Online Annex Figure 1.11.1. Model Simulations—Transition to a $150 Carbon Tax

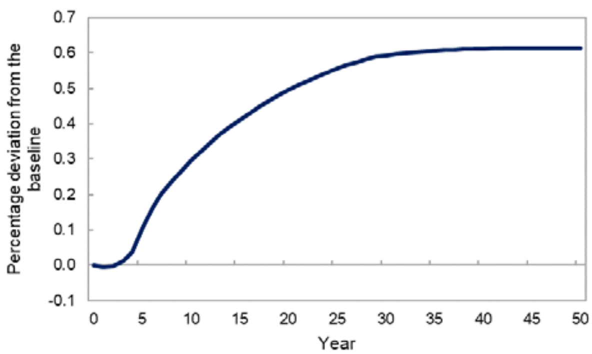
1. Tax Wedge (tax rate, percent)



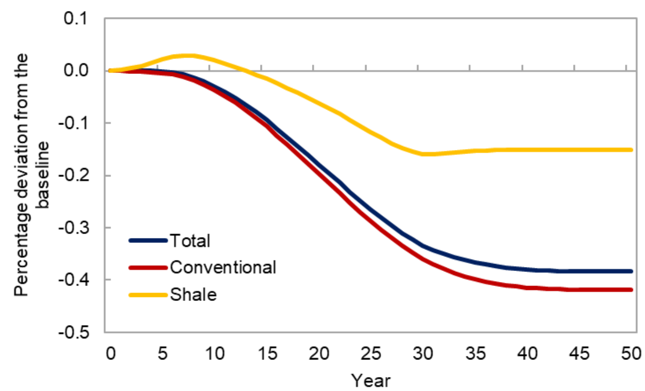
2. Producer Price of Oil



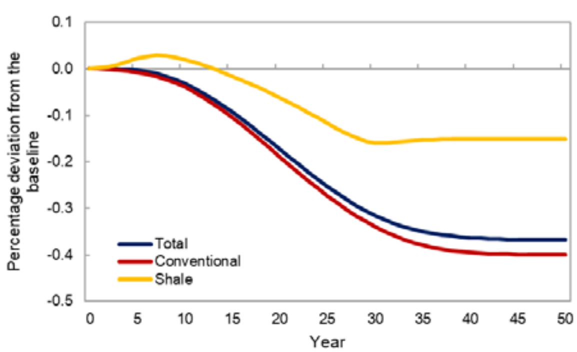
3. Consumer Price of Oil



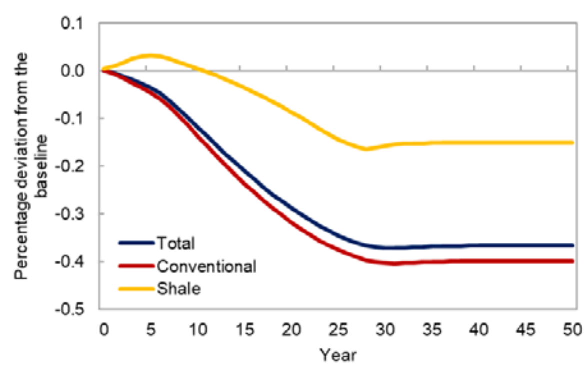
4. Oil Production



5. Oil Sector Capital Stock



6. Oil Sector Investment



Source: IMF staff estimates.
Note: See Table 1.11.1 for the evolution of the carbon tax shock and underlying assumptions.

Online Annex 1.12. Literature Review of Possible Financial Policies to Reinforce Mitigation Incentives

Financial policies could play an important role in mitigating climate change, but a consensus has yet to emerge on an appropriate set of policies. This annex provides an overview of recent proposals on how financial policies could support climate change mitigation.

Financial policies can complement fiscal policies to foster switching investment toward less-carbon-intensive sources. At present, investment in low-carbon technologies is too low because the payoff would be reaped many years—possibly decades—from now and profitability is very uncertain (see, for example, Carney 2015). Two major sources of risk differentiate these investments from other long-term investments: uncertainty about their ability to deliver carbon abatement and uncertainty about the future profitability of avoiding emissions. Financial policies could play a useful role by creating incentives for financial actors to divest from carbon-intensive activities and invest more in low-carbon projects (including renewable energy; energy efficiency; land use; and urban, transportation, infrastructure, and industrial systems), thereby helping decarbonize the productive structure of the economy, while maintaining macro-financial stability. While some of these ideas are unorthodox, the urgency of climate change mitigation suggests that they need to be considered.

Studies in this area can be divided into four broad categories (Krogstrup and Oman, 2019):

1. *Financial policies to correct underpricing and lack of transparency regarding climate risks in financial markets and prudential frameworks:* Prudential frameworks could give more favorable treatment to financial assets associated with low-carbon activities (Schmidt 2014). To mobilize capital for green investments, policymakers could engage with stakeholders to develop a taxonomy on economic activities that contribute to the low-carbon transition and those that are more exposed to climate-related risks (NGFS 2019). Prudential and collateral frameworks could also be adapted to incorporate climate-related financial risks, conditional on a thorough assessment of the financially systemic nature of climate risks (Monnin 2018, Schoenmaker and Tilburg 2016). One proposal is to introduce a "green supporting factor" in prudential rules to increase banks' demand for financing green investments (EU High-Level Expert Group on Sustainable Finance 2018).

2. *Policies to help reduce the short-term bias and improve governance frameworks of financial institutions:* Policies targeting corporate governance and the financial sector's interactions with regulation and accounting standards could correct the bias against the financing of long-term uncertain investments that are typical of mitigation investments. Biases are related to corporate governance that is heavily biased in favor of short-term financial returns, with managers' compensation typically dependent on financial targets (Admati 2017). Moreover, environmental, social, and governance (ESG) criteria could be given a greater role in the composition of equity indices used by institutional investors, with passive investment strategies based on the notion that the optimal allocation strategy is to diversify financial portfolios by tracking benchmark stock market indices. Likewise, central banks could incorporate ESG aspects into their portfolio management (NGFS 2019). ESG factors could also be progressively incorporated into corporate accounting standards (Investment Leaders Group 2014).

3. *Policies to support the development of markets for green financial markets and instruments:* Issues of sustainable finance, notably ESG criteria, are covered in the *Global Financial Stability Report* (IMF 2019), with an emphasis on the need to further develop transparent standards and disclosures.

4. *Using central bank asset purchases and funding and collateral policies to favor climate-friendly activities:* These proposals are among the most controversial because they add new goals to central bank policies. One

proposal is to use central bank asset purchases to reallocate financial resources toward green economic activities and steer the allocation of assets and collateral toward low-carbon sectors (De Grauwe 2019). Another is for central banks to ensure better access to funding systems for commercial banks that invest in low-carbon projects or to amend forward guidance policies to raise market expectations regarding green investments (Campiglio 2016). Public guarantees have also been proposed to boost the financing of the investments needed to gear national production structures toward the low-carbon economy (Dasgupta and others 2019). To enable financial actors to lock in returns to mitigation investments that are commensurate with their social value—and hence facilitate their financing—Aglietta and others (2015) propose so-called carbon remediation assets at a politically accepted predetermined return (corresponding to the social value of mitigation action) per ton of emissions avoided. The rationale behind this proposal is that it could help prevent the fragmentation of climate finance initiatives by fostering a new class of long-term, low-carbon assets, thus mobilizing large savings for low-carbon investments.