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Mitigation Policies for the Paris Agreement: An Assessment for G20 Countries

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Abstract

Following submission of greenhouse gas (GHG) mitigation commitments or pledges (by 190 countries) for the 2015 Paris Agreement, policymakers are considering specific actions for their implementation. To help guide policy, it is helpful to have a quantitative framework for understanding: i) the main impacts (on GHGs, fiscal balances, the domestic environment, economic welfare, and distributional incidence) of emissions pricing; ii) trade-offs between pricing and other (commonly used) mitigation instruments; and iii) why/to what extent needed policies and their impacts differ across countries. This paper provides an illustrative sense of this information for G20 member countries (which account for about 80 percent of global emissions) under plausible (though inevitably uncertain) projections for future fuel use and price responsiveness. Quantitative results underscore the generally strong case for (comprehensive) pricing over other instruments, its small net costs or often net benefits (when domestic environmental gains are considered), but also the potentially wide dispersion (and hence inefficiency) in emissions prices implied by countries' mitigation commitments.

JEL Classification Numbers: Q48, Q54, Q58, H23

Keywords: Paris Agreement, carbon pricing, G20 countries, instrument choice, air pollution mortality, tax incidence, welfare effects, climate mitigation

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I. INTRODUCTION AND SUMMARY

The landmark 2015 Paris Agreement lays the foundations for meaningful action to begin slowing atmospheric accumulation of heat-trapping gases. The centerpiece of the Agreement is commitments by 190 countries to reduce greenhouse gas (GHG) emissions, as specified in their 'nationally determined contributions' (NDCs).[1] While these contributions are not consistent with containing mean projected warming to 2ºC,[2] are partially dependent (for some countries) on external finance, and are not legally binding[3], countries are expected to report progress on meeting their NDCs (every two years starting 2018) and to submit updated NDCs (every five years). For G20 countries specifically—which collectively accounted for 81 percent of global carbon dioxide (CO_2) emissions in 2015[4]—NDCs target emissions (or, for China and India, emissions relative to GDP) mostly for 2030, though pledges differ in nominal stringency and baseline years against which targets apply (Table 1).

It is long established in theoretical literature[5] and increasingly appreciated among policymakers, international organizations, businesses, and others[6] that carbon pricing would ideally be a key element of (energy-related) CO_2 mitigation strategies[7]for two reasons. First, comprehensive carbon pricing provides across-the-board incentives for reducing energy use and shifting to cleaner fuels. Second, (just like existing fuel taxes) carbon pricing raises significant revenues: an important concern for finance ministries, as this allows the reduction of other burdensome taxes, funding of growth-enhancing investment, or alleviation of fiscal pressures. There is not a one-size-fits-all approach to mitigation, however: carbon pricing may be difficult politically in some countries, not least because of its first-order impact on energy prices, which underscores the importance of understanding trade-offs with other mitigation instruments.

To move policy forward, it is helpful to have quantitative assessments of the CO_2, fiscal, local health and environmental, economic, and incidence impacts (across households and firms) of carbon pricing at the country level and of trade-offs among mitigation instruments: carbon taxes,

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[1] To date, 195 countries have signed the Agreement and 180 have ratified it, though not all signatories have submitted mitigation pledges (WBG 2018, pp. 33).

[2] The goal of the Paris Agreement is to contain warming to 1.5-2.0ºC. According to UNEP (2017) current NDCs are consistent with an emissions trajectory limiting warming to 3.0ºC.

[3] The United States, for example, announced in 2017 its intention to withdraw from the Agreement in 2020.

[4] IEA (2017a), pp. 94.

[5] For example, Baumol and Oates (1971), Dales (1968), Kneese and Bower (1968), Montgomery (1972).

[6] See for example WBG/OECD (2015), Farid et al. (2016) and www.carbonpricingleadership.org/carbon-pricing-panel.

[7] These emissions are easily the most important GHG at the global level, accounting for 70 percent at present and likely a higher share in the future (UNEP 2017), and are the most practical to price.

emissions trading systems (ETSs), taxes on individual fuels, energy efficiency incentives, and so on. This information helps policymakers: choose among instruments; design policy specifics (e.g., policy stringency, use of potential revenues, compensation for vulnerable groups); and communicate the case for policy reform. At the international level, assessing whether countries are likely to fall short, meet, or exceed their targets under (explicit or implicit) carbon price scenarios informs dialogue on future NDC revisions and the possible need for coordination mechanisms.

This paper uses a reduced form model[8] to provide an illustrative sense of this information for G20 countries. The model projects country-level fuel use by sector in a business-as-usual (BAU) scenario, assuming (for transparency of comparisons) no new mitigation policies. The environmental, fiscal, and economic welfare impacts of carbon pricing and other mitigation instruments are then computed, with all policies (again for transparency) scaled to impose the same explicit or implicit CO_2 price,[9] and using assumptions for fuel price elasticities, emission rates, and local externalities (e.g., air pollution mortality). Incidence analysis is also conducted for Canada, China, India, and the United States[10] by linking the model to input-output tables and household expenditure surveys.

A large number of other (far more detailed) models have been used at the individual country (especially US), regional, and global level to assess the emissions implications of pricing CO_2 (and sometimes other GHGs).[11] Our approach is meant to complement this large body of literature in several respects, by: providing consistent comparisons across a broad range of countries[12]; evaluating policies against a broad range of metrics (emissions, fiscal, health, economic welfare

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[8] A variant of the model was previously applied to China (Parry and others 2016) and India (Parry, Mylonas and Vernon 2017).

[9] Implicit carbon prices refer to the price on CO_2 emissions affected by a non-price instrument that would cause the same reduction in those emissions as the non-price instrument.

[10] Data and time constraints preclude applying the incidence analysis to all G20 countries.

[11] For a sampling of recent literature see, for example: Aldy et al. (2016) on emissions prices for mitigation pledges needed for large countries and regions; Barron and others (2018) on carbon pricing for the United States; IPCC (2014), IEA (2017), and Stern and Stiglitz (2017) on prices for global climate stabilization targets; and the Energy Modelling Forum (https://emf.stanford.edu) for further modelling exercises. Many country authorities are also doing their own, or commissioning, modelling (see www.thepmr.org).

[12] Prior studies focus on fewer countries (not least given the more intensive data and computational requirements for country applications), for example, Aldy et al. (2016) distinguish five G20 countries (plus the EU and Africa).

and incidence)[13]; comparing pricing with a range of alternative mitigation instruments;[14] and providing transparent explanations for why results differ across countries, policies, and parameter scenarios. Our reduced-form model is highly simplified, but it is parameterized such that it approximates projections and underlying behavioral responses for fuel use and emissions generated by more disaggregated, structural models (e.g., that account for detail on emerging technologies or feedback effects on fuel use from general equilibrium effects). Caveats to the analysis are extensively discussed below (see section II.B.), and are important to bear in mind, though in many cases they mainly involve choices over parameter values, and the implications of alternative assumptions are discussed through a sensitivity analysis (see section III.D.).

Some quantitative findings are summarized as follows.

Under a carbon tax alone, *assumed here to have full coverage* (i.e., the tax is applied to the carbon content of fossil fuel supply) and reaching, for illustration, a price of \$70 per ton[15] of CO_2 by 2030, seven countries meet or exceed the CO_2 component targets implied by their NDCs (Argentina, China, India, Indonesia, Russia, South Africa, and Turkey), another six countries would need further emissions reductions of up to 10 percent (Brazil, Germany, Japan, Korea, Mexico, and United States), and six countries would need further emissions reductions of above 10 percent (Australia, Canada, France, Italy, Saudi Arabia, and United Kingdom). These cross-country differences reflect differences in both the stringency of NDCs and in the relative price-responsiveness of emissions. For the whole G20, however, a carbon price of \$35 per ton in 2030 is consistent with the total of current NDCs (given the disproportionate influence of China and India).

Carbon taxes can also raise substantial revenues, around 1-2.5 percent of GDP in most cases for the \$70 per ton tax in 2030, and considerably more than that in a few cases. They also reduce deaths from local air pollution due to fuel combustion by roughly the same proportion as the reduction in CO_2 emissions—the value of the reduction in local pollution deaths per ton of CO_2 reduced in China, for example, is estimated at a striking \$100. The pure welfare costs of the \$70 per ton tax are generally not too large (less than 0.8 percent of GDP in all but three cases). However, accounting for local environmental benefits (but not global warming), the net welfare impacts are around zero to strongly positive in all but three cases.[16]

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[13] Fiscal, health, and economic welfare impacts—at least with the latter defined net of local environmental benefits—are often not reported in other studies. The (unpriced) domestic environmental costs of fuel use are just as real as the supply costs however and in our view should be factored into welfare calculations.

[14] Only a few studies compare a diverse range of instruments and only for one country (e.g., Krupnick and others 2010 and Parry, Evans, and Oates 2014).

[15] All prices and monetary values are expressed in US \$2015.

[16] Other studies have also documented the significant air pollution deaths avoided as a by-product of carbon pricing (e.g., Nemet and others 2010, West and others 2013).

Coal taxes can be especially effective environmentally, achieving over 75 percent of the CO_2 reductions under the carbon tax in six countries. For the same price and coverage, an ETS would have equivalent emissions impacts as the carbon tax in this analysis—hence the 'carbon tax' policy can also be interpreted as a fully comprehensive ETS. However, following typical practice to date (and to distinguish it analytically from the carbon tax), ETSs are assumed to cover large stationary emission sources only and as a result reduce emissions by between about 40 and 75 percent of the reductions under the (equally priced) carbon tax in most countries. A tax on CO_2 emissions from power generation typically achieves 80 percent or more of the emissions reductions under ETSs. Energy efficiency policies, even if implemented nationwide (which would be practically challenging), typically reduce emissions by between 25 and 40 percent of that under the carbon tax. Road fuel taxes are a relatively weak instrument, typically reducing emissions by less than 10 percent of that under the carbon tax. Taxes on electricity output, rather than CO_2 emissions from generating electricity, are also a weak instrument in countries with ample opportunities for switching to low-emission generation fuels.

Potential revenues from other instruments are generally well below those from carbon taxes—around 40-80 percent lower for (limited scope) ETSs (even with allowance auctions) and power sector taxes, and more than 70 percent lower for road fuel taxes and (China, India, and South Africa aside) coal taxes. The performance of other carbon mitigation policies at reducing air pollution deaths, relative to the carbon tax, follows a similar pattern (with some exceptions) to that of the relative reductions in CO_2 emissions. Finally, the economic welfare comparison of other policy instruments can be largely anticipated. For instance, the welfare gains from coal taxes in China and India are close to those from the carbon tax, while those for road fuels are less than one-seventh of those for the carbon tax.

In short, the quantitative results, while illustrative, underpin three important (though qualitatively not especially novel) themes about carbon pricing. First is the generally strong environmental, fiscal, and economic welfare case for carbon taxes (or similar pricing instruments) as well as their positive domestic welfare gains (or at least zero/generally modest net costs) relative to other instruments. This supports the central role of carbon pricing in mitigation and that it can be in countries' own national interests to move ahead unilaterally. Second, however, the high (and politically challenging) carbon prices implied by some NDCs underscore the importance of complementary measures to compensate vulnerable groups and facilitate clean technology investment (potentially enhancing the behavioral responses to carbon pricing). Third, the large cross-country dispersion in prices implied by current NDCs may need to be partially addressed in future revisions to NDCs and through complementary international mechanisms (if applicable), like price floor arrangements.

The rest of this paper is organized as follows. Section II outlines the model and related assumptions. Section III presents the main results and sensitivity/incidence analyses. Section IV elaborates on the practicalities of moving policy forward and concludes.

II. METHODOLOGY

This section briefly overviews the model, caveats, data sources, and policy scenarios, with details on the model equations and parameter justifications provided in Appendices 1 and 2.

A. Analytical Framework

Five fossil fuels are distinguished, namely coal, natural gas, gasoline, road diesel, and other oil products (used in power generation, petrochemicals, home heating, non-road vehicles, etc.). The model projects, out to 2030, annual use of fossil and non-fossil fuel use in three sectors—power generation, road transport, and an 'other energy' sector, where the latter represents an aggregation of direct energy use by households, firms, and non-road transport.

(i) Power sector

In the power sector, electricity demand (aggregated over intermediate and final users) in the BAU increases over time with growth in GDP, according to the income elasticity[17] for electricity, and changes in electricity prices, which are a function of associated fuel supply cost projections. Higher electricity prices reduce electricity demand through promoting both energy efficiency and less use of electricity-consuming products/capital. Energy efficiency also improves autonomously over time with technological progress (e.g., due to the natural retirement of older, less efficient capital).

Power is potentially generated from coal, natural gas, oil, nuclear, biomass, hydro, and other renewables like solar and wind (not all G20 countries use all seven fuels) where higher unit generation costs for one fuel cause switching to other fuels (in proportion to their generation shares). Autonomous technological progress, assumed to be fastest for renewables, gradually reduces unit generation costs for each fuel over time. Changes in electricity demand induce proportional changes in generation from each fuel, and, in turn, electricity prices reflect a share-weighted average of unit generation costs.

(ii) Road transport

The road transport sector distinguishes gasoline (light-duty) vehicles and diesel (heavy- and, in some cases, light-duty) vehicles, though implicitly an increase in average on-road, fleet fuel economy can represent a shift towards hybrid and electric vehicles as well as higher efficiency of petroleum vehicles. Again, future fuel use varies positively with GDP (through income elasticities for vehicle use), negatively with fuel prices (through shifting to more fuel-efficient vehicles and less driving), and negatively with autonomous improvements in fuel economy.

(iii) Other energy

The other energy sector disaggregates small fuel users (households, low-emitting firms) from large (industrial) users (e.g., steel, aluminum, cement, refining, chemicals, construction, domestic aviation) to distinguish ETSs which often (e.g., in the EU) only cover the latter.[18] Fuels potentially

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[17] All income and price elasticities are taken to be constant (a standard assumption).

[18] ETSs can be applied (and are at the regional level in California and Canada) midstream to cover road and heating fuels, though this may overlap with existing administration for collecting fuel excises.

used by the other energy sector include coal, natural gas, oil products, biomass (e.g., for home cooking and lighting), and other renewables. Future fuel use varies positively with GDP (through income elasticities) and negatively with fuel prices (through changes in energy efficiency and product usage) and autonomous improvements in energy efficiency.

(iv) Externalities

Fossil fuel use produces CO_2 emissions, according to the carbon content of fuels. It also causes premature deaths from exposure to air pollution (equal to deaths per unit of fuel use times fuel consumption, where the death rate is generally trending down over time as air pollution emission rates per unit of fuel use fall with greater deployment of control technologies).[19] In addition, road fuels are implicitly associated with externalities from vehicle use (congestion, accidents, and road damage), which feed into the calculations of welfare impacts.[20]

B. Caveats

BAU is defined with no new mitigation policies beyond those already implicit in recently observed energy use and prices and therefore excludes, for example, future policies for faster deployment of renewables or raising of carbon prices or energy taxes. This is a common approach in developing BAU scenarios,[21] avoids (somewhat speculative) assumptions on future policy specifics and provides clean comparisons of alternative mitigation instruments to the BAU and across countries.[22] More detailed modelling of other prospective policies would be needed at the national level however, as individual countries tailor their own, idiosyncratic policy packages to implement NDCs.

While the assumed fuel price responses (see Section C) seem reasonable for modest fuel price changes, they may not be for dramatic price changes that might drive major technological advances, or non-linear adoption of technologies like carbon capture and storage (CCS), and

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[19] Local air pollution causes a range of other impacts beyond mortality (morbidity, impaired visibility, building corrosion, crop damage, lake acidification, etc.) but previous studies suggest their combined costs tend to be modest relative to mortality costs (e.g., US EPA 2011, WBG/SEPAC 2007).

[20] Externalities from nuclear power (e.g., from accident risk, storage of spent fuels, and terrorist sabotage) are not included due to the lack of evidence on their magnitude.

[21] For example, EIA (2016a), IEA (2017).

[22] Any remaining domestic energy subsidies in oil producers are assumed to phase out progressively to 2030, following recent reform trends. Note that for EU countries, new mitigation policies are assumed to have no effect on the ETS price—in reality (with no adjustment to the ETS) the EU-wide price would fall, leading to offsetting emissions increases in other EU countries.

even the potential growth of well-established technologies may be highly uncertain.[23] For this reason, and questions over the political viability of high prices—the current global average CO_2 price is only about $1 per ton[24]—carbon prices above $70 per ton are not considered.[25]

The three energy sectors in the model are de-coupled from one another and from the broader economy. The former assumption is becoming questionable as penetration of electric vehicles adds to electricity demand, though only modestly (in proportionate terms) for the foreseeable future. The latter assumption seems reasonable, for the most part, because the assumed price responsiveness of fuel use is broadly consistent with that implied by econometric evidence (Appendix 2) and (as noted below) results from macro-energy models which do account for these linkages. The main concern in this regard is the welfare calculations which exclude (potentially important) linkages with the broader fiscal system (see below).

A further caveat is the focus on longer term impacts (of anticipated, gradually phased, policies)—the model is effectively comparative static with fuel use responding instantly and fully to fuel price changes. Also of interest (but beyond our scope) is the shorter term, in which fuel price responsiveness is more muted—these dynamic responses might be explored, for example, with computable models incorporating gradual turnover of capital stocks. The model also assumes perfectly elastic fuel supply curves (which shift up in response to new taxes) and does not account for international trade (given the focus of NDCs on emissions from domestic fuel consumption). If major economies move forward simultaneously with significant mitigation measures, there will be some reduction in international fuel prices, an offsetting increase in fuel demand, and terms of trade effects, but again these impacts (which are sensitive to assumed policy scenarios and modelling of international fuel markets) are beyond our scope.

C. Parameterization

2014 fuel use for each G20 country is taken from IEA (2017b)[26], aggregated to ensure consistency with the model's energy sectors, and projected forward for the BAU using relationships discussed above (with mathematical specifics detailed in Appendix 1). Projected GDP is from IMF (2017) (assuming growth continues after 2022 at the same rate as projected for 2022) and rates of autonomous technological change are based on typical modelling assumptions.

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[23] For example, the prospects for expansion of nuclear power to replace fossil fuel generation are subject to substantial uncertainties surrounding both economics and political acceptability (e.g., Davis and Hausman 2015).

[24] Calculated from WBG (2017).

[25] Although speculative, widespread deployment of CCS might become viable at carbon prices in the ballpark of $70 per ton (Darmstadter and Mares 2017).

[26] As noted in Appendix 2, fuel use data for 2015 is available but most likely does not fully reflect adjustments to the sharp fall in international energy prices between 2014 and 2015. Country authorities may also have more recent (but not publicly available) data.

Fuel taxes (or subsidies) by country are based on estimates using the price-gap approach—that is, the difference between (publicly available) retail prices and supply prices—and implicitly reflect the combined effect of excises, any favorable general sales tax (GST) provisions for household fuels, regulated or monopoly price distortions, and carbon pricing. Supply prices (or more precisely opportunity costs) are international reference prices for finished fuel products, with adjustments for transport and distribution margins, and are projected forward by averaging over (rising) international price projections in EIA (2018) and (generally flat) projections in IMF (2017) yielding real prices for coal and oil that are 31 and 42 percent higher in 2030 compared with 2015[27], and between about 0 and 30 percent higher for natural gas in different regions (Table 1, Appendix 2). BAU emissions projections, and the percent emissions reductions from carbon pricing, are both increased with lower fuel price projections (the latter because carbon pricing has a greater proportionate impact on fuel prices).

Income elasticities for energy products (between 0.5 and 0.8) are based on empirical evidence (see Appendix 2), with some country-specific adjustments (e.g., lower for China as a way of reflecting re-balancing away from energy-intensive activity, and higher for India to reflect expanding grid access and vehicle ownership). Fossil fuel use projections would be broadly in line with those in IEA (2017a) for the same energy price projections in the seven G20 countries they report; however, our lower price projections lead to significantly higher BAU fuel use and CO_2 emissions (Table 2, Appendix 2), implying higher CO_2 prices may be needed to meet mitigation pledges.

Price elasticities[28] for electricity demand, road fuels, and fuels in the other energy sectors are taken to be -0.5 (see Appendix 2), with half of the response coming from reduced use of energy-consuming products and half from higher energy efficiency (e.g., due to technological advances). In the power sector, the (conditional) price elasticities for fossil fuels are taken to be -0.7 based on empirical evidence and an upward adjustment to reflect the growing potential for switching to renewable generation. The same elasticities are used for all countries in the absence of systematic evidence to the contrary.[29] As discussed in Appendix 2, there is a sizable (cross-country) empirical literature to draw on for these elasticities and (as noted below) the price responsiveness of emissions is in line with that of other models.

CO_2 emissions per unit of fuel use are taken from the International Energy Agency (there is little cross-country variation in emission rates per unit of energy for a given fuel product). Local air pollution mortality rates per unit of fossil fuel use are obtained from updating detailed, country-

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[27] The scope for rising future oil prices is likely constrained by the potential for shale oil development and electric vehicle penetration (e.g., Cherif and Hasanov 2017).

[28] These are constant, a standard assumption implying convex marginal abatement costs for CO_2.

[29] See, for example, Appendix 2 and Charap et al. (2013).

by-country estimates[30] using trends in urban population exposure and declining emission rates. Policy-induced welfare impacts are calculated using applications of standard formulas (Appendix 1). These formulas do not account for linkages with the broader fiscal system and the efficiency of revenue use[31] and they understate economic costs by ignoring transitory adjustment costs (e.g., idled labor and capital) and possible macroeconomic impacts from price changes, but such effects are especially challenging to model on a cross-country basis.

D. Policy Scenarios

The analysis considers a carbon tax (imposed on top of any existing fuel taxes) as well as other policies scaled so that their carbon prices (for the emissions they reduce) match those of the carbon tax—other policies, as defined here, are less effective at reducing emissions and raising revenue as the carbon tax but it is still important to have a quantitative sense of the differences (e.g., other policies may be more politically acceptable).[32] A less stringent version of the carbon tax is also considered (but not for other policies).

The carbon tax is assumed to cover all fossil fuel CO_2 emissions thereby promoting all opportunities for mitigating these emissions (switching to cleaner fuels, improving energy efficiency, conserving on energy-using products) across the three energy sectors. From an administrative perspective, the tax is best levied on the carbon content of fuel supply (at the point of extraction, processing/distribution, and import, ideally extending existing capacity for fuel excises or royalties).[33] The carbon tax (initially zero) is assumed to rise in annual increments of \$5 per ton of CO_2 each year from 2017 onwards to reach \$70 per ton by 2030. The 'modest' version of the tax rises at \$2.5 per ton a year to reach \$35 per ton by 2030.

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[30] These estimates incorporate country-specific data on population exposure to air pollution, mortality rates for pollution-related illness, air emission rates, and (albeit contentious) valuations of health risks, as well as evidence from 'concentration response' functions. See Parry and others (2014).

[31] Up to a point, the 'double dividend' literature suggests a modest net gain in economic efficiency from swapping carbon taxes for broader labor income taxes when the full range of distortions from the latter (reducing labor supply, promoting informality, shifting to fringe benefits and other tax-favored spending, etc.) are properly considered, though estimates are sensitive to which taxes are being cut (e.g., on low- or high-income individuals) and behavioral responses. In contrast, using revenues for transfer payments instead greatly increases the welfare costs of carbon taxes, and undermines the efficiency rationale for taxes relative to regulatory approaches. See, for example, Bento and others (2018), Parry, Veung, and Heine (2014), and Parry and Williams (2012).

[32] Alternatively, policies could be compared based on their costs for a common emissions reduction. For policies with narrow emissions coverage however, there would be considerable uncertainty surrounding the explicit or implicit emissions prices needed to reduce economy-wide emissions by a substantial amount.

[33] See Calder (2015), Horowitz and others (2017), and Metcalf and Weisbach (2009).

In terms of global emissions coverage, ETSs are the most common form of carbon pricing.[34] They are often applied, and as assumed here to differentiate them from carbon taxes, downstream on large stationary emitters, although in principle they could be extended to the supply of transportation and heating fuels (though this would essentially duplicate fuel excise administration). The ETS is modelled implicitly by the emissions price established by the cap (set equal to the price in the carbon tax scenario), applied to the carbon content of fuels used by power generators and other large energy users;[35] allowances are assumed to be fully auctioned with no earmarking of revenues (in practice many allowances, e.g. in the EU, are often given away for free).

Some G20 countries impose coal excises, but not at meaningful levels from a climate change perspective.[36] A simple excise is modelled here, mimicking the coal charge portion of the broader carbon tax. Many countries also impose excises on final electricity consumption, though they are generally modest when averaged across both intermediate and final consumption and expressed in terms of CO_2 equivalent.[37] A tax on all electricity output is modelled here, where the tax equals the induced annual electricity price increase in the carbon tax scenario (which varies by country with the emissions intensity of generation). More effective still would be to tax electricity CO_2 emissions (to promote switching to cleaner fuels) and therefore a charge on the carbon content of power generation fuels is considered (with the same CO_2 price as the carbon tax). The difference between the electricity emissions tax and the electricity tax approximately indicates the effect of a policy (e.g., a CO_2 per kilowatt-hour standard) to lower the carbon intensity of the power sector.

All G20 countries either tax or (in the case of Indonesia, South Africa, and Saudi Arabia) subsidize road fuels so it is useful to assess the CO_2 impacts of price reform. Higher gasoline and road diesel taxes (or corresponding subsidy reductions) are considered, where the tax increases are the CO_2 emissions factors for the fuels times the CO_2 price in the carbon tax scenario. Sector-specific energy efficiency policies have limited environmental effectiveness relative to economywide carbon taxation and are not considered here.[38] Instead, an energy efficiency combination policy is considered with a shadow price that rewards CO_2 reductions from energy efficiency improvements across all sectors, leaving aside the (non-trivial) practical challenges in

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[34] WBG (2017).

[35] Given the model is deterministic, it does not capture the volatility of prices under an ETS.

[36] For example, the United States collects a coal tax at the first point of sale to fund compensation for black lung disease and India imposes an excise on unprocessed coal (the Clean Environment Cess) equivalent to about US $3 per ton of CO_2.

[37] See OECD (2015).

[38] For modelling results see, for example, Krupnick et al. (2010), Parry, Evans and Oates (2014), and Parry and others (2016).

covering all products and equating implicit emissions prices across products and sectors.[39] Finally, incentives for renewables are not modelled here due to the difficulty of obtaining clean country comparisons when barriers to scaling them up (e.g., availability of sunny/windy sites, compatibility of intermittent power) differ considerably across countries.[40]

III. RESULTS

This section describes the BAU scenarios; the carbon and broader environmental, fiscal, and economic welfare impacts of carbon taxes; the relative performance of other mitigation instruments; sensitivity analyses; and (for four countries) incidence results. The focus is mostly on 2030, the target year for meeting most NDCs, to indicate potential impacts of policies when fully phased in and the extent to which they reach NDC targets.

A. BAU Scenarios

(i) CO_2 and fuel mix projections

Figure 1 shows percent changes in BAU CO_2 emissions by G20 country between 2015 and 2030, broken down by the contribution from changes in GDP, the ratio of primary energy to GDP, and the ratio of CO_2 to primary energy. Growth in GDP (for given energy/GDP and CO_2/energy ratios) would cause large CO_2 increases in emerging market economies like China (140 percent), India (213 percent) and Indonesia (121 percent), while in other countries the increase is more modest (between 11 percent in Japan to 71 percent in Turkey). On the other hand, the energy intensity of GDP falls significantly, causing offsetting reductions in CO_2 of between 20 percent (in Russia) to over 40 percent (Argentina, China, India, Indonesia), reflecting a combination of below-unitary income elasticities for energy products, autonomously improving energy efficiency, and the dampening demand effect of gradually rising fuel prices. By contrast, changes in the CO_2 intensity of energy are modest and there is no systematic pattern to the direction, despite faster technological change in renewables (but from a low base and with no new renewables incentives). The net result of these three trends is rapid CO_2 emissions increases in India (123 percent), more modest increases (between 0 and 42 percent) in nine cases, and modest (and perhaps surprising) reductions (up to 17 percent) in nine cases.

Figure 2 shows the BAU primary fuel mix in 2030 (fuel shares are generally not that different from those in 2015 given the absence of new policies, or large changes in relative fuel prices, that would significantly shift the fuel mix). The high coal users include Australia (29 percent of primary energy), China (59 percent), India (52 percent), and South Africa (60 percent); intermediate users

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[39] The policy might also address broader market failures causing under-investment in energy efficiency (e.g., due to people misperceiving discounted energy savings), implying (up to a point) a negative economic cost from raising energy efficiency. The issue is contentious however, with the balance of recent evidence (e.g., Alcott and Knittel 2017, Parry, Evans and Oates 2014, Sallee 2013) seeming to cast some doubt on the existence of a large market failure.

[40] For some discussion of how renewables incentives compare with other mitigation policies in the US context, see Krupnick et al. (2010).

(with shares between 10 and 30 percent) include, Germany, Indonesia, Japan, Korea, Turkey, UK and US; and low users (with shares of 10 percent or less) include Argentina, Brazil, Canada, France, Italy, Mexico, Russia, and Saudi Arabia. Natural gas shares vary from less than 12 percent of primary energy in Brazil, France, India, and South Africa to about 30 percent or more in Argentina, Australia, Canada, Italy, Japan, Mexico, Russia, Saudi Arabia, Turkey, UK and US. Oil shares vary from 23 percent in France to over 50 percent in Brazil, Mexico, and Saudi Arabia. Nuclear accounts for about 30 percent of energy use in France, but about 10 percent or less in other G20 countries. Renewables (including biomass) represent around 5-20 percent in most cases, and about 30 percent in Brazil and 34 percent in France.

(ii) Air pollution mortality

Figure 3 shows BAU annual premature deaths in 2030 from fossil fuel outdoor air pollution.[41] The death rate is highest in China, at 900 per one million of the population, reflecting China's high coal use and high population exposure to pollution. In contrast, the coastal location of many coal plants in South Africa (where a large portion of emissions disperse offshore) and lower average population density imply a much lower mortality rate (about 50 per one million). Mortality rates from all fossil fuels are about 400 per million people in Russia, 240 in India, 185 in Korea, and 110 in Germany but below 100 per million in all other cases. In absolute terms, annual mortality is highest in China (about 680,000), followed by India (380,000), Russia (55,000), and the United States (25,000).

(iii) Emissions reductions implied by Paris pledges

Figure 4 indicates the percent reduction in fossil fuel CO_2 emissions in 2030 below BAU emissions in 2030[42] needed to meet NDCs, assuming no tightening of mitigation policies (e.g., the EU ETS) in the BAU beyond 2014 and CO_2 reduction targets proportional to those (listed in Table 1) for total GHGs.[43] These reductions are substantial in many cases—over 40 percent in Australia and Canada, between 30 and 40 percent in European countries, Korea, South Africa, and United

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[41] These are extrapolated (see Appendix B) from Parry and others (2014) (the estimates in that study are broadly consistent with those in Lelieveld and others 2015, Extended Data Table 3). Total air pollution deaths are significantly higher than the estimates in Figure 3 due to non-fossil outdoor sources (e.g., agriculture, outdoor biomass emissions, and natural sources like dust) and indoor air pollution (e.g., WBG/IHME 2016).

[42] Assumed, for Brazil and the US, to be the same percent reduction as required in 2025 (the target year of their NDC). For China and India, absolute CO_2 emissions targets are obtained from their GDP growth and targets for the emissions intensity of GDP.

[43] The exceptions are Brazil and Indonesia where reductions in forestry emissions would play a major role in meeting NDCs—for illustration, the target CO_2 reduction from fossil fuels is set equal to one-third and one-half of the percent GHG reduction target for Brazil and Indonesia respectively.

States[44], between 20 and 30 percent in five cases, and less than 20 percent in Argentina, China, India, Indonesia, and Russia. This variation reflects differences in both the percent reduction targets and in the baseline year against which 2030 reductions apply: for example, for Australia, if the baseline year were 2030 rather than 2005, the required emission reduction would be 27 percent.[45] For the G20 as a whole (using the 2030 BAU emissions share-weighted average), pledges amount to a reduction of about 21 percent below BAU levels in 2030.

B. Impacts of Carbon Taxes

(i) CO_2 emissions

Figure 5 shows the percent reduction in CO_2 emissions in 2030 (again relative to 2030 BAU CO_2) induced by the two carbon tax scenarios. Under the tax rising to $70 per ton by 2030, seven countries meet or exceed their NDCs (Argentina, China, India, Indonesia, Russia, South Africa, and Turkey), another six countries would need further emissions reductions of up to 10 percent (Brazil, Germany, Japan, Korea, Mexico, Turkey, and United States), and six countries would need further emissions reductions of above 10 percent (Australia, Canada, France, Italy, Saudi Arabia, and United Kingdom) suggesting that prices well above $70 per ton would be needed in the latter cases.

This wide dispersion in required carbon prices to meet NDCs reflects both differences in their stringency (as just discussed) and in the relative price responsiveness of emissions—for example, the $70 carbon tax cuts emissions by well over 30 percent in coal-intensive China, India, and South Africa; by around 15-25 percent in Argentina, Brazil, Canada, Indonesia, Japan, Mexico, Russia, Turkey, United Kingdom and United States; and by less than 15 percent in France and Saudi Arabia (where coal use is zero or minimal).[46] Also noteworthy is that emissions reductions

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[44] For EU countries, BAU emissions in 2030 are similar to 1990 levels (emissions for these countries fell significantly between 1990 and 2015—IEA 2017a) hence the required percent reductions for 2030 are similar to their pledged percent reductions, even though the latter is defined relative to 1990.

[45] The emission reductions in Figure 4 are broadly consistent with estimates from four integrated assessment models reported in Aldy et al. (2016), Table 1, for the US and EU countries, at the top end of the range of estimates for India and China, and somewhat higher for Japan and Russia. These differences are largely explained by the lower future international fuel prices (and hence generally larger BAU emissions) assumed here.

[46] Broadly speaking, the relation between carbon prices and proportionate emissions reductions is consistent with other recent studies. Crudely expressing results in terms of the carbon price divided by the percent CO_2 reductions, in Aldy et al. (2016), Table 1, this ratio is 1.9, 2.4, 2.9 and 3.1 for different US models (compared with 2.6 here); for China 1.5, 1.7, and 2.3 (1.7 here); for Japan 2.1, 5.4, and 14.2 (3.6 here); and for the EU 1.8, 3.0, 3.6 and 5.5 (compared with 2.5 to 5.4 for EU countries here). And averaging across several US models, the ratio is approximately 2.8 in Barron and others (2018), Figure 1, and for the global economy approximately 2.7 in Nordhaus (2017). Some other studies imply substantially greater responsiveness of emissions to pricing, for example, in Goulder and Hafstead (2018) the carbon price/percent CO_2 reduction ratio for the United States is about 1.2 (i.e., US emissions are more than twice as responsive to pricing as in our analysis), which principally reflects their assumptions of much greater

under the $70 carbon tax are less than double those under the $35 tax, especially in coal intensive countries—in China, for example, the $35 carbon tax raises coal prices by 116 percent relative to the BAU in 2030 (cutting emissions 30 percent), but further raising it from $35 to $70 increases coal prices (relative to prices with the $35 tax) by a much smaller 54 percent (cutting emissions by a further 12 percent).

Coal accounts for more than two-thirds of the CO_2 reductions in nine countries, and more than four-fifths in six cases (Australia, China, Germany, India, Korea, and South Africa), reflecting both coal's significant share in emissions and its relatively high responsiveness to carbon pricing (e.g., the percentage increase in coal prices is typically around 10-15 times the percentage increase in road fuel prices). In contrast, reductions in oil use account for about 30 percent or less of CO_2 reductions in all but three cases (Brazil, France and Saudi Arabia). Natural gas accounts for 30 percent or less of CO_2 emissions reductions in all but six cases (Argentina, Canada, Italy, Mexico, Russia, and Saudi Arabia).

A final noteworthy point from Figure 5 is that, at the G20 level, even the $35 CO_2 price is sufficient to meet the (2030 BAU emissions share-weighted average) Paris pledge (given the disproportionate weight attached to the more modest mitigation pledges of China and India).

(ii) Revenue

Figure 6 shows revenue from the carbon tax in 2030. Revenues are potentially large, typically around 1-2.5 percent of GDP for the $70 tax, and substantially higher in a few countries with high CO_2 intensity of GDP including India, Russia, Saudi Arabia, and South Africa. Revenues are about 70-85 percent higher under the $70 per ton tax compared with the $35 tax (they are less than double due to the reduction in fuel demand). For a given tax rate (though not shown in the figure), revenues as a percent of GDP decline gradually over time with the declining emissions intensity of GDP—for example, a $70 tax in China in 2020 would raise revenues of 3.7 percent of GDP compared with 3.2 percent in 2030.[47]

(iii) Health

Figure 7 indicates the percent reduction in fossil fuel air pollution deaths below BAU levels in 2030 from carbon taxes. Comparing with Figure 5, the percent reductions are moderately larger than the percent CO_2 reductions (for the corresponding carbon tax) in some cases where coal accounts for a larger share of economy-wide air pollution deaths than for economywide CO_2

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ease of scaling up renewables and nuclear power generation fuels and unitary price elasticities (imposed through functional form restrictions rather than parameterization) for gasoline, electricity, and other energy products.

[47] The US Treasury adjusts carbon tax revenue estimates downwards by 25 percent to account for the impact of higher energy costs on indirectly reducing tax bases for labor and capital (Horowitz et al. 2017) though there would be a counteracting increase in these tax bases if carbon tax revenues were used to cut taxes on labor and capital.

emissions. More noteworthy perhaps are the considerable differences in average lives saved per 1 million tons of CO_2 reduced, which are about 5-20 in nine cases, 4 or less in Argentina, Australia, Canada, Mexico, and Saudi Arabia, but about 50 and 80 in China and India respectively. If, for illustration, the value of a statistical life for China is $1 million[48] the domestic environmental benefit per ton of CO_2 reduced in China (from reduced local air pollution not the reduced CO_2 itself) would be about $100.

(iv) Economic welfare gains

Figure 8 shows the economic welfare costs (i.e., losses in consumer surplus less government revenue gains) of carbon taxes and their net domestic welfare gains (i.e., domestic environmental benefits—excluding global climate benefits—less welfare costs) in 2030 as a percent of GDP. Economic costs are less than 0.5 percent of GDP under the modest tax, and less than 0.8 percent of GDP under the $70 tax in all but three cases—China, India, and South Africa where costs are 1.0-1.6 percent of GDP. However, for the modest carbon tax, domestic environmental benefits are about as large as, or larger than, these costs in all cases (mostly due to domestic air pollution benefits), so net welfare gains are zero or positive. Even for the $70 tax, although there are net welfare losses in three cases (in two cases these losses are only 0.1 percent of GDP, while in South Africa they amount to 0.7 percent of GDP), there are large net welfare gains of: 0.7 percent of GDP in Korea, 2.3 percent in India, 3.7 percent in Russia, and 6.7 percent in China. These results suggest that many G20 countries can move ahead unilaterally with carbon pricing and perhaps make themselves better off in net terms or incur only small net costs[49] (for reasons noted earlier economic costs may be understated).

C. Comparison of Alternative Mitigation Policies

Table 2 shows the impacts of other mitigation instruments, relative to the $70 carbon tax, for CO_2 reductions, revenue, and reductions in air pollution deaths (first three quadrants)[50] as well as absolute welfare impacts (as a percent of GDP) in the fourth quadrant.

The coal tax is quite effective in some cases, achieving around three quarters or more of the reductions under the $70 carbon tax in Australia, China, Germany, India, Korea, and South Africa, and over 60 percent of the CO_2 reductions in Indonesia, Japan, and Turkey. The ETS is significantly less effective than the carbon tax (not because of the instrument itself but rather its assumed coverage of large emissions sources only)—it reduces emissions by between about 40 and 75 percent of the reductions under the carbon tax in 16 cases, only 27 percent in France, and about 80 percent or more in Australia and India. In fact, in 10 cases the coal tax is about as effective, or more effective, than the ETS—only in Argentina, Canada, Italy, Mexico, Russia, and Saudi Arabia is the ETS substantially more effective. The electricity (CO_2) emissions tax achieves

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[48] Approximately based on Parry and others (2014), pp. 76-80.

[49] For further discussion see Parry, Veung, and Heine (2014).

[50] The effectiveness of other instruments relative to the carbon tax looks very similar in years prior to 2030 when all policies are proportionately less stringent.

80 percent or more of the CO_2 reductions under the ETS in all but two cases. In general, the electricity output tax is substantially less effective than the electricity emissions tax (as it does not promote switching among power generation fuels), though in a few cases (e.g., South Africa with limited possibilities for fuel switching) the difference is relatively modest. Road fuel taxes have weak effectiveness, well below 10 percent that of the carbon tax for all but one case (given their sectoral focus and the relatively modest proportionate impact of carbon charges on road fuel prices). The energy efficiency combination policy is more effective, typically reducing emissions by between 25 and 40 percent that of the carbon tax (though as noted above there are practical obstacles to its comprehensive, cost-effective implementation).

Coal taxes are relatively less effective at raising revenue than reducing CO_2 emissions—in 16 cases coal tax revenues are around 30 percent or less of carbon tax revenues, given that coal accounts for a minor fraction of total emissions and its disproportionately high responsiveness to carbon pricing (the notable exceptions are China, India, and South Africa where revenues are 63-76 percent of carbon tax revenue). The revenue potential of ETSs is generally around 20-60 percent that of the carbon tax, primarily because ETSs tend to miss about half of the potential revenue base (and the portion they do cover is typically more mobile due to relatively low-cost mitigation opportunities in the power sector). Generally, revenues from taxes on electricity, or electricity emissions, are moderately less than those from ETSs (as they do not tax emissions from large industrial firms). On the other hand, road fuel taxes are relatively more effective at raising revenues than they are at reducing CO_2 emissions, raising around 15-30 percent of the revenues under the carbon tax. The energy efficiency combination slightly erodes bases for pre-existing fuel taxes, but the revenue losses are very small.

The performance of other carbon mitigation policies at reducing air pollution deaths, relative to the carbon tax, follows a broadly similar pattern to that of the relative reductions in CO_2 emissions, though with some nuances. For example, in some cases, the relative performance of the coal tax is better.

Welfare results can be largely anticipated by the previous discussion. For example, in India the welfare gains from the carbon tax, coal tax, ETS, electricity output tax, electricity CO_2 tax, road fuel tax, and energy efficiency combination are 2.3, 1.8, 1.5, 0.5, 1.3, 0.3 and 0.8 percent of GDP respectively. In many other cases, welfare impacts are far less striking. For example, in the United States the carbon tax, road fuel tax, and energy efficiency combination generate modest net benefits (0.04-0.06 percent of GDP) while the other policies generate modest net costs (0.02-0.05 percent of GDP). However, only the carbon tax comes close to meeting the Paris pledge.

D. Sensitivity Analysis

The relative impacts of other mitigation policies are either approximately robust to alternative parameter assumptions, or affected in largely predictable ways (e.g., increasing road fuel price elasticities increases the environmental effectiveness of road fuel taxes in rough proportion). The discussion here, therefore, focuses on the emissions impacts of carbon pricing and how it compares with the Paris mitigation targets, varying the main uncertain parameters by plus and minus 50 percent (which, loosely speaking, is in line with parameter ranges discussed in Appendix 2).

In cases (Argentina, Indonesia, Korea, Mexico, and Turkey) where Paris pledges specify percent reductions below BAU levels in 2030 (Table 1), changes in absolute 2030 BAU emissions, due to parameter variations, do not affect the required percent reductions in 2030. In other cases, where Paris pledges are relative to historical emissions, increases in 2030 BAU emissions will increase the required percent reduction in 2030 and vice versa for reductions in BAU emissions. In this regard, changes in GDP growth rates, income elasticities, and fuel price elasticities all noticeably affect the required percent reductions in 2030, while changes in the rates of autonomous technological change and international energy prices have a smaller effect. Required percent CO_2 reductions in China (and to a lesser extent India) are especially sensitive to GDP and income elasticity assumptions—for example, higher GDP growth, combined with the baseline assumption of low income elasticities for energy products, lowers the emissions intensity of GDP and China's Paris pledge is met in the BAU.

Percent reductions in CO_2 below 2030 BAU levels induced by the $70 carbon tax are not very sensitive to assumptions about GDP growth, income elasticities, or autonomous rates of technological change.[51] They are, however, sensitive to fuel price elasticities: percent CO_2 reductions fall by about two-fifths when elasticities are 50 percent smaller in size than in the baseline, and increase by around one-third when elasticities are 50 percent larger. They are also almost as sensitive to different scenarios for international energy prices, as these affect the proportionate increase in prices from BAU levels induced by carbon charges.

E. Incidence Analyses

Standard procedures involving input-output tables and household expenditure surveys, as described in Appendix 3, are used to obtain first order approximations of incidence effects (i.e., abstracting from behavioral responses) for carbon taxes in four countries, assuming full pass-through of taxes into consumer prices in domestic markets.[52]

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[51] These factors have no, or at best modest, impacts on the percent change in fuel prices induced by carbon charges and fuel price elasticities.

[52] See Fabrizio et al. (2016) for discussion of an online tool using the same general approach.

The burden of carbon taxation on households and firms is discussed below for Canada, China, India, and the United States, focusing on year 2020[53] (since these impacts are of immediate concern as the tax is phased in), and a tax of $20 per ton of CO_2.[54]

(i) Households

Figure 9 shows the burdens as a percent of total expenditure for household consumption quintiles. Burdens are defined relative to consumption rather than income as the former is generally viewed as a better proxy for 'permanent' or lifetime income.[55] There are several noteworthy points.

First, the carbon tax is moderately regressive in China, significantly more regressive in the United States, mildly progressive in India, and initially progressive then regressive in Canada. Burdens on the bottom and top income deciles are 4.5 and 3.3 percent of consumption respectively in China, 2.8 and 1.4 percent respectively in the United States, 1.9 and 2.6 percent respectively in India, and 1.1 and 1.3 percent respectively in Canada.[56]

Second, in China, India, and the United States the regressivity or progressivity of the tax is largely driven by differing budget shares for electricity—declining for higher consumption households in China and the United States, and rising for such households (partly reflecting higher rates of grid access) in India. The indirect burdens from the higher prices of consumer goods in general (induced by higher energy prices) are larger in China and India than in Canada and the United States (reflecting, in the former, the greater dependence of consumption on domestically manufactured products whose prices rise from carbon pricing)—and are approximately proportional to expenditure across household quintiles (which significantly moderates the overall regressivity or progressivity of the carbon tax).

Third, the fiscal costs of compensating the bottom income quintile for these burdens are not too large (as most of the burden of higher prices is borne by higher income groups): about 11 percent of the carbon tax revenues in Canada, 13 percent in the United States, 5 percent in India,

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[53] This provides a reasonable (near-term) first-order approximation of the incidence of carbon taxation on households and industry. Our framework would predict burdens about three times as large in 2030 (due to the higher tax rates). Nevertheless, this would constitute a substantial overstatement, due to the failure to account for behavioral responses that are likely to come into effect in the medium term.

[54] Although not reported here, in relative terms the distributional incidence of other mitigation policies across households follows a similar pattern to that for the carbon tax, though the absolute burdens are significantly lower as other policies are less comprehensive.

[55] For example, Poterba (1991), Hassett and others (2009). Moreover, income tends to be significantly underreported in household surveys (e.g., Horowitz and others 2017).

[56] The US findings are broadly in line with other studies using the same basic methodology (e.g., Morris and Mathur 2015, Horowitz et al. 2017).

and 8 percent in China.[57] Full compensation would nonetheless become increasingly challenging as the carbon price is progressively ramped up over the longer term.[58]

(ii) Industry

Figure 10 indicates the average percent cost increases for most vulnerable (i.e. those incurring the highest cost increases) exporting industries (weighted by each industry's share in total exports)[59] for the same countries and $20 per ton carbon tax in 2020. For instance, in India the 20 percent of most vulnerable exporters face weighted average cost increases of 5.4 percent (the largest increase is 10 percent for non-ferrous basic metal exports which account for 1.8 percent of total exports), the 40 percent of most vulnerable exporters face weighted average cost increases of 3.8 percent, and across all exports the weighted average cost increase is 2.2 percent. Looking across countries, cost increases are largest for China (with a weighted average increase across all exporters of 8.2 percent) reflecting the high energy-intensity of exports and carbon intensity of energy, and smallest for Canada (with a weighted average cost increase across all exporters of 0.7 percent) given its limited use of coal.

IV. CONCLUSION

One robust theme from the above quantitative analysis is the substantial environmental, fiscal, and welfare advantage of (comprehensive) carbon taxes (or equivalent instruments) over other mitigation policies across G20 countries. Such taxes can be in many countries' own national interests when accounting for the domestic environmental benefits (before even counting climate benefits). This raises the issue of how to move carbon pricing forward at the domestic level.[60]

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[57] Compensating low-income households is most realistic where adjustments to fiscal and social safety net systems can be carefully targeted (e.g., Dinan 2015). However, even poorly targeted measures (e.g., a poll subsidy) might do a lot to protect the poorest without necessarily absorbing all available revenues.

[58] However, the burden of the tax on low-income (and other) households rises by significantly less than in proportion to the tax rate. Household budget shares for electricity and fossil fuels would decline over time with GDP growth (due to below-unity income elasticities) and dampening demand for these products as rising carbon taxes raise their relative prices. Supply prices would also increase by less than in proportion to rising carbon taxes as firms respond by increasing energy efficiency and reducing the carbon intensity of their production mix.

[59] These exclude fuel exporters as they would not be subject to carbon pricing.

[60] Although carbon pricing is proliferating rapidly (see WBG 2017)—with EU countries and over 30 other national and sub-national governments imposing some form of it—these schemes still cover only 15 percent of global GHGs and prices ($18 per ton or less for ETSs, $27 per ton or less for carbon taxes outside of France, Scandinavia and Switzerland) are generally well below what is needed to meet mitigation pledges.

Previous experience with energy price reform[61] suggests a mix of ingredients may be needed to advance domestic carbon pricing. One is to have a comprehensive plan addressing stakeholder concerns (e.g., from legislators, industry, consumer groups, unions), with clearly stated objectives, timetables, and specifics (e.g., on revenue use). Another ingredient is an effective communications plan informing the public about both the global and the national (environmental, health, and fiscal) benefits of reform. Gradual reforms providing firms and households time to adjust are also desirable. The biggest challenge consists of addressing burdens on vulnerable groups, which requires: improved targeting of social safety nets; displaced worker programs;[62] and possible temporary tax reliefs for energy-intensive industries (though on efficiency grounds these should be progressively phased out, especially if other countries are acting on their Paris pledges).

Another robust theme is the high carbon prices—at least given evidence on fuel price responsiveness and the assumption of no other mitigation policies—that might be needed to meet NDCs in some cases. This might imply increases in energy prices (and burdens on vulnerable groups) that push the bounds of political acceptability. There is also a need to complement carbon pricing with other policies to enhance its environmental effectiveness, such as infrastructure upgrades to accommodate renewable generation, carbon capture and storage, electric vehicles and so on.

A third theme is the potentially wide cross-country dispersion in prices needed to implement mitigation pledges, suggesting opportunities for improving cost-effectiveness through some degree of price coordination at the international level. A relative tightening of lax NDCs would promote some carbon price convergence. An explicit carbon price floor arrangement (presumably among large emitters and as a reinforcement—not substitute—for the NDC process) could also help. Such an arrangement (similar to carbon price floor requirements at the provincial/territorial level in Canada[63] and, more generally, for indirect taxes incorporated into national legislation for EU member states) provides some degree of protection against competitiveness concerns, allows countries flexibility to set prices higher than the floor if needed for their NDCs, and could benefit all participants.[64]

The type of model developed here, with consistent and transparent comparisons across policies, metrics, countries, and parameter scenarios, has a useful role in informing dialogue on the domestic and international design of carbon pricing and related mitigation policies (subject to the caveats and uncertainties detailed above).

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[61] Clements et al. (2012).

[62] See, for example, Morris (2016) on coal miners.

[63] See www.canada.ca/en/services/environment/weather/climatechange/pan-canadian-framework/guidance-carbon-pollution-pricing-benchmark.html as well as Parry and Mylonas (2018).

[64] Countries for which the price floor over-achieves their NDC could sell 'Internationally Transferred Mitigation Outcomes' to others falling short of their NDCs through Article 6.2 of the Paris Agreement (e.g., Parry 2017), thereby benefitting both parties.

Table 1. Paris Mitigation Pledges, Emissions Intensity and Emissions Per Capita, 2014

Country	Mitigation pledge	2014		
		share of global CO_2	tons CO_2/\$1,000 GDP	tons CO_2 per capita
Argentina	Reduce GHGs 15% below BAU in 2030 by 2030	0.6	0.39	4.7
Australia	Reduce GHGs 26-28% below 2005 by 2030	1.0	0.25	15.4
Brazil	Reduce GHGs 37% below 2005 by 2025	1.5	0.22	2.6
Canada	Reduce GHGs 30% below 2005 by 2030	1.5	0.30	15.1
China	Reduce CO_2/GDP 60-65% below 2005 by 2030	28.5	0.98	7.5
France	Reduce GHGs 40% below 1990 by 2030	0.8	0.11	4.6
Germany	Reduce GHGs 40% below 1990 by 2030	2.0	0.19	8.9
India	Reduce GHG/GDP 33-35% below 2005 by 2030	6.2	1.10	1.7
Indonesia	Reduce GHGs 29% below BAU in 2030 by 2030	1.3	0.52	1.8
Italy	Reduce GHGs 40% below 1990 by 2030	0.9	0.15	5.3
Japan	Reduce GHGs 25% below 2005 by 2030	3.4	0.25	9.5
Korea	Reduce GHGs 37% below BAU in 2030 by 2030	1.6	0.42	11.6
Mexico	Reduce GHGs 25% below BAU in 2030 by 2030	1.3	0.37	3.9
Russia	Reduce GHGs 25-30% below 1990 by 2030	4.7	0.83	11.9
S. Arabia	Reduce GHGs 130 million tons below BAU in 2030 by 2030	1.7	0.79	19.5
S. Africa	Limit GHGs to 398-614 million tons in 2025 and 2030	1.4	1.40	9.0
Turkey	Reduce GHGs up to 21% below BAU in 2030 by 2030	1.0	0.37	4.5
UK	Reduce GHGs 40% below 1990 by 2030	1.2	0.14	6.5
US	Reduce GHGs 26-28% below 2005 by 2025	14.5	0.30	16.5

Note: BAU denotes business as usual with no new mitigation measures and CO_2 is from fossil fuels. Some countries (Argentina, Indonesia, Mexico) specify both conditional (contingent on external finance) and unconditional (not contingent) pledges—in these cases the unconditional pledges are included above.
Source: http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspxc and https://data.worldbank.org/indicator.

Table 2. Impacts of Other Policies Relative to Carbon Tax, 2030

Country	CO$_2$ Reduction under Other Policies Relative to $70 Carb. Tax							Revenue under Alternative Policies Relative to $70 Carb. Tax						
	Carbon tax	Coal tax	ETS	Elect. output tax	Elect. CO2 tax	Road fuel taxes	En. effic. comb.	Carbon tax	Coal tax	ETS	Elect. output tax	Elect. CO2 tax	Road fuel taxes	En. effic. comb.[a]
Argentina	1.00	0.09	0.48	0.19	0.44	0.05	0.38	1.00	0.02	0.34	0.29	0.28	0.19	0.00
Australia	1.00	0.77	0.79	0.36	0.77	0.03	0.29	1.00	0.24	0.41	0.41	0.36	0.19	0.00
Brazil	1.00	0.35	0.45	0.04	0.39	0.15	0.33	1.00	0.08	0.23	0.15	0.14	0.33	0.00
Canada	1.00	0.24	0.39	0.03	0.35	0.06	0.34	1.00	0.07	0.14	0.11	0.11	0.24	0.00
China	1.00	0.95	0.70	0.20	0.64	0.01	0.28	1.00	0.67	0.42	0.29	0.23	0.09	0.00
France	1.00	0.28	0.27	0.00	0.22	0.05	0.39	1.00	0.13	0.07	0.03	0.03	0.23	0.00
Germany	1.00	0.76	0.76	0.18	0.74	0.01	0.22	1.00	0.28	0.25	0.26	0.22	0.15	0.00
India	1.00	0.95	0.89	0.36	0.86	0.01	0.25	1.00	0.63	0.62	0.64	0.48	0.12	0.00
Indonesia	1.00	0.65	0.74	0.32	0.69	0.06	0.32	1.00	0.17	0.38	0.34	0.31	0.20	0.00
Italy	1.00	0.34	0.58	0.15	0.55	0.04	0.30	1.00	0.12	0.27	0.25	0.24	0.20	0.00
Japan	1.00	0.67	0.60	0.25	0.55	0.02	0.35	1.00	0.21	0.49	0.43	0.41	0.12	0.00
Korea	1.00	0.84	0.74	0.24	0.71	0.00	0.26	1.00	0.33	0.42	0.44	0.38	0.06	0.00
Mexico	1.00	0.18	0.56	0.35	0.52	0.06	0.41	1.00	0.05	0.33	0.30	0.29	0.22	0.00
Russia	1.00	0.28	0.48	0.18	0.46	0.02	0.36	1.00	0.11	0.37	0.36	0.35	0.07	0.00
S. Arabia	1.00	0.00	0.59	0.38	0.51	0.07	0.44	1.00	0.00	0.52	0.44	0.43	0.08	0.00
S. Africa	1.00	0.95	0.65	0.46	0.62	0.03	0.42	1.00	0.76	0.55	0.50	0.47	0.14	0.00
Turkey	1.00	0.60	0.58	0.25	0.53	0.01	0.36	1.00	0.21	0.40	0.38	0.36	0.10	0.00
UK	1.00	0.51	0.56	0.17	0.54	0.02	0.32	1.00	0.21	0.25	0.24	0.22	0.15	0.00
US	1.00	0.54	0.68	0.25	0.66	0.06	0.30	1.00	0.18	0.31	0.32	0.29	0.27	0.00

Country	Reductions in Air Pollution Deaths Relative to $70 Carb. Tax							Welfare Impacts, percent GDP						
	Carbon tax	Coal tax	ETS	Elect. output tax	Elect. CO2 tax	Road fuel taxes	En. effic. comb.	Carbon tax	Coal tax	ETS	Elect. output tax	Elect. CO2 tax	Road fuel taxes	En. effic. comb.
Argentina	1.00	0.31	0.89	0.03	0.07	0.60	0.48	0.05	0.00	-0.05	-0.03	-0.06	0.05	0.04
Australia	1.00	0.84	0.84	0.34	0.74	0.16	0.30	-0.13	-0.19	-0.16	-0.07	-0.16	0.02	-0.02
Brazil	1.00	0.32	1.45	0.01	0.15	0.65	0.43	0.05	-0.03	-0.02	0.00	-0.02	0.04	0.04
Canada	1.00	0.28	0.72	0.03	0.35	0.18	0.34	-0.08	-0.05	-0.07	-0.01	-0.07	0.05	-0.01
China	1.00	0.99	0.61	0.17	0.53	0.00	0.32	6.67	6.38	3.86	1.05	3.32	0.15	2.20
France	1.00	0.59	0.57	0.00	0.34	0.09	0.33	0.09	0.04	0.02	0.00	0.02	0.01	0.03
Germany	1.00	0.85	0.86	0.19	0.81	0.01	0.19	0.22	0.15	0.15	0.04	0.15	-0.01	0.05
India	1.00	0.99	0.94	0.32	0.76	0.01	0.28	2.31	1.82	1.46	0.53	1.26	0.30	0.79
Indonesia	1.00	0.73	1.10	0.30	0.64	0.15	0.33	0.17	-0.13	-0.07	-0.04	-0.09	0.12	0.11
Italy	1.00	0.52	0.65	0.17	0.60	0.15	0.29	-0.06	-0.02	-0.04	-0.01	-0.04	-0.03	-0.02
Japan	1.00	0.59	0.66	0.27	0.58	0.08	0.34	0.12	-0.08	-0.03	-0.02	-0.04	0.05	0.07
Korea	1.00	0.90	0.79	0.25	0.74	0.02	0.25	0.72	0.35	0.32	0.10	0.30	0.05	0.26
Mexico	1.00	0.33	0.44	0.23	0.35	0.47	0.44	-0.14	-0.04	-0.18	-0.12	-0.17	0.01	-0.04
Russia	1.00	0.60	0.32	0.12	0.30	0.17	0.41	3.58	0.93	0.16	0.03	0.07	0.50	1.77
S. Arabia	1.00	0.00	0.43	0.28	0.38	0.45	0.45	0.35	0.00	0.06	0.03	0.04	0.13	0.17
S. Africa	1.00	0.92	0.46	0.27	0.37	0.08	0.45	-0.71	-0.97	-0.77	-0.56	-0.76	0.24	-0.26
Turkey	1.00	0.99	0.41	0.16	0.33	0.01	0.41	0.42	0.41	0.07	0.01	0.03	0.07	0.20
UK	1.00	0.93	0.72	0.22	0.67	0.00	0.27	0.17	0.21	0.13	0.04	0.13	-0.03	0.04
US	1.00	0.63	0.84	0.26	0.67	0.08	0.29	0.06	-0.04	-0.05	-0.02	-0.05	0.07	0.04

Source: See text and Appendix.

Note: [a]Due to rounding, slight reductions in revenues from the energy efficiency combination are not apparent.

Table 3. Sensitivity of CO_2 Reductions from Paris Pledge and $70 Carbon Tax, 2030

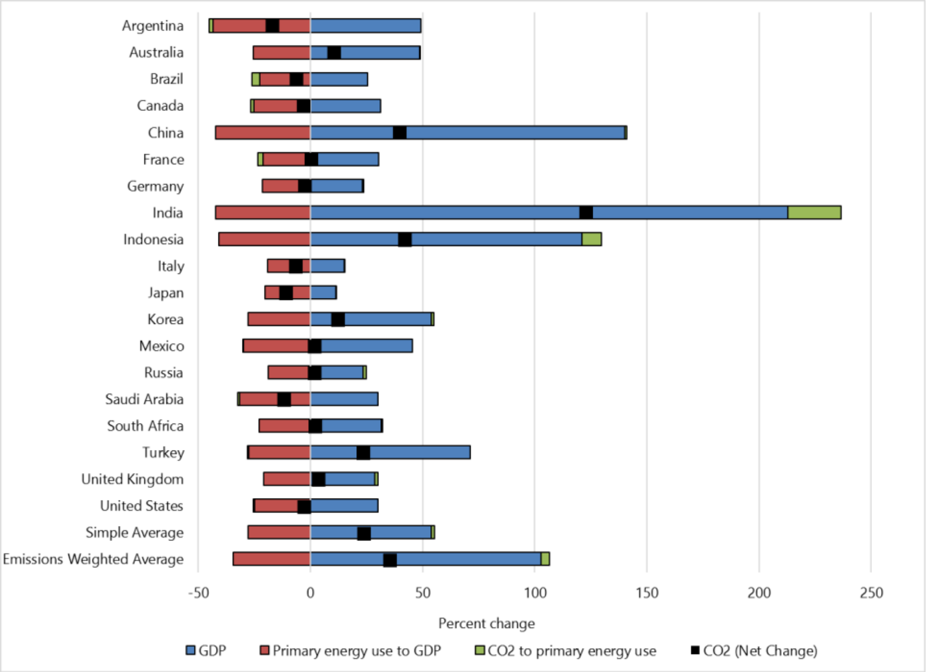
Country	% CO2 reduction from	Baseline	GDP growth rate		Income elastcities		Auton. rate of tech. change		Internat. energy prices		Fuel/elect. price elasticities	
			increased 50%	decreased 50%	increased 50%	decreased 50%	increased 50%	decreased 50%	increased 50%	decreased 50%	increased 50%	decreased 50%
Argentina	Paris pledge	15	15	15	15	15	15	15	15	15	15	15
	$70 CO2 tax	20	20	20	20	20	20	20	18	24	25	13
Australia	Paris pledge	43	51	34	51	34	43	44	43	44	46	39
	$70 CO2 tax	27	27	26	27	26	27	26	22	35	32	16
Brazil	Paris pledge	21	23	19	22	20	21	21	21	21	23	20
	$70 CO2 tax	16	16	16	16	16	16	16	13	23	21	9
Canada	Paris pledge	47	52	41	52	41	46	47	47	47	50	43
	$70 CO2 tax	22	22	22	22	22	22	22	17	31	29	13
China	Paris pledge	17	-2	33	36	-7	17	17	17	17	22	11
	$70 CO2 tax	42	41	42	41	42	42	41	35	53	52	25
France	Paris pledge	38	44	32	44	32	38	39	38	38	42	34
	$70 CO2 tax	13	13	13	13	13	13	13	10	19	18	7
Germany	Paris pledge	31	36	26	36	26	28	33	30	34	39	22
	$70 CO2 tax	28	28	28	28	28	29	28	23	38	37	16
India	Paris pledge	12	0	23	45	-41	12	11	12	11	23	0
	$70 CO2 tax	42	43	41	43	41	43	41	42	43	55	25
Indonesia	Paris pledge	15	15	15	15	15	15	15	15	15	15	15
	$70 CO2 tax	21	21	21	21	21	21	21	17	29	26	13
Italy	Paris pledge	35	38	31	38	31	33	36	34	36	42	27
	$70 CO2 tax	16	16	16	16	16	17	16	13	24	21	9
Japan	Paris pledge	27	30	25	30	24	26	28	27	28	29	23
	$70 CO2 tax	19	19	19	19	19	19	20	15	28	22	12
Korea	Paris pledge	37	37	37	37	37	37	37	37	37	37	37
	$70 CO2 tax	27	27	26	27	26	27	27	22	36	32	17
Mexico	Paris pledge	25	25	25	25	25	25	25	25	25	25	25
	$70 CO2 tax	18	19	18	19	18	19	18	14	27	24	10
Russia	Paris pledge	11	19	2	17	5	10	11	11	12	20	0
	$70 CO2 tax	18	18	18	18	18	18	18	13	28	22	11
Saudi Arabia	Paris pledge	24	24	24	24	24	24	24	24	24	24	24
	$70 CO2 tax	11	12	11	12	11	12	11	8	19	16	6
South Africa	Paris pledge	27	27	27	27	27	27	27	27	27	27	27
	$70 CO2 tax	34	34	34	34	34	34	34	28	45	43	20
Turkey	Paris pledge	21	21	21	21	21	21	21	21	21	21	21
	$70 CO2 tax	21	21	21	21	21	21	21	16	31	24	14
United Kingdom	Paris pledge	33	40	27	40	27	32	34	33	35	40	26
	$70 CO2 tax	19	19	19	19	19	19	19	15	27	25	11
United States	Paris pledge	32	37	25	37	25	31	32	31	32	36	27
	$70 CO2 tax	27	27	27	27	27	27	27	22	36	35	16

Source: See text and Appendix.

Note: Due to rounding, in some cases slight changes in baseline CO_2 reductions due to parameter variations are not apparent.

Figure 1. Change in BAU CO₂ Emissions, 2015-2030

(In percent)

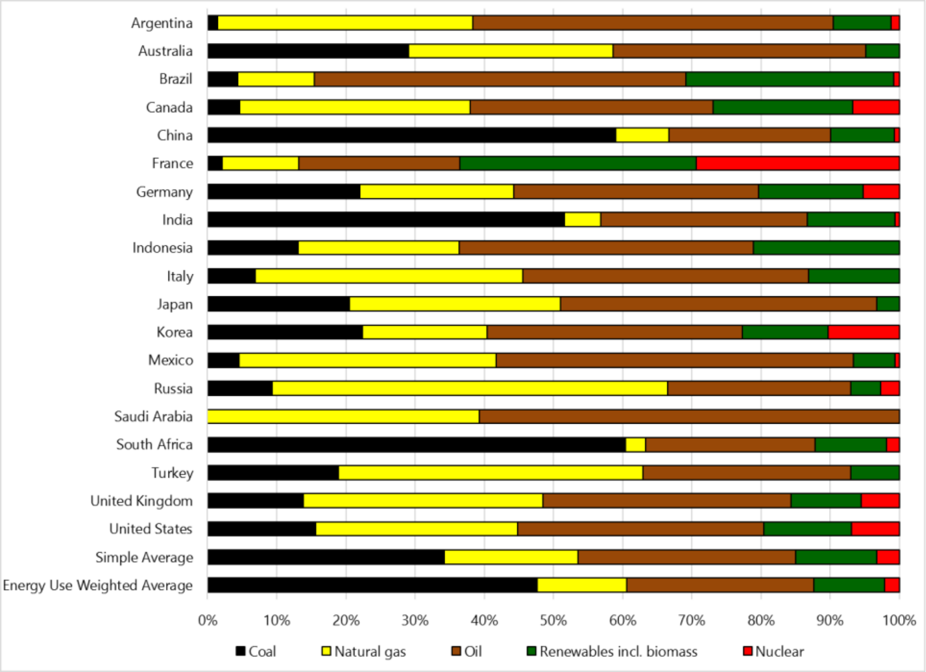


Source: See text and Appendix.

Notes: BAU projections assume no new, or tightening of existing, CO_2 mitigation polices beyond those implicit in 2014 fuel use data. The bars indicate changes in CO_2 emissions from changes in GDP, the energy intensity of GDP, and the CO_2 intensity of energy, while the boxes indicate the net effect.

Figure 2. BAU Primary Fuel Mix, 2030

(In percent)

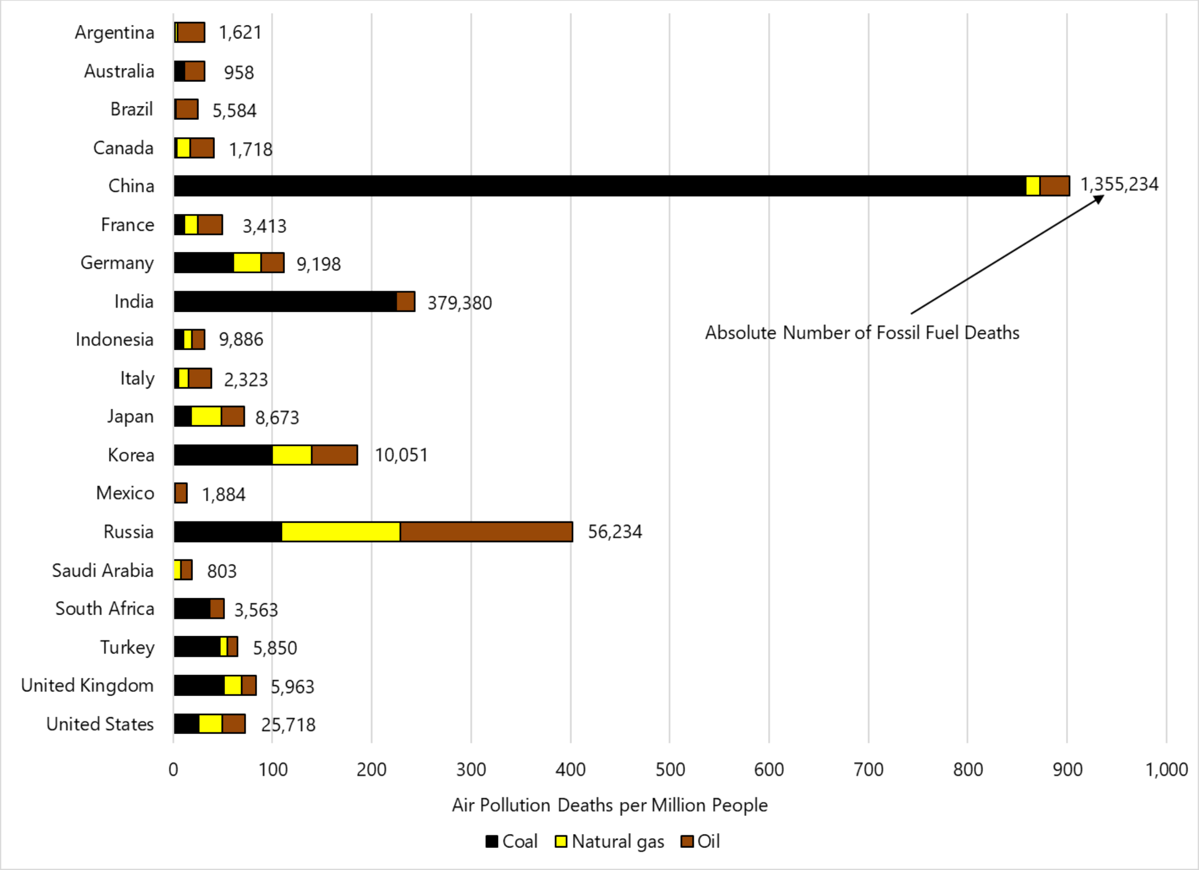


Source: See text and Appendix.

Notes: BAU projections abstract from the possibility of enhanced policy incentives for renewables beyond 2014.

Figure 3. BAU Outdoor Air Pollution Death Rates from Fossil Fuels, 2030

(In units per million people)

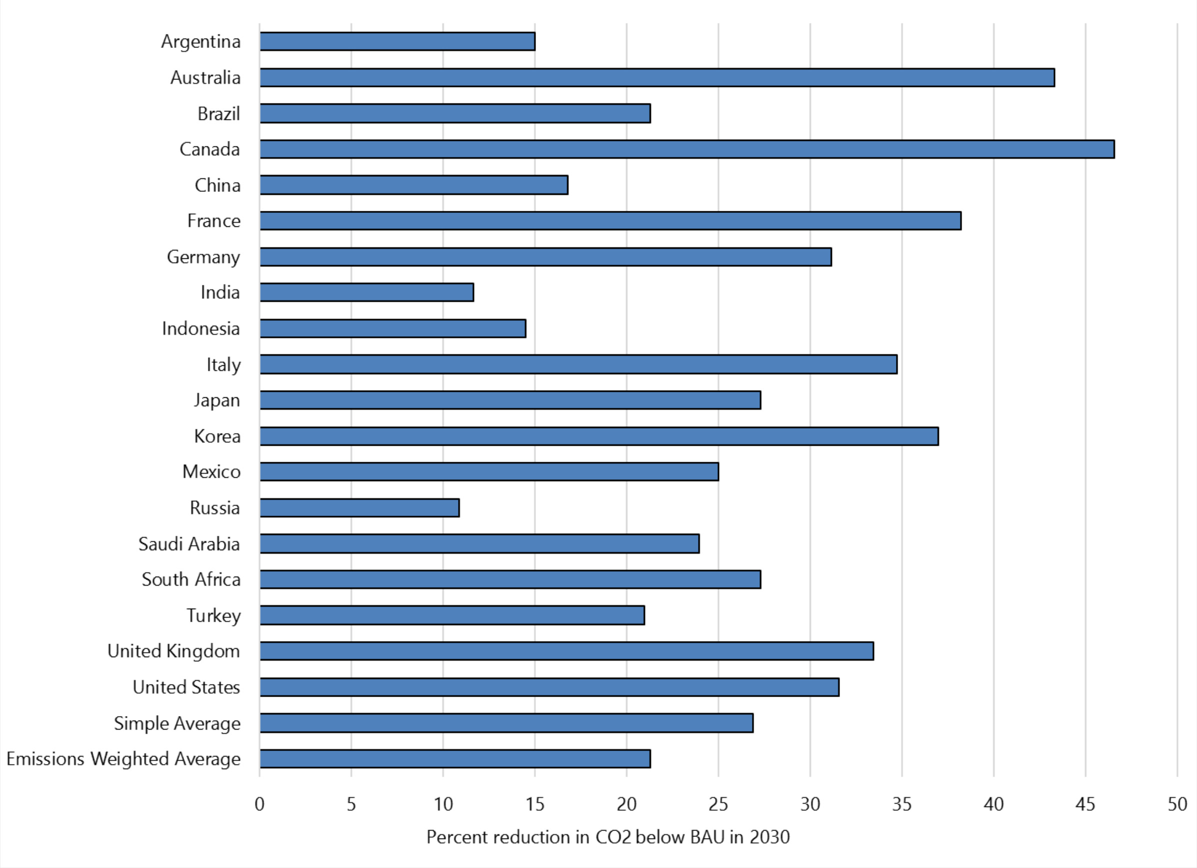


Source: See Appendix 2.

Notes: Estimates project forward country level mortality rates per unit of fuel use in Parry and others (2014) accounting for declining air emissions rates and (for China and India) rising urban population exposure to a given level of pollution. Estimates excludes deaths from indoor air pollution and non-fossil pollution.

Figure 4. Percent Reduction in BAU CO_2 Emissions Implied by Paris Pledge, 2030

(In percent)

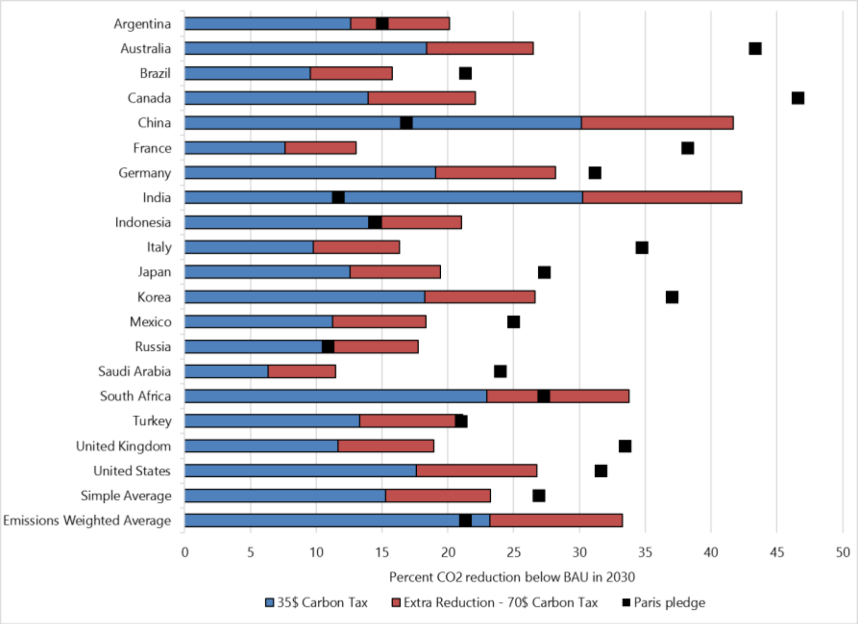


Source: See text.

Notes: Estimates are the percent reduction in BAU emissions in 2030 needed to meet NDC targets, assuming fossil fuel CO_2 emissions fall by the same proportion (relative to the baseline year in the Table 1 target) as implied by the percent GHG reduction targets, aside from Brazil and Indonesia where (due to the disproportionate contribution from forestry) CO_2 is assumed to fall by 33 and 50 percent respectively of the percent GHG reduction. For Brazil and the United States, percent reductions in BAU emissions below 2030 levels are assumed equal to the percent reductions below BAU emissions in 2025 implied by their Paris targets.

Figure 5. Reduction in CO_2 Emissions from Carbon Taxes, 2030

(In percent)

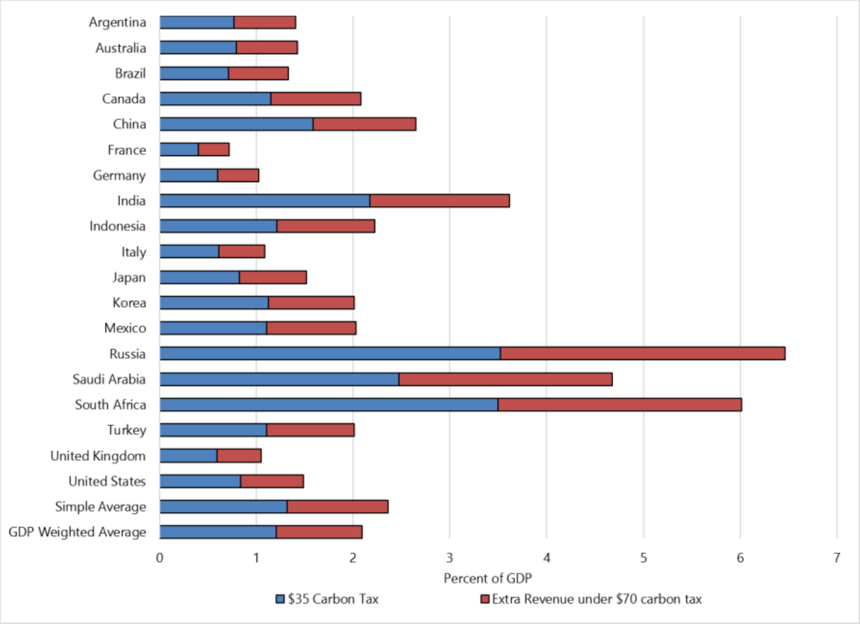


Source: See text.

Notes: Blue and brown bars indicate percent CO_2 reductions under the $35 carbon tax and additional reductions under the $70 carbon tax respectively, relative to 2030 BAU emissions. The black squares indicate the target CO_2 reductions as defined in Figure 4.

Figure 6. Revenue from Carbon Taxes, 2030

(In percent of GDP)

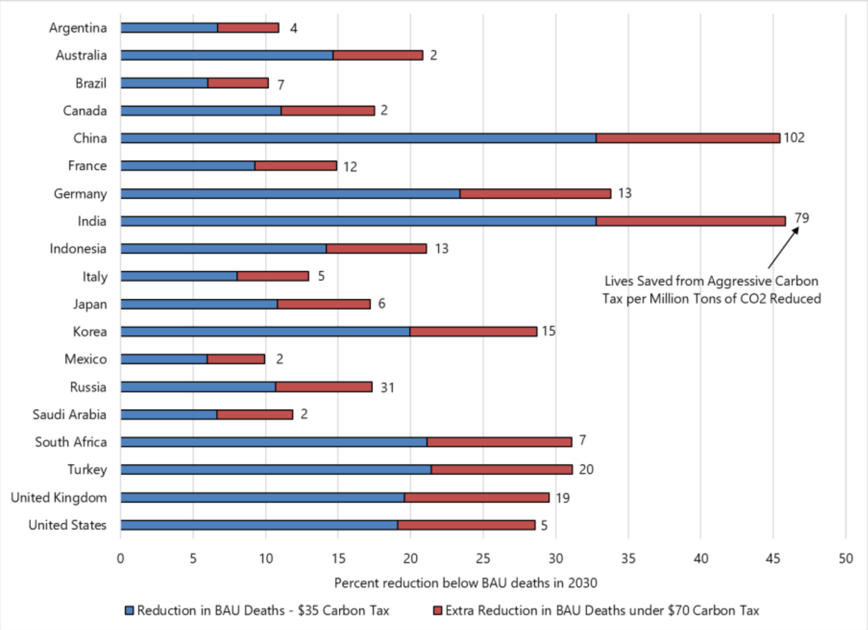


Source: See text.

Notes: Calculations account for induced changes in revenues from pre-existing fuel taxes but not from the broader fiscal system (see text footnote).

Figure 7. Reductions in Air Pollution Deaths from Carbon Taxes, 2030

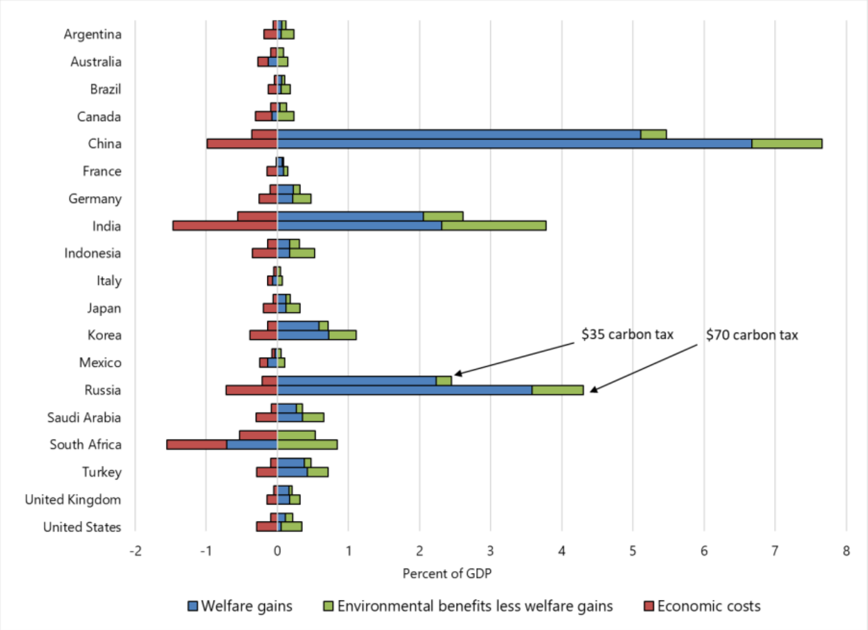
(In percent)



Source. See text.

Figure 8. Domestic Welfare Effect of Carbon Taxes, 2030

(In percent of GDP)

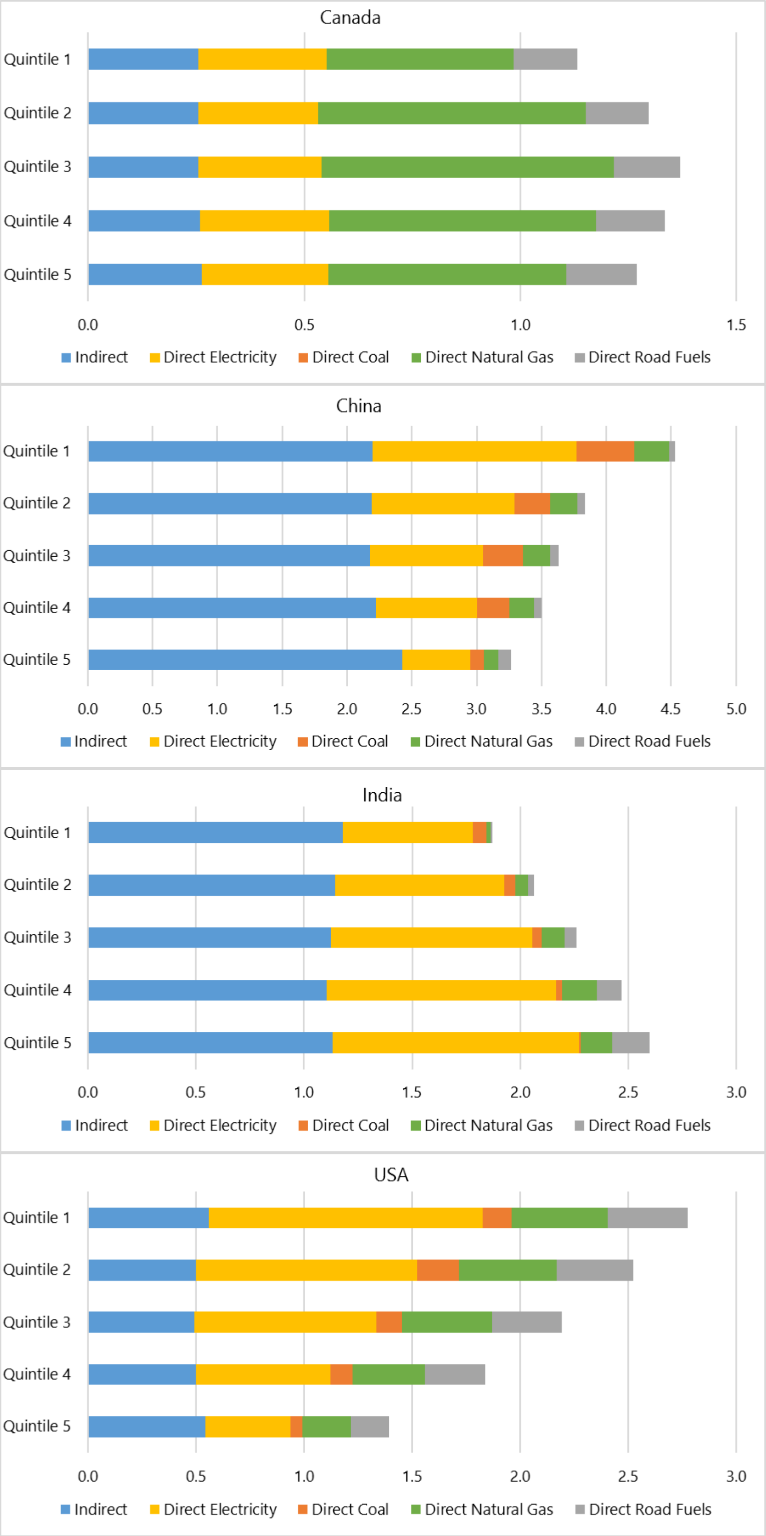


Source: See text.

Note: Environmental benefits include reduced domestic air pollution mortality, traffic congestion, traffic accidents, and road damage, but exclude global climate benefits. Welfare costs reflect losses in consumer surplus in fuel markets from carbon charges net of revenue gains to the government accounting for any erosion of revenues from pre-existing fuel taxes (there are no changes in producer surplus given perfectly elastic supply curves). The net welfare gain is the domestic environmental benefit less the economic cost.

Figure 9. Burden of $20 Carbon Tax on Household Consumption Quintiles, 2020

(In percent of total household consumption)

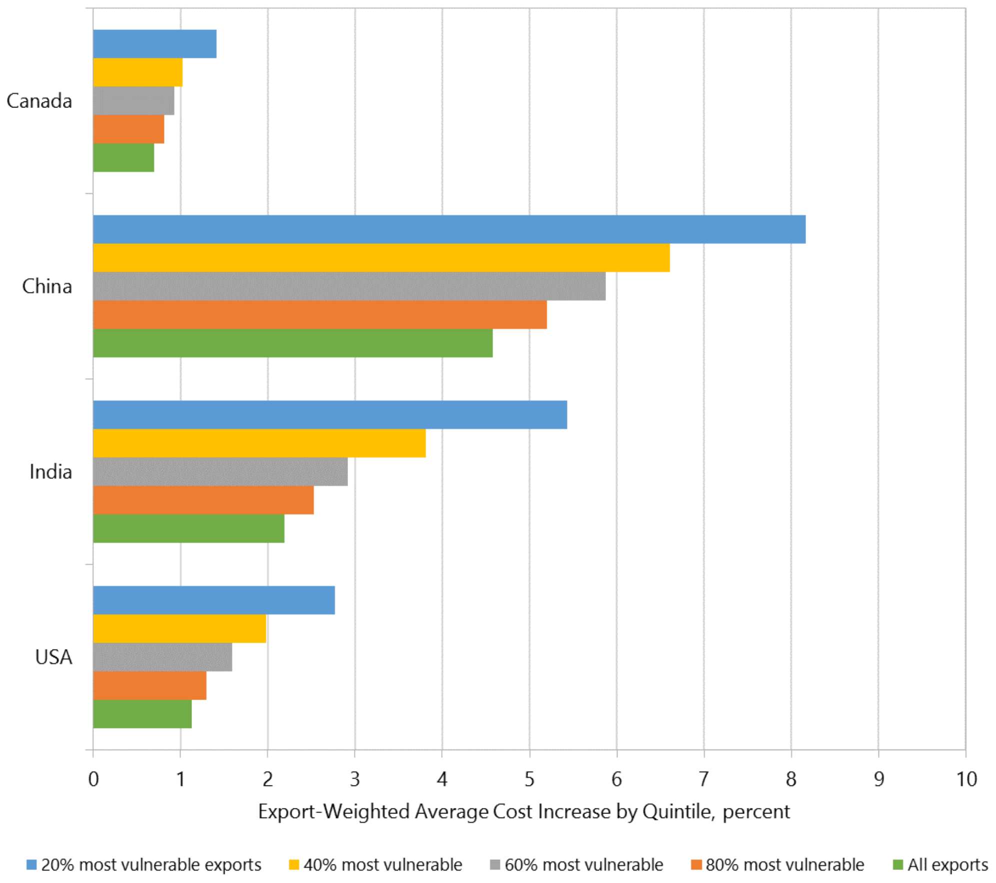


Source: See text.

Note: Quintiles 1 and 5 are the lowest and highest consumption groups respectively.

Figure 10. Cost Increases from $20 Carbon Tax by Exporter Quintile, 2020

(In percent of total costs)



Appendix 1. Analytical Model

A discrete time-period model is used where $t = 0 \ldots \bar{t}$ denotes a year (though most focus is on 2030). Fossil fuels are first discussed, followed by fuel use in the power, road transport, and other energy sectors.

(i) Fossil Fuels

Coal, natural gas, gasoline, road diesel and other oil products are denoted by i = *COAL*, *NGAS*, *GAS*, *DIES*, and *OIL* respectively. The user fuel price at time *t*, denoted p_t^i, is:

(A1) $p_t^i = \tau_t^i + \hat{p}_t^i$

τ_t^i is the tax or subsidy (if negative) on fuel i reflecting (a) the combined effect of any pre-existing excises, favorable treatment under general sales tax for household fuels, and distortions from regulated or monopoly pricing and (b) any carbon charge. For most countries, τ_t^i is large for road fuels and zero for coal and gas (or a small positive for the latter two fuels in countries covered by the EU ETS). $\hat{p}_t^i$ is the pre-tax fuel price or supply cost (the international commodity price adjusted for processing/distribution margins). For fuel products used in multiple sectors, pre-tax prices and taxes are taken to be the same for all fuel users (for non-road oil products taxes are zero, except for EU countries to the extent they are covered by the ETS).

(ii) Power Sector

Residential, commercial, and industrial electricity consumption is aggregated into one economy-wide demand for electricity in year *t*, denoted Y_t^E, and determined by:

(A2) $Y_t^E = \left(\frac{U_t^E}{U_0^E} \cdot \frac{h_t^E}{h_0^E}\right) \cdot Y_0^E$, $\frac{U_t^E}{U_0^E} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^E} \cdot \left(\frac{h_t^E p_t^E}{h_0^E p_0^E}\right)^{\eta^{UE}}$, $\qquad \frac{h_t^E}{h_0^E} = (1 + \alpha^E)^{-t} \cdot \left(\frac{p_t^E}{p_0^E}\right)^{\eta^{hE}}$

U_t^E is usage of electricity-consuming products or capital (i.e., the stock of electricity-using capital times its average intensity of use). h_t^E is the electricity consumption rate (e.g., kWh per unit of capital usage), the inverse of energy efficiency. Product use increases with gross domestic product (GDP_t) according to υ^E, the (constant) income elasticity of demand for electricity-using products. Product use also varies inversely with proportionate changes in unit electricity costs—the electricity consumption rate times the user electricity price p_t^E. $\eta^{UE} < 0$ is the (constant) elasticity of demand for use of electricity-consuming products with respect to unit energy costs.[65] The electricity consumption rate declines (given other factors) at a fixed annual rate of $\alpha^E \geq 0$, reflecting autonomous energy efficiency improvements (e.g., due to gradual retirement of older, less efficient capital). Higher electricity prices further increase energy efficiency, implicitly through adoption of more efficient technologies: η^{hE} is the elasticity of the energy consumption rate with

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[65] Improvements in energy efficiency reduce unit electricity costs, thereby increasing use of electricity-consuming products. However, this 'rebound effect' is not too large (for electricity or other energy-using products) in the model—increased energy demand offsets roughly 10 percent of the energy savings from higher energy efficiency.

respect to energy prices. Note that (A2) can be implemented with U_0^E and h_0^E normalized to unity (absolute values for these parameters are not needed).

Power generation fuels potentially include coal, natural gas, oil, nuclear, hydro, biomass and (non-hydro, non-biomass) renewables (principally wind and solar), where the latter are denoted by i = *NUC*, *HYD*, *BIO*, and *REN*. To accommodate flexible assumptions for the degree of substitution among fuels, the share of fuel i in generation, denoted θ_t^{Ei}, is defined:

$$\text{(A3) } \theta_t^{Ei} = \theta_0^{Ei} \left\{ \left(\frac{g_t^i}{g_0^i} \right)^{\tilde{\varepsilon}^{Ei}} + \sum_{j \neq i} \theta_0^{Ej} \left[1 - \left(\frac{g_t^j}{g_0^j} \right)^{\tilde{\varepsilon}^{Ej}} \right] \Big/ \sum_{l \neq j} \theta_0^{El} \right\}$$

where i, j, l = *COAL*, *NGAS*, *OIL*, *NUC*, *HYD*, *BIO*, *REN*. g_t^i is the full cost of generating a unit of electricity using fuel i (fuel, labor, capital, transmission/distribution costs). $\tilde{\varepsilon}^{Ei} < 0$ is the conditional (indicated by ~) own-price elasticity of generation from fuel i with respect to generation cost. Conditional here means the elasticity reflects the percent reduction in use of fuel i due to switching from that fuel to other generation fuels, per one-percent increase in generation cost for fuel i, holding total electricity generation fixed. Generation cost elasticities are larger than corresponding fuel price elasticities as an incremental increase in fuel and non-fuel generation costs has a bigger impact than an incremental increase in fuel costs alone.

From (A3) fuel i's generation share decreases in own generation cost. It also increases in the generation cost of fuel $j \neq i$, where the increase in fuel i's generation share is the reduced share for fuel j (i.e., θ_0^{Ej} times the term in square brackets) multiplied by the (initial) share of fuel i in generation from all fuel alternatives to j (i.e., $\theta_0^{Ei} / \sum_{l \neq j} \theta_0^{El}$).

Use of fossil fuel i in power generation at time t, denoted F_t^{Ei}, is given by:

$$\text{(A4) } F_t^{Ei} = \frac{\theta_t^{Ei} \cdot Y_t^E}{\rho_t^{Ei}}$$

Fuel use equals the generation share times total electricity output—assumed equal to total electricity demand—and divided by ρ_t^{Ei}, the productivity of fuel use or electricity generated per unit of F_t^{Ei}.

Unit generation costs are determined by:

$$\text{(A5)} \quad g_t^{Ei} = \frac{p_t^i + k_t^{Ei}}{\rho_t^{Ei}}, \ i\text{=COAL, NGAS, OIL;} \qquad g_t^{Ei} = \frac{k_t^{Ei}}{\rho_t^{Ei}}, \ i\text{=NUC, HYD, BIO, REN;}$$
$$\rho_t^{Ei} = (1 + \alpha^{\rho i})^t \rho_0^{Ei}$$

where k_t^{Ei} is non-fossil fuel costs per unit. Unit generation costs decline with rising productivity (which, for a given generation type, is assumed to reduce fossil-fuel and non-fuel costs by the same proportion). Productivity of generation by fuel i increases at rate $\alpha^{\rho i} \geq 0$ per year (again, for example, due to retirement of older, less efficient plants).

Finally:

(A6) $p_t^E = \sum_i \theta_t^{Ei} \cdot g_t^{Ei} + \tau_t^E$

The user price of electricity is the generation shares times unit generation costs summed over fuels (pre-existing electricity taxes are taken to be zero

(iii) Road Transport Sector

Analogous to (A1), gasoline and road diesel fuel demand in period *t*, denoted F_t^{Ti} , where i = *GAS*, *DIES* is gasoline and diesel respectively, is:

(A7) $F_t^{Ti} = \left(\frac{U_t^{Ti}}{U_0^{Ti}} \cdot \frac{h_t^{Ti}}{h_0^{Ti}}\right) F_0^{Ti};$ $\quad \frac{U_t^{Ti}}{U_0^{Ti}} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^{Ti}} \cdot \left(\frac{h_t^{Ti} p_t^i}{h_0^{Ti} p_0^i}\right)^{\eta^{UTi}};$ $\quad \frac{h_t^{Ti}}{h_0^{Ti}} = (1 + \alpha^{hTi})^{-t} \cdot \left(\frac{p_t^i}{p_0^i}\right)^{\eta^{hTi}}$

U_t^{Ti} is kilometers (km) driven by vehicles with fuel type i and h_t^{Ti} is average fuel use per vehicle km (the inverse of fuel economy). km driven in vehicle type i increases with GDP, according to the income elasticity of demand υ^{Ti}, and varies inversely with proportionate changes in fuel costs per km $h_t^{Ti} p_t^i$, where $\eta^{UTi} < 0$ is the elasticity of vehicle km driven with respect to per km fuel costs.[66] $\alpha^{Ti} \geq 0$ is an annual reduction in the fuel consumption rate due to autonomous technological change improving fuel economy. Higher fuel prices also reduce fuel consumption rates according to the elasticity of the fuel consumption rate $\eta^{hTi} \leq 0$—this encompasses both improvements in petroleum vehicles (better engine efficiency, lighter weight materials, shifting to smaller vehicles, etc.) as well as shifting to electric and hybrid vehicles.

(iv) Other Energy Sector

The other energy sector is decomposed into large and small energy users, the latter representing households and small firms (with emissions below a threshold), denoted by *q* = *LARGE*, *SMALL*, respectively. Use of fuel i in the other energy sector, by group *q*, at time *t*, denoted F_t^{Oqi}, is:

(A8) $F_t^{Oqi} = \left(\frac{U_t^{Oqi}}{U_0^{Oqi}} \cdot \frac{h_t^{Oqi}}{h_0^{Oqi}}\right) F_0^{Oqi};$ $\quad \frac{U_t^{Oqi}}{U_0^{Oqi}} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^{Oi}} \cdot \left(\frac{h_t^{Oqi} p_t^i}{h_0^{Oqi} p_0^i}\right)^{\eta^{UOi}};$

$\frac{h_t^{Oqi}}{h_0^{Oqi}} = (1 + \alpha^{Oi})^{-t} \cdot \left(\frac{p_t^i}{p_0^i}\right)^{\eta^{hOi}}$

where i = *COAL*, *NGAS*, *OIL*, *BIO*, and *REN*. The interpretation for (A8) is analogous to that for (A2) and (A7) with U_t^{Oqi} and h_t^{Oqi} denoting respectively, use of products requiring fuel i at time *t* by group *q* and its fuel consumption rate. Parameters υ^{Oi}, η^{UOi}, η^{hOi}, and α^{Oi} have analogous interpretations to previous notation and are taken to be the same across large and small users.

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[66] The model abstracts from formal substitution between use of gasoline and diesel vehicles, given that carbon pricing tends to increase user prices for gasoline and diesel in roughly the same proportion (and for many countries, heavy vehicles—which do not really compete with light-duty, gasoline vehicles—account for most diesel consumption).

(v) Modelling Policies

The carbon tax is modelled by incorporating into the tax for fuel i a charge of $\tau_t^{CO2} \cdot \mu^{CO2i}$, for i = *COAL*, *NGAS*, *GAS*, *DIES*, and *OIL*, where τ_t^{CO2} is a uniform tax on CO_2 emissions in period t and μ^{CO2i} is fuel i's CO_2 emissions factor (positive for fossil fuels and zero for renewables, hydro, biomass, and nuclear).[67] The ETS is modelled in the same way, but with charges applying only to fuels used by power generators and large users in the other energy sector. The coal tax is the same policy as the carbon tax, but with charges applying only to coal use, and similarly the road fuel tax applies the carbon charges to road fuels only. The electricity tax, denoted τ_t^E, increases electricity prices by the same amount as they increase in the carbon tax scenario. The electricity emissions tax is the same policy as the ETS but with charges applied to power generation fuels only (not large industrial users). The energy efficiency policy applies a 'virtual' carbon charge to fuel prices in the equations governing energy efficiency, but not to fuel prices in the equations governing the usage of energy-consuming products.[68]

(vi) Metrics for Comparing Policies

CO_2 emissions. CO_2 emissions from fossil fuel use at time t are:

(A9) $$\sum_{ji} F_t^{ji} \cdot \mu^{CO2i}$$

where j = E, T, O denotes the electricity, road transport and other energy sector respectively.

Revenue. Revenue from fuel and electricity taxes is:

(A10) $$\sum_{ji} F_t^{ji} \cdot \tau_t^i + Y_t^E \cdot \tau_t^E$$

Deaths from fossil fuel air pollution. At time t these are given by:

(A11) $$\sum_{ij} F_t^{ji} \cdot m_t^{ji}$$

m_t^{ji} is mortality per unit of (fossil) fuel i used in sector j, which may differ by sector due to differing use of air emissions control technologies and local population exposure to emissions.

Economic welfare gains. The economic costs and net welfare gains of policies are calculated using applications and extensions of long-established formulas in the public finance literature[69] based,

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[67] There can be significant variation in CO_2 emissions factors among different coal types, but this is less of an issue when (as here) emission rates are defined per unit of energy.

[68] See, for example, Parry, Evans, and Oates (2014).

[69] See, for example, Harberger (1964).

for simplicity, on second order approximations.[70] The information required to apply these formulas includes the size of price distortions in fuel and electricity markets (i.e., the difference between social and private costs due to any domestic environmental costs net of any fuel taxes), any induced quantity changes in markets affected by these distortions (an output from the model), and any new source of distortions created by carbon policies.[71]

The economic welfare gains (excluding the global climate benefits) from a carbon tax in period *t* are computed using:

$$\text{(A12)} \quad \sum_{ji} \left(\Gamma_t^{ji} - \frac{\mu^{CO2i} \cdot \tau_t^{CO2}}{2} \right) \cdot \left(-\Delta F_t^{ji} \right)$$

$$\text{(A13)} \quad \Gamma_t^{ji} = VMORT_t \cdot m_t^{ji} - \hat{\tau}_t^i, \text{ for } j \neq T,\ i = COAL, NGAS, OIL$$

$$\Gamma_t^{Ti} = VMORT_t \cdot m_t^{Ti} + \left(\frac{\eta^{UTi}}{\eta^{hTi} + \eta^{UTi}} \right) \cdot \beta_t^{Ti} - \hat{\tau}_t^i$$

$$\text{(A14)} \quad \Delta F_t^{ji} = F_t^{ji} - \hat{F}_t^{ji}$$

where a ^ denotes a BAU value and Γ_t^{ji} is the price distortion in a fuel market.

In (A13), Γ_t^{ji} consists, for non-road fossil fuels, of local air pollution costs, equal to premature mortalities per unit of fuel use times $VMORT_t$, the value per premature mortality—Γ_t^{ji} is defined net of any pre-existing fuel taxes but these are modest at most for non-road fuels. For road fuels, there is an additional environmental cost equal to the external costs of traffic congestion, accidents, and road damage expressed per unit of fuel use, β_t^{Ti}. The latter is multiplied by the term in parentheses, which amounts to the fraction of the induced change in fuel use due to changes in vehicle km driven as opposed to (long run) improvements in fuel economy.[72]

In (A14), ΔF_t^{ji} is the change in fuel use, relative to its BAU level $\hat{F}_t^{ji}$.

From equation (A12), the welfare change from the tax increase for a fossil fuel in a sector consists of: (i) the reduction in use of a fuel product in a particular sector times the pre-existing price distortion associated with that product/sector and aggregated over fuels/sectors, less (ii) the 'Harberger triangle', equal to the reduction in fuel use times one-half of the tax increase, where the latter is the product of the fuel's CO_2 emissions factor and the CO_2 price at time *t*.

The above formula is also used to calculate the net welfare change from the ETS, coal tax, road fuel taxes, and energy efficiency policies, where the charges apply to fuel use (or virtually to energy efficiency) and sectors as described above.

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[70] That is, taking fuel and electricity demand curves to be linear over the range of policy-induced fuel changes.

[71] Induced quantity changes in markets with no price distortions have no implications for economic welfare.

[72] See Parry and others (2014), Ch. 5.

Appendix 2. Model Parametrization

The model pivots off fuel use data for 2014. Data for 2015 is available, but does not fully reflect the sharp drop in energy prices between 2014 and 2015 (i.e., 2015 fuel data may significantly understate current equilibrium fossil fuel use).

(i) Fossil Fuels

Supply prices for coal, natural gas, gasoline, diesel, and oil products for 2014-2015 by country are from the IMF [73] and reflect international reference prices of the finished product (e.g., gasoline) adjusted, where appropriate, using standard (absolute) markups for transport and distribution costs.[74] The international (crude) component of these prices is projected forward using actual and projected international energy prices obtained by averaging over projections in IMF (2017)[75] and EIA (2018), Tables 12, 13 and 15.[76] The IMF projections suggest coal prices increase 30 percent between 2015 and 2030, oil prices stay the same,[77] and North American gas prices change little, though prices for European gas and liquefied natural gas decline. EIA (2018) projects an 86 percent increase in oil prices, a 32 percent increase in coal prices, and gas price increases of 23-66 percent (Table Appendix 1). BAU CO_2 emissions, and CO_2 prices needed to induce a given percent reduction in emissions, are generally higher when future international energy prices are assumed to be lower.

Table 1. Comparison of Future Fuel Price Assumptions

	2015 (Actual)	2030 (Projected)		
		EIA (2018)	IMF (2017)	Current analysis
Coal, $/ton	59.9	78.8	77.9	78.4
Oil, $/barrel	50.8	94.4	49.5	71.9
Natural gas, $/MMBtu				
LNG	11.0	14.5	8.4	11.4
North America	2.6	4.3	2.5	3.4
Europe	7.3	9.0	5.2	7.1

Note: All prices in $2015. '2015 (Actual)' prices are from IMF (2017).

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[73] See www.imf.org/external/np/fad/subsidies/data/subsidiestemplate.xlsx.

[74] These markups are held fixed in real terms across future periods.

[75] These projections go to 2022 and are extrapolated to 2030.

[76] IEA (2017b) publishes price projections but not on an annual basis.

[77] The indices for coal and oil are an average of Australian and South African and an average of Brent, West Texas Intermediate, and Dubai Fateh spot prices respectively.

For electricity (generally a non-traded good), the supply cost for 2014-2015 in the IMF database is the domestic production cost or cost-recovery price, with costs evaluated at international reference prices. Electricity prices are projected forward using (A6), and changes in fuel prices and generation shares in a future year relative to 2014 levels.

For G20 countries, 2014-2015 prices to fuel users are available from the IMF and the difference between these prices and supply prices, after the latter (for household fuels) have been marked up for GST, gives the estimated fuel tax (or subsidy). Pre-existing fuel taxes are taken as constant (in real terms) from 2016 onwards in the BAU while (given recent attempts to liberalize domestic energy prices in many energy-exporting countries) any subsidies (primarily for natural gas in Argentina and road fuels in Saudi Arabia) are assumed to phase out progressively by 2030.

(ii) Power Sector Electricity Consumption.

This is obtained for 2014 from IEA (2017c) focusing on domestic generation (i.e., including exported generation where fuels are combusted domestically, but not imported generation), as this is what matters for a country's CO_2 emissions.

Income elasticity of demand for electricity-using products. Empirical studies for different countries suggest a range for this elasticity of around 0.5-1.5.[78] For all but two G20 countries we use a baseline value of 0.75, and for China and India values of 0.5 and 0.9 respectively, which (along with other assumptions) imply trends in the ratio of electricity consumption to GDP that are broadly consistent with projections in IEA (2017) when we use their energy price projections. The lower value for China makes an adjustment for the ongoing rebalancing of the economy away from energy-intensive industries to services[79], while a higher value in India makes an adjustment for the expected progressive expansion in grid access among lower income households.

Price elasticities for electricity. A simple average across the 26 estimates of long-run electricity demand elasticities reported for different countries in Jamil and Ahmad (2011), Table 1, is about -0.5, and nearly all estimates lie within a range of about -0.15 to -1.0.[80] A study for China suggests

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[78] For example, Jamil and Ahmad (2011), Table 1, report 26 estimates of long-run income elasticities for electricity from 17 studies, almost all of them lying within the above range. Many energy-climate models assume an income elasticity of unity (Webster et al. 2008, Table 1), though a review for industrializing countries suggests an elasticity of around 0.6 (Hill et al. 2017).

[79] See, for example, Green and Stern (2016), IMF (2015).

[80] See Madlener et al. (2011) for further discussion and Webster et al. (2008), Table 1, for a summary of energy demand elasticities assumed in energy climate models, most of which are between -0.3 and -0.7. A meta-analysis by Labandeira and others (2017) of studies from around the world reports a mean long-run price elasticity for electricity of -0.4. A review of a limited number of studies for China, India, and Mexico by Hill et al. (2017) puts the long run electricity demand elasticity at -0.46. Studies for residential electricity

an elasticity of -0.35 to -0.5.[81] Evidence for the United States suggests the long-run price elasticity for electricity demand is around -0.4, with about half the response reflecting reduced use of electricity-consuming products and half improvements in energy efficiency.[82] Values of -0.25 are assumed for both the usage and energy consumption rate elasticities for all countries, implying a total electricity demand elasticity of -0.5.

Annual rate of efficiency improvement for electricity-using products. This parameter (which is of moderate significance for the BAU) is taken to be 1 percent a year.[83]

Generation shares. These are obtained from IEA (2017c) by the electricity produced from each fuel type divided by total electricity generation.

Own-price elasticities for generation fuels (conditional on total electricity output). Empirical studies tend to suggest that coal is only moderately price responsive. For example, one survey of eight studies for various advanced countries, China, and India put the coal price elasticity at -0.15 to -0.6.[84] And for the United States, simulations from a variant of the US Department of Energy's National Energy Modeling System (NEMS) model suggested a coal price elasticity of around -0.15 (with fuel switching rather than reduced electricity demand accounting for over 80 percent of the response).[85] Other studies suggest somewhat larger responsiveness however, for example, EIA (2014) estimate a $34 per ton carbon tax raising coal prices by about 150 percent reduces US coal use by 32 percent in 2040, while an $85 per ton carbon tax reduces coal use 90 percent).[86] And a study for China reports coal price elasticities of -0.3 to -0.7.[87] Our judgment is that the

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demand in the United States suggest a long-run elasticity of around -0.3 to -0.8 (Alberini and Filippini 2011), pp. 889 and 895.

[81] Zhou and Teng (2013).

[82] For example, Myers et al. (2009), Parry, Evans and Oates (2014), Sanstad and McMahon (2008).

[83] Typical assumptions in other models are between about 0.5 and 1 percent (e.g., Webster et al. 2008, Table 1, Cao et al. 2013, pp. 389-90). Significantly higher values for energy products in general seem unlikely—for example, Nordhaus (2016) puts the annual rate of decline in the CO_2 intensity of GDP at 1.5 percent (in the absence of new policies) which reflects not only improving energy efficiency but other factors (e.g., below-unity income elasticities, shifting towards low-carbon fuels).

[84] Trüby and Paulus (2012), Table 5.

[85] See Krupnick et al. (2010). This simulation was for a carbon price which also raises natural gas prices, thereby dampening some of the reduction in coal use.

[86] Much of the difference between EIA (2014) and Krupnick et al. (2010) is due to different assumptions about the expansion of nuclear power and renewables in response to higher coal prices—Krupnick et al. (2010) adjusted the NEMS model to limit this expansion to reflect practical constraints (e.g., public opposition to site development).

[87] Burke and Liao (2015).

rapid (and continued future) decline in the costs of renewable energy will likely increase the price responsiveness of coal use relative to previous estimates, and could induce significant technological innovation[88], and a coal price elasticity of -0.7 is assumed here for all countries.[89] The same elasticity is assumed for other fossil generation fuels. The elasticities in equation (A3) are defined with respect to generation costs rather than fuel costs and can be obtained by dividing the fuel price elasticity by the share of fuel costs in generation costs, which for coal generation is taken to be 0.25 (see below).

Fossil fuel consumption and productivity. Consumption of coal, natural gas, and oil used in power generation is taken from IEA (2017c) for 2014. Electricity generated from a fossil fuel, divided by input of that fuel, gives the productivity of the fuel.

Annual rate of autonomous productivity improvement. Productivity improvements at power plants reflect improvements in technical efficiency and gradual retirement of older, less efficient plants. For coal, annual average productivity growth is taken to be 0.5 percent based approximately on IEA (2015), Figure 2.16. For natural gas, nuclear, and hydro, there is likely a bit more room for productivity improvements and baseline annual growth rate of 1 percent is assumed. For renewables, a productivity growth rate of 5 percent is used (i.e., costs halve every 15 years).

Non-fuel generation costs. For coal and oil plants, non-fuel generation costs are taken to be three times 2014 fuel costs and for natural gas plants (which have low capital costs) non-fuel generation costs are taken to be 50 percent of fuel costs.[90] Generation costs for nuclear, biofuels, and renewables (implicitly including any subsidies) in 2014 are taken to be 100 percent of those for coal, and for hydro 90 percent of those for coal.[91]

(iii) Road Transport Sector

Fuel use. Consumption of road gasoline and diesel in 2014 is taken from IEA (2017c).

Income elasticity of demand for vehicle km. Estimates of this parameter for advanced countries are typically between about 0.35 and 0.8, although a few estimates exceed unity (Parry and Small

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[88] For example, Fried (2018) estimates that induced innovation increases the price-responsiveness of US CO_2 emissions by about a fifth.

[89] The degree of substitution among fossil and non-fossil generation sources is, however, limited in practice, for example, due to the intermittency of renewables, their location away from population centers, and public opposition to nuclear power.

[90] For US coal and natural gas plants, fuel costs account for about 70 and 85 percent respectively of operating costs, and operating costs for about 35 and 80 percent respectively of total (‘levelized’) costs (EIA 2016, Table 8.4, EIA 2015, Table 1).

[91] EIA (2015), Table 1.

2005). A value of 0.6 is used here, aside from China and India, where values of 0.8 are assumed, given the greater potential of higher income to affect vehicle ownership rates.[92]

Fuel price elasticities. Numerous studies have estimated road fuel (especially gasoline) price elasticities for different countries and some studies decompose the contribution of reduced vehicle km from long-run improvements in average fleet fuel efficiency. Based on this literature, a value of -0.25 is used for each of these elasticities and for both gasoline and diesel—the total price elasticities for each fuel are therefore -0.5.[93]

Annual rate of autonomous decline in vehicle fuel consumption rates (from technological improvements). As for electricity, this parameter is set at 1 percent a year (and implicitly encompasses progressive penetration of electric and hybrid vehicles).

(iv) Other Energy Sector

Fuel use. We assume 75 percent of fuel consumption by industry is by large firms that would be covered by the ETS.[94]

Income and price elasticities for other energy products. Evidence on income and price elasticities for fuels used in the industrial and residential sectors is more limited. Income elasticities of 0.5 are assumed for products using coal, oil, and biomass, and 1.0 for products using natural gas[95] and renewables—these assumptions imply BAU projections of these fuels outside of the power and transport sector in 2030 that are broadly consistent with corresponding data for countries reported in IEA (2017a) when we use comparable price projections (see below). Price elasticities for fuels used in the other energy sector are taken to be the same as for electricity and road fuels.

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[92] Studies tend to suggest somewhat higher income elasticities for industrializing countries, for example, a review by Hill et al. (2017), Figure 7, suggests an income elasticity for gasoline of around unity (0.8 in China but well above unity for India).

[93] There is significant variation among studies however: for example, Sterner (2007) reports globally averaged (long-run) gasoline price elasticities of around –0.7, Hill et al. (2017) suggest an elasticity of -0.6 for industrializing countries, while individual country estimates in Dahl (2012) are closer to about –0.25 on average and a meta-analysis by Havranek and others (2012) of international studies puts the long run gasoline price elasticity at -0.3 (see Charap et al. 2013 for further discussion). The responsiveness of fuel efficiency to taxation will be dampened in the presence of binding fuel economy regulations on new vehicles in some countries, though an adjustment is not made for this given the difficulty of gauging how binding these regulations are and the preference here for clean comparisons between fuel efficiency policies and other mitigation policies.

[94] This fraction will depend on the threshold emissions level determining whether entities are covered by pricing schemes, which depends in part on administrative considerations. See WBG (2016) for some discussion of emissions coverage in existing ETSs.

[95] Burke and Yang (2016) put the income elasticity for natural gas at about unity, based on a meta-analysis for 44 countries.

Annual rate of autonomous productivity improvements. These are assumed to follow those for the same fuel as used in the power sector.

(v) Miscellaneous

GDP growth. Projected GDP out to 2022 is from IMF (2017) and annual GDP growth between 2023 and 2030 is assumed equal the projected growth rate for 2022.

CO_2 emissions factors. These are calculated by dividing, for 2014, CO_2 emissions by fuel use from IEA (2016) by fuel use (from IEA 2017b).

Mortality rates from fuel combustion. The major pollutant from power plant coal combustion causing premature mortality is $PM_{2.5}$, fine particulate matter with diameter up to 2.5 micrometers, which is small enough to penetrate the lungs and bloodstream. $PM_{2.5}$ can be produced directly during fuel combustion and is also formed indirectly (and generally in greater quantities) from chemical reactions in the atmosphere involving sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions. Although most countries are taking steps to reduce local air emission rates (e.g., by requiring new coal plants incorporate post-combustion SO_2 emissions control technologies), air pollution damages can still be substantial (e.g., many existing plants may not have control technologies, control technologies do not remove 100 percent of the SO_2, the technologies may not always be switched on, NO_x might be subject to lighter regulation, and partially offsetting lower emission rates over time is the higher valuation of health effects as per capita incomes rise and possibility greater urban population exposure to emissions).

Air pollution emissions, mortality, and damage estimates by country are taken from Parry and others (2014), with some adjustments. Parry and others (2014) provide this data for representative coal plants with emissions control technologies, and industry-wide damages averaging over plants with and without control technologies, for 2010. Air emission rates from power plant coal combustion are assumed to converge linearly from the industry average in 2010 to the emission rate from plants with control technologies by 2030.[96] A linear upward adjustment in the annual mortality rate is made for China and India (growing at 1.3 and 2.6 percent a year respectively) to account for (steadily) rising urban population exposure.[97] For large industrial coal users, the same mortality rates as for coal power plants in each year is assumed. For small-scale coal users, mortality rates in 2010 are assumed equal to the industry average for coal plant emissions while for natural gas, gasoline, diesel, and oil products rates are also based on Parry and others (2014) (in all cases for China and India rates rise with urban population).[98]

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[96] For the United States, for example, this implies a 75 percent reduction in SO_2 emissions between 2010 and 2030.

[97] See Parry and others (2016, 2017).

[98] Mortality rates for other oil products (which were not estimated by Parry and others 2014) are taken to be the same as for road diesel. For gasoline and road diesel, emission rates are assumed to linearly converge between 2010 and 2030 from the vehicle fleet average in 2010 to the emission rates for

One caveat is that people's physical channels for absorbing air pollution may become saturated at very high outdoor pollution concentrations implying, paradoxically, that the health benefits from incremental pollution reductions are smaller at high pollution concentrations than at more moderate concentrations. By ignoring this possibility, our analysis may overstate the domestic health benefits of carbon mitigation policies in highly polluted countries, though the evidence on this issue is unsettled.[99]

(vi) BAU Comparisons with Other Studies

Table 2 compares, for 2030, BAU projections for fuel use and CO_2 emissions expressed relative to the corresponding projections in IEA (2017a)'s Current Policies scenario for the seven individual countries that IEA distinguishes. If IEA (2017a) energy price projections were used, our BAU projections tend to be about the same or moderately higher than in IEA (2017a), for example, CO_2 projections are 20 percent higher for China, about the same for India, and lower for Brazil. However, BAU CO_2 emissions for 2030 are 7-36 percent higher across countries when the averaged prices discussed above are used.

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representative vehicles in 2010 with advanced emission control technologies. The same adjustment is made for other oil products but not (due to lack of data) for natural gas, though air pollution damages from gas are relatively small. Overall, the BAU mortality estimates are broadly consistent with Lelieveld et al. (2015) who apportion observed mortality rates to air pollution versus other causes, and then sub-divide the former according to the sectoral source of emissions.

[99] For example, Pope et al. (2015).

Table 2. Comparison of Projected Fuel Use and CO_2 with IEA (2017a)

(2030 projections expressed relative to IEA 2017a)

	Current analysis				Current analysis with IEA (2017a) prices			
Country	coal	oil	natural gas	CO_2	coal	oil	natural gas	CO_2
Brazil	0.97	1.56	1.09	1.07	0.89	1.35	1.08	0.91
China	1.41	1.55	1.05	1.36	1.24	1.32	1.07	1.20
India	1.40	1.62	1.07	1.28	1.03	1.49	1.20	0.98
Japan	0.86	1.64	1.73	1.30	0.79	1.33	1.72	1.17
Russia	0.72	1.46	1.30	1.16	0.66	1.18	1.28	1.09
South Africa	1.21	1.59	1.09	1.16	1.11	1.39	1.08	1.05
United States	1.27	1.37	1.25	1.27	1.12	1.12	1.25	1.14

Appendix 3. Incidence Analysis

Methods for assessing the household and industry incidence for Canada, China, India, and the United States from a \$20 carbon tax in 2020 are discussed below.

(i) Household Incidence

A first-order approximation of the burden on household income group $h = 1 \ldots H$ from higher consumer prices induced by carbon taxes is given by:[100]

(C1) $\sum_g \pi_t^{hg} \cdot \rho_t^{hg}$

g denotes major categories of consumer goods, π_t^{hg} is the share of household h's budget spent on good g at time t, and ρ_t^{hg} is the percent increase in price of good g induced by the carbon tax. If the budget share for a product is, say, 5 percent, this formula implies a 10 percent increase in its price will decrease the household group's consumption by the equivalent of 0.5 percent.

Budget shares are from the Survey of Household Spending[101] for Canada, the China Family Panel Studies[102] for China, the 68th Round of the National Sample Survey (NSS)[103] for India, and the Consumer Expenditure Survey (CEX)[104] for the United States. Households were 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.

Policy-induced impacts on fuel and electricity prices are taken from the model. Indirect price increases for other consumer goods are calculated, assuming full pass through of the burden from producers to consumers in domestic markets (i.e. horizontal supply curves), using input/output tables with more granular product classifications than in the household data. For

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[100] See, for example, Coady and Newhouse (2006) for further discussion.

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

[102] 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.

[103] 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.

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

Canada, the national input-output table is for 2013,[105] for China 2012,[106] for India 2007-2008[107], and for the United States 2007.[108] Industries are mapped to the relevant product classification in the household data, and within that classification are weighted by their contribution to the value of spending on that product. Although more recent input-output tables are available from other sources[109], they only cover a (standardized) set of (56) industries, which does not provide the necessary level of disaggregation (i.e. 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 projecting to 2020, the shares of different industries in total output, and their energy intensity of production, are assumed to be the same as in the years of the input/output data. The household budget shares for electricity and direct fuel consumption are however, scaled by the corresponding 2020 energy prices relative to prices in the year of the household survey.

There are some caveats to using the formula in (C1). The energy intensity of production in different sectors will tend to fall in response to higher energy prices, implying use of input/output tables overstates the consumer price increases. However, this overstatement is likely modest for the policy scenarios considered here. The formula also overstates consumer surplus loss by ignoring the reduction in household quantity demanded for energy-intensive products caused by higher energy prices, though again this effect should be modest.[110]

Furthermore, some (likely minor) fraction of the burden of fuel taxes may be passed backwards in lower producer prices, if fuel supply curves remain upward sloping in the medium to longer term. To the extent this lowers the net of tax return to capital, some of the incidence of the fuel tax is borne by owners of capital, though if the net tax returns are largely determined in world capital markets, the burden of lower producer prices should be largely borne by workers in the form of lower wages. The resulting incidence effects become tricky to estimate as they depend, for example, on whether energy-intensive firms disproportionately hire high- or low-wage workers,

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[105] The latest version published by Statistics Canada, and which disaggregates 230 industries.

[106] The latest version published by the National Bureau of Statistics, covering 139 industries.

[107] 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

[108] From the US Bureau of Economic Analysis (see www.bea.gov/industry/io_annual.htm), covering 389 industries. See: https://www.bea.gov/industry/io_annual.htm

[109] See, for example, the World Input-Output database (www.wiod.org/home) covering 43 countries over the period 2000-2014.

[110] For example, from simple geometry the first-order approximation (a rectangle equal to initial consumption times the price change) overstates the loss of consumer surplus (a trapezoid to the left of the demand curve between the pre- and post-tax price) by only about 5 percent when demand for a fuel product falls by 10 percent.

and substitution elasticities between energy and other inputs[111]. Nevertheless, though some studies for advanced countries suggest these incidence effects are not that large and may disproportionately harm higher income groups.[112] Alternatively, policy costs may not be fully passed forward in energy markets with regulated pricing, but again who ultimately bears the burden of the resulting losses to state-owned enterprises and government budgets is unclear.

(ii) Industry Impacts

The percent increases in unit production costs for different industries caused by carbon taxes are assumed equal to the percent price increases obtained from the input-output calculations just described.

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[111] For example, Fullerton and Heutel (2011).

[112] For example, Rausch et al. (2011).

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