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Carbon Taxation for International Maritime Fuels: Assessing the Options

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Abstract

The International Maritime Organization (IMO) announced in April 2018 a target of cutting greenhouse gas (GHG) emissions from the sector by 50 percent below 2008 levels by 2050 and subsequent meetings of the IMO will develop a strategy for making headway on this commitment. This paper seeks to inform dialogue about the possibility of a carbon tax as a key element of GHG mitigation policy for international maritime transport. The paper discusses the case for the tax over alternative mitigation instruments, options for the practical design issues, and then presents estimates of the impacts of carbon taxation and other instruments from an analytical model of the maritime sector.

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Contents

Executive Summary

It is an especially opportune time to consider market-based mechanisms (MBMs), or more specifically, an international maritime carbon tax or fuel levy (i.e., a tax/levy on shipping fuel in proportion to carbon content, referred to here as a carbon tax). International maritime fuels are underpriced from an environmental perspective as there is no charge for their greenhouse gas (GHG), particularly carbon dioxide (CO_2), emissions (which are significant and expected to expand steadily without policy action). The International Maritime Organization (IMO) announced, in April 2018, a pledge to cut emissions by 50 percent by 2050 relative to the 2008 level, and the next step is to develop near- and longer-term policies for making progress on this goal.

This paper seeks to promote dialogue about the possibility of a carbon tax as a key element of a GHG mitigation strategy for international maritime transport. The paper discusses the case for the tax over alternative mitigation instruments, options for the practical design issues, and then presents estimates of the impacts of carbon taxation and other instruments.

The environmental case for a maritime carbon tax is increasingly recognized. Unlike most alternative mitigation instruments (e.g., standards for the technical efficiency of new ships), maritime carbon taxes promote, and strike the cost-effective balance between, the full range of potential opportunities (given the current state of technology) for reducing emissions (e.g., technical and operational improvements for both new and existing ships, shifting the fleet towards larger, more efficient vessels) and unlike other pricing instruments (e.g., emissions trading systems, offset schemes) a tax provides more certainty over prices and is simpler to administer and comply with.

Although some design specifics of carbon taxes may appear contentious, there are workable options for moving policy forward. As regards:

- *Responsibility for implementation*—maritime carbon taxes could be collected domestically (through extending administrative capacity for domestic fuel taxes), but the more immediately relevant option (given delegation of GHG mitigation strategy to the IMO) would be international collection from ship operators (based on required reporting of their fuel consumption) through establishment of an IMO-administered fund;
- *Tax rates*—economic models are available for assessing the future emissions impacts of carbon taxes though, for practical purposes, it may be challenging to implement prices considerably higher than in other pricing schemes (typically around \$5-\$30 per tonne of CO_2 at present);
- *Compensation for vulnerable countries*—compensation mechanisms, if required to reconcile the principle of common but differentiated responsibilities and respective capabilities (CBDRRC) and global application of the maritime carbon tax (preferred

due to the high mobility of the tax base and the undesirability of introducing trade distortions), should be practical, not least because the burden of maritime carbon taxation is generally small in relation to countries' GDP;

- *Revenue use*—allocation of the (potentially sizable) revenues is highly contentious (e.g., some see maritime taxes as a natural and urgent source of climate finance and others a funding source for technology and other programs within the maritime sector) though an option (which might permit more aggressive pricing) is to limit revenues raised (while preserving mitigation incentives) by charging ship operators for the difference between their emissions and a benchmark level.

Some noteworthy modelling results include:

- An illustrated carbon tax rising to US$75 per tonne[1] of CO_2 in 2030 ($240 per tonne of bunker fuel), and $150 per tonne in 2040, by itself reduces maritime CO_2 emissions below business-as-usual (BAU) levels by nearly 15 percent in 2030 and 25 percent in 2040, raises revenues of about $75 billion in 2030 and $150 billion in 2040, while increasing shipping costs by 0.075 percent of global GDP in 2030;
- A revenue neutral carbon tax with the same emissions price (i.e., one that taxes operators with relatively high emissions intensity and subsidizes operators with relatively low emissions intensity) is only slightly less effective at reducing CO_2 and increases average shipping costs by a tiny 0.005 percent of global GDP in 2030;
- A performance standard for new ships (currently implemented by IMO) has only one-third of the effectiveness of carbon taxes (for the same implicit CO_2 price).

In short, maritime carbon taxes are an economically and administratively promising instrument; there are different candidate designs for carbon taxes that should be considered, including the possibility of a revenue-limiting tax; and the global burden of the tax appears to be rather small. Taxes would need to be accompanied by measures to develop and deploy alternative fuel technologies if the deep emissions reductions envisioned by mid-century are ultimately to be achieved. Nonetheless, maritime carbon taxation deserves serious attention at upcoming IMO deliberations as part of a comprehensive strategy to progress on mitigation commitments.

I. Introduction

Although the aspirational goal of the 2015 Paris Agreement on climate change is to contain long-range, mean-projected planetary warming to 2^{o}C above pre-industrial levels (and make efforts to achieve stabilization at 1.5^{o}C), the more immediate policy framework is the country-level mitigation pledges in Nationally Determined Contributions (NDCs) submitted

[1] All monetary figures are expressed in constant, 2016 US$.

(continued…)

for the Agreement by 169 countries.[2] A typical NDC among advanced G20 countries (Table 1) is to reduce GHGs by around 30 percent by 2030 relative to historical emissions in some cases, or projected business as usual (BAU) emissions in others.[3]

The international maritime sector accounted for 2.6 percent of global CO_2 emissions in 2012[4] (only four countries produced more emissions—Table 1) and its emissions would expand steadily in the absence of mitigation policy.[5] Exemption of the fuel from excise taxes (routinely applied to road fuels) appears to reflect informal convention and especially, extreme mobility of the tax base.[6] As noted below, international maritime is also subject to a lighter business tax regime than other industries.

Global application of a maritime carbon tax would be consistent with the IMO's guiding principle of non-discriminatory treatment of all ships regardless of the flag state. At the same time, member states emphasize the principle of common but differentiated responsibilities and respective capabilities (CBDRRC)—that countries in some way have a differentiated responsibility for their contributions towards GHG mitigation in recognition of their economic status and respective capabilities[7]—should be addressed in any IMO GHG strategy, though there is presently little consensus on how to achieve this. The IMO acknowledges the need to avoid adverse impacts on low-income countries (LICs) and small island developing states.[8] The tension between the non-discrimination and CBDRRC principles may need to be addressed, one possibility (see below) being through compensation schemes, though it may be acceptable to limit these schemes only to cases where the burden of higher shipping costs is deemed significant.

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[2] Not all 197 signatories to the Agreement have submitted NDCs and the United States announced its intention to withdraw from the Agreement (which cannot occur till November 2020).

[3] Although pledges are not enforceable, countries are required to report progress on meeting pledges every two years (starting 2018) and update them every five years (starting 2020).

[4] IMO (2014), Table 1.

[5] IMO (2014), Table 1. Whilst shipping produces other GHGs (methane and nitrous oxide), these contributed only 2.5 percent to maritime GHGs in 2012 (IMO 2014, Table 1) and the discussion here is therefore confined to CO_2.

[6] Large ships can undertake very long voyages on single bunkering of fuel (fuel can be used as ballast and replaced with water as the fuel is used) enabling them, without significantly adding to operational costs, to re-tank at ports with lower fuel prices. The practicality of regional pricing schemes, levied on voyage emissions at ports where charges are applied, is discussed in Dominioni and others (2017) but is not considered here given the focus on global application.

[7] UN (1992), Article 3.1.

[8] See IMO (2015). Developing countries as a group play a large role in international shipping, accounting for 63 percent of unloaded tonnage in 2015 (UNCTAD 2016, Table 1.4b), however the case for fully compensating middle, and especially high, income developing countries is questionable.

Box 1. CO_2 Mitigation Initiatives for International Aviation and Maritime

Aviation

ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will require airlines to purchase international emission offsets for any CO_2 emissions exceeding 2020 levels. There is considerable uncertainty over future credit prices however, which depend on: (i) the extent and cost of future emission reduction projects in developing countries; (ii) the strictness of verification procedures meant to ensure projects are 'additional' (i.e., they would not have gone ahead anyway without the offset payment); (iii) competition for offsets from other carbon pricing schemes; and (iv) the willingness of countries (where offsets projects are undertaken) to not 'double count' these reductions when reporting progress on their Paris mitigation pledges.

Several design elements are meant to ease the transition to CORSIA, including:

- The scheme is not mandatory until 2026, though 72 countries (e.g., China, the EU and US) have volunteered for a sub-global pilot phase from 2021 onwards;
- Small island developing states, LICs, landlocked developing countries, and states with small shares in global aviation are all exempted from the scheme;
- Initially, operators need credits for the difference between average industry-wide and 2020 emissions (which favors faster growing operators in emerging markets), though a transition to operator specific emissions growth will begin after 2030; and
- New airline entrants are exempt from the scheme for three years (or until they reach 0.1 percent of 2020 global emissions).

CORSIA applies to routes between participating states (regardless of where operators are registered), but if either departure or arrival state is exempt the route is excluded from the offset obligation.

Maritime

In 2017, the IMO agreed on a timeframe for developing a comprehensive strategy for reducing GHG emissions from ships, following the establishment of a global data collection system (for ships of 5,000 gross tonnage and above accounting for about 85 percent of international maritime CO_2) for fuel consumption and other characteristics associated with individual shipping voyages.[/1]

The centerpiece of mitigation efforts to date is the Energy Efficiency Design Index (EEDI), providing ship-specific requirements for grams of CO_2 per capacity-mile, which entered into force in 2013. This carbon intensity standard leaves the choice of technologies in ship design to the industry, with the standard tightened every five years in line with the requirement of reducing emission rates relative to a baseline efficiency by 10 percent for ships built from 2015 to 2020; 20 percent for ships built between 2020 and 2025; and 30 percent for those built after 2025.

Sources. www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx and www.imo.org/en/MediaCentre/hottopics/ghg/pages/default.aspx.

[/1] The European Parliament has declared its intention to proceed with regional carbon pricing in the absence of a global agreement. For an analysis of the challenges facing regional carbon pricing schemes for international maritime transport, see Dominioni and others (2018).

The International Civil Aviation Organization (ICAO) has announced a strategy to stabilize that sector's emissions at 2020 levels through an international offset scheme, though there are significant exemptions and implementation delays and verification procedures remain unclear (Box 1). And the IMO announced in April 2018 a commitment to cut emissions by 50 percent below 2008 levels of 1,135 million tonnes by 2050.[9] The next step is to agree on specific policies to begin making headway on this pledge—previously, the IMO has implemented new vessel carbon intensity standards for technical efficiency (Box 1) and considered proposals for market-based mechanisms (MBMs) to reduce CO_2.[10]

This paper seeks to inform dialogue about the possibility of a carbon tax as a key element of GHG mitigation policy for international maritime transport—design specifics for complementary measures to develop alternative fuel technologies that will ultimately be needed, is largely beyond our scope.[11] The first half of the paper reviews the case for the tax, how it differs from some other mitigation instruments, and design options. The second half presents an analytical model of the international maritime sector providing a transparent assessment of its environmental, fiscal, and economic impacts and trade-offs with other instruments.

II. Conceptual Rationale for, and Design of, an International Maritime Carbon Tax.

This section discusses the conceptual rationale for maritime carbon taxes, elaborates on key design issues, and compares taxes (qualitatively) with selected other mitigation instruments.

A. Rationale for a Maritime Carbon Tax

As increasingly recognized[12], a key rationale for carbon taxation is that it is the most effective instrument for promoting all potential behavioral responses for mitigating international maritime emissions (given the state of technology) and striking the cost-

[9] Following earlier proposals, for example, by ICS (2017).

[10] See, for example, Lamotte (2011).

[11] One reason is that a modelling framework for quantifying the economically efficient amount of R&D and technology deployment, and the trade-offs across different instruments at different stages in the innovation process (e.g., research subsidies versus technology prizes or technology deployment subsidies versus feed-in tariffs), has not been developed for the maritime sector. For a general discussion of clean technology policies see, for example, Acemoglu and others (2012), Dechezleprête and Popp (2017) and Newell (2015).

[12] For example, AGF (2010), ICS (2016), IMF-WBG (2011), ITF (2017), and UNCTAD (2016).

(continued…)

effective balance among them. As the carbon tax is passed forward in higher prices for carbon-based fuels,[13] this signal promotes the following responses:[14]

(1) *improvements in technical design efficiency of new vessels*, for example, design modifications to lower their empty weight, increase engine/propulsion efficiency, and accommodate lower carbon technologies like batteries, biofuels, liquefied natural gas (LNG), and (in the longer term) hydrogen;

(2) *improvements in operational efficiency* (for a given cargo weight), for example, optimizing average vessel speeds, route lengths, and port dwell time and better maintenance or retrofitting engines, propellers, and hulls of existing ships;[15]

(3) *other operator responses to lower carbon intensity*, primarily shifting to larger (more fuel-efficient) ships (within a broad cargo classification) and increasing load factors; and

(4) *shifting consumer demand away from heavy/long-distance products*, whose prices rise relative to light/short-distance products (e.g., high-value electronics) and non-shipped goods and services.

Cost-effectiveness is achieved because the carbon tax provides the same reward per tonne of CO_2 reduced, regardless of how it is achieved, which promotes equalization of the cost of the last tonne reduced across mitigation responses. And in a dynamic context, setting a robust and predictable carbon tax is likely the single most important instrument for promoting emissions-saving investment.[16]

Carbon taxes can also raise significant revenues. If taxes were collected domestically, it would be logical for this revenue to go to national budgets, but with international collection, climate finance might be a more natural use of the revenue, as national governments have a weaker claim on the tax base (which is combusted in international waters). In fact, it might be especially timely to raise a new revenue source for the Green Climate Fund (GCF), given that many developing countries' (more ambitious) mitigation commitments are contingent on

[13] Simulations across a broad range of parameter assumptions in IMF-WBG (2011) suggest that typically 95 percent or more of bunker fuel taxes would be passed forward into higher fuel prices.

[14] See Calleya and others (2015) and Smith and others (2016) for more in-depth discussion of responses.

[15] The latter responses are not always viewed as operational improvements, though separating them out in the analytical model below would not affect the results.

[16] For example, Newell (2015). Beyond reducing CO_2, the carbon tax may reduce other environmental impacts like ecological damages from oil spills, transport of invasive species in ballast water, and air quality problems in ports (e.g., Eide and others 2013). These effects are not considered here as they are localized, better addressed through other instruments (e.g., oil spill liability, low sulfur requirements) and difficult to quantify at the global level—this omission leads to some (likely modest) overstatement of the net economic welfare costs from carbon taxation.

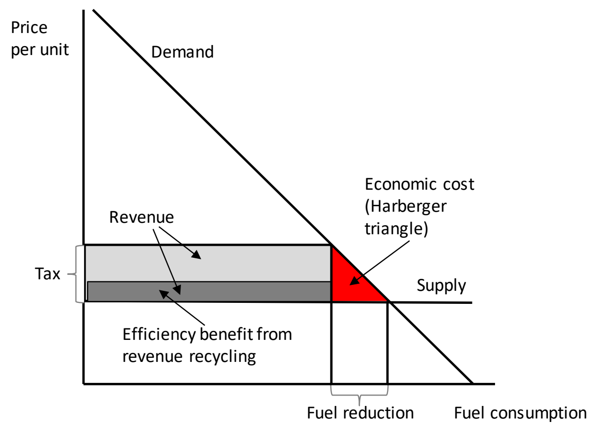
(continued…)

receiving external finance. Alternatively, some funds might be retained by the industry, most obviously for clean technology research and deployment, though the efficient amount of spending is likely a small fraction of potential carbon tax revenues[17]—put another way, if tax rates were set based on industry spending needs they may fall well short of the levels needed for meaningful mitigation incentives.

Box 2. Revenue-Recycling and the Costs of Carbon Taxation

The environmental tax literature has demonstrated the significant difference in (economy-wide) costs between emissions pricing instruments that do, and do not, exploit the potential gains in economic efficiency from recycling revenues. Consider the figure below where imposition of a fuel tax reduces fuel use and causes an economic welfare cost—commonly termed the 'Harberger triangle'—and defined prior to netting out the benefits from reduced future climate change. This cost is the red triangle, equal to the loss of consumer benefits (the trapezoid area under the demand curve integrated over the fuel reduction) less reductions in fuel production costs (the corresponding area under the supply curve), and the cost increases approximately in proportion to the square of the tax rate. In addition, the tax raises revenue indicated by the grey rectangles combined. The darker grey rectangle is also the economic efficiency benefit from recycling the revenue, that is, the revenue times the efficiency gain per dollar recycled reflecting, for example, reductions in various distortions in the economy (like disincentives for work effort and investment, excessive informality and other tax-sheltering behavior) from cutting taxes on labor income. Suppose, for illustration, that the efficiency gain is 30 cents per dollar of revenue recycled, then from simple geometry, the revenue recycling benefit is 5.4 times and 2.4 times the Harberger triangle for fuel reductions of 10 and 20 percent respectively.

Figure 1. Costs, Revenue, and Benefits from Fuel Taxes



There is another, counteracting, effect to consider however, termed the 'tax-interaction effect', which refers to the efficiency loss from the impact of higher product costs on reducing the overall level of economic activity, which in turn (slightly) compounds the dampening effect of taxes on labor and capital on work effort and investment. Under plausible assumptions, up to a point the revenue-recycling benefit exceeds the tax-interaction effect, but the latter effect can also be large relative to the Harberger triangle—hence the need to counteract it through efficient revenue recycling. If, however, the carbon tax is designed not to raise revenues (as discussed in the text) the tax-interaction effect is substantially reduced, as there is no pass through of (large) tax payments in higher product costs.[/1]

[/1] For elaboration of these issues see, for example, Parry (2003), Parry and Williams (2012).

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[17] Newell (2015) puts the efficient amount of R&D spending on clean technology programs in general at about 5 percent of the revenue from a nationwide tax on US carbon emissions.

There is probably little basis for full retention of carbon tax revenues within the industry on compensation grounds either if, as noted above, most of the tax passes forward into higher fuel prices rather than squeezing shipping margins.

In short, if diverting significant revenues from the industry is not (initially) viable, a way forward might be to design the carbon tax to avoid raising large revenues in the first place, by taxing the difference between emissions and a benchmark level. This also limits the broader burden of the tax on economic activity because of the weaker impact on shipping costs (i.e., there is less pass through of tax revenue into these costs). Box 2 elaborates on the broader, though somewhat technical, implications for economic costs.

B. Other Instruments

This subsection discusses the main alternative mitigation instruments and, conceptually, how they differ from maritime carbon taxes.

(i) ETS

An ETS would require operators to acquire allowances for the CO_2 emissions associated with their fuel use—total allowances, and hence emissions, would be capped with allowance trading establishing an allowance or emissions price.[18] In principle (for equivalently scaled instruments), an ETS promotes similar mitigation responses as the pure carbon tax; auctioning of allowances generates the same revenue; and allowance requirements could be modified (i.e., set in reference to a baseline emissions) to mimic a revenue-limiting tax scheme discussed below.

The ETS is potentially less cost effective than a carbon tax in a dynamic sense, to the extent that short term volatility in emissions prices causes significant differences in (discounted) incremental abatement costs at different points in time, though empirical studies for more general carbon pricing schemes suggest this effect is of only moderate importance.[19] Besides being volatile, prices in ETSs to date have also been depressed[20], partly due to their incompatibility with other mitigation instruments—for example, if a carbon intensity

[18] Manipulation of allowance markets, and transactions costs, might be issues for an ETS given, respectively, significant concentration in the international maritime sector (eight companies account for about 60 percent of shipping capacity—UNCTAD 2016, Table 2.4) and that nevertheless a large quantity of ship owners often have only a few ships and therefore small back offices with limited capacity for participating in trading markets.

[19] For example, for carbon pricing at the national (US) level, Fell and others (2012) estimate that short-term price volatility in a typical ETS raises costs by around 15 percent relative to a carbon tax (for a the same cumulative emissions reduction).

[20] See, for example, Green (2017).

(continued…)

standard for ships is combined with an ETS this lowers the allowance price without affecting emissions which are fixed by the cap (under a carbon tax the emissions price is fixed so the standard would reduce emissions).[21]

(ii) Carbon intensity standards—design

Carbon intensity standards—as currently implemented by IMO for the technical design efficiency of new ships—are less effective than carbon taxes (for the same implicit CO_2 price). Unless accompanied with a mechanism to review the design specification of existing ships in a comparable manner, they are limited in application to newbuild ships, and therefore do not promote responses in (2), (3) and (4) above. Carbon intensity standards, moreover, do not provide an automatic mechanism for equating incremental costs of CO_2 reductions across different operators which undermines cost effectiveness. Furthermore, the environmental economics literature suggests that non-pricing mitigation instruments are generally less effective at promoting clean technology investment than pricing instruments.[22]

Carbon intensity standards may have some reinforcing role if carbon pricing is constrained (e.g., by political acceptability issues) and, arguably, to overcome obstacles to technology deployment (though there is potential for overlap if industry-retained funds are used for similar purposes). Ideally standards should include flexibility provisions, like out-of-compliance fees allowing operators to fall short of the standard (if meeting it is relatively high-cost for them) and rebates for operators exceeding the standard (if meeting it is relatively low-cost for them).

(iii) Carbon intensity standards—operation and design

Generalizing the concept of a carbon intensity standard on design specification to include operation by (i) applying it to existing (rather than just new) ships and (ii) accounting for both technical and operational efficiency in the standard, would substantially increase its environmental effectiveness. Moreover, allowing operators who exceed the standard to sell credits to those falling short of the standard, would promote cost effectiveness (i.e., trading provides an alternative flexibility mechanism to the fee/rebate provision just mentioned).[23] The approach, as previously proposed by the United States[24], and as represented below, may do little to promote response (3) above however as, for practical purposes, it would involve

[21] The same effect applies if emissions-saving technologies in shipping are promoted through green bonds in the presence of a fixed emissions cap (e.g., Gevorkyan and others 2018).

[22] For example, Fischer and others (2003), Jaffe and others (2005).

[23] For example, Burtraw and others (2012).

[24] US (2010).

significant disaggregation of vessel types (e.g., different size container ships) with different standards applied to those types, which can limit incentives for shifting to larger ship sizes (if this implies meeting a tighter standard).

A technical challenge for carbon intensity standards for operation and design is whether a carbon intensity metric can be obtained which is environmentally effective, compatible with available or collectable data, and does not unintentionally penalize ships with special operational requirements (which would distort shipping markets)—these issues can increase the administrative burden and political acceptability of such standards. More generally, as with ETSs, the standards provide less certainty over (implicit) emissions prices than a carbon tax.

(iv) Offsets

Finally, under an offset scheme (like that for international aviation) operators would be required to purchase credits for emission reduction projects outside of the maritime sector for any excess of their CO_2 emissions above a benchmark level. In theory, by establishing a uniform reward for each tonne of CO_2 reduced (i.e., the need to purchase fewer offset credits), this approach can cost-effectively promote similar, within-industry behavioral responses as under carbon taxes (albeit the revenue-neutral version—see below), as well as promoting outside-industry emissions reductions. In practice however, the supply, and therefore price, of future offsets is highly uncertain (Box 1).

(v) Summary

A key theme from the above discussion is that design details matter. A carbon tax should be considered as a preferable mitigation instrument, so long as a robust and predictable price is established and (large) revenues are either used efficiently or the tax is on the difference between emissions and a benchmark amount to limit revenues. An ETS could be a reasonable alternative, but the same issues apply, and price stability mechanisms are then needed. Carbon intensity standards can have a reinforcing role, though they should be designed flexibly given heterogeneity in compliance costs among ship operators, and applied broadly to promote more mitigation opportunities, even though this adds administrative complexity. Offsets provide an alternative form of emissions pricing, but considerable uncertainties surround their price and credibility.[25]

C. Design Issues for Carbon Taxes

(i) Administration

[25] For further discussions of instrument choice issues in a broader carbon context see, for example, Goulder and Parry (2008), Hepburn (2006), and Jones and others (2013).

International maritime carbon taxes could be collected on shipping fuels at the refinery gate as an extension of fuel tax administration procedures long-established in most countries and this would involve collection from a small number of large, easily identifiable, taxpayers. Collection at the international level from ship operators, through an IMO-administered fund, appears the more relevant option however, given delegation of maritime mitigation strategy to the IMO, and to avoid difficulties in coordinating policy across national governments.[26] Capacity for measuring shipping fuel use by trip is being developed and operators could pay the tax on either an annual or individual route basis, with denial of port access, or ship arrest, for non-compliant operators potential enforcement mechanisms.[27]

More precisely, a ship operator's tax liability would be given by

$$\tau^{CO2} \cdot F^{SHIP} \cdot \beta^{CO2}$$

where: τ^{CO2} is the tax rate on CO_2 emissions; F^{SHIP} is the ship's fuel use; and β^{CO2} is the emissions factor for the fuel being used, which are well known (e.g., lower for LNG per unit of energy than for conventional heavy fuel oil sold as bunker fuel).[28]

Revenue-neutral variant. Under a variant of the carbon tax that limits the amount of revenue raised, the tax liability for the operator would instead be given by:

$$\tau^{CO2} \cdot (F^{SHIP} \cdot \beta^{CO2} - BENCH^{SHIP})$$

where $BENCH^{SHIP}$ is an (exogenous) benchmark level of emissions assigned to the operator, so operators pay taxes or receive subsidies depending on whether their emissions are above or below their benchmark. If the benchmark is set at the emissions that would have been generated on the operator's routes by the average ship within a cargo classification (e.g., container ships) then overall this carbon tax variant will be revenue neutral (tax payments

[26] A precedent for international tax administration is the International Oil Pollution Compensation (IOPC) Funds, collected from oil-receiving entities in ports and disbursed in compensation for oil spill damages—the IMO established, and has oversight over, the IOPC (see www.iopcfunds.org).

[27] Under current practice, where a state becomes a party to an IMO convention, it agrees to make the convention part of its national law and to enforce it—the tax could be paid to the fund, but any non-payment would be enforced by the states. Compliance costs for international collection might be somewhat larger than for national collection due to the greater number of taxpayers—the world fleet comprised about 50,000 ships in 2016 (UNCTAD 2016, Table 2.3) (though the majority are small ships that might be excluded initially from the tax) while there are about 700 oil refineries worldwide (https://hrcak.srce.hr/file/65010)—however this is a fairly minor consideration.

[28] In general, the emissions factor for a fuel can be taken as fixed though conceivably exhaust devices might be fitted on ships to capture CO_2 emissions (for subsequent onshore sequestration)—these technologies could be promoted through an appropriate system of rebates for captured carbon.

from operators with above-average emissions intensity would offset rebates to operators with below-average emissions intensity). In this case the benchmark could be calculated by:

$$BENCH^{SHIP} = TM^{SHIP} \cdot \left(\frac{CO2}{TM}\right)^{AV}$$

where TM^{SHIP} is tonne-miles for the individual operator and $(CO2/TM)^{AV}$ is emissions per tonne-mile for the average ship within the relevant classification. Scaling back the benchmark (for all ships) would result in a positive amount of revenue on net, and the scheme would converge to a pure revenue-raising carbon tax if the benchmark is reduced to zero.

The revenue-neutral carbon tax provides the same incentives as the pure (revenue-raising) carbon tax (for a given CO_2 price) for responses (1) and (2) above, but essentially fails to promote response (4) as there is no pass through of (large) emissions tax payments into higher shipping costs for heavy or long-distance products. Response (3) is promoted, as operators benefit from reduced tax payments or increased in rebates from, for example, shifting to larger, more efficient ships (at least within a vessel classification).

(ii) CO_2 prices

In principle, the CO_2 tax rate trajectory might be based on the following possibilities:

- The ‘social cost of carbon’ (SCC) (i.e., the discounted value of worldwide damages from the future global climate change associated with an additional tonne of CO_2 emissions), but reaching agreement across IMO member states would be challenging, not least given widely differing estimates of the SCC in the literature;[29]
- Global emissions price trajectories consistent with the 2°C target in the Paris Agreement, but a recent review[30] suggests global CO_2 prices of $40-80 per tonne (in addition to any pre-existing fuel taxes) would be needed in 2020, which is highly ambitious given the current global average price of about $1 per tonne of CO_2;[31]
- Estimated emissions prices countries will need to phase in by around 2030 to implement their Paris Agreement mitigation pledges, but estimates are uncertain, vary

[29] For contrasting perspectives see, for example, Stern (2013), Nordhaus (2014), Pindyck (2016), US IAWG (2016), Weitzman (2011).

[30] Stern and Stiglitz (2017).

[31] Inferred from WBG (2017).

(continued…)

considerably across countries[32], emissions targets may be adjusted in the interim, and regulatory instruments may be used in part to meet targets;

- Modelling assessments of the price trajectory consistent with emissions goals for the maritime sector (given candidate technologies and expected growth in shipping demand) but extremely high prices (perhaps over $300 per tonne) might be needed in the absence of other technology deployment policies;[33] and
- Prices in other carbon pricing schemes, the main point being that tax rates for maritime considerably higher than prices elsewhere might be challenging from a political perspective.

On pragmatic grounds, the last option might be the most practical and is used to infer an illustrative price path in the modelling below.

(iii) Addressing differentiated responsibilities

One possible, indirect solution to the CBDRRC issue might be to remit carbon tax revenues to the GCF, which would in turn be allocated for climate adaptation and mitigation projects in targeted developing countries[34]—funding allocations might also be skewed towards countries most vulnerable to higher shipping costs, to provide more finely-tuned compensation.

Another approach might be to allocate some carbon tax revenue to compensation mechanisms for specific countries (e.g., small island developing states and LICs). There are at least a couple of alternative approaches, though neither by itself may be entirely satisfactory. For example, reimbursing target countries for taxes attributed to their maritime fuel sales would overcompensate some countries (hubs where ships frequently refuel prior to offloading cargo in other countries) while undercompensating others (like small island developing states where ships frequently offload cargo without re-tanking).[35] Another possibility is to base compensation on countries' shares of global import values,[36] but import value is not necessarily a reliable predictor of CO_2 (e.g., light electronic equipment has a low

[32] Depending on the stringency of their emissions commitments and the responsiveness of a country's emissions to pricing (e.g., Aldy and others 2016, Parry and others 2018).

[33] Smith and others (2016).

[34] The GCF (www.greenclimate.fund) allocates much more funding to the poorest economies than to middle income countries and truncates funding after a certain level of development.

[35] In principle, this problem could be addressed if hubs only claim fuel tax rebates when ships unload, or if small island developing states claim rebates for fuel tax payments for shipped products, but administration is potentially complex (not least because shipping trips frequently involve unloading at several countries).

[36] Stochniol (2011).

(continued…)

ratio of CO_2 to import value) and some of the incidence also stems from higher costs for exporters.

Workable compensation schemes should be practical however, given the generally modest to tiny incidence (see below) of carbon taxation. As measured here, incidence is the loss of consumer surplus—the first order revenue payment plus the second order economic welfare cost, as indicated by the (combined) gray rectangles and red triangle in the figure in Box 2 (there are no losses in producer surplus given the assumption of full pass through of fuel taxes in higher prices).[37]

III. QUANTITATIVE POLICY ANALYSIS

This section describes an analytical model (implemented in a spreadsheet) for evaluating international maritime carbon taxes and other mitigation instruments, data used to parameterize the model, and results and sensitivity analyses. The mathematical specifics of the model, along with data documentation, are described in the Appendix.

A. Analytical Model

(i) Model Description

The model distinguishes (to allow a comparison of segment-specific policies) the two main (and quite distinct) types of shipping, namely wet/dry bulk (e.g., oil products, steel, iron ore, coal, grain). The main behavioral responses for reducing emissions, as classified above, are also distinguished. A discrete time-period model is used, going out to 2040, though distant projections are especially speculative (e.g., due to uncertainty over the future availability and cost of low-emission technologies).

The model begins with 2016 maritime fuel use, 334 million tonnes, equivalent to 1,051 million tonnes of CO_2 emissions, with 55 percent of it allocated to bulk shipping and the rest to container shipping. Fuel use is then projected forward in a BAU scenario (with no mitigation measures beyond those implicit in recently observed fuel use) using global GDP (assumed, based on IMF forecasts, to expand 20 percent between 2017 and 2023, and grow at 2.9 percent a year thereafter) along with income elasticities[38] of 0.5 and 0.8 for bulk and container products respectively. Future fuel use also depends on bunker fuel prices, which

[37] Another reflection of the limited incidence is the modest impact of (at least more moderate) carbon pricing on the price of landed imports—a tax of $25 per tonne of CO_2 raises most product prices by less than 1 percent, shipped oil by about 0.3 percent, and up to about 2-3 percent for some commodities—impacts which are all small relative to commonly observed swings in fuel and commodity prices. For further discussion, see AGF (2010), pp. 38, ITF (2017), Stochniol (2011), UNCTAD (2010).

[38] That is, percent increases in demand for shipped products per one percent increase in GDP.

(continued…)

are based on the crude oil price assumed to remain constant in real terms at $70 per barrel ($513 per tonne) and a (permanent) one-off price increase of $13.4 per barrel ($100 per tonne) from 2020 onwards reflecting low sulfur requirements. Higher fuel prices reduce carbon intensity through technical design, operational, and other improvements (as defined above), with each corresponding elasticity[39] taken to be -0.15 (the combined elasticity, -0.45, is approximately consistent with other, technology-based modelling for the maritime sector), and through changes in the demand for tonne-miles, though the latter response is modest given the small share of fuel costs in the price of landed imports. Other factors aside, carbon intensity is assumed to decline autonomously at a rate of 0.5 percent a year (e.g., due to gradual turnover of older, less fuel-efficient ships).

To the extent other fuels are used, these are implicitly expressed in terms of the bunker fuel that would yield the equivalent amount of CO_2 emissions, therefore the CO_2 emissions factor in the model is fixed (the emissions effect of shifting to cleaner fuels is implicitly included in the technical design and operational efficiency elasticities).

(ii) Policy scenarios

Six alternative mitigation policies are considered, where policies are compared for a given explicit price, or implicit 'shadow price', they place on CO_2 emissions—policies therefore differ in their effectiveness at reducing CO_2, depending on the behavioral responses they promote. The policies include:

Pure (revenue-raising) carbon tax—this policy increases future fuel prices according to the CO_2 emissions factor for bunker fuels (3.15 tonnes of CO_2 per ton of bunker fuel). For illustration, a carbon tax starting in 2021 and rising at $7.5 per tonne of CO_2 each year (equivalent to $24 per ton of bunker fuel) to reach $75 per tonne of CO_2 ($240 per ton of fuel) by 2030 and $150 per tonne of CO_2 ($480 per ton of fuel) by 2040. In carbon pricing schemes elsewhere (see Table 2), prices were around $5-$20 per tonne of CO_2 in ETSs and $5-$30 per tonne in carbon tax regimes in 2017, however: prices are likely to rise over time; Scandinavian countries have much higher tax rates; Canada is requiring provinces to phase in a US$40 per tonne carbon price floor by 2022; and France's carbon tax (for non-ETS emissions) is slated to rise to $100 per tonne by 2022. The carbon tax trajectory illustrated here seems broadly in line with (and perhaps at the high end of) prices that might emerge in other carbon pricing schemes in the next decade or two.

Revenue-neutral carbon tax—this policy causes the same fuel price increase as the pure carbon tax, though there is no first-order pass through of tax revenues in higher shipping costs.

[39] That is, the percent reduction in carbon intensity due to the particular behavioral response, per one percent increase in fuel price.

Carbon intensity standards—three variants of this policy are considered and implemented in the model through various shadow prices. One applies (denoted CIS—DES) to the technical design efficiency (of new ships)—it imposes a shadow price that promotes technical design efficiency but does not exploit the other three mitigation responses discussed above. Second is a standard (denoted CIS—DES/OP) that also applies to operational efficiency (of new and used ships), and exploits (cost-effectively) the first two of the above behavioral responses. Third is a carbon intensity standard (denoted CIS—DES/BULK) promoting technical design efficiency improvements for bulk shipping only. In each of these policies, the shadow prices are aligned with the CO_2 prices under the pure carbon tax.

Offsets—finally, an offset scheme is modelled that has the equivalent effect on promoting carbon intensity reductions as the pure carbon tax (because for each tonne of CO_2 reduction there is less need to purchase emissions offsets at the same price as assumed under the carbon tax) though, as under the revenue-neutral carbon tax, there is no pass through into shipping costs of charges for infra-marginal emissions. Given the lack of data for parameterizing the future offset supply curve (which, as noted above, is highly speculative) two purely illustrative scenarios are considered—a 'low cost' scenario where the marginal cost of offset reductions is approximately the same as that for reducing the CO_2 intensity of shipping, and a 'high-cost' scenario where the marginal cost of offsets is three times as high. The offset supply curve determines the additional emissions reductions that occur outside of the maritime sector, though in practice there might be considerable difficulty in establishing that offset projects are additional (i.e., would not have gone ahead in the absence of the offset payment).

(iii) Caveats

One caveat is that the model is static in the sense that fuel use adjusts instantly to fuel price changes (rather than gradually as the shipping fleet turns over), though this simplification seems reasonable given that policies are likely anticipated, phased in gradually, and the model's focus is on longer-term impacts—the elasticities in the model therefore represent long-run responses (allowing for significant turnover of the vessel fleet).

Most of the price-responsiveness of fuel use in the model reflects reductions in carbon intensity rather than in shipping volumes. One implication is that, even though revenue-neutral carbon taxes and emission offset prices do not charge for infra-marginal emissions the resulting difference in environmental effectiveness compared with a pure carbon tax is not very significant. Another implication is that it should be reasonable to omit the capital and labor costs of efficiency improvements in computing fuel use changes from mitigation policies,[40] and fiscal or market power distortions in the shipping market in computing their economic welfare effects.[41]

Furthermore, the model does not capture the possibility of non-linear responses that might result from sudden switching from current fuels to a clean fuel alternative—however, this possibility seems a distant prospect and, as already noted, with current technical knowledge would likely require carbon prices far above those considered below.

B. Results

This subsection discusses BAU projections, the impacts of carbon taxes, the emissions impacts of other instruments, and sensitivity analyses for carbon taxes.

(i) BAU Scenario

Figure 1 shows the BAU scenario with no mitigation measures (beyond those implicit in recently observed fuel use). World GDP is 33 percent and 77 percent higher in 2030 and 2040 respectively, compared with 2020. The expansion in bunker fuel use or CO_2 emissions is far more gradual, however—14 percent by 2030 and 31 percent by 2040 (CO_2 emissions are 1,172 and 1,343 million tonnes in 2030 and 2040 respectively), that is, CO_2 to GDP falls by 14 percent and 26 percent by 2030 and 2040 respectively below the 2020 level. This reduction reflects both the assumption of below-unity income elasticities and improving energy efficiency.[42]

(ii) Carbon Taxes

The (pure) carbon tax, rising at $7.5 per tonne from 2021 onwards, reduces CO_2 emissions by 14 percent below BAU levels in 2030 and 23 below BAU in 2040 (Figure 2a), which would roughly stabilize emissions at just over 1,000 million tonnes in these years—approximately

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[40] Technical or operational efficiency improvements would have some price effect (e.g., as the costs of installing fuel-saving technologies, or higher labor costs due to slower shipping speeds, are passed forward) but the effect on emissions would be very small (given the small contribution of reductions in shipping volumes to overall fuel/emissions reductions).

[41] International maritime is subject to tonnage taxes amounting, very roughly, to 10 percent of normal corporate income taxes (if the latter is, say, 15 percent, shipping is effectively subject to a 13.5 percent subsidy—see Elschner 2013, Keen and others 2013), though an offsetting factor could be monopoly pricing in some segments of the market (e.g., where a limited number of container ship operators supply small island states—see Christea and others 2013, Hummels and others 2008, and above). Carbon mitigation policies should have a relatively small impact on offsetting/compounding these distortions because most of its effect comes through reductions in carbon intensity rather than reductions in shipping volumes (see also Keen et al 2013, pp. 728).

[42] BAU projections in some other studies suggest higher emissions growth. For example, in Smith and others (2016) BAU emissions grow about 50 percent between 2016 and 2030 reflecting, primarily, higher GDP growth and income elasticity assumptions than assumed here.

the BAU level in 2020. The policy increases bunker fuel prices by about 40 percent above BAU levels in 2030 and 75 percent above BAU levels in 2040 and 96 percent of the CO_2 reductions reflect reductions in the carbon intensity per tonne-mile (i.e., behavioral responses (1)-(3) from Section 2 combined), while 4 percent reflects reductions in tonne-miles (response (4)). Half of the CO_2 reductions in 2030 comes from bulk shipping (whose emissions share is gradually declining over time the BAU) and half from container/other shipping. CO_2 reductions from the revenue-neutral carbon tax are almost as large as under the pure carbon tax as this policy has the same effect on reducing carbon intensity per tonne-mile but (to an approximation) does not affect tonne-miles.

The two carbon taxes differ dramatically in revenue raised—the pure tax raising 0.07 percent of world GDP, or $76 billion in 2030, and 0.11 percent of GDP, or $155 billion, in 2040 (Figure 2b). By design (and given there are no pre-existing fuel taxes), the revenue-neutral carbon tax has no revenue implications. Intermediate cases, with some positive amount of revenues raised, could be obtained by adjusting the benchmark emissions accordingly.

Figure 2(c) indicates the economic welfare cost of the tax (as defined by the triangle in Box 2), which does not account for the benefits of reducing future global warming. Although the economic welfare costs of the two policies rise over time faster than the tax rate, welfare costs are still modest—roughly 0.006 percent of GDP, or $6.2 billion, in 2030 and 0.016 percent, or $23.4 billion, in 2040 for both carbon tax policies.

The sum of the revenue and welfare cost from Figures 2(b) and (c) indicate the overall burden or incidence of the carbon tax at the global average level, again underscoring the relatively small size of these impacts relative to global GDP—under the pure tax, a modest 0.075 percent of GDP in 2030, and under the revenue-neutral variant, a pretty tiny 0.005 percent of GDP.

(iii) Policy Comparisons

As indicated in Figure 3, the CIS—DES policy reduces CO_2 emissions by about 5 and 8 percent below BAU levels in 2030 and 2040 respectively, that is, it has about a third of the effectiveness of that for the (pure) carbon tax, as it only promotes one of the four behavioral responses. Limiting the policy to bulk ships only (the CIS—DES/BULK policy) further reduces environmental effectiveness, by about half, so this policy only has about 15 percent of the effectiveness of the pure carbon tax. On the other hand, the carbon intensity standard promoting technical and operational improvements across new and existing ships (CIS—DES/OP) is twice as effective as the CIS—DES policy. The offset policies have about the same impact on reducing within-sector maritime emissions as the revenue-neutral carbon tax, given they are taken to establish the same emissions price (and hence reward for reducing within-industry emissions) but (to an approximation) do not pass through a first-order tax payment into tonne-mileage prices. The policies also reduce CO_2 emissions outside of the maritime sector, thereby implying total emissions reductions that, in the high- and low-cost offset cases, are 28 and 85 percent higher than those under carbon taxation. Whether offset schemes could establish the level of prices assumed here is highly questionable however and, most likely, not all offsets would be fully additional.

C. Sensitivity Analysis for Carbon Taxes

Table 3 shows the sensitivity of BAU emissions and the emissions, revenue, and welfare impacts of carbon taxes in 2030, to alternative assumptions for GDP growth, income elasticities, autonomous rates of carbon intensity reduction, international crude oil prices, and elasticities affecting carbon intensity.

BAU emissions are moderately sensitive to different parameter assumptions, for example, under different future oil prices—between $35 and $105 per barrel—BAU emissions are between 14 percent lower and 7 percent higher than when oil prices are $70 per barrel.

The percent reduction in emissions below BAU levels induced by the carbon tax is sensitive to two parameter variations. First, it is 25 percent smaller under the higher oil price and 50 percent greater under the lower oil price, as a given carbon tax has a smaller or larger proportionate effect on fuel prices when BAU oil prices are higher and lower respectively. Second, increasing and decreasing the carbon intensity elasticities by 50 percent increases and decreases the percent reduction in emissions by around 40-45 percent.

Revenues raised by the carbon tax are moderately sensitive to different parameter assumptions, varying between $68 and $84 billion across the different cases in Table 3. And, not surprisingly, welfare losses are most sensitive to the parameter variations that have most effect on the percent emissions reductions—for example, they vary between $3.5 and $8.4 billion under the different elasticity assumptions.

IV. CONCLUSION

Developing an environmentally effective, low-cost, mitigation strategy for the international maritime sector is important not only for its own sake, but also to enhance the prospects that policy will be sustained and strengthened over time. In this regard, a carbon tax deserves serious scrutiny as a key element of mitigation strategy as it:

- Can cost effectively exploit the full range of behavioral responses to reduce emissions within the sector, given available technologies;
- Can be designed to raise significant revenues (if there is agreement on productive use of these revenues), or limit revenues (if dispute over revenue use would otherwise hold up introduction of an environmentally effective tax); and
- Is straightforward to implement from a technical perspective (given that capacity for reporting of fuel use and emissions by ship trip is being developed), through establishment of an IMO-supervised fund.

Several ingredients might potentially increase the likelihood of successful implementation of the carbon tax.[43] Most important is to develop, in consultation with stakeholders, a comprehensive strategy with clear objectives (e.g., for future tax rates) and use of revenues. Another key ingredient is to address the sensitivities, particularly the concerns of small island developing states and LICs, which might require direct or indirect compensation mechanisms (though workable schemes should be practical). Phasing in the tax gradually over time would also give shipping companies time to adjust (e.g., by altering their fleet mix) thereby helping to minimize disruptions. By itself the tax will not be sufficient however, as alternative fuel technologies will ultimately be needed to meet the deep emissions reductions envisioned for the maritime sector by mid-century.

[43] For a broader discussion of how to move forward with fuel price reform, drawing on lessons from numerous case studies, see Clements and others (2013).

II. Appendix. Analytical Model and its Parameterization

A. Mathematical representation of the analytical model

The analytical model comprises the following equations:

$$(1)\ F_t = \sum_{i=C,B} F_t^i, \qquad F_t^i = TM_t^i \cdot f_t^i = \left(\frac{TM_t^i}{TM_0^i} \cdot \frac{f_t^i}{f_0^i}\right) \cdot F_0^i$$

$$(2)\ \frac{TM_t^i}{TM_0^i} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^i} \cdot \left(\frac{p_t^{TMi}}{p_0^{TMi}}\right)^{\eta^{TMi}} \cdot \left(\frac{p_t^{TMj}}{p_0^{TMj}}\right)^{\eta^{TMij}}$$

$$(3)\ p_t^F = p_t^{CRUDE} + \delta^{SO2} + (\tau_t^{CO2} + \tau_t^{OFF}) \cdot \beta^{CO2}$$

$$(4)\ \frac{p_t^{TMi}}{p_0^{TMi}} = \theta_0^{Fi} \cdot \frac{f_t^i \cdot p_t^F - (\tau_t^{CO2} \cdot \bar{f}_t^{CO2i} + \tau_t^{OFF} \cdot \bar{f}_t^{OFFi}) \cdot \beta^{CO2}}{f_0^i \cdot p_0^F} + 1 - \theta_0^{Fi},$$

$$(5)\ \frac{f_t^i}{f_0^i} = \left(1 + \alpha^i\right)^{-t} \cdot \left(\frac{p_t^F}{p_0^F}\right)^{\eta^{DESi} + \eta^{OPi} + \eta^{OTHERi}} \cdot \left(1 + \frac{\beta^{CO2} \cdot \lambda_t^{DESi}}{p_t^F}\right)^{\eta^{DESi}} \cdot \left(1 + \frac{\beta^{CO2} \cdot \lambda_t^{DES/OPi}}{p_t^F}\right)^{\eta^{DESi} + \eta^{OPi}}$$

$$(6)\ \tau_t^{OFF} = \beta_t^{OFF} \cdot \sum_{i=C,B} OFF_t^i, \quad \beta_t^{OFF} = \left(\frac{GDP_0}{GDP_t}\right) \cdot \beta_0^{OFF}$$

$$(7)\ CO2_t^{MAR} = \beta^{CO2} F_t, \quad CO2_t^{NET} = CO2_t^{MAR} - \sum_{i=C,B} OFF_t^i$$

$$(8)\ REV_t = \tau_t^{CO2} \cdot \beta^{CO2} \cdot F_t$$

Where subscript $t = 0\ldots$ denotes a year, 0 is the current period, and $i, j = B, C$; $i \neq j$.

In equation (1) F_t, global bunker fuel equivalent (defined below), is the sum of fuel use from the two shipping types, (wet/dry) bulk and container/other, denoted by *B* and *C* respectively, where fuel use is tonne-miles, TM_t^i, times average fuel use per tonne-mile, f_t^i. Future fuel use per shipping type can be calculated from initial fuel use and proportionate changes in tonne-miles and fuel consumption rates.

In equation (2), tonne-miles for shipping type *i* increases as (real, global) gross domestic product, GDP_t, expands over time, where υ^i denotes the income elasticity of demand (i.e., the percent increase in tonne-mileage per one percent increase in GDP, which is assumed to be constant).[44] Tonne-mileage also varies inversely with proportionate changes in the (average) price of landed imports, expressed per tonne-mile, and offloaded by shipping type *i*, p_t^{TMi}, where $\eta^{TMi} < 0$ is the (constant) own-price elasticity of demand (i.e., the percent

[44] In principle, as countries take future actions to reduce use of coal and oil in response to the Paris mitigation pledges, this will lower the growth of bulk shipping—this trend is incorporated through using a lower value for υ^B.

change in tonne-miles per one percent increase in price). This response reflects consumers and firms substituting away from shipped products to other (non-shipped) products. Furthermore, $\eta^{TMCB} > 0$ is a cross-price elasticity, that is, the increase in tonne-miles for container (high-value) shipping per one percent increase in the tonne-mile price for bulk cargo and vice versa for $\eta^{TMBC} > 0$.

In equation (3), p_t^F denotes the effective price of using bunker fuel. This consists of: (i) the average crude oil price p_t^{CRUDE}; (ii) the additional cost from meeting low-sulfur requirements, δ^{SO2}, assumed fixed from 2020 onwards and zero in previous years; (iii) a possible carbon charge, a tax (or emissions price from an ETS) equal to the charge per tonne of CO_2, τ_t^{CO2}, times the emissions factor β^{CO2} (tonnes of CO_2 per unit of bunker fuel combustion) which converts the emissions charge to the effective fuel tax; and (iv) a possible cost to purchasing emission offsets at a price of τ_t^{OFF} per tonne (again weighted by the emissions factor). To the extent other fuels are used, these are implicitly expressed in terms of the bunker fuel that would yield the equivalent amount of CO_2 emissions, therefore β^{CO2} is fixed. There are no pre-existing taxes on bunker fuel.

In equation (4), the price of tonne-miles changes over time with proportionate changes in unit fuel costs—where these costs equal the fuel consumption rate times the bunker fuel price—multiplied by the initial share of fuel costs in the price per tonne-mile, θ_0^{Fi} (i.e., fuel costs are fully passed forward, as noted above). In the case of a revenue-neutral carbon tax, there is a downward adjustment to the price per tonne-mile, because the carbon tax is effectively applied to the difference between the bunker fuel consumption rate and an (exogenous) benchmark rate $\bar{f}_t^{CO2i}$. Similarly, there is a downward adjustment under an offset policy, to the extent by which offsets are effectively needed for the difference between the bunker fuel consumption rate and a baseline rate $\bar{f}_t^{OFFi}$. Labor, capital, and other non-fuel costs (accounting for fraction $1 - \theta_0^{Fi}$ of the initial price per tonne-mile) are taken as constant (in real terms) over time.

In equation (5), the bunker fuel equivalent consumption rate for each shipping type varies with changes in technical design efficiency, denoted *DES*, operational efficiency, denoted *OP*, and other factors, denoted *OTHER*, as reflecting behavioral responses (1)-(3) in the main text respectively—with fuel use defined in terms of bunker equivalents, changes in technical efficiency encompass both improvements in energy efficiency and shifting to lower carbon fuels. Overall efficiency improves autonomously (i.e., in the absence of other factors) reducing bunker fuel consumption rates by α^i a year (decomposing the respective contribution from technical, operational, and other factors would not affect the results).

Higher bunker fuel prices reduce fuel consumption rates according to elasticities η^{DESi}, η^{OPi}, and $\eta^{OTHERi} < 0$, which reflect the percent changes due to technical design, operational, and other improvements respectively, per one percent increase in the fuel price. A carbon intensity standard for design efficiency is represented by the 'shadow price' λ_t^{DESi}, that is, the implicit reward per tonne of CO_2 reduced from technical design improvements—the incentives to reduce bunker fuel use is the shadow emissions price times the emissions factor.[45] In contrast, a carbon intensity standard for design and operational efficiency, establishing a shadow price of $\lambda_t^{DES/OPi}$, is defined here to promote the same technical and operational improvements (across all new and existing ships) as the analogous tax, but not the other responses.

Equation (6) defines the supply, or marginal cost, curve for offsets (e.g., from mitigation projects in developing countries), where β_t^{OFF} is the slope of this curve (assumed constant) and OFF_t^i is tonnes of CO_2 offset credits (equal to the offset price divided by the slope) purchased by shipping type *i*. The supply of offsets for any given offset price is taken to expand in proportion to global GDP. Actual CO_2 reductions from offsets are less than the total amount of offsets purchased for the maritime sector, $\sum_{i=C,B} OFF_t^i$, to the extent by which mitigation projects elsewhere would have gone ahead anyway without the offset payment.

In equation (7) $CO2_t^{MAR}$ is CO_2 emissions from the maritime sector itself, that is, bunker fuel consumption times the CO_2 emissions factor, while $CO2_t^{NET}$ is maritime emissions net of offset credits. Finally, in equation (8) REV_t is revenue collected from a carbon tax—offset payments by the industry are not deducted, as they are effectively a mitigation cost.

B. Data sources

The most recent data on fuel use and prices is first obtained and then projected forward to 2040 in a BAU case, using the above equations with no new mitigation measures beyond those implicit in current fuel use (i.e., τ_t^{CO2}, τ_t^{OFF} , λ_t^{DESi} and $\lambda_t^{DES/OPi}$ are set to zero) and the impacts of policies relative to the BAU are then calculated. The parameterization of the BAU is first described, followed by the policy scenarios, and how their impacts are calculated. Insofar as possible, parameter values are based on available evidence and data, though in some cases they are necessarily based on judgment—although, as indicated in sensitivity analysis, the relative effectiveness of policies at reducing CO_2 emissions is fairly robust to different assumptions, despite inherent uncertainties in the BAU projections.[46] Unless otherwise noted, parameters for the two different shipping types are taken to be the same. All monetary values are expressed in year 2016 US$.

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[45] These measures are assumed to increase technical efficiency cost-effectively—to the extent this is not the case (due to heterogeneity in compliance costs across operators) the inferior cost-effectiveness of these measures compared with carbon pricing is understated in the results.

[46] See also IMO (2014) where the projected growth in BAU CO_2 emissions to 2050 is between 50 and 250 percent.

(continued…)

International maritime fuel use for 2016 is taken to be 334 million tonnes as projected from the CO_2 emissions and CO_2 emissions factors discussed below, with bulk and container shipping accounting for 55 and 45 percent of fuel use respectively.[47]

Using IMF projections[48] (real) global GDP is assumed to expand 20 percent between 2017 and 2023 and grow at 2.9 percent a year thereafter. The income elasticities are taken to be 0.8 for container (which supplies goods in general) and 0.5 for bulk shipping, implying an average elasticity of about 0.65,[49] while the (tonne-mile) price elasticity for both shipping types is taken to be -0.7.

The global crude oil price is taken to be $513 per tonne ($70 per barrel) from 2018 and is assumed to stay at this level to 2040.[50] There is an assumed, one-off, permanent price increase of $100 per tonne ($13.6 per barrel)[51] from 2020 onwards to reflect the 0.5 percent sulfur requirement (which will require shifting from heavy fuel oil to low-sulfur diesel or, in limited cases, installation of exhaust scrubbers).

The initial share of maritime fuel costs in the price (per tonne-mile) of shipped products is taken to be on average about 5 percent[52], but three times as high for bulk (6 percent) as opposed to container (2 percent) shipping. The average emissions factor for bunker fuel is

[47] Fuel shares are based on emissions shares in IMO (2014), Figure 1, lumping cruise, ferry, general cargo, and roll on-roll off together with container shipping.

[48] IMF (2018).

[49] A below unitary income elasticity for container shipping might be appropriate to the extent households increase budget shares for services, and purchase higher quality products (rather than higher quantities of products) in response to higher income. Income elasticities for crude oil—a major component of bulk shipping—are typically estimated at around 0.5 to 1.0 (e.g., Xiong and Wu 2009 for China; Gately and Huntington 2001, and Huntington and others 2017 for developed and developing countries; Ghouri 2001 for Canada, Mexico and the United States; and Krichene 2002 for the world)—the lower bound is chosen here to take some account of likely future efforts to curb fossil fuel use. A casual look at the 53 percent expansion in global GDP between 2000 and 2015 and the 124 percent expansion in shipping tonnage (from IMF 2018 and UNCTAD 2016, figure 2.1) might suggest much larger income elasticities but there were confounding factors at work (e.g., the opening up of China, expansion of the Panama Canal) during this period.

[50] As of writing (June 2018), the Brent crude oil price is $75 per barrel. IMF (2018) projects generally flat oil prices (based on futures markets).

[51] Based on the lower bound estimates in ITF (2017).

[52] Shipping costs are approximately 10 percent of average landed import prices (Keen and others 2013, Table 4) and fuel costs are approximately 50 percent of ship operating costs (ITF 2017). A 20 percent increase in current fuel prices (roughly the effect of a $25 per tonne CO_2 charge) therefore increases average import prices by 1 percent, which is broadly consistent with estimates discussed in Keen and others (2013).

(continued…)

taken as 3.15 tonnes CO_2 per tonne of bunker and CO_2 emissions are taken to be 938 million tonnes in 2012[53], implying fuel use of 297 million tonnes—2016 fuel use and emissions are assumed to be 12 percent higher (i.e., 334 million tonnes and 1,051 million tonnes respectively) than 2012 levels.[54]

Autonomous efficiency improvements are assumed to reduce fuel consumption rates by 0.5 percent a year. The elasticity of the bunker fuel consumption rate with respect to the fuel price is taken to be -0.45 as this generates percent reductions in CO_2 emissions that approximately replicate results from the GloTraM model[55] (see below)—the individual elasticities for technical design efficiency, operational efficiency, and other factors cannot be inferred from GloTraM, however, and are (based on judgment) each taken to be -0.15.

Given the lack of data for parameterizing the future offset supply curve (which, as noted above, is highly speculative) two illustrative scenarios are considered—a 'low-cost' scenario where the marginal cost of offset reductions is approximately the same as that for reducing the CO_2 intensity of shipping, and a 'high-cost' scenario where the marginal cost of offsets is three times as high.

C. Mitigation policies

The carbon tax rate schedule is described above and this price applies to both carbon tax variants, the shadow price for the CES policies, and the emissions offset price. For the revenue-neutral carbon tax, $\bar{f}_t^{CO2i} = f_t^i$, as there is no first-order impact of the tax on shipping prices per tonne-mile.[56] For the offset policy, $\bar{f}_t^{OFFi} = f_t^i - OFF_t^i/\beta^{CO2}$ as, substituting this expression into (4), and using (3), gives offset payments relative to fuel costs.

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[53] Both from IMO (2014).

[54] IEA (2017b) puts 2015 world bunker fuel use at 9 percent higher than 2012 levels (absolute fuel use data is not taken from IEA 2017b as it is incomplete).

[55] This model incorporates a detailed treatment of technology adoption for different shipping segments. See Smith and others (2016).

[56] There is an indirect effect from the reduction in fuel consumption rate which lowers fuel costs per tonne-mile, thereby increasing the demand for shipped products but the resulting increase in fuel use (commonly referred to as the 'rebound effect') is trivial in the current model.

(continued…)

The impacts of policies on CO_2 emissions and revenue are easily calculated from equations (7) and (8) above. Economic welfare costs of policies are calculated using standard formulas, though broader fiscal linkages (see Box 2) are not considered.[57]

REFERENCES

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn and David Hemous, 2012. "The Environment and Directed Technical Change." *American Economics Review* 102: 131–166.

AGF (2010). *Report of the Secretary-General's High-level Advisory Group on Climate Change Financing*. New York, United Nations.

Aldy, Joseph, et al., 2016. "Economic Tools to Promote Transparency and Comparability in the Paris Agreement." *Nature Climate Change* 6: 1,000–1,004.

Burtraw, Dallas, Art Fraas, and Nathan Richardson, 2012. "Tradable Standards for Clean Air Act Carbon Policy." Discussion paper 12-05, Resources for the Future, Washington, DC.

Calleya, J.; Pawling, R.; Greig, A., 2015. "Ship Impact Model for Technical Assessment and Selection of Carbon Dioxide Reducing Technologies (CRTs)." *Journal of Ocean Engineering* 97, 82-89.

Clements, Benedict, David Coady, Stefania Fabrizio, Sanjeev Gupta, Trevor Serge Coleridge Alleyne, Carlo A Sdralevich, eds. 2013. *Energy Subsidy Reform: Lessons and Implications*. Washington DC, International Monetary Fund.

Cristea, A., D. Hummels, L. Puzzello, and M. Avetisyan, 2013. "Trade and the Greenhouse Gas Emissions from International Freight Transport." *Journal of Environmental Economics and Management* 65: 153-173.

Dechezleprête, Antoine and David Popp, 2017. "Fiscal and Regulatory Instruments for Clean Technology Development." In I. Parry, K. Pittel and H. Vollebergh (eds.), *Energy Tax and Regulatory Policy in Europe: Reform Priorities*. MIT Press, Cambridge, MA.

Dominioni, Goran, Dirk Heine, and Beatriz Martinez Romera, 2017. "Regional Carbon Pricing for International Maritime Transport: Challenges and Opportunities for Global

[57] Welfare costs are approximated by one half times the CO_2 reduction times the (explicit or implicit) price on CO_2 emissions—equivalently they can be calculated from the fuel reductions and the implicit or explicit fuel tax (see Harberger 1964 for a general discussion of welfare cost measurement).

Geographical Coverage." World Bank Policy Research Paper 8319, World Bank, Washington DC.

Eide M., Dalsøren S., Endresen Ø., Samset B., Myhre G., Fuglestvedt J., Berntsen T., 2013. "Reducing CO_2 from shipping—do non-CO_2 effects matter?" *Atmospheric Chemistry and Physics* 13: 4,183–4,201.

Elschner, C., 2013. "Special Tax Regimes and the Choice of Organizational Form: Evidence from the European Tonnage Taxes." *Journal of Public Economics* 97: 206–16.

Farid, Mai, Michael Keen, Michael Papaioannou, Catherine Pattillo, and Anna Ter-Martirosyan, 2016. *After Paris: Fiscal, Macroeconomic, and Financial Implications of Climate Change*. Staff Discussion Note 16/01, IMF, Washington, DC.

Fell, Harrison, Ian A. MacKenzie, and William A. Pizer, 2012. "Prices versus Quantities versus Bankable Quantities." *Resource and Energy Economics* 34: 607–23.

Fischer, Carolyn, Ian W.H. Parry and William A. Pizer, 2003. "Instrument Choice for Environmental Protection when Technological Innovation is Endogenous." *Journal of Environmental Economics and Management* 45: 523-545.

Gately, D. and Huntington, H.G., 2001. *The Asymmetric Effects of Changes in Price and Income on Energy and Oil Demand*. C.V. Starr Center for Applied Economics, New York University.

Gerarden, Todd D., Richard G. Newell, and Robert N. Stavins, 2017. "Assessing the Energy Efficiency Gap." *Journal of Economic Literature* 55: 1,486-1,525.

Gevorkyan, Arkady, Dirk Heine, Mariana Mazzucato, Michael Flaherty, Siavash Radpour and Willi Semmler, 2018. "Financing Low-Carbon Transitions through Carbon Pricing and Green Bonds." Working Paper, forthcoming, International Monetary Fund, Washington, DC.

Ghouri, S.S., 2001. "Oil demand in North America: 1980-2020". *OPEC Review* 25(4) 339-355.

Goulder, Lawrence H. and Ian W.H. Parry, 2008. "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy* 2: 152–74.

Green, Jessica F, 2014. "Don't Link Carbon Markets." *Nature* 543, March, 484-486.

Harberger, Arnold C., 1964. "The Measurement of Waste". *American Economic Review* 54: 58-76.

Hepburn, Cameron, 2006. "Regulating by Prices, Quantities or Both: An Update and an Overview." *Oxford Review of Economic Policy* 22: 226–47.

Hummels, D., V. Lugovskyy and A. Skiba, 2008. "The Trade-reducing Effects of Market Power in International Shipping." Mimeo, Purdue University.

Huntington, Hillard G., James B. Barrios, and Vipin Arora, 2017. "Review of Key International Demand Elasticities for Major Industrializing Economies." Working paper, Stanford Energy Modelling Forum, Stanford University, Stanford, CA.

ICS, 2017. *ICS Commits Shipping to Ambitious CO_2 Reduction Objectives*. International Chamber of Shipping, London, available at: www.ics-shipping.org/news/press-releases/view-article/2017/05/15/ics-commits-shipping-to-ambitious-co2-reduction-objectives.

IEA, 2017a.*World Energy Outlook 2017*. International Energy Agency, Paris, France.

_____, 2017b. *World Energy Balances*. International Energy Agency, Paris, France.

IMF-WBG, 2011a. *Market-based Instruments for International Aviation and Shipping as a Source of Climate Finance*. International Monetary Fund and World Bank Group, Background Paper for the Report to the G20 on Mobilizing Sources of Climate, Washington, DC.

_____, 2017b. *World Economic Outlook Database*. International Monetary Fund, Washington, DC. www.imf.org/external/pubs/ft/weo/2017/01/weodata/index.aspx.

IMO, 2014. *Third IMO Greenhouse Gas Study*. International Maritime Organisation, London.

_____, 2015. *High-Level Action Plan of the Organization and Priorities for the 2016-2017 Biennium*. International Maritime Organisation, London.

ITF, 2017. *ITF Transport Outlook 2017*. International Transport Forum, OECD, Paris.

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins, 2005. "A Tale of Two Market Failures: Technology and Environmental Policy." *Ecological Economics* 54: 164-174.

Jones, Ben, Michael Keen and Jon Strand, 2013. "Fiscal Implications of Climate Change." *International Tax and Public Finance* 20: pp.29-70.

Keen, Michael, Ian W.H. Parry and Jon Strand, 2013. "Ships, Planes, and Taxes: Charging for International Aviation and Maritime Emissions." *Economic Policy* 28: 701–749.

Krichene, N., 2002. "World Crude Oil and Natural Gas: a Demand and Supply Model." *Energy Economics* 24: 557-576.

Lamotte, Henri, 2011. "Carbon Pricing in International Air and Maritime Transportation." Ministry of Economy, and Finance and Industry, Government of France.

Newell, Richard, G., 2015. "The Role of Energy Technology Policy Alongside Carbon Pricing". In I. Parry, A. Morris and R. Williams (eds.), *Implementing a US Carbon Tax: Challenges and Debates*, Routledge, London, 2015.

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

OECD, 2016. *2020 projections of Climate Finance towards the $100 billion goal: Technical Note*. Organisation for Economic Cooperation and Development, Paris, France.

Parry, Ian W.H., 2003. "Fiscal Interactions and the Case for Carbon Taxes Over Grandfathered Carbon Permits." *Oxford Review of Economic Policy* 19: 385-399.

_____, and Roberton C. Williams, 2012. "Moving US Climate Policy Forward: Are Carbon Tax Shifts the Only Good Alternative?" In Robert Hahn and Alistair Ulph (eds.), *Climate Change and Common Sense: Essays in Honor of Tom Schelling*, Oxford University Press, 173-202.

_____, Victor Mylonas, and Nate Vernon, 2017. "Policies for Implementing the Paris Climate Agreement: An Assessment for G20 Countries." Unpublished manuscript, International Monetary Fund, Washington, DC.

Pindyck, Robert S., 2016. "The Social Cost of Carbon Revisited." National Bureau of Economic Research Working Paper No. 22807, Cambridge, MA.

Smith, T., Raucci, C., Haji Hosseinloo S., Rojon I., Calleya J., Suárez de la Fuente S., Wu P., Palmer K., 2016. *CO_2 emissions from international shipping. Possible reduction targets and their associated pathways*. Prepared by UMAS, London.

Stern, Nicholas, 2013a. "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto already narrow Science Models." *Journal of Economic Literature* 51: 838-859.

_____, Stiglitz, Joseph, for CPLC, 2017b. "Report of the High Level Commission on Carbon Pricing." Paper of the Carbon Pricing Leadership Coalition of the World Bank Group, Washington.

Stochniol, Andre, 2011. "Securing additional climate financing, beyond budgetary contributions, by Ensuring No Net Incidence on Developing Countries from Carbon Pricing of International Transport (Rebate Mechanism), Outline and RM keys." Available at: www.imers.org/docs/RM_outline_and_keys.pdf.

UN 1992. *United Nations Framework Convention on Climate Change*. United Nations, New York City, NY.

UNCTAD, 2010, "Oil Prices and Maritime Freight Rates: An Empirical Investigation", UNCTAD/DTL/TLB/2009/2, April 1, 2010. Available at: www.unctad.org/en/docs/dtltlb20092_en.pdf

_____, 2016. *Review of Maritime Transport 2016*. United Nations Conference on Trade and Development.

US, 2010. *Prevention of Air Pollution from Ships: Further details on the United States proposal to reduce greenhouse gas emissions from international shipping*. Proposal submitted by the United States of America to the Marine Environment Protection Committee.

US IAWG, 2016. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. Interagency Working Group on Social Cost of Carbon, United States Government, Washington, DC.

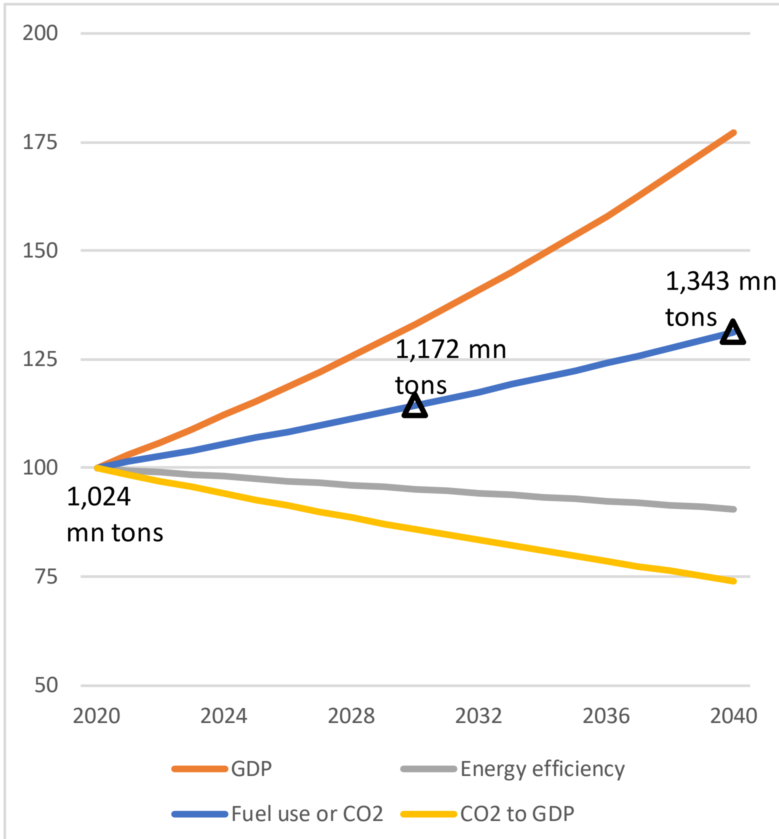
Vollebergh, Herman, R.J. and E. van der Werf, 2014. "The Role of Standards in Eco-Innovation: Lessons for Policymakers." *Review of Environmental Economics and Policy* 8: 230-248.

WBG, 2017. *State and Trends of Carbon Pricing 2017*. World bank Group, Washington, DC.

Weitzman, Martin L. 2011. "Fat-Tailed Uncertainty and the Economics of Climate Change." *Review of Environmental Economics and Policy* 5: 275–292.

Xiong, J. and Wu, P., 2009. "An analysis of forecasting model of crude oil demand based on cointegration and vector error correction model (VEC). In *2008 International Seminar on Business and Information Management*, ISBIM 2008, pp. 485-488.

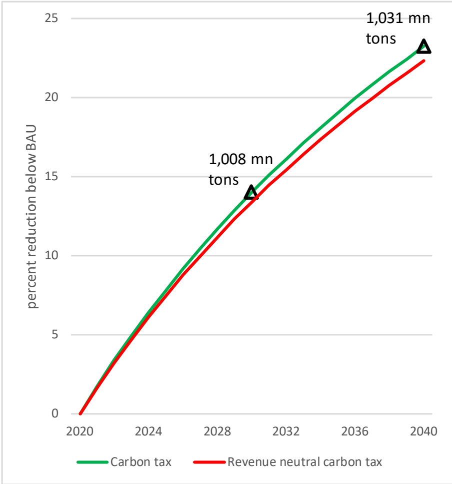
Figure 1. BAU GDP, Energy Efficiency, and Fuel Trends, 2020=100



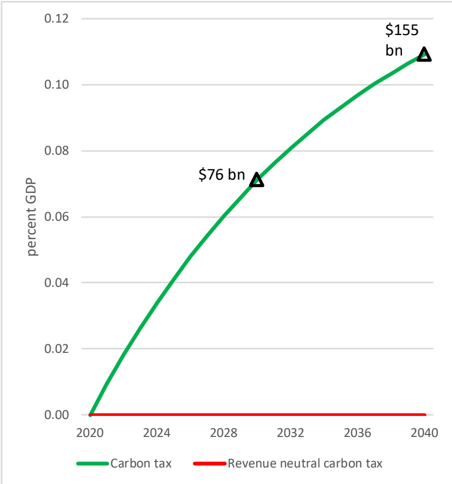
Source. See text.

Figure 2. Impacts of Carbon Taxes

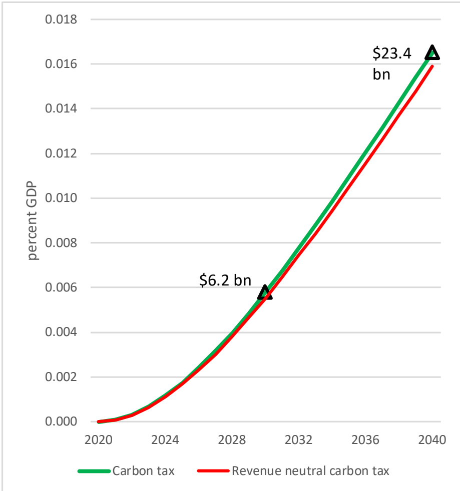
(a) CO_2 Reductions, percent below BAU



(b) Revenue, percent GDP



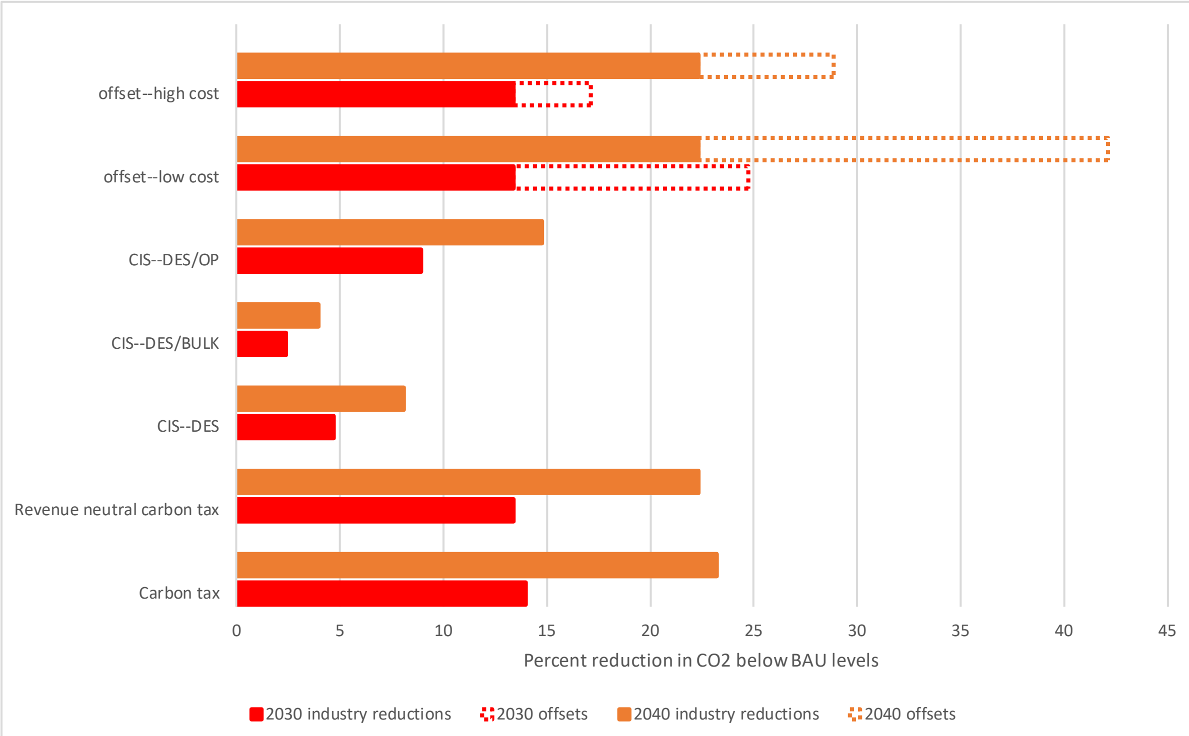
(c) Welfare Cost, percent GDP



Source. See text.

Note. Welfare calculations abstract from linkages with the broader fiscal system (see Box 2).

Figure 3. CO_2 Reductions Under Alternative Mitigation Instruments



Source. See text.

Table 1. Mitigation Pledges for the 2015 Paris Agreement, G20 Countries

Country	Mitigation pledge	2014		
		share of global CO_2	tons CO_2/\$1,000 GDP	tons CO_2 per capita
Argentina	Reduce GHGs 30% below BAU in 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	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	1.6	0.42	11.6
Mexico	Reduce GHGs 25% below BAU in 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 by 2030	1.7	0.79	19.5
S. Africa	Reduce GHGs 398-614 million tons in 2025 and 2030	1.4	1.40	9.0
Turkey	Reduce GHGs up to 21% below BAU 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

Source. http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspxc and https://data.worldbank.org/indicator.

Note. BAU denotes business as usual with no new mitigation measures. Some developing countries specify both conditional (contingent on external finance) and unconditional (not contingent) pledges—in these cases the conditional pledges are included above.

Table 2. Carbon Prices, Selected Countries and Regions, 2017

Government/ region	year introduced	Price US$/ton CO2, 2017 unless noted	Coverage, % of GHGs	Government/ region	year introduced	Price US$/ton CO2, 2017 unless noted	Coverage, % of GHGs
CARBON TAXES				Sweden	1991	140	42
Chile	2014	5	55	Sweden	1991	140	42
Colombia	2017	5	40	Switzerland	2008	87	33
Denmark	1992	27	45	UK	2013	24	25
Mexico	2014	1-3	46	TRADING SYSTEMS			
Finland	1990	60-65	15	California	2012	15	85
France	2014	100[a]	35	EU	2005	6	45
Iceland	2010	12	50	Kazakhstan	2013	2	50
Ireland	2010	24	40	Korea	2015	18	68
Japan	2012	3	66	N. Zealand	2008	13	52
Norway	1991	56	50	RGGI	2009	4	21
Portugal	2015	8	25	PRICE FLOORS			
South Africa	2016	10	80	Canada	2016	40[a]	80

Source. WBG (2017) and previous editions of this publication, and authors calculations (for Colombia and Canada).

Note. [a]Slated price for 2022 (in 2017$).

Table 3. Sensitivity of (Pure) Carbon Tax Impacts to Alternative Parameters, 2030

	BAU	Carbon tax			
Parameter	CO_2 emissions, mn tonnes	CO_2 emissions, mn tonnes	% CO_2 reduction below BAU	revenue, $billion	welfare cost, $billion
Central case	1,172	1,008	14.0	76	6.2
Annual GDP growth rate beyond 2023					
3.5 percent	1,208	1,039	14.0	78	6.3
2.3 percent	1,141	981	14.0	74	6.0
Income elasticities					
increased 33 percent	1,277	1,099	14.0	82	6.7
decreased 33 percent	1,075	924	14.0	69	5.6
Annual rate of auton. carbon intensity reduction					
increased to 0.75 percent	1,132	974	14.0	73	5.9
decreased to 0.25 percent	1,212	1,042	14.0	78	6.4
2030 crude oil price (exc. low sulfur costs)					
$105 per barrel	1,202	1,076	10.5	81	4.7
$35 per barrel	1,093	863	21.0	65	8.6
Carbon intensity elasticities					
increased 50 percent	1,127	902	19.9	68	8.4
decreased 50 percent	1,218	1,125	7.7	84	3.5

Source. See text.