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# PARIS AFTER TRUMP: AN INCONVENIENT INSIGHT

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**Abstract**

With his announcement to pull the US out of the Paris Agreement US President Donald Trump has snubbed the international climate policy community. Key remaining parties to the Agreement such as Europe and China might call for carbon tariffs on US imports as a sanctioning instrument to coerce US compliance. Our analysis, however, reveals an inconvenient insight for advocates of carbon tariffs: given the possibility of retaliatory tariffs across all imported goods, carbon tariffs do not constitute a credible threat for the US. A tariff war with its main trading partners China and Europe might make the US worse off than compliance with the Paris Agreement but China, in particular, should prefer US defection to a tariff war.

**JEL-Classification:** Q58, D58

**Keywords:** Paris Agreement, US withdrawal, carbon tariffs, optimal tariffs, tariff war, computable general equilibrium

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# I. Introduction

The 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in December 2015 set an important milestone in international climate policy. For the first time, not only industrialized countries but also developing countries signaled their willingness to reduce greenhouse gas emissions in order to keep the global mean surface temperature less than 2 degrees Celsius above pre-industrial levels. The Paris Agreement (UNFCCC, 2015) builds on global cooperation and coordination of emission abatement where more than 190 countries contribute via voluntary pledges – so-called Intended Nationally Determined Contributions (INDCs).[1] The Agreement entered into force on November 4, 2016 after all the world top emitters – most notably, China, the United States, and the European Union who together account for more than 50% of global greenhouse gas emissions – ratified.

However, the outcome of the 2016 US presidential elections threw a serious wrench in the international climate policy works. Opposing the policies of Barack Obama who pushed Paris as a "turning point for the planet", presidential candidate Donald Trump has called climate change a "hoax" on the campaign trail and promised to scrap the deal. Once in office, President Trump signed an executive order on March 28, 2017 that initiated a review of the Clean Power Plan – the cornerstone Obama administration policy to reduce carbon dioxide emission from electricity generation. In addition, the moratorium on coal mining on US federal lands was rescinded. On June 1, 2017 President Trump officially announced that he will withdraw the United States from the Paris Climate Agreement, a sweeping step fulfilling his campaign promise. US withdrawal would not only end implementation of US INDCs which aimed to reduce greenhouse gas emissions by 26-28% over a decade. Trump also declared the US would stall all contributions to the United Nations' Green Climate Fund – an important instrument under the Paris Agreement to foster greenhouse gas emission reduction in developing countries.

Leaders around the world have condemned Trump's denials of climate change science and his announced withdrawal from the Paris Agreement. Given that the US is the world's second largest emitter and the world's largest economy, the international community is worried about the consequences of US withdrawal for global efforts to curb global warming. Yet, other key parties to the Paris Agreement – most notably the EU and China – immediately confirmed that they will maintain their targets, and may even make them more aggressive because of Trump's short-sighted action.

At the same time, there have been calls for "punitive" measures, reflecting that climate change action is widely considered a yardstick for international solidarity in the battle against man-made climate change. One popular proposal for such punitive measures involves the taxation of carbon emissions

[1] http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

embodied in imported goods. Such carbon tariffs discourage foreign emissions by pricing the emissions generated in the production of imported goods. For example, imported steel from countries without domestic carbon controls might face a tax based on direct emissions (those due to the combustion of fossil energy in steel production) as well as indirect emissions (such as emissions created by the generation of electricity for use in steel production). Carbon tariffs are appealing in various respects. Economists appraise them as a second-best instrument to reduce the relocation of emissions to countries without emission regulation (so-called emission leakage) and improve thereby global cost-effectiveness of sub-global emission regulation. Environmentalists embrace them as a means of capturing the carbon footprint of imported products where the importing country takes responsibility for emissions related to the production of its imports. Stakeholders of emission-intensive and trade-exposed industries welcome carbon tariffs as a corrective measure that levels the playing field in international trade of emission-intensive goods. And policy makers maintaining domestic emission regulation may view carbon tariffs as a means to shift some economic abatement burden to trading partners who free-ride in international climate policy.

As a matter of fact, prior to the Paris Agreement the US itself considered carbon tariffs as a legitimate sanction against important trading partners – in particular China – that would not adopt sufficiently stringent domestic emission controls. Notably, carbon tariffs have been a prominent feature of the Waxman-Markey American Clean Energy and Security Act – H.R. 2454 – that was passed in the United States House of Representatives in 2009. It comes as bitter irony in climate policy history that "Paris after Trump" might now see reversed roles in the use of carbon tariffs: Rather being a sender of carbon tariff sanctions, the US could find itself a recipient. Various policy makers have already called for carbon tariffs against the US during the election campaign in 2016.[2] Following President Trump's announcement of US withdrawal, prominent economists call for the use of carbon tariffs to sanction the US.[3] A serious risk of carbon tariffs imposed on US goods, however, is that they may spark a tit-for-tat response from the Trump administration with the potential of a major trade conflict.[4] Given the pertinent complaints of the new US administration on unfair trade practices, carbon tariffs might even serve as a standing invitation for US protectionism.

Against this policy background, we investigate the credibility of carbon tariffs as a sanctioning in-

[2]"A carbon tariff against the United States is an option for us" Rodolfo Lacy Tamayo, Mexico's under secretary for environmental policy and planning, Nov. 2016. "Well, I will demand that Europe put in place a carbon tax at its border, a tax of 1-3 per cent, for all products coming from the United States, if the United States doesn't apply environmental rules that we are imposing on our companies" Nicolas Sarkozy, former French President, Nov. 2016.

[3]As a prime example, Nobel laureate in economics J.E. Stiglitz pushes the idea that "if Trump wants to withdraw the U.S. from the Paris climate agreement, the rest of the world should impose a carbon-adjustment tax on U.S. exports that do not comply with global standards." (http://www.marketwatch.com/story/how-to-punish-trump-the-world-could-impose-a-carbon-tax-on-the-us-2017-06-02?mod=mw_share_twitter).

[4]See e.g. the controversial discussion on the role of carbon tariffs among climate policy negotiators in the run-up to COP22 at Marrakesh, 2016 (Davenport, 2016).

strument against the US. Our computable general equilibrium (CGE) analysis based on the most recent global economic dataset by the Global Trade Analysis Project (GTAP9 – Aguiar et al., 2016) reveals an inconvenient insight: Carbon tariffs do not constitute a credible threat for the US when accounting for the possibility of retaliatory tariffs. Carbon tariffs stand-alone might make the US worse off as compared to compliance with the Paris agreement. Yet, in a strategic setting in which the political value of cooperation are discounted, US would clearly prefer to exit the Paris Agreement and impose optimal unilateral tariffs on trading partners as a response to carbon tariffs. Our results indicate that the risk of a tariff war with its key trading partners China and Europe does not come as a serious threat to the US: While best tariff responses by China and Europe can induce economic losses for the US which exceed the potential US compliance cost under the Paris Agreement, it is particularly China as the most trade-intensive region that must be afraid of such a tariff war.

The remainder of this paper is organized as follows. Section 2 reviews the literature on carbon tariffs. Section 3 lays out the data base underlying our empirical analysis. Section 4 provides a non-technical summary of the CGE model used for policy assessment. Section 5 describes alternative climate policy scenarios and reports on our simulation results. Section 6 presents sensitivity analysis. Section 7 concludes.

## II. Literature Review

Carbon tariffs have been appraised in the theoretical literature as a second-best instrument to reduce emission leakage and improve global cost-effectiveness of sub-global climate policy.[5] Markusen (1975) shows that a sufficiently large country or a coalition of countries can use import tariffs to discourage foreign production of pollution-intensive goods. Hoel (1996) generalizes Markusen's analysis and produces a similar result for the case of sub-global action against a global carbon externality. The abatement coalition should supplement a uniform domestic carbon tax with carbon tariffs. The optimal tariffs for the abatement coalition thereby consist of two components. The first component accounts for a terms-of-trade effect: a tariff reduces imports, which in general reduces the import price and improves the terms of trade. The second component accounts for the effect on foreign emissions: a tariff reduces emissions abroad by contracting foreign supply. If the objective is to minimize global cost of emission reduction through unilateral action, the strategic incentive to exploit terms of trade disappears. In this case, the optimal tariff on an imported good from some non-regulating region is

[5] In comprehensive border carbon adjustment regimes, carbon tariffs on the import side would be combined with export rebate where exports to non-regulating countries would get a full refund of carbon payments at the point of shipment. Full border adjustments thus combine import tariffs with export subsidies, effectively implementing destination-based carbon pricing (Lockwood and Whalley, 2010). In practice, the policy debate focuses on the use of import tariffs since export rebates may constitute an inappropriate subsidy under the WTO's Agreement on Subsidies and Countervailing Measures (Cosbey et al., 2012).

based on the domestic price of carbon scaled in proportion to the marginal responsiveness of global emissions to a change in the imported good.[6]

Several empirical studies have quantified the implications of carbon tariffs, considering alternative designs of the coverage of embodied carbon and the range of sectors (goods) subjected to the tariff. An Energy Modeling Forum (EMF) cross-comparison study investigates the environmental and economic impacts of carbon tariffs (Böhringer et al., 2012). In line with other meta-analyses (Zhang, 2012; Branger and Quirion, 2014) the main findings are that carbon tariffs (i) markedly reduce leakage, (ii) have only minor implications for global cost-effectiveness of unilateral action, (iii) shift larger shares of abatement cost to trading partners, and (iv) can attenuate adverse production impacts for domestic emission-intensive and trade-exposed industries in unilaterally regulated countries.

The limited global efficiency gains of carbon tariffs are partly traced back to the inaccuracy of tariff designs. In fact, carbon tariffs investigated so far in the policy modeling literature are almost exclusively based on average embodied carbon content and not targeted towards the individual firm or shipment (one exception is Winchester, 2012). This average may for instance be calculated for each exporting region, referred to as region-specific tariffs.[7] Such tariffs do not give individual polluters abroad incentives to reduce the emission-intensity of their production. Böhringer et al. (2017) analyze carbon tariff systems designed to target the specific emission-intensities of foreign producers. They find that firm-targeted tariffs can deliver stronger leakage reduction and higher gains in global cost-effectiveness than tariff designs operated at the industry level; however, the overall gains in cost-effectiveness remain still quite limited. Furthermore these additional gains trade off with higher monitoring and implementation cost of more specific tariff designs. Böhringer et al. (2016a) investigate the efficiency properties of taxing the full carbon footprint of imports. They highlight that these tariffs are too high from the perspective of optimal environmental policy because they fail to acknowledge a key behavioral response by industries subjected to the tariffs — the incentive to re-direct output to other markets in the world economy. In numerical simulations that adopt less comprehensive carbon metrics (reflecting second-best consideration) they find that the potential for efficiency gains remains still limited because carbon tariffs do not set direct incentives to individual polluters abroad for adopting less emission-intensive production techniques.

Regarding their potential for efficiency gains, carbon tariffs should also be viewed from a strategic perspective. Game-theoretic analyses show that international cooperation on transboundary pollution control may be advanced by the use of trade sanctions as an enforcement tool (Spagnolo, 1999;

[6]See Gros (2009) or Balistreri et al. (2012) for similar findings.

[7]Alternatively, the carbon tariff for a certain good could be equal across exporting regions, based on either emission intensities in all exporting regions jointly, the importing region's emission intensities, or best available technology (see e.g. Ismer and Neuhoff, 2007).

Conconi and Perroni, 2002; Ederington, 2001; Limão, 2005; Barrett, 2011; Nordhaus, 2015). The burden shifting effect of carbon tariffs identified by the quantitative literature suggests that carbon tariffs have the potential to confer substantial terms-of-trade gains to countries that use them and terms-of-trade losses to those subjected to them. Thus, the threat of carbon tariffs alone could lead to more effective climate policy if unregulated countries prefer to adopt domestic emission controls than to face carbon tariffs. However, the literature on the strategic value of carbon tariffs so far has paid little attention to the possibility of retaliatory responses on behalf of the sanctioned parties. One notable exception is Böhringer et al. (2016b) who study a discrete Nash game where regions outside an international climate policy regime my not only respond to carbon tariffs by abating or ignoring the tariffs but also by retaliating. They find that China's trade orientation together with low-cost domestic abatement opportunities establish carbon tariffs as a credible threat even for the case of retaliatory options. However, their analysis of retaliation focuses on the very special case of a uniform import tariff on emission-intensive and trade-exposed goods from the abatement coalition (which threatens tariffs) such that the added revenue generated by the uniform tariff equals the revenue generated by the carbon tariffs imposed on them. The rigid limitation of response options may substantially underestimate the value of retaliation provided by optimal tariffs across all traded goods. In the policy context of US withdrawal from the Paris Agreement, the present analysis expands the scope for retaliation to optimal tariffs. Furthermore, we assess the implications of a tariff war between the US, Europe, and China based on a large-scale multi-sector multi-region CGE model for the world economy calibrated to empirical data.

## III. Data

We base our quantitative analysis on most recent GTAP data which features national input-output tables together with bilateral trade flows and tariffs across 140 regions and 57 sectors for the year 2011 (Aguiar et al., 2016). Below we lay out the aggregation towards a more composite dataset for our numerical simulation analysis and discuss important features of the base-year data.

### A. *Aggregation of sectors and regions*

In our core simulations we maintain the full GTAP sector disaggregation to track as detailed as possible the cost implications of carbon pricing and the ability of countries to extract rents from setting strategic tariffs. The choice of regions is motivated by our focus on the three most important single geopolitical players in international trade and climate policy: We explicitly consider the US (USA), China and Europe as individual strategic players that might enter a mutual tariff war.[8] All other regions in the GTAP dataset are grouped by economic performance and treated in a non-strategic manner to avoid an aggregation bias in our policy assessment. [9] The composite of other OECD includes all OECD regions apart from the US and European countries. G20 in our dataset summarizes the remaining members to the G20 forum. Given the downward pressure of declining fuel demands on international fuel prices, we summarize major oil exporters (except those included in G20) into a composite region which is particularly vulnerable to energy demand reductions triggered by stringent climate policies. Finally, we aggregate all remaining countries in the GTAP dataset into two composite regions distinguished by income classification of the World Bank: middle income countries and low income countries. Table 1 provides an overview of the regions represented in our simulation analysis.

Table 1: Regions in the aggregate dataset

| | |
|---|---|
| | Strategic regions |
| USA | United States of America |
| China | China (incl. Hong Kong) |
| Europe | EU-28 and EFTA |
| | Other composite (non-strategic) regions |
| Other OECD | Australia, Canada, Japan, New Zealand, South Korea, Turkey |
| Remaining G20 | Argentina, Brazil, India, Indonesia, Mexico, Russia, South Africa |
| Oil exporting countries | Bahrain, Iran, Kuwait, Qatar, United Arab Emirates, Venezuela, Iran, Saudi Arabia |
| Middle income countries | Other middle income countries |
| Low income countries | Other low income countries |

## B. *Base-year statistics*

Central to the efficacy of carbon tariffs as a sanctioning instrument are the embodied carbon content and the export supply share by commodity of the sanctioned region as well as the level of carbon prices in the importing sanctioning regions. There are alternative proposals on the coverage of embodied carbon which range from only direct emissions (Mattoo et al., 2009) to total input-output embodied emissions (Böhringer et al., 2016b). In line with the bulk of economic analyses assessing embodied carbon tariffs we focus on direct emissions from fossil fuel inputs and indirect emissions from electricity use only. This metric constitutes a policy-relevant compromise. On the one hand, it is significantly more comprehensive than using just direct emissions since electricity is an important carbon-intensive input to many traded goods. On the other hand, it is also simple enough to be implemented in practical policy design. The effective carbon tariffs then emerge as the product of the

[8]In our analysis, Europe is composed of EU-28 and EFTA – these countries are largely integrated with coordinated climate and economic policies.

[9]Treating these aggregated regions as unitary actors has the potential to misrepresent the degree of market power their constituent countries hold. In our simulation analysis, we therefore eliminate the option for these composite regions to retaliate.

emission price in the importing region and the embodied carbon content of the imported goods.

In Figure 1 we compare the average embodied carbon content (covering direct emissions plus indirect emissions from electricity) and export share (the share of export value over production value) for traded goods across our core regions USA, China and Europe. It becomes apparent that the US and Europe ceteris paribus will be less vulnerable to carbon tariffs than China which stands out for both the highest embodied carbon content as well as the highest export shares.

Table 2 breaks down the export intensity – as the share of exports over domestic production – across destination countries (in addition, the number in brackets indicates the percentage share in total exports). Furthermore, we report the bilateral tariff rates averaged across the 57 GTAP commodities across our three key regions.[10]

Figure 1: Base-year average embodied carbon content and export intensity

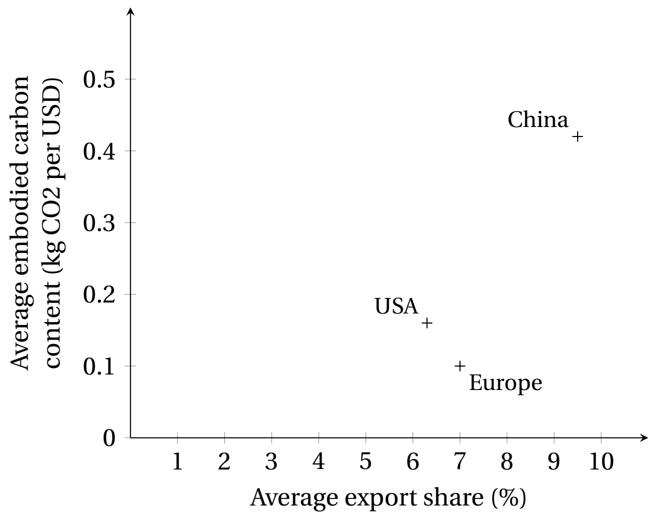



Table 2: Base-year export shares and bilateral tariff rates from row region to column region

| | Average export shares (in %) | | | | |
|---|---|---|---|---|---|
| | USA | China | Europe | Rest | Total |
| USA | – | 0.5 (8) | 1.8 (28) | 4.2 (64) | 6.5 (100) |
| China | 2.1 (22) | – | 2.2 (23) | 5.0 (55) | 9.3 (100) |
| Europe | 1.5 (22) | 0.8 (11) | – | 4.7 (67) | 7.0 (100) |
| | **Average bilateral tariff rates (in %)** | | | | |
| | USA | China | Europe | | |
| USA | – | 4.3 | 1.3 | | |
| China | 2.7 | – | 3.2 | | |
| Europe | 0.9 | 6.2 | – | | |

The US delivers just 8% of its exports to China while exports to Europe amount to 28%. China

[10]We omit the negligible tariff rates which show up in the GTAP data base as a result of attributing Hong Kong to China and EFTA to Europe (EU-28).

is export-oriented towards both Europe as well as USA with exports shares amounting to 22% and 23% respectively. For Europe, the US as an export destination is twice as important in percentage terms (22%) as is China (11%). The initial tariff protection level is highest for imports from Europe to China (6.2%) and from the US to China (4.3%) while the average import tariffs on goods traded between US and Europe are just close to 1%. It should be kept in mind that the specific bilateral tariff rates for individual commodities can deviate markedly from the average rate. For example, the GTAP data reports tariff rates of 26% (49.8%) for sugar exports from China to the US (Europe) or 14% (9.9%) for leather exports from China to the US (Europe). In the response scenarios to carbon tariffs discussed below (see section 4) we allow that countries behave strategically in setting optimal tariffs across all 57 GTAP commodities that maximize their domestic welfare.

Table 3 highlights the importance of the US, China, and Europe with respect to global $CO_2$ emissions and GDP where the three together account for more than 50% in both categories for the 2011 GTAP base year. The trade intensity as the sum of exports and imports of goods and services over gross domestic product is by far highest for China followed by Europe and the US pointing to the highest vulnerability of China for the case of a multilateral tariff war.

Table 3: Base-year $CO_2$ emissions, GDP, and trade intensity

| | $CO_2$ share (% of global $CO_2$ emissions) | GDP share (% of global GDP) | Trade openness (trade in % of GDP) |
|---|---|---|---|
| USA | 17.7 | 21.7 | 29.5 |
| China | 25.4 | 10.6 | 50.3 |
| Europe | 13.5 | 26.4 | 31.6 |

## C. *Emission reduction targets*

The stringency of INDC emission constraints will be a key driver of the economic adjustment cost towards decarbonization and the efficacy of carbon tariffs. To a first approximation, the cost of emissions reduction is determined by two factors (Weyant, 1993): (i) the distance to the target, i.e. the effective emission reduction target from baseline levels, and (ii) the ease of emission abatement (technically speaking the steepness of a country's marginal abatement cost curve) implied by technological options and consumer preferences. Cost increase as the effective emission reduction goes up or as a country faces a steeper cost curve. With higher marginal abatement cost, i.e. higher emission prices, the punitive effect of carbon tariffs will increase as well.

For our Paris-after-Trump climate policy scenarios we must translate the Intended Nationally Determined Contributions (INDCs) into effective emission reduction targets across regions. Under the Paris Agreement legally binding greenhouse gas emission reduction targets as previously imposed under the Kyoto Protocol to signatory industrialized countries are replaced with voluntary INDCs for more than 190 countries. The INDCs differ in emission metrics, reduction targets, and timelines complicating a straight derivation of effective emission abatement burdens. Table 4 provides an overview of INDCs for the US, China, and Europe as well as the other OECD and remaining G20 regions in our dataset.

The US and Europe both adopted explicit reduction targets in absolute GHG emissions. The US pledged to reduce its overall emissions by 26-28% from 2005 reference emission levels until the target year 2025 while Europe committed itself to a 40% emission reduction from 1990 levels until 2030. China's pledge is to peak its greenhouse gas emissions around 2030 or before, and to lower its emissions per unit of GDP in 2030 by 60-65% from the 2005 level. Likewise, the nature of pledges varies across other OECD and the remaining G20 countries.

Table 4: Intended Nationally Determined Contributions (INDCs)

| Region | Metric | Target (in %) | Reference year | Target year |
|---|---|---|---|---|
| | | USA, China, Europe | | |
| USA | Emissions | 26-28 | 2005 | 2025 |
| China | Emission intensity | 60-65 | 2005 | 2030 |
| Europe | Emissions | 40 | 1990 | 2030 |
| | | Other OECD countries | | |
| Australia | Emissions | 26-28 | 2005 | 2030 |
| Canada | Emissions | 30 | 2005 | 2030 |
| Japan | Emissions | 25.4 | 2005 | 2030 |
| South Korea | Emissions | 37 | 2030 | 2030 |
| New Zealand | Emissions | 30 | 2005 | 2030 |
| Turkey | Emissions | 21 | 2030 | 2030 |
| | | Remaining G20 countries | | |
| India | Emission intensity | 33-35 | 2005 | 2030 |
| Argentina | Emissions | 15 | 2030 | 2030 |
| Brazil | Emissions | 37 | 2005 | 2030 |
| Mexico | Emissions | 25 | 2030 | 2030 |
| Russia | Emissions | 25 | 1990 | 2030 |
| Indonesia | Emissions | 29 | 2005 | 2030 |

*Source:

`http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx`

Since the INDCs are stated with respect to 2025 or 2030 as target years there is substantial uncertainty on the future economic and technological development which will ultimately influence the effective emission reduction targets. In view of the baseline uncertainty, we abstain from a forward projection of our economic dataset. Instead we take the empirical data for 2011 as the business-as-usual (*BaU*) and transform the INDCs into effective emission reduction requirements from 2011 levels using historical data on countries' greenhouse gas emissions and GDP by the World Resources Institute (WRI, 2014) as well as macroeconomic projections on GDP and emissions by the Energy Information Agency

(EIA, 2016). For regions which provided a range of targets we adopt the lower bound of the range. For China and India the emission intensity target would not require any emission reduction compared to 2011. As to China, we reflect its increasingly pro-active role in the international climate negotiations to translate at least into an effective emission reduction requirement of 5% below *BaU* levels. The derived emission reduction targets applied to $CO_2$ emissions as the most important greenhouse gas are then as follows: USA 19%, Europe 30%, China 5%, other OECD 27%, and the remaining G20 8%. While these targets must be viewed as a lose translation of the INDCs, they reflect broader disparities in asserted abatement efforts where developed high-income countries lead the effort to reduce greenhouse gas emissions. In this vein, we postulate that middle- and low-income countries as well as oil exporting regions will not assume any effective emission reduction target in our climate policy scenarios.

## IV. The Computable General Equilibrium Model

For our impact assessment of alternate climate policy futures we draw on computable general equilibrium (CGE) analysis – a standard numerical approach for the economic impact assessment of policy reforms. CGE models combine data from input-output tables with assumptions about market structure and elasticities that govern how responsive supply and demand are to price changes. They are used to compute the outcome of how the economy adjusts to policy interventions. CGE models are rooted in general equilibrium theory combining assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions: producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints.

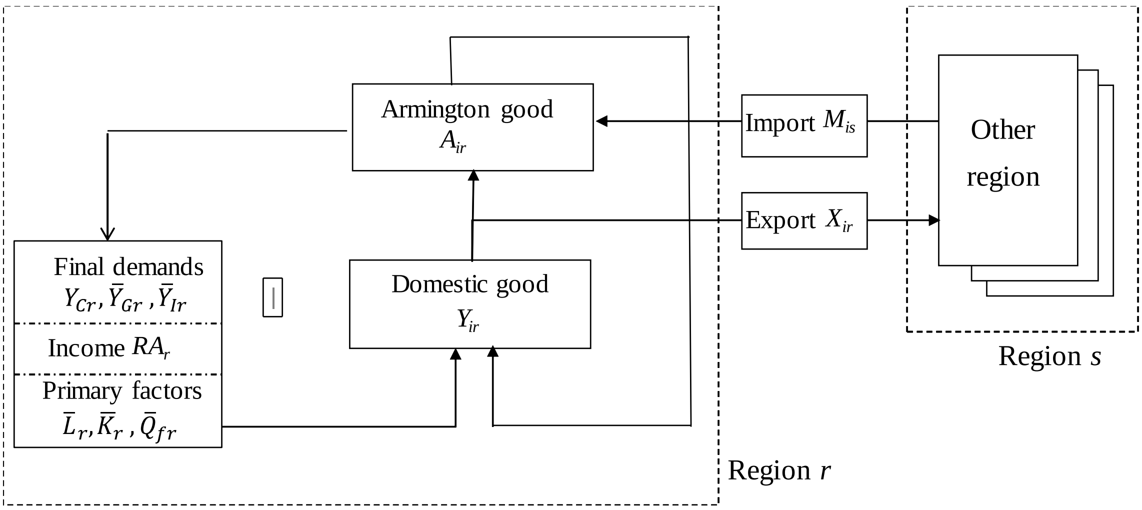
For our current analysis, we start from a generic multi-sector multi-region CGE model of global trade (Lanz and Rutherford, 2016) extended to represent energy demand and supply (Böhringer et al., 2016b). In this framework output and factor prices are fully flexible and markets are perfectly competitive. Preferences and technological constraints are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to policy-induced changes in relative prices.

A central model feature is its multi-sector multi-region structure which links national economies through bilateral trade flows. In this framework, international prices are endogenous and policy shocks will affect a country's terms of trade (measured as the ratio of a country's export price index to its import price index). Countries are assumed to produce regionally differentiated goods under perfect competition with constant returns to scale. The proposition to differentiate products by country of origin is referred to as the Armington assumption, after its seminal notion and application by Armington (1969).

Imported and domestically produced goods of the same variety are demanded as imperfect substitutes in intermediate and final demand subject to a constant elasticity of substitution (the so-called Armington elasticities). The Armington structure has several empirical advantages, as (i) it accommodates the empirical observation that a country imports and exports the same good (cross-hauling of data), (ii) it avoids over-specialization implicit to trade in homogeneous goods, and (iii) it is consistent with empirical evidence of trade in geographically differentiated products. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region. Figure 2 depicts the generic model structure.

In each region there is a representative agent that receives income from tax revenues and three primary factors which are in fixed supply: labor $\bar{L}_r$, capital $\bar{K}_r$ and specific resources $\bar{Q}_{fr}$ in the production of fossil fuels $f$.[11] By default, labor and capital are treated mobile across sectors within a region while specific resources are tied to sectors. The representative agent spends income on aggregate private consumption $Y_{Cr}$, exogenous investment (savings) demand $\bar{Y}_{Ir}$, and exogenous government demand $\bar{Y}_{Gr}$. Production output $Y_{ir}$ of commodity $i$ in each region $r$ enters final demand of the representative agent ($Y_{Cr}$, $\bar{Y}_{Ir}$, $\bar{Y}_{Gr}$), export demand $X_{ir}$ and input demand for Armington production $A_{ir}$. Armington production for each good $i$ in region $r$ is based on a CES technology that combines the domestically produced good and imports $M_{is}$ from other regions $s$. Armington outputs $A_{ir}$ serve as intermediate inputs to the production $Y_{ir}$ of all commodities including final demands.

Figure 2: Model structure

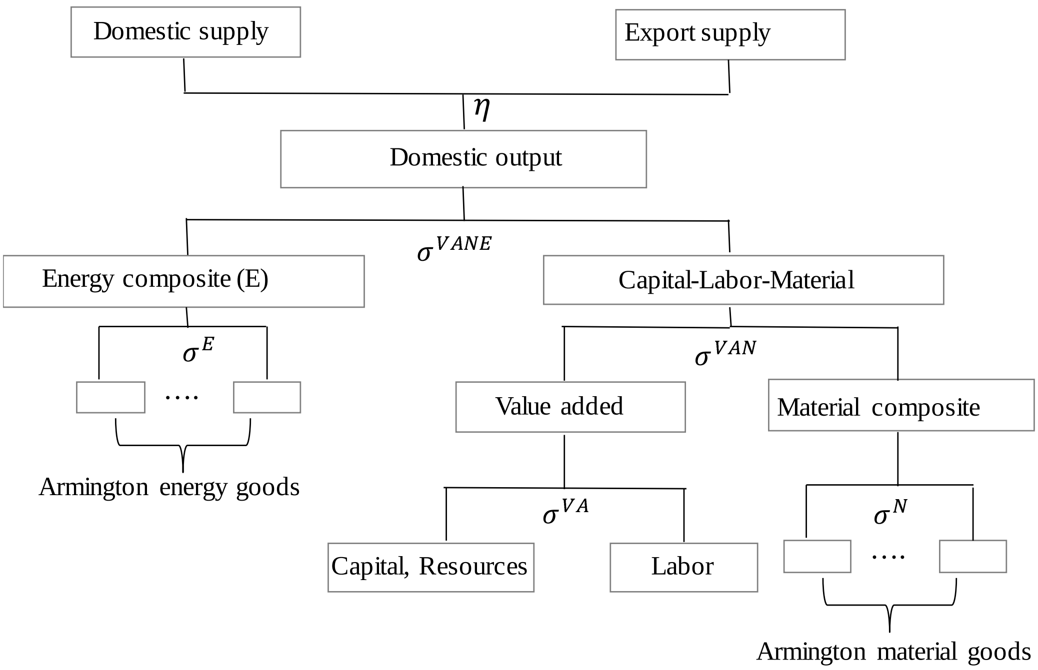



Production is given as a nested CES function which captures price-responsive substitution possibilities between factor and intermediate inputs. On the output side, the tradeoff between supply to

[11] For the sake of simplicity, we omit the explicit representation of tax revenues in our graphical model exposition. Variables which are assumed to be exogenous are labeled with an overbar.

the domestic market and supply to the export market is governed by a constant elasticity of transformation. Figure 3 displays the nesting structure in production. At the third (bottom) level, labor, and capital (incl. sector-specific resources) form a CES value-added composite. This value-added composite enters at the second level in fixed proportions with non-energy intermediate inputs while all energy inputs form a CES energy composite. At the top-level the energy composite trades off with the non-energy aggregate (composed of value-added and non-energy intermediate goods) subject to a constant elasticity of substitution.

Figure 3: Production structure ($\sigma$ denoting the respective cross-price substitution elasticities)




$CO_2$ emissions are linked in fixed proportions to the use of fossil fuels, with $CO_2$ coefficients differentiated by the specific carbon content of fuels (coal, crude oil, and natural gas). Economy-wide restrictions to the use of $CO_2$ emissions in production and consumption are implemented through explicit emission pricing of the carbon associated with fossil fuel use either via $CO_2$ taxes or the auctioning of $CO_2$ emission rights. $CO_2$ emission abatement then takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).

As is customary in CGE analysis, base-year data – in our case GTAP data for 2011 – and exogenous elasticities determine the free parameters of the model's functional forms that characterize technologies and preferences. Elasticities in international trade as well as substitution elasticities in value-added of production are readily included in the GTAP database.

Three classes of conditions characterize the economic equilibrium for our model: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for all goods and factors, and income-balance conditions for the representative agent in each region. An equilibrium allocation determines the economic variables that are associated with the economic equilibrium conditions: zero-profit conditions pin down the activity levels of production, market-clearance conditions determine prices for goods and factors, and income-balance conditions identify the income levels of the representative agents.

An innovative and powerful feature of our CGE model framework is the possibility to identify optimal choices in policy instruments. More specifically, we can compute the set of optimal tariffs across imported goods that a region would pick to maximize its welfare. The numerical analysis is then cast as a policy optimization problem subject to economic equilibrium conditions:

$$\max_{\tau} U^r \; s.t. \; F(z,\tau) = 0$$

where:

| | |
|---|---|
| $Z = \begin{pmatrix} p \\ q \\ M \end{pmatrix} \in \mathbb{R}^n$ | is the vector of endogenous prices ($p$), quantities ($q$) and income levels ($M$) determined by the general equilibrium conditions, |
| $\tau \in \mathbb{R}^m$ | is a vector of tariffs as the strategic choice variables, |
| $F : \mathbb{R}^{n+m} \rightarrow \mathbb{R}^n$ | is a system of equations coverning the general equilibrium conditions, and |
| $U^r$ | is the policy objective function by region $r$, which in our case refers to welfare maximization by region $r$. |

The rationale behind tariffs as a strategic policy instrument is rooted in the theoretical trade literature since more than a century (Edgeworth, 1894). As domestic economic agents fail to exercise their joint market power on the world market, import tariffs essentially cause the economy to behave as a monopsonist in its international trade relationships: The tariff reduces the amount that the country wants to import, so foreign exporters lower their price. In order to make tariffs welfare improving for the adopting country, the tariff rate must be chosen such that its terms-of-trade gains more than offset the deadweight loss of restricted trade – the latter showing up as the overall loss in economic surplus from the perspective of a small open economy where international prices would be exogenous. The tariff rate that makes the net gain to the importing country as large as possible is referred to as optimal tariff. As a special case of the general Ramsey rule of optimal taxation (Ramsey, 1927) it can be shown that the optimal tariff rate is inversely related to the price elasticity of foreign supply of the country's imports. The less elastic is foreign supply, the higher the optimal tariff.

While the intuition behind optimal tariffs is straightforward, the derivation of tariff rates in an economy-wide setting requires sophisticated computable general equilibrium analysis. The reason is that the foreign supply elasticity cannot be considered as a numerical value but must be taken as a formula. In fact, the foreign supply elasticity is a variable which relates in very complicated ways to the whole general equilibrium structure of the economy, and the value of the elasticity variable depends crucially on where it is evaluated (Balistreri and Markusen, 2009). With many traded goods, the optimal tariff scheme of a single country is a set of interrelated differentiated tariff rates that maximizes the country's economic welfare. In the analysis of Paris-after-Trump climate policies we adopt our optimal choice CGE framework to compute (i) retaliatory optimal tariffs by the US as a response to the imposition of carbon tariffs and (ii) the Nash outcome for the US, China and Europe when entering a tariff war. We provide a detailed algebraic model summary in the appendix.

# V. Climate Policy Analysis: Scenarios and Results

## A. *Policy Scenarios*

Our primary research interest is to investigate the potency of carbon tariffs as a sanctioning instrument against US withdrawal from the Paris Agreement. The starting point for our analysis is the situation where signatory parties to the Paris Agreement – including the US – comply with their INDC targets. We take this situation as our reference scenario *Paris* against which we quantify the economic impacts of a US withdrawal for several policy-relevant variants. Scenario *USout* denotes the policy counterfactual where the US defects from the Paris Agreement without any sanctions by trading partners. Scenario *CarbonTariff* reflects the situation where the remaining regions to the Paris Agreement levy carbon tariffs on US imports at their respective domestic emission prices. Scenario *Retaliation* follows up with retaliating optimal tariffs as a strategic response by the US. Scenario *TariffWar* finally describes a tariff war outcome, where the three strategic players in our policy game – the US, China, and Europe – end up in a tariff war: The Nash equilibrium identifies best-response bilateral tariff rates levied by the US on imports from China and Europe and conversely from China as well as Europe on US imports (note that bilateral tariff rates between China and Europe as complying Paris parties remain unchanged).

We assume that countries compliant to the Paris Agreement use domestic carbon pricing in order to fulfill their emission reduction requirements as derived from the INDCs (see section III). Domestic carbon pricing can take place either via an emission tax which is set sufficiently high or a domestic cap-and-trade emissions system. The revenues from emission taxes or auctioning of emission allowances are recycled lump-sum to the representative agent in each region. In scenarios where the US drops out from the Paris Agreement, Europe and China as the major geopolitical opponents to US withdrawal apply carbon tariffs to the embodied carbon of US imports at their domestic emission price. The base for embodied carbon includes direct emissions associated with the combustion of fossil fuels to produce a commodity plus indirect emissions from intermediate electricity inputs. Carbon tariff revenues accrue to the importing region. As with revenues from domestic emission pricing, the revenues from carbon tariffs get recycled lump-sum to the representative agent. Likewise, we maintain the proposition of lump-sum recycling for the strategic policy scenarios *Retaliation* and *TariffWar* with optimal tariffs.

In our central case simulations, we hold global emissions constant at the outcome of the *Paris* reference scenario. This accommodates a coherent cost-effectiveness comparison of alternative climate policy regimes without the need to evaluate the external cost of $CO_2$ emissions. There is also a policy rationale for holding global emissions constant. The Paris Agreement has been appraised as a critical step to limit global warming to no more than 2° Celsius above pre-industrial levels (UNFCCC, 2015). However, it is also clear that the INDCs constitute just a first step towards much more drastic long-run emission reduction requirements (Rose et al., 2017). To preserve the environmental integrity and climate effectiveness of the Paris Agreement, the remaining parties have to make up for US withdrawal with compensating emission reductions. Such compensation to preserve global public good provision also reinforces the moral position of compliant regions to impose carbon tariffs against the US. Technically, the global emission constraint is warranted through an endogenous uniform scaling of emission budgets across the compliant Paris regions with effective emission reduction requirements.[12] Table 5 provides a summary of our main policy scenarios.

Table 5: Overview of Paris-after-Trump climate policy scenarios

| Scenario label | Characteristics |
|---|---|
| *Paris* | $CO_2$ emission reductions (in %) from 2011 emission levels are implemented via domestic emission pricing in the following regions: USA (19%), China (5%), Europe (30%), Other OECD (27%), Remaining G20 (8%) |
| *USout* | Same as *Paris* but without US compliance |
| *CarbonTariff* | Same as *USout* but with embodied carbon tariffs on US imports levied by Europe and China |
| *Retaliation* | Same as *CarbonTariff* but with retaliating optimal tariffs of the US against China and Europe |
| *TariffWar* | Same as *CarbonTariff* but with Nash tariff war between the US versus China and Europe (i.e., no change in bilateral tariff rates between China and Europe) |

[12]Note that these regions then also adjust their emission budgets to account for emission leakage from other Paris parties without effective INDCs – in our case oil exporting countries, middle income countries, and low income countries.

## B. *Simulation results*

Table 6 reports emission changes, leakage rates, carbon prices, and welfare effects for our central policy regimes. Welfare impacts are defined as Hicksian equivalent variations in income as a percentage of the pre-policy – business-as-usual (*BaU*) – equilibrium levels.

The *BaU* equilibrium is one in which no region pursues climate policy or uses carbon or countervailing tariffs. A positive number in the table represents a welfare gain and a negative number a welfare loss (i.e., a positive cost). When we summarize welfare changes across regions, we adopt a utilitarian (Benthamite) perspective being agnostic on the cost distribution.

For scenario *Paris*, emission changes for Paris parties with effective reduction requirements simply reflect their INDCs. Emissions in regions without emission pricing increase as a consequence of shifts in comparative advantage which primarily emerge from policy-induced changes in the international prices of emission-intensive goods and fossil fuels. The leakage rate defined as the ratio of the emission change in regions with emission regulation over the emission change in unregulated regions amounts to just 6.7% reflecting the fact that abating regions in scenario Paris account for more than 80% of base-year emissions. As the US which alone accounts for nearly 18% of base-year $CO_2$ emissions withdraws from the Paris Agreement, the leakage rate markedly increases to 11.6% (scenario *USout*). In order to preserve the global climate policy objective of the Paris Agreement, the remaining Paris parties with effective reduction pledges compensate for US withdrawal through increased abatement efforts. The imposition of carbon tariffs attenuates the emission increase by the US, reduces the global leakage rate, and thereby slightly scales down the necessary abatement efforts by the remaining Paris parties with effective INDCs. Retaliation on behalf of the US and a tariff war between the US, China, and Europe has only minor implications on the regional emission patterns obtained in scenarios *USout* or *CarbonTariff*.

The emission prices reflect differences in the effective reduction targets as well as the ease of substituting away from carbon in regional production and consumption activities. Europe and other OECD stand out with the highest $CO_2$ emission prices to achieve ambitious emission reduction targets starting off from relatively $CO_2$ efficient production and consumption (their average $CO_2$ emission intensities rank lowest in the base year). China has an emission price of only 5 USD per ton of $CO_2$ which echoes its rather moderate effective emission reduction target and cheap abatement options (the latter mainly rooted in shifting away from massive coal combustion in Chinese electricity generation). The US with a $CO_2$ price of 36 USD per ton of $CO_2$ ranks in between China at the lower and Europe at the upper end. As the US drops out, $CO_2$ prices for the remaining parties must increase to prevent global emission levels from going up. The marginal abatement cost in terms of emission prices are a reasonable indicator for the direct inframarginal economic adjustment cost to emission constraints in the absence of international price adjustments.

Table 6: Impacts on emissions, leakage, carbon prices and welfare

| | *Paris* | *USout* | *CarbonTariff* | *Retaliation* | *TariffWar* |
|---|---|---|---|---|---|
| | A. Emission change (in% from *BaU*) | | | | |
| USA | -19.0 | 3.2 | 2.5 | 2.7 | 2.4 |
| China | -5.0 | -11.8 | -11.7 | -11.7 | -11.7 |
| Europe | -30.0 | -35.0 | -34.9 | -34.9 | -34.9 |
| Other OECD | -27.0 | -32.3 | -32.1 | -32.1 | -32.1 |
| Remaining G20 | -8.0 | -14.6 | -14.5 | -14.5 | -14.5 |
| Oil exporting countries | 2.4 | 2.7 | 2.9 | 2.6 | 2.9 |
| Middle income countries | 6.3 | 7.4 | 7.5 | 7.5 | 7.5 |
| Low income countries | 4.4 | 5.2 | 5.3 | 5.3 | 5.3 |
| GLOBAL | -11.8 | -11.8 | -11.8 | -11.8 | -11.8 |
| USA-CHN-EUR | -15.3 | -12.7 | -12.8 | -12.7 | -12.8 |
| OOE-G20 | -14.8 | -20.9 | -20.8 | -20.8 | -20.7 |
| OEX-MIC-LIC | 5.2 | 6.0 | 6.1 | 6.0 | 6.2 |
| | B. Leakage rate (in %) | | | | |
| USA | | 4.2 | 3.4 | 3.5 | 3.3 |
| Oil exporting countries | 0.9 | 0.9 | 1.0 | 0.9 | 1.0 |
| Middle income countries | 5.6 | 6.2 | 6.3 | 6.3 | 6.4 |
| Low income countries | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| GLOBAL | 6.7 | 11.6 | 11.0 | 11.1 | 11.0 |
| | C. Emission price (in USD per ton of $CO_2$) | | | | |
| USA | 36 | | | | |
| China | 5 | 11 | 10 | 10 | 10 |
| Europa | 162 | 221 | 223 | 221 | 220 |
| Other OECD | 102 | 141 | 141 | 141 | 141 |
| Remaining G20 | 11 | 19 | 19 | 19 | 19 |
| | D. Welfare change (in % HEV) | | | | |
| USA | -0.25 | -0.01 | -0.21 | -0.04 | -0.49 |
| China | 0.09 | -0.28 | -0.16 | -1.43 | -1.18 |
| Europa | -0.92 | -1.39 | -1.30 | -1.51 | -1.41 |
| Other OECD | -0.53 | -0.87 | -0.82 | -0.66 | -0.59 |
| Remaining G20 | -0.89 | -1.17 | -1.13 | -0.95 | -0.87 |
| Oil exporting countries | -3.14 | -4.05 | -3.79 | -4.26 | -3.46 |
| Middle income countries | -0.57 | -0.69 | -0.63 | -0.43 | -0.31 |
| Low income countries | -0.90 | -0.92 | -0.98 | -0.65 | -0.81 |
| GLOBAL | -0.63 | -0.84 | -0.84 | -0.87 | -0.90 |
| USA-CHN-EUR | -0.51 | -0.66 | -0.70 | -0.86 | -0.98 |
| OOE-G20 | -0.70 | -1.00 | -0.96 | -0.79 | -0.71 |
| OEX-MIC-LIC | -1.07 | -1.32 | -1.23 | -1.14 | -0.92 |

Key: GLOBAL – all countries; USA-CHN-EUR – composite of USA, China and Europe; OOE-G20 – composite of other OECD countries and remaining G20 countries; OEX-MIC-LIC – composite of oil exporting countries as well as middle and low income countries.

Policy regulation in open economies, however, does not only cause adjustment of domestic production and consumption patterns but also influences international prices via shifts in exports and imports. The changes in international prices, i.e., the terms of trade – measured as the ratio of a country's exports to its imports in value terms – imply an indirect economic benefit or burden which can dominate the direct cost of emission regulation (Böhringer and Rutherford, 2002). A prime example is the depression of international fossil fuel prices triggered by lower fuel demands of larger economies with $CO_2$ emission regulation. Likewise, emission pricing of emission-intensive exports can shift the economic cost of abatement from the domestic economy towards trading partners to the extent that they function as strategic substitutes for optimal tariffs (Krutilla, 1991; Anderson, 1992).

Implementation of the Paris Agreement induces gross economic adjustment cost to emission pricing regions that range from close to 1% of real income for Europe to a negative cost of around 0.1% for China. With very low abatement efforts, the direct abatement cost for China is more than offset through terms-of-trade gains on international markets. China benefits both from declining international fuel prices (as a fuel importer) and from shifts in comparative advantage on markets for energy-intensive goods since major competitors in industrialized countries levy much higher carbon prices. The USA faces a moderate income loss of 0.25%. The highest burden, in fact, is borne by the oil exporting countries that suffer from the decline of oil export revenues. At the global level, the aggregate economic adjustment cost amounts to 0.63% of world-wide income. The issue of burden shifting becomes apparent when comparing the compliance cost for the Paris parties with effective emission reduction constraints to the induced cost for countries without emission pricing (here: the composite of OEX-MIC-LIC). For the case of US withdrawal (scenario *USout*), the cost burden for the US falls to zero, whereas the remaining Paris parties with effective reduction targets face higher cost – due to compensating abatement efforts but also due to competitiveness losses vis-à-vis the US. China now also faces a non-negligible economic burden. From a global cost-effectiveness perspective, US withdrawal implies that the total cost of securing the *Paris* emission outcome goes up by roughly a third: Emission pricing across regions becomes more disparate and thus more inefficient compared to a hypothetical first-best benchmark with equalized marginal abatement cost across all regions.

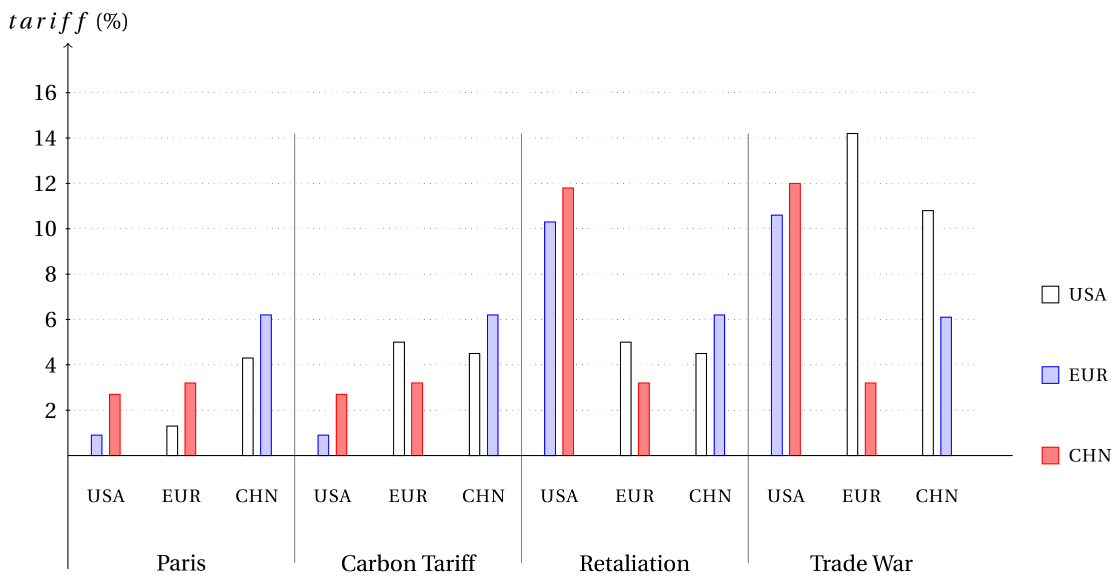
In our central case simulations, carbon tariffs fall short of being an effective instrument to prevent US withdrawal even if the US were to abstain from retaliatory measures (scenario *CarbonTariffs*): While the sanctioning Paris parties – China and Europe – can lower their economic adjustment cost compared to the situation where US defects (scenario *USout*) and thereby induce damage to the US, the US still performs slightly better under carbon tariffs compared to the initial Paris Agreement (scenario *Paris*). Carbon tariffs thus are not sufficient to induce US cooperation and remain a blunt instrument to foster global efficiency gains (Böhringer et al., 2016a) as they do not trigger an effective enlargement of the abatement coalition (in our case: the shift back from *USout* to *Paris*).

While the efficacy of carbon tariffs will increase if domestic emission prices for major US trading partners go up (e.g. as a consequence of more ambitious abatement targets in China), the credibility and strategic value of carbon tariffs as a sanctioning instrument will crucially hinge on the scope and effects of retaliatory measures. By levying optimal import tariffs against Europe and China, the US can roughly restore its welfare situation under *USout* while inducing substantial economic losses to Europe and in particular to China. Strategic US retaliation does not constitute a zero-cost game at the global level. However, the global excess cost is limited as regions which are not subjected to US retaliation pick up some international market shares.

When China and Europe go for best-response tariffs on US imports, the US faces an economic loss which markedly exceeds its compliance cost to the Paris Agreement. At the same time, however, the tariff war (scenario *TariffWar*) makes China much worse off as compared to the *USout* situation (Europe gets only slightly worse off). As a consequence, strategic carbon tariffs do not qualify as a robust sanctioning instrument against the US: It is in particular China with its high trade openness and vulnerability to trade restrictions that must be afraid of strategic responses by the US including the possibility of a tariff war. The negative repercussions of a tariff war between the US, China and Europe for the global economy remain limited as regions outside the tariff war on aggregate pick up some welfare gains through re-outing of international trade flows.

Figure 4 reports the average bilateral tariff rates between the three strategic geopolitical players. The tariff rates apply to exports from the X-axis regions to the Y-axis regions. Note that the bilateral tariff rates for scenario *Paris* are identical to the *BaU* (base year) tariff rates and as such carry over to scenario *USout*.

Figure 4: Bilateral tariff rates between the US (USA), China (CHN), and Europe (EUR)




From scenario *CarbonTariffs* we can read off how the imposition of carbon tariffs changes the effective average tariff rates for exports from the US to China and Europe. Reflecting the difference in domestic emission prices between China and Europe, we see that the increase of import tariffs on trade flows from the US to China is rather negligible (from 4.3% to 4.5%) whereas the increase of import tariffs on trade flows from US to Europe is substantial (from 1.3% to 5.0%). US retaliation via unilaterally optimal tariffs leads to a strong increase of average tariff rates from 2.7% to 11.8% on Chinese imports and from 0.9% to 10.3% on European imports. The unilaterally optimal US tariff rates remain robust in a tariff war with Europe and China indicating that the strategic choice of tariff rates for the US are hardly affected by changes in tariffs imposed from Europe and China on US imports. As Europe and China enter the tariff war, both raise their tariffs on US imports: For Europe, Nash tariffs amount to 14.2% on US imports (compared to base-year tariffs of 1.3%); for China, average tariff rates on US imports increase from the base-year level of 4.3% to 10.8%.

# VI. Sensitivity Analysis

## A. *Compensating abatement efforts*

Across our central case simulations, we have kept global emission levels at the outcome of the Paris Agreement when all parties with effective reduction requirements including the US comply (scenario *Paris*). In case of US withdrawal the remaining parties with effective reduction requirements kick in and compensate for US defection holding global emissions constant. This amounts to assuming that there is full crowding in to climate services as a global public good. The reasoning behind is that the remaining Paris parties view the ambition level of the Paris Agreement as a minimum threshold to avoid dangerous anthropogenic interference with the climate system. The increased effort level also might foster the moral justification to use carbon tariffs as a sanctioning instrument to US withdrawal. While the constant global public good provision, i.e. constant global emission reduction, allows for a coherent global cost-effectiveness analysis, it may be perceived as overly optimistic from the perspective of non-cooperative behavior.

In the sensitivity analysis, we drop the assumption of compensating efforts at the emission level of the *Paris* scenario. Instead we assume that the remaining parties to the Paris Agreement simply stick with the global emission level emerging from scenario *USout*, i.e. the stringency level of the Paris Agreement without US compliance. This implies that scenario *Paris* stands out for higher global emission reduction (11.8%) compared to the counterfactual scenarios without US compliance (8%). We therefore can no longer compare global cost-effectiveness across all scenarios (since we abstain from the valuation of the external cost of greenhouse gas emissions). As remaining parties no longer hold global emission levels at the more stringent Paris outcome but only at the level of scenario *USout* their compliance cost under the Paris Agreement are roughly the same when transiting from *Paris* to *USout*. Emission prices outside the US remain at the *Paris* level which lowers the punitive effect of European and Chinese carbon tariffs for the US as compared to our central case simulations where the remaining parties to Paris with effective emission reduction requirements compensated for US defection with increased abatement, i.e. higher domestic emission prices. Carbon tariffs then lose further bite as a sanctioning instrument: The US would even prefer a tariff war to Paris compliance while China would avoid any risk of unilateral US retaliation or a tariff war given the large negative repercussions on its economy.

## B. *Stringency of Chinese INDCs*

The translation of emission pledges under the Paris Agreement to effective emission reduction targets from business-as-usual emission levels is not straightforward. More specifically, the emission pledges across countries differ in metrics (absolute emissions versus emission intensity) and future target years making effective targets dependent on hypothetical economic developments. The economic cost of target compliance will furthermore hinge on future speculative technological progress. In our derivation of effective targets, we have excluded such baseline uncertainties by taking the GTAP 2011 base year as our reference situation. The effective reduction targets attributed to key players in international climate policy reflect differences in mid-term ambition levels where industrialized countries lead the way. China as the biggest and further growing source of greenhouse gas emissions assumes only an effective reduction target of 5% in our central case simulations which may be perceived as too moderate given the more recent pro-active role of China in international climate policy.

In our sensitivity analysis, we tighten the Chinese targets to 10% and 20%, respectively. With more ambitious Chinese targets, the global emission reduction under *Paris* increases from 11.8% to 13%, and 15.5% respectively. Chinese emission prices per ton of $CO_2$ go up from USD 5 to USD 9 and USD 18 respectively, while real income no longer slightly increases as an outcome of *Paris* but will decrease by 0.43% for the 20% abatement target which then is nearly twice the cost for the US and half the adjustment cost incurred by Europe. Higher emission prices in China imply a higher carbon tariff on US imports to China but the threat of *CarbonTariffs* remains practically unchanged compared to our core simulations – on the one hand, Chinese emission prices are still low at USD 18 per ton of $CO_2$; on the other hand, US emission-intensive producers do not have China as a major destination for exports. The incentives for the US retaliation remain the same and so are the US welfare impacts of a tariff war. With higher initial abatement targets, the negative repercussions of US retaliation and a tariff war for the Chinese economy become even more pronounced.

## C. *Cooperation*

In his withdrawal address on June 1, 2017 US President Trump announced the intent to renegotiate the Paris Agreement in order to get a “better deal". As an immediate response, the leaders of France, Italy and Germany indicated in a joint statement that the US could not unilaterally renegotiate the agreement. The United Nations body that facilitated the Paris Agreement confirmed that the agreement “cannot be renegotiated based on the request of a single party." Given that US retaliation to carbon tariffs and a tariff war are especially detrimental for China, one could ask the question whether more cooperation on behalf of China could lure in the US to keep its commitment. This perspective could be fostered by considerations that China (i) is the largest $CO_2$ emitter, (ii) disposes of rather low cost abatement options, and (iii) starts out with relatively modest effective emission reduction targets. In this vein, we perform sensitivity analysis where we increase (double) the Chinese contribution to achieve the global emission level as implied by the initial Paris Agreement (scenario *Paris*) while at the same time lowering the abatement efforts of other Paris parties (including the US) with effective emission reduction requirements.[13]

Another option for appeasement with potentially large cost savings would be the installment of an emission trading system between US, China, and Europe leading to an equalization of marginal abatement cost across these major economies. In both settings, the economic cost for the US would decline as compared to the initial Paris Agreement and be eventually preferable to the welfare losses inflicted by carbon tariffs – the carrot would beat the stick. Yet, the US would still fare better compared to both variants when leaving the Paris Agreement (scenario *USout*).

## D. *Trade responsiveness*

In our mulitlateral impact assessment of climate policy scenarios trade elasticities play a critical role. Trade elasticities govern the ease of substitution between varieties of the same good produced in different countries. With asymmetric emission pricing across trading partners, the trade elasticities affect the degree to which consumers can look elsewhere for emission-intensive goods when the varieties they would have purchased from trading partners become differential emission price tags. Trade elasticities are also central for the magnitude of terms-of-trade gains a region can expect to gain by using tariffs. When these elasticities take on smaller values, export supply from trading partners becomes less elastic, implying a higher optimal tariff. In sensitivity runs, we double and halve the central-case values of trade elasticities.

The choice of trade elasticities has important implications for the market power in international trade and thus the scope of terms-of-trade gains which can be exploited through optimal tariffs. With lower trade elasticities, retaliation makes the US actually better off as compared to business-as-usual (0.52% HEV). In this situation, the US would actually embrace carbon tariffs as a trigger for strategic

[13] Note that this setting differs from section VI C. where higher Chinese reduction commitments are not used to offset emission reduction requirements of other Paris parties but imply higher global emission reductions.

trade policy. The outcome of a tariff war would be less costly for the US than compliance to the Paris Agreement. With low trade elasticities the cost of retaliatory US tariffs for China increase drastically from 1.43% to 3.65% and in the case of tariff war from 1.18% to 2.98%.

Inversely, higher trade elasticities reduce market power and potential gains from unilaterally optimal tariffs. In this case, retaliatory tariffs make the US still better off than sticking to the Paris Agreement but its terms-of-trade gains are markedly lower. In a tariff war, the US fares worse than fulfilling its Paris commitments but losses will come close to the adjustment cost for the case of compliance with the Paris Agreement. Europe would actually face slightly lower welfare losses under low trade responsiveness for the tariff war as compared to US defection (scenario *USout*) but due to higher losses of China tariffs will still not work as a credible sanction. With low trade responsiveness the global excess cost of either US retaliation or the trilateral tariff war are negligible. Overall, the choice of trade elasticities changes the magnitude but not the qualitative pattern of regional adjustment cost triggered by emission pricing as well as the supplemental imposition of carbon tariffs.

## E. *Ease of carbon substitution*

The cross-price elasticity of substitution between energy demand and non-energy demand in sectoral production and final consumption determines the ease of substituting, i.e., the steepness of a country's marginal abatement cost curve. In our sensitivity analysis we lower and increase the central case value for this key elasticity by 50%. As expected, domestic emission prices to meet the Paris reduction requirements go up (down) with lower (higher) energy demand elasticities. Likewise, the inframarginal cost of climate policies increase (decrease). Again, the pattern of cost incidence across scenarios does not change with the variations in energy demand elasticities such that all findings remain robust.

## F. *Capital market closure and capital mobility*

In our central case simulations capital is mobile across sectors within a country but cannot move across borders. The alternative assumption of global capital mobility does not change the pattern of cost incidence across scenarios thereby confirming all our key findings.

By default, we use a capital market closure where we hold the aggregate capital stock and investment constant. As a static long-run analysis, we can impose a steady-state constraint where the level of investment and capital stock adjusts so that investment is consistent in the long-run with the return to capital. We find that the welfare cost of emission constraints are getting substantially larger in the steady-state setting because the long-run capital stock endowment shrinks, leaving fewer real resources to be employed. Yet, the welfare ranking of scenarios by the strategic players remains the same such that our insights from the central case simulations remain robust.

### G. *Sectoral aggregation*

Our central case simulations are based on the full set of 57 commodities included in the global GTAP database. The main advantage of keeping the dataset in the commodity space as disaggregate as possible is that we capture the potential of market power constituent countries have at a detailed empirical level. Combining sectors upstream in the dataset and working with averages can introduce aggregation bias. In sensitivity runs, we test the robustness of our results with respect to sectoral aggregation – the latter having the potential advantage of reducing computational time. We employ two alternative datasets. One highly aggregated dataset with 6 commodities where we keep the five primary and secondary energy goods (coal, crude oil, gas, refined oil, electricity) which are central to the assessment of $CO_2$ emission abatement but aggregate all other sectors into one single macro-commodity. And another more disaggregate dataset with 23 commodities where we explicitly consider – beyond the five energy commodities – further energy- and emission-intensive goods. We find that the latter dataset provides a close approximation to the results produced by the full GTAP sector disaggregation whereas the macro dataset leads to substantial quantitative deviations. However, across all datasets our conclusion that carbon tariffs do not provide a credible sanctioning instrument against the US remains robust.

## VII. Concluding Remarks

Upon dissemination in December 2015, the Paris Agreement has been signed by more than 190 countries. It came into force on November 4, 2016. The Agreement commits signatory parties to limit global temperature increase below 2° as compared to the pre-industrial temperature level. The 2° target has been adopted as the critical threshold of what climate scientists regard as the limit of safety, beyond which climate change may become catastrophic. Compared to its precursor climate treaty – the Kyoto Protocol – the Paris Agreement has been appraised as a fundamental breakthrough for combating dangerous anthropogenic climate change. It features – albeit on a voluntary base – emission reduction pledges of most countries including all top greenhouse gas emitters such as the US, China, and Europe. With the new US administration led by President Donald Trump, however, the seemingly bright Paris perspective for an effective climate protection has been put at serious risk. President Trump has disguised the concept of climate change as a hoax “created by and for the Chinese in order to make U.S. manufacturing non-competitive." and started to roll back domestic emission reduction plans initiated by the previous Obama administration. On June 1, 2017 Trump then officially announced US withdrawal from the Paris agreement. Faced with the US withdrawal, there are ongoing debates on how the remaining parties to the Paris Agreement could effectively impose sanctions against the US.

One option is carbon tariffs levied on the embodied carbon content of US exports at the carbon prices prevailing in importing countries. The economic analysis presented in this paper, however, indicates that carbon tariffs do not come as a credible threat to the US when we account for the realistic option of retaliatory tariffs and even the possibility of a tariff war. Our numerical assessment based on an empirical dataset for the global economy points to sufficient market power in international trade that the US could exploit to deter Europe and in particular China from the use of carbon tariffs. With retaliatory optimal tariffs on imports from China and Europe, US could revert most of the damage induced by carbon tariffs towards its main trading partners and be clearly better off than complying with the Paris Agreement. Even the prospect of a tariff war where China and Europe levy best-response tariffs on US imports would not come as a credible threat: The US might suffer in this regime more than fulfilling its Paris commitment but at the same time it is particularly China as the most trade-intensive region which would incur a drastic economic loss from such a tariff war. Thus, it is in first place China that must be afraid of carbon tariffs which could backfire through US retaliatory tariffs and a potential tariff war.

From the perspective of countries that are worried about the environmental integrity of the Paris Agreement our analysis conveys an inconvenient insight: In the case of the US, carbon tariffs as a potential cure could turn out worse than the disease.

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# A Algebraic Model Summary

Below we provide an algebraic description for the multi-sector multi-region CGE model underlying our quantitative simulation analysis. Tables A.1 – A.5 contain the notations for variables and parameters employed within our algebraic exposition. The algebraic summary is organized in three sections that state the three classes of economic equilibrium conditions constituting a competitive market outcome: zero-profit conditions for constant-returns-to-scale producers, market-clearance conditions for commodities and factors, and income balances for consumers. In equilibrium, these conditions determine the variables of the economic system: zero-profit conditions determine activity levels of production, market-clearance conditions determine the prices of goods and factors, and income-balance conditions determine the income levels of consumers.

By default, we formulate the market equilibrium as a mixed complementarity problem (MCP) which explicitly represents weak inequalities and complementarity between decision variables and equilibrium conditions (Cottle et al., 1992; Rutherford, 1995). Complementarity methods (Dirkse and Ferris, 1995) are used to solve the MCP formulation of our general equilibrium model. When we endogenize import tariffs as a strategic policy instrument (scenarios *Retaliation* and *TariffWar*), we keep the equilibrium conditions as a side constraints of a nonlinear optimization problem where the strategic representative agent picks optimal import tariffs to maximize domestic welfare. The resulting MPEC (mathematical program subject to equilibrium constraints) is then solved with nonlinear optimization methods (Drud, 2002). In the solution of the strategic tariff war between the US, China, and Europe we build on a simple diagonalization algorithm where we loop over the strategic regions to find unilaterally optimal tariffs while taking the tariff rates of all other regions as given. We then can solve iteratively for the Nash equilibrium in best responses and find that our iterative algorithm quickly converges.

In our algebraic exposition, the notation $\Pi_{ir}^{z}$ is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for production with constant returns to scale of sector $i$ in region $r$, where $z$ is the name assigned to the associated production activity.[14] Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. We use $i$ (aliased with $j$) as an index comprising all sectors including final consumption ($i = C$), public good provision ($i = G$), and investment ($i = I$). The index $r$ (aliased with $s$) denotes regions.

[14]Note that we can decompose production in multiple stages (nests) and refer to each nest as a separate sub-production activity. In our exposition below, we specify for example the choice of capital-labor inputs as a price-responsive sub-production: $\Pi_{ir}^{KL}$ then denotes the zero-profit condition of value-added production in sector $i$ and region $r$.

Table A.1: Indices

| | |
|---|---|
| $i$ (alias $j$) | Index for all sectors (goods) – including the composite private consumption good ($i = C$), the composite public consumption good ($i = G$), and the composite investment good ($i = I$) |
| $r$ (alias $s$) | Index for regions |

Table A.2: Variables

| | |
|---|---|
| | Activity levels |
| $VA_{ir}$ | Value-added composite in sector $i$ and region $r$ |
| $E_{ir}$ | Energy composite in sector $i$ and region $r$ |
| $Y_{ir}$ | Production in sector $i$ and region $r$ |
| $M_{ir}$ | Import composite for good $i$ and region $r$ |
| $A_{ir}$ | Armington composite for good $i$ in region $r$ |
| | Price levels |
| $p_{ir}^{VA}$ | Price of value-added composite in sector $i$ and region $r$ |
| $p_{ir}^{E}$ | Price of energy composite in sector $i$ and region $r$ |
| $p_{ir}^{D}$ | Domestic supply price of good $i$ produced in region $r$ |
| $p_{ir}^{X}$ | Export supply price of good $i$ produced in region $r$ |
| $p_{ir}^{M}$ | Price of import composite for good $i$ imported to region $r$ |
| $p_{ir}^{A}$ | Price of Armington good $i$ in region $r$ |
| $w_r$ | Wage rate in region $r$ |
| $v_r$ | Price of capital services in region $r$ |
| $q_{ir}$ | Rent to sector-specific resources in sector $i$ and region $r$ |
| $p_r^{CO_2}$ | $CO_2$ emission price in region $r$ |
| $t_{isr}^{M}$ | Tariff rate on commodity $i$ imported from region $s$ to region $r$ |
| | Income levels |
| $INC_r$ | Income level of representative household in region $r$ |

Table A.3: Cost shares

| | |
|---|---|
| $\theta_{Kir}^{VA}$ | Cost share of capital $K$ in value-added composite of sector $i$ and region $r$ |
| $\theta_{Lir}^{VA}$ | Cost share of labor $L$ in value-added composite of sector $i$ and region $r$ |
| $\theta_{Qir}^{VA}$ | Cost share of specific resource $Q$ in value-added composite of sector $i$ in region $r$ |
| $\theta_{jir}^{E}$ | Cost share of energy input $j$ in energy composite of sector $i$ and region $r$ |
| $\theta_{jir}^{N}$ | Cost share of non-energy input $j$ in material input of sector $i$ and region $r$ |
| $\theta_{isr}^{M}$ | Cost share of imports of good $i$ from region $s$ to region $r$ |
| $\theta_{ir}^{A}$ | Cost share of domestic variety in Armington good $i$ of region $r$ |

Key: KLEM – value-added, energy and non-energy; KLE – value-added and energy

Table A.4: Elasticities

| | |
|---|---|
| $\sigma_{ir}^{VA}$ | Substitution between labor, capital, and specific resources in value-added composite |
| $\sigma_{ir}^{E}$ | Substitution between energy inputs in energy composite |
| $\sigma_{ir}^{N}$ | Substitution between inputs into non-energy (material) composite |
| $\sigma_{ir}^{VAN}$ | Substitution between VA composite and non-energy (material) composite |
| $\sigma_{ir}^{VANE}$ | Substitution between energy composite and the composite of all other non-energy inputs |
| $\sigma_{ir}^{M}$ | Substitution between imports from different regions |
| $\sigma_{ir}^{A}$ | Substitution between the import aggregate and the domestic input |
| $\eta_{ir}$ | Transformation between domestic supply and export supply |

Table A.5: Endowments and emissions coefficients

| | |
|---|---|
| $\overline{L}_r$ | Aggregate labor endowment in region $r$ |
| $\overline{K}_r$ | Aggregate capital endowment in region $r$ |
| $\overline{Q}_{ir}$ | Endowment with natural resource $i$ in region $r$ $(i \in FF)$ |
| $\overline{G}_r$ | Public good provision in region $r$ |
| $\overline{I}_r$ | Investment demand in region $r$ |
| $\overline{B}_r$ | Balance of payment deficit or surplus in region $r$ |
| $\overline{CO_2}_r$ | $CO_2$ emission endowment for region $r$ |
| $\alpha_i^{CO_2}$ | $CO_2$ emission coefficient for energy good $i$ |
| $\epsilon_{ir}^{CO_2}$ | Embodied $CO_2$ content of good $i$ produced in region $r$ |

**Zero profit conditions**

Production of goods

Production of commodities is captured on the input side by a three-level constant elasticity of substitution (CES) function describing the price-dependent use of capital, labor, energy, and non-energy (material) inputs in production.[15] At the third (bottom) level, a CES function captures substitution possibilities within the value-added composite of capital, labor, and sector-specific resources; at the same level, non-energy material inputs form a CES composite. At the second level, the value-added composite combines with the non-energy composite towards a CES aggregate; at the same level all energy goods form a sector-specific CES energy composite. At the top level, the energy composite trades off with the aggregate of non-energy and value-added subject to a CES.

The unit-profit function for the value-added composite is:

$$\Pi_{ir}^{VA} = p_{ir}^{VA} - \left(\theta_{Kir}^{VA} v_r^{1-\sigma_{ir}^{VA}} + \theta_{Lir}^{VA} w_r^{1-\sigma_{ir}^{VA}} + \theta_{Qir}^{VA} q_{ir}^{1-\sigma_{ir}^{VA}}\right)^{\frac{1}{1-\sigma_{ir}^{VA}}} \leq 0$$

[15]Note that the specification of the unit-profit function also includes the production of final demand components for private consumption $(i = C)$, public consumption $(i = G)$, and composite investment $(i = I)$. In these cases, entries in the value-added nest are zero.

The associated variable $VA_{ir}$ is the activity level of producing the value-added composite of sector $i$ in region $r$.

The unit-profit function for the energy composite is:

$$\Pi_{ir}^{E} = p_{ir}^{E} - \left( \sum_{j \in EG} \theta_{jir}^{E} \left( p_{jr}^{A} + p_{r}^{CO_2} \alpha_{j}^{CO_2} \right)^{1-\sigma_{ir}^{E}} \right)^{\frac{1}{1-\sigma_{ir}^{E}}} \leq 0$$

where $EG$ denotes the set of energy goods. The associated variable $E_{ir}$ is the activity level of producing the energy composite for sector $i$ in region $r$. Carbon emission pricing enters at the regional emission price $p_r^{CO_2}$ on the specific carbon content $\alpha_j^{CO_2}$ of the energy good $j$.

The value-added composite and the energy composite enter the unit-profit function at the top level together with a CES composite of non-energy (material) intermediate input. Total production splits between domestic supply and export supply subject to a constant elasticity of transformation:

$$\begin{aligned}\Pi_{ir}^{Y} = & \left[ \theta_{ir}^{D} p_{ir}^{D^{1-\eta_{ir}}} + \left(1-\theta_{ir}^{D}\right) p_{ir}^{X^{1-\eta_{ir}}} \right]^{\frac{1}{1-\eta_{ir}}} \\ & - \left[ \theta_{ir}^{VAN} \left[ \theta_{ir}^{VA} p_{ir}^{VA^{1-\sigma_{ir}^{VAN}}} + \left(1-\theta_{ir}^{VA}\right) \left( \sum_{j \notin EG} \theta_{jir}^{N} p_{jr}^{A^{1-\sigma_{ir}^{N}}} \right)^{\frac{1-\sigma_{ir}^{VAN}}{1-\sigma_{ir}^{N}}} \right]^{\frac{1-\sigma_{ir}^{VANE}}{1-\sigma_{ir}^{VAN}}} \right. \\ & \left. + \left(1-\theta_{ir}^{VAN}\right) p_{ir}^{E^{1-\sigma_{ir}^{VANE}}} \right]^{\frac{1}{1-\sigma_{ir}^{VANE}}} \leq 0\end{aligned}$$

The associated variable $Y_{ir}$ is the activity level of producing good $i$ in region $r$.

Import aggregate across regions

Imports of the same variety from different regions enter the import composite subject to a CES. The unit-profit function for the import composite is:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left[ \sum_{s} \theta_{isr}^{M} \left[ \left( p_{is}^{X} + \epsilon_{is}^{CO_2} p_{r}^{CO_2} \right) \left( 1 + t_{isr}^{M} \right) \right]^{1-\sigma_{ir}^{M}} \right]^{\frac{1}{1-\sigma_{ir}^{M}}} \leq 0$$

The associated variable $M_{ir}$ is the activity level of forming the import composite for good $i$ in region $r$. Carbon tariffs emerge as the domestic carbon price $p_r^{CO_2}$ in region $r$ applied to the carbon content $\epsilon_{is}^{CO_2}$ embodied in commodity $i$ which is imported from region $s$. Import tariffs are levied as bilateral ad-valorem taxes $t_{isr}^{M}$ on imports from region $s$ into region $r$. In the calculation of optimal tariffs (scenarios *Retaliation* and *TariffWar*) the tariff rates $t_{isr}^{M}$ are endogenous policy instruments of the region which is maximizing domestic welfare subject to the general equilibrium conditions.

Armington aggregate

All goods used on the domestic market in intermediate and final demand correspond to a so-called Armington composite that combines the domestically produced good and a composite of imported goods of the same variety subject to a constant elasticity of substitution. The unit-profit function for the Armington aggregate is:

$$\Pi_{ir}^{A} = p_{ir}^{A} - \left[ \theta_{ir}^{A} p_{ir}^{\gamma^{1-\sigma_{ir}^{A}}} + \left(1-\theta_{ir}^{A}\right) p_{ir}^{M^{1-\sigma_{ir}^{A}}} \right]^{\frac{1}{1-\sigma_{ir}^{A}}} \leq 0$$

The associated variable $A_{ir}$ is the activity level of forming the Armington composite for good $i$ in region $r$.

**Market-clearance conditions**

Labor

Labor is in fixed supply and can move freely across domestic sectors. The market-clearance condition for labor is:

$$\overline{L}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial w_r}$$

The associated variable $w_r$ is the wage rate in region $r$.

Capital

Capital is in fixed supply and can move freely across domestic sectors. The market-clearance condition for capital is:

$$\overline{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial v_r}$$

The associated variable $v_r$ is the price of capital services in region $r$.

Sector-specific resources

Sector-specific resources are in fixed supply. The market-clearance condition for the sector-specific resource is:

$$\overline{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial q_{ir}} + \sum_{is} X_{irs} \frac{\partial \Pi^X_{irs}}{\partial q_{ir}}$$

The associated variable $q_{ir}$ is the rent to the specific resource in sector $i$ and region $r$.

Value-added composite

The market-clearance condition for the value-added composite is:

$$VA_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{VA}_{ir}}$$

The associated variable $p^{VA}_{ir}$ is the price of the value-added composite in sector $i$ and region $r$.

Energy composite

The market-clearance condition for the energy composite is:

$$E_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{E}_{ir}}$$

The associated variable $p^{E}_{ir}$ is the price of the energy composite in sector $i$ and region $r$.

Output for domestic supply

Output destined for the domestic intermediate markets enters Armington demand. The market-clearance condition for domestic output entering intermediate Armington demand is:

$$Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{D}_{ir}} \geq \sum_{j} A_{jr} \frac{\partial \Pi^A_{jr}}{\partial p^{D}_{ir}}$$

The associated variable $p^{D}_{ir}$ is the price of the commodity $i$ produced in region $r$ and destined for domestic intermediate demand.

Output of public good production ($i = G$) enters the domestic market only and covers fixed domestic government demand. The market-clearance condition for the public good composite is:

$$Y_{Gr} \geq \overline{G}_r$$

The associated variable $p^D_{Gr}$ is the price of the composite public good in region $r$.

Output of investment good production ($i = I$) enters the domestic market only and covers fixed investment demand. The market-clearance condition for composite investment is:

$$Y_{Ir} \geq \overline{I}_r$$

The associated variable $p^D_{Ir}$ is the price of the composite investment good in region $r$.

Output of composite final good production ($i = C$) enters the domestic market only and covers private consumption demand which is limited by the available income of the representative agent in region $r$. The market-clearance condition for composite private consumption is:

$$Y_{Cr} \geq \frac{INC_r}{p^D_{Cr}}$$

The associated variable $p^D_{Cr}$ is the price of the composite final consumption good in region $r$.

Output for export supply

Output destined for exports must satisfy the import demand by other regions. The market-clearance condition is:

$$Y_{ir}\frac{\partial \Pi^Y_{ir}}{\partial p^X_{ir}} \geq \sum_s M_{is} \frac{\partial \Pi^M_{is}}{\partial\left(\left(p^X_{ir} + \epsilon^{CO_2}_{ir} p^{CO_2}_s\right)\left(1 + t^M_{irs}\right)\right)}$$

The associated variable is the price $p^X_{ir}$ of the export commodity $i$ produced in region $r$.

Armington aggregate

Armington supply enters all intermediate and final demands. The market-clearance condition for domestic output is:

$$A_{ir} \geq \sum_j Y_{jr} \frac{\partial \Pi^Y_{jr}}{\partial \left(p^A_{jr} + p^{CO_2}_r \alpha^{CO_2}_j\right)}$$

The associated variable is the price $p^A_{ir}$ of the Armington good $i$ in region $r$.

Import aggregate

Import supply enters Armington demand. The market-clearance condition for the import composite is:

$$M_{ir} \geq A_{ir} \frac{\partial \Pi^A_{ir}}{\partial p^M_{ir}}$$

The associated variable is the price $p^M_{ir}$ of the import composite $i$ in region $r$.

Carbon emissions

A fixed supply of $CO_2$ emissions limits demand for $CO_2$ emissions in region $r$, effectively establishing a domestic emissions cap-and-trade system. The market-clearance condition for $CO_2$ emissions is [16]:

$$\overline{CO_2}_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial p^{CO_2}_r}$$

**Income-balance conditions**

Income balance

Net income of the representative agent consists of factor income, revenues from $CO_2$ emission pricing, carbon tariffs, import tariffs, and other tax revenues minus subsidies (referred to as $OTS_r$ below) adjusted for expenditure to finance fixed government and investment demand and the base-year balance of payment. The income-balance condition for the representative agent is[17]:

[16] In scenarios where we impose a global emission constraint to accommodate the coherent global cost-effectiveness analysis of unilateral carbon pricing policies the carbon budgets of countries with effective emission reduction commitments is scaled uniformly such that emissions across all regions in the model do not exceed the (exogenous) global emission constraint. In our central case simulations we set the global emission constraint to the global emission level emerging from scenario *Paris.*

[17] For the sake of a more compact algebraic representation, we abstain from the explicit representation of other taxes /subsidies (incl. factor taxes, output taxes, intermediate input taxes, consumption taxes, export duties) and simply denote the (endogenous) net tax revenues with $OTS_r$ in the budget constraint.

$$INC_r = w_r \overline{L}_r + v_r \overline{K}_r + \sum_i q_{ir} \overline{Q}_{ir} - p^Y_{Ir} \overline{Y}_{Ir} - p^Y_{Gr} \overline{Y}_{Gr} + \overline{B}_r + OTS_r$$

$$p_r^{CO_2} \overline{CO_2}_r + \sum_{is} M_{ir} \frac{\partial \Pi^M_{ir}}{\partial \left( \left( p^X_{is} + \epsilon^{CO_2}_{is} p_r^{CO_2} \left(1 + t^M_{isr}\right) \right) \right)} \left( \epsilon^{CO_2}_{is} p_r^{CO_2} + p^X_{is} t^M_{isr} \right)$$

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