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Abstract: This article summarizes insights from the 36th Energy Modeling Forum study (EMF36) on the magnitude and distribution of economic adjustment costs of greenhouse gas emission reduction targets. Under the Paris Agreement, countries have committed to emission reduction targets – so-called Nationally Determined Contributions (NDCs) – in order to combat global warming. The study suggests that aligning NDCs with the commonly agreed 2°C temperature target will induce global economic costs of roughly 1% in 2030. However, these costs are unevenly distributed across regions. Countries exporting fossil fuels are most adversely affected from the transition towards a low-carbon economy. In order to reduce adjustment costs at the global and regional level, comprehensive emissions trading which exploits least-cost abatement options is strongly desirable to avoid contentious normative debates on equitable burden sharing. Lump-sum recycling of revenues from emissions pricing, in equal amounts to every household, appeals as an attractive strategy to mitigate regressive effects and thereby improving the social acceptability of stringent climate policy.

Keywords: Paris Agreement; emissions pricing and trading; revenue recycling
JEL-Classification: D58, H23, Q54, Q58
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1. Introduction

Anthropogenic climate change may cause irreparable harm to the ecosystems on which mankind depends. The international community has recognized the threat represented by man-made climate change since the early 1990s, and called for rigorous abatement of greenhouse gas emissions to prevent "dangerous human interference with the climate system" (UNFCCC, 1994). However, attempts to halt global warming have been met with limited progress so far. One reason is that climate protection constitutes a global public good. Each single country has a strong incentive to benefit from the emission abatement of other countries while cutting back on its own emission reduction to reduce abatement costs. International agreements lack real teeth when it comes to coercing common action since they lack a supranational authority. Another fundamental impediment to climate protection is the asymmetric timing of costs and benefits from emission abatement. While the decarbonization of production and consumption patterns induces economic adjustment costs in the short- and mid-term, most of the benefits of avoided climate damages will will take decades to materialize given the physical inertia of the climate system.

This discrepancy in the time scale of costs and benefits explains why climate policy has historically been dominated by heated debates on the magnitude of emission abatement costs and their distribution. The United Nations Framework Convention on Climate Change (UNFCCC) refers to international burden sharing through the notion of Common but Differentiated Responsibilities (CBDR), where all countries share the obligation to address the threat of climate change but responsibilities differ due to different historical contributions to global emissions and different capabilities. The CBDR principle is reflected in the Kyoto Protocol which placed the focus of greenhouse gas emission reduction on industrialized countries, while developing countries were exempted from binding climate targets. While celebrated as the first international climate treaty to become effective in 2005, the Kyoto Protocol fell short of providing a blueprint for effective climate policy based on common burden sharing. First of all, the US – responsible for a large part of historical greenhouse gas emissions – withdrew from the Kyoto Protocol in 2001. The US government expressed concerns about the domestic compliance costs and feared that other big emitters such as China or India would gain competitive advantage from the Kyoto deal without emission reduction commitments. For similar reasons, Canada ceased to be a Party to the Kyoto Protocol in 2012 and other major industrialized regions such as Japan and Russia indicated that they will not accept new Kyoto-type commitments after the initial five year commitment period ranging from 2008-2012.

Aware of the difficulties of reaching mandatory agreements for industrialized countries only, the Paris Agreement in 2015 marked a major shift in focus. The Paris Agreement sets out a global framework to avoid dangerous climate change with the goal to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. The change in emphasis is twofold. First, the Paris Agreement calls for the contribution of *all* countries to mitigate global warming – not only from industrialized countries as in the case of the Kyoto Protocol. As of December 2020, all 196 members of the UNFCCC have signed the agreement and 189 have become parties.[1] Hence, the Paris Agreement is the first universal, legally binding global climate change agreement. Second, the Paris Agreement marks a shift away from top-down mandated reduction targets towards a bottom-up strategy where individual countries voluntarily commit themselves to Nationally Determined Contributions (NDCs) (UNFCCC, 2020).

The Paris Agreement is celebrated as an international breakthrough to deal with the challenge of global warming in a comprehensive manner. However, individual NDCs submitted so far fall short of aligning emission pathways with the target to limit global warming below 2°C.[2] Recognizing that the initial voluntary pledges are inadequate to achieve the long-term temperature goal of the Paris Agreement, countries are asked to review and revise their NDCs every five years until the collective pledges are deemed sufficient to achieve the objective – with the hope that the effectiveness of the voluntary NDC approach could be fostered by naming and shaming of defaulting countries. Meanwhile, more stringent climate policy actions up to 2030 which are in line with the Paris temperature goal will cause substantially higher economic adjustment costs (Vandyck et al., 2016; Hof et al., 2017).

On critical inspection, the Paris Agreement may not be perceived as a game changer but rather as the acknowledgement that international climate policy critically hinges on voluntary, bottom-up consensual decision making. This insight not only echoes the experience of the preceding Kyoto Protocol but also reflects the limitations limitations met by international negotiators when it comes to feasibility, determined by the domestic political environment: Emission reduction pledges submitted abroad must indeed build on sufficient political support at home. Although the societal awareness of the risks imposed by climate change has grown significantly over the last decade in many countries – not least because of grassroot

[1] The only significant emitters still not parties are Iran and Turkey. The United States announced its withdrawal from the agreement on June 1, 2017 under then-President Donald Trump which took effect on November 4, 2020, one day after the 2020 presidential election, but the nation rejoined the agreement in 2021 immediately after the inauguration of President Joe Biden (Viser et al., 2020; United Nations, 2021).

[2] Several studies including Vrontisi et al. (2018), Fujimori et al. (2016a) and van Soest et al. (2017) find that the NDCs are not in line with the 2°C target.

movements such as Fridays for Future – decision makers are concerned about the adverse economic effects of more stringent climate policies not only on the national economy as a whole, but more specifically on competitiveness for emission-intensive industries and in particular on the economic burden for lower-income households. Concern over the regressive impacts of climate policies across households are well justified. Putting a price on energy or energy-related pollutants such as CO_2 will raise consumer prices for energy goods such as electricity, natural gas, heating oil, or gasoline. Since these goods constitute a larger share of the budget in poor households compared to richer households, higher energy or emission prices tend to be regressive. Even in countries which are seemingly rich on average, populist protests for economic justice have been initially sparked by rising fuel prices – the yellow vests movement in France that started in October 2018 is a case in point.

In this context, the 36th Energy Modeling Forum study on "Carbon Pricing after Paris" (EMF36) is designed to help policymakers chart sensible climate policies which balance the unequivocal need for drastic greenhouse gas emission abatement with normative considerations on fair burden sharing both at the international level but also within domestic boundaries. Our starting point is to take stock of the economic impacts associated with the implementation of the initial NDCs under the Paris Agreement by 2030, thereby focusing on CO_2 emissions from fossil fuel combustion as the major source of anthropogenic greenhouse gas emissions. We assume that individual countries have a vested interest in meeting their domestic emission reduction pledges at minimum compliance costs, and therefore strong impetus to exploit the cheapest abatement options domestically. Cost-effective emission reduction will be achieved by uniform emissions pricing which can be implemented in terms of an economy-wide emissions tax or an emissions cap-and-trade system. We next investigate the question of how the magnitude and regional distribution of economic adjustment costs changes as we transit towards more ambitious emission reduction targets, ultimately aligning the current NDCs by 2030 with the long-run 2°C temperature goal. Starting from this reference situation, our primary objective is to sketch the design of climate policies associated with lower economic costs for emission reduction at the international and domestic level and thereby help to increase the likelihood of reaching the ambitious Paris temperature targets through collective action. Economic theory provides fundamental guidelines which can be translated into tangible numbers by means of applied economic analysis, such as the EMF36 study. The first fundamental guideline is to exploit efficiency gains from where-flexibility at the international level. Since greenhouse gas emissions are a global externality it does not matter where emissions are reduced, as long as they are removed from the atmosphere. Cost-effective global climate policy then implies to abate greenhouse gases where it is the cheapest, i.e., to equate the costs of abatement at the margin across all abatement options. Basic economic theory suggests that NDC parties should strive for uniform global emissions pricing through international trade in emission pledges. The EU emissions trading system, which started 2005, provides a landmark for cost-efficient where-flexibility in abatement across multiple countries. There is widespread evidence of substantial cost savings from emissions trading, both at the level of subnational as well as multilateral jurisdictions (Weyant and Hill, 1999; Metcalf, 2009; Böhringer et al., 2009; Akimoto et al., 2017; Fujimori et al., 2016b). The second guideline is that emissions pricing creates revenues of which recycling can drastically affect the overall incidence of emission reduction policies (Fullerton and Muehlegger, 2019). More specifically, economic theory suggests that lump-sum recycling of revenues from emissions pricing to households can more than compensate the regressive effects of emissions pricing (Chiroleu-Assouline and Fodha, 2014; Klenert and Mattauch, 2016). Indeed, since each household receives an equal share of revenues, the lump-sum transfer constitutes a larger share of additional disposable income for lower-income households; if sufficiently high, the transfers can mitigate or even overcompensate initially regressive effects of emissions pricing.

The EMF36 study provides quantitative insights into the magnitude and distribution of Post-Paris climate policy designs up to 2030, paying special attention to the role of where-flexibility and revenue recycling for making stringent emission reduction politically feasible. Based on simulations with several established energy-economy models operated by internationally recognized experts, our key findings are as follows. First, narrowing the NDCs towards 2030 in line with the 2°C temperature target will induce global economic adjustment costs of roughly 1% by 2030 relative to a business-as-usual case. Across regions, countries exporting fossil fuels are most adversely affected from the transition towards a low-carbon economy. Second, international emissions trading can substantially reduce adjustment costs at the global and regional level, thereby reducing the propensity for contentious normative debates on equitable burden sharing. Global cost savings from comprehensive global emissions trading as compared to only domestic action range from 50-90% depending on the stringency of the NDC pledges. Third, lump-sum revenue recycling in equal shares to households offsets the regressive effects of emissions pricing which might be crucial to improve the social acceptability of more ambitious climate policy.

Our main findings can be summarized in a climate policy triad of 'Pledge, Trade, and Recycle': To achieve the Paris temperature target, more ambitious reduction pledges are necessary in the short-term. Their political feasibility will hinge on cost reductions through international emissions trading and progressive revenue recycling at the domestic level.

The remainder of this article is organized as follows. Section 2 lays out the study design with respect to key research questions and specific policy scenarios to be shared across all modeling groups. Section 3 presents a cross-comparison of model results. Section 4 concludes.

2. Study design

Our analysis is based on a systematic cross-comparison of results from 17 internationally established energy-economy models – 15 multi-region models and two single-country models – which simulate pre-defined policy scenarios with harmonized assumptions. Table 1 provides a summary of the groups participating in the model-comparison study, their models, institutions, and people involved.

Hereafter we briefly discuss model characteristics and data inputs. We then lay out and motivate the policy scenarios that are investigated in the model-cross comparison.

2.1. Models and data

All models that participate in the cross-comparison are computable general equilibrium (CGE) models. CGE models constitute a powerful numerical simulation method to perform economy-wide impact assessments of policy reforms based on microeconomic theory and empirical data. More specifically, CGE models are rooted in general equilibrium theory that combines assumptions regarding the optimizing behavior of economic agents with the analysis of equilibrium conditions (Shoven and Whalley, 1992). Producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers maximize their well-being subject to budget constraints and preferences. Substitution and transformation possibilities in production and consumption are typically described by means of continuous functional forms where economic responses are driven by empirical estimates of elasticities and initial value shares derived from empirical economic accounts.

A key strength of CGE models is their comprehensive coverage of market interactions through price and income-responsive supply and demand reactions on behalf of economic agents. The disaggregation of macroeconomic production, consumption, and trade activities at the sector level based on regional input–output matrices

Table 1: Expert teams participating in the EMF36 model comparison study

Model	Institution	People
CEPE	ETH Zürich	Florian Landis, Gustav Fredriksson, Sebastian Rausch
ICES	Euro-Mediterranean Center on Climate Change (CMCC)	Ramiro Parrado
DART Kiel	Kiel Institute for the World Economy (IfW)	Sonja Peterson, Malte Winkler, Sneha Thube
DREAM	Fudan University	Haoqi Qian, Shuaishuai Zhang, Libo Wu
EC-MSMR	Environment and Climate Change Canada	Nick Macaluso, Peter Johnston, Madanmohan Ghosh, Elisabeth Gilmore
EDF-GEPA	Environmental Defense Fund (EDF)	Gökçe Akin-Olçum, Ruben Lubowski, Margaret McCallister
JRC-GEM-E3	Joint Research Center (JRC), Sevilla - EU Commission	Toon Vandyck, Matthias Weitzel, Krzysztof Wojtowicz, Luis Rey Los Santos, Anamaria Maftei, Sara Riscado
ENVISAGE	Purdue University	Maksym Chepeliev, Israel Osario-Rodarte, Dominique van der Mensbrugghe
SNoW	Statistics Norway	Taran Fæhn, Hidemichi Yonezawa
TEA	COPPE - Universidade Federal do Rio de Janeiro (UFRJ)	Rafael Garaffa, Bruno Cunha, Talita Cruz, Paula Bezerra, André Lucena, Angelo Gurgel
TUB	TU Berlin	Mohammad M. Khabbazan, Christian von Hirschhausen
C-GEM	Tsinghua University	Duan Maosheng, Li Mengyu
UOL	University of Oldenburg	Christoph Böhringer, Jan Schneider
WEGDYN	Wegener Center for Climate and Global Change - University of Graz	Jakob Mayer, Anna Dugan, Gabriel Bachner, Karl Steininger
PACE	Zentrum für Europäische Wirtschaftsforschung (ZEW)	Sebastian Rausch
IEG*	Institute of Economic Growth India (IEG)	Basanta Pradhan, Joydeep Ghosh
BC3*	Basque Centre for Climate Change (BC3)	Xaquín Garcia Muros, Jennifer Morris, Sergey Paltsev

* Single-country model.

enables to track structural change.

Policy reforms such as CO_2 pricing do not only affect the prices of consumer goods, but also sources of income, such as wages and returns to capital. Compared to partial equilibrium approaches as bottom-up energy system models or microsimulation models for instance, CGE models do not only capture the incidence of changes in relative prices on the expenditure side but also on the income side. With an explicit representation of different economic agents such as firms, households, and governments, CGE models can quantify the distributional impacts of policy measures.

To summarize: CGE models incorporate key dimensions of economy-wide impact assessment in a micro-consistent framework, thereby accommodating a systematic quantitative trade-off analysis between policy objectives for economic performance, income distribution, and environmental quality.

As is customary in applied general equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of functional forms. For base-year calibration all models of the EMF36 study share input data of the Global Trade Analysis Project (GTAP) database which includes detailed accounts of production, consumption, bilateral trade, as well as data on physical energy flows and CO_2 emissions for up to 141 regions and 65 sectors (Aguiar et al., 2019, 2016; Chepeliev, 2020; Peters, 2016). As discussed below, the business-as-usual projection of the models towards 2030 is based on common data inputs from the International Energy Outlook (IEO) 2017 (EIA, 2017) and the World Energy Outlook (WEO) 2018 (IEA, 2018), respectively.

The regions and sectors of the GTAP dataset are aggregated towards the specific requirements of the EMF study. With respect to regional coverage, the composite dataset includes major industrialized and developing regions which play a key role in the international climate policy negotiations. With respect to sectoral coverage, the composite dataset maintains all primary and secondary energy carriers in GTAP: coal, crude oil, natural gas, refined oil products, and electricity. The explicit treatment of these primary and secondary energy carriers is essential in order to distinguish energy goods by CO_2 intensity and the degree of substitutability (fuel switching). In addition, we incorporate a composite sector for energy-intensive and trade-exposed industries (EITE) which are most vulnerable to emissions pricing. The remaining sectors of the GTAP dataset are categorized in four additional composite sectors: transport, agriculture, other manufacturing, and services.

Table 2 lists the set of regions and sectors (commodities) that are covered by all models to warrant a coherent cross-comparison of results.

2.2. Scenarios

The primary objective of our analysis is to quantify the medium-term economic impacts of CO_2 pricing in the aftermath of the Paris Agreement for alternative NDC ambition levels and for different degrees of international cooperation through emissions trading. We take 2030 as the policy-relevant target year for the impact assessment which constitutes the milestone to which most Paris parties have submitted their first-round NDCs.

Against this background, we devise the EMF36 core scenarios along two dimensions which are critical for the magnitude and distribution of economic adjustment costs to Post-Paris climate policies: (i) the stringency of future NDCs (ambition), and (ii) the scope of international emissions trading across sectors and regions (co-

Table 2: EMF36 sectors and regions

Countries and regions	Sectors
Countries	*Energy*
United States (USA)	Coal
Canada (CAN)	Petroleum and coal products
Japan (JPN)	Crude oil
South Korea (KOR)	Natural gas
Russia (RUS)	Electricity
China (CHN)	*Other sectors/aggregates*
India (IND)	Energy-intensive and trade-exposed (EITE)**
Brazil (BRA)	Transport
Aggregated regions	Agriculture
Australia and New Zealand (ANZ)	Other manufacturing
Europe (EUR)*	Services
Middle East (MEA)	
Africa (AFR)	
Other Americas (OAM)	
Other Asia (OAS)	

* Includes EU27 + UK + EFTA members.
** Includes chemical products; basic pharmaceutical products; rubber and plastic products; non-metallic minerals; mining of metal ores; iron and steel; non-ferrous metals; paper, pulp, and print.

operation). Table 5 at the end of this section presents an overview of the fifteen core scenarios that emerge as the cross-product of the two scenario dimensions for three NDC variants and five emissions trading variants.

The default policy instrument to achieve emission reduction is emissions pricing which can be equally implemented via an emissions tax or an emissions cap-and-trade system. To address public concerns on the regressive impacts of emissions pricing, revenues are recycled lump-sum to the consumers. A subgroup of models (see Table 3) distinguishes consumers by income deciles and investigates the extent to which the progressive effect of an equal-per-household rebate offsets the regressive effect of higher energy prices.[3,4] CO_2 revenues are recycled lump-sump in equal shares to households. Since CO_2 pricing typically depresses other government tax revenues, we adopt the convention that the government recycles the remaining CO_2 revenues after balancing its budget in order to keep government expenditures constant.

[3] The single-country models BC3 and IEG use business-as-usual projections and CO_2 emission reduction targets for the countries under investigation (BC3 – Spain; IEG – India) which are in line with our specifications in Sections 2.2.1 and 2.2.2.

[4] The CEPE modeling group's analysis is based on household-level data from Eurostat's 2010 Household Budget Survey (HBS) and Eurostat's 2010 European Union Statistics on Income and Living Conditions (EU-SILC). The responsibility for all conclusions drawn from these data lies entirely with the CEPE modeling group. The results and conclusions are solely those of the CEPE modeling group, and not those of Eurostat, the European Commission or any of the national statistical authorities whose data have been used.

Table 3: Models with household impact analysis

Model	**Specification**	**Specific country**
BC3	Single-country	Spain
IEG	Single-country	India
TEA	Multi-region	Brazil
CEPE	Multi-region	Belgium, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Poland, Portugal, Slovakia, Slovenia, Spain, United Kingdom, Bulgaria, Croatia, Romania
JRC-GEM-E3	Multi-region + soft-link*	Austria, Belgium, Czech Republic, Germany, Estonia, Greece, Spain, Finland, France, Italy, Romania
SNoW	Multi-region	Norway
DREAM	Multi-region	China
UOL	Multi-region	Germany

* JRC-GEM-E3 feeds its macroeconomic results for 11 European countries into the EUROMOD-ITT (Indirect Tax Tool) in order to perform the household impact assessment.

The impacts of a policy reform (in our case: the implementation of NDCs) are usually quantified with respect to a reference situation where the reform is not in place, the so-called business-as-usual (BaU). Comparative-static analysis then provides a comparison of two different economic situations, before and after a change in specific exogenous parameters such as the imposition of emission reduction pledges. If policy targets and measures refer to the future there is the need to establish a business-as-usual projection which captures the hypothetical evolution of the economy in the absence of these targets and measures. In the following, we describe our business-as-usual assumptions and subsequently lay out the two core scenario dimensions, i.e., the ambition level of NDCs and the degree of cooperation in multilateral climate policies through international emissions trading.

2.2.1. Business-as-usual (BaU) projections

The costs of complying with future emission constraints are directly linked to the structural characteristics of an economy exhibited in a hypothetical business-as-usual (BaU) situation without such emission constraints (Dellink et al., 2020). The BaU projections do not only determine the magnitude of the effective abatement requirement, i.e.,the difference between the future business-as-usual emissions and the exogenous emission ceiling, but also the ease of emission abatement as reflected by the curvature of marginal abatement cost curves.

Due to the importance of BaU projections for the economic impact assessment of future climate policy constraints, we perform sensitivity analysis with respect to assumptions on future GDP growth and CO_2 emissions in 2030 from two official, widely-used sources: the International Energy Outlook (IEO) 2017 (EIA, 2017) and the World Energy Outlook (WEO) 2018 (IEA, 2018).

Table 4 shows the CO_2 emissions and GDP values for 2011 which, based on the GTAP data, serve as the historical base-year for the model study together with the respective growth indices up to 2030 that are derived from the IEO and WEO projections.

Table 4: BaU projections on CO_2 and GDP in 2030

Region	**CO_2**			**GDP**		
	2011	2030		2011	2030	
		IEO	WEO		IEO	WEO
	Mt of CO_2	2011=1	2011=1	billion USD	2011=1	2011=1
United States (USA)	5107	0.89	0.90	15533	1.51	1.46
Canada (CAN)	523	1.08	1.02	1778	1.38	1.45
Japan (JPN)	1028	0.90	0.80	5905	1.13	1.18
South Korea (KOR)	501	1.20	1.44	1202	1.57	2.14
Russia (RUS)	1503	0.95	1.05	1904	1.26	1.33
China (CHN)	7098	1.14	1.28	7567	2.72	2.92
India (IND)	1771	1.86	2.47	1880	3.01	3.80
Brazil (BRA)	372	1.25	1.19	2476	1.32	1.39
Australia & New Zealand (ANZ)	411	1.10	1.32	1550	1.64	2.14
Europe (EUR)	4211	0.89	0.80	19182	1.29	1.34
Middle East (MEA)	1808	1.28	1.29	3372	1.74	1.77
Africa (AFR)	952	1.33	1.40	2076	1.98	2.00
Other Americas (OAM)	1167	1.15	1.12	3471	1.60	1.55
Other Asia (OAS)	2128	1.48	1.70	3569	2.07	2.31

2.2.2. Nationally Determined Contributions (NDCs)

We use the initial NDCs submitted by the Paris parties to the UNFCCC (UNFCCC, 2020) to derive three different ambition levels for emission reductions – referred to as *NDC*, *NDC+*, and *NDC-2C*.

Our starting point are the NDCs under the Paris Agreement as listed in Kitous et al. (2016). Various countries have provided two different pledges – unconditional pledges which we label as *NDC* and more ambitious pledges that are conditional on reduction efforts of other regions which we label as *NDC+*. We translate these NDCs into region-specific reduction requirements for CO_2 emissions from fossil fuel combustion in percent from the 2030 business-as-usual emission levels projected by IEO and WEO.[5] Given that total emission reduction pledges even for the more am-

[5]Note that we impose a minimum reduction target of 5% for countries that state their NDCs as

bitious *NDC+* fall substantially short of what is deemed to be necessary in 2030 for meeting the long-run Paris temperature goal, we construct a third ambition level – called *NDC-2C*. For the *NDC-2C* targets we scale emission levels in *NDC+* uniformly across regions in order to comply with an emission reduction for 2030 compliant with the 2°C emission trajectory suggested by integrated assessment analysis.[6]

Figure 1 visualizes the region-specific reduction targets across the three ambition levels with respect to BaU emissions projected by IEO and WEO. The blue bars represent reduction targets under *NDC*, and the orange and green incremental bars illustrate the additional reduction requirements under *NDC+* and *NDC-2C*, respectively. For regions without an orange incremental bar, *NDC* and *NDC+* are identical.

Global reduction requirements are of roughly 10% for *NDC* and 12% for *NDC+* compared to the BaU projections. For a 2°C emission trajectory (*NDC-2C*), the global reduction requirement is of 27% for the BaU based on WEO and 21% for the BaU based on IEO. The difference is primarily due to higher projected CO_2 emissions growth in China and India in WEO as compared to IEO. Our budget approach for *NDC-2C* where we scale to a given level of global emissions then implies a higher reduction requirement against WEO than IEO projections.

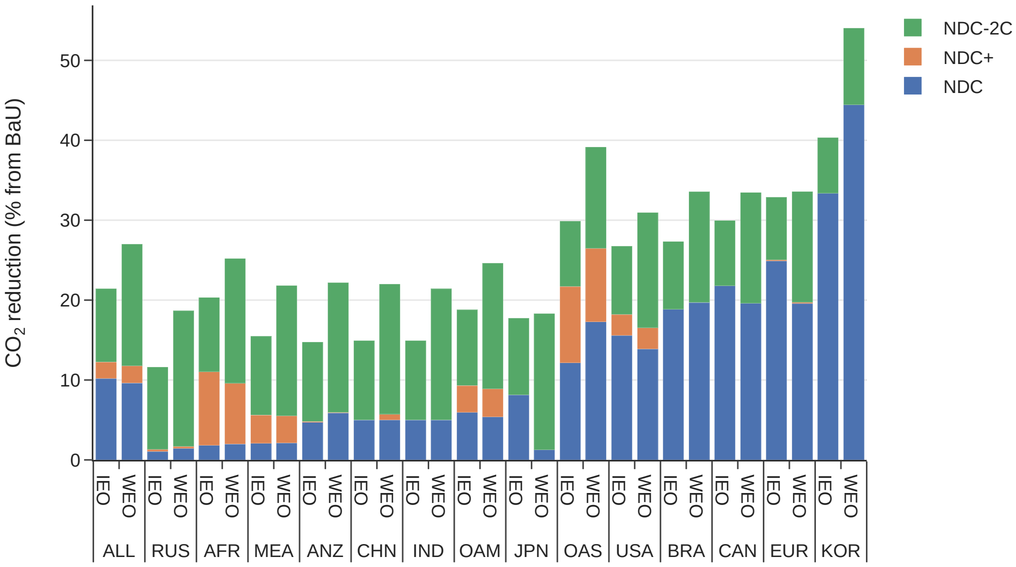
Compared to global average reduction requirements we see that Africa, Middle East, and Russia have rather low reduction targets under *NDC*, while Brazil, Canada, Europe, and South Korea have substantially stricter targets. The consideration of conditional targets (*NDC+*) primarily plays a role in Africa, Middle East, as well as Other Americas and Other Asia.

A region generally faces a higher reduction target against that BaU – WEO or IEO – which projects higher CO_2 emissions for the respective region in 2030. For example, Europe has an effective target of 25% against IEO projections and of 20% against WEO projections, whereas South Korea faces a higher reduction target against WEO projections.

an emission intensity target assuming that such a target will lead to some degree of effective CO_2 pricing, even if BaU projections suggest that targets are reached without CO_2 pricing. These minimum targets are binding for China and India against both BaU projections, such that they have the same reduction targets of 5% under *NDC* despite different CO_2 emission projections in IEO and WEO. For countries that state their target as a physical emission level (e.g. by specifying an own BaU emission path), we translate this emission level into effective reduction targets against the IEO and WEO BaUs. For more details on the derivation of BaU projections and NDCs, see Appendix A.

[6] We use an average value for reductions in global CO_2 emissions from energy use in 2030 compared to 2011 in 2°C scenarios derived from data provided by the IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (Huppmann et al., 2019).

Figure 1: Reduction targets for CO_2 emissions from fossil fuel combustion for different ambition levels (in % from 2030 BaU projections based on IEO or WEO)



Note—. ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

2.2.3. International emissions trading

Our second scenario dimension considers five different degrees of international cooperation via emissions trading across sectors and regions. On the one extreme (*ref*), we assume that there is no international emissions trading at all, i.e., regions meet their reduction targets by strictly domestic emissions pricing.[7] On the other extreme (*global*), we assume full where-flexibility such that there is only one global emission price applying to all sectors and regions. In between the two polar cases, we specify three intermediate cases that sketch more likely variants of cross-country cooperation in coordinating abatement efforts via joint emission markets. The variant *partial* prescribes emissions trading only in energy-intensive and trade-exposed (EITE) sectors (as well as the power sector) where stakeholders are most concerned on adverse impacts of stringent emission constraints.[8] In this case, regional CO_2 emissions in other sectors are kept at *ref* levels. Furthermore, we set up two "Club-Trading" cases which might occur within the next few years: Variant *eur-chn* considers emissions trading between Europe and China while variant *asia* considers emissions trading between China, Japan, and South Korea. For both "Club-Trading" cases, we assume partial trading across sectors, i.e. there is a joint emission market for EITE and power sectors, while all other sectors face a domestic emission constraint set at the *ref* emission level. Note that across all where-flexibility specifications, global emissions remain constant at the same level warranting a coherent cost-effectiveness analysis.

We denote specific scenarios composed of one ambition level and one international cooperation variant with their respective acronyms separated by a slash ("/"). For example, the scenario where regions implement their unconditional nationally determined contributions domestically without international emissions trading is labelled *NDC/ref*. We also refer to scenario *NDC/ref* as the central case, since it describes the status quo of the Paris Agreement.

[7] Note that composite regions reach their reduction targets through one overall emissions budget constraint, i.e., implicitly we assume that there is emissions trading within composite regions.

[8] These sectors are also covered in existing national and supranational emissions trading schemes such as the EU emissions trading scheme.

Table 5: EMF36 core scenarios

Acronyms	Description
Ambition	
NDC	Translation of unconditional nationally determined contributions
NDC+	Translation of conditional nationally determined contributions
NDC-2C	Scaling of *NDC+* emission levels to reach 2°C temperature goal
Cooperation	
ref	Reference case where each region reaches its reduction target without further international emissions trading
global	Emissions trading across all regions and sectors
partial	Emissions trading across all regions in EITE and power sectors
eur-chn	Emissions trading between Europe and China in EITE and power sectors
asia	Emissions trading between China, Japan and South Korea in EITE and power sectors

3. Results

We focus on results for the year 2030 and begin our presentation with global (average) CO_2 prices and global welfare impacts. Subsequently, we discuss regional effects, before summarizing findings on welfare implications of equal-per-household revenue-recycling across income deciles.

CO_2 prices are measured in 2011-USD per tCO_2. Welfare changes are measured in terms of Hicksian equivalent variation (HEV) in income denoting the amount of money that is necessary to add to or deduct from the BaU income of households so that they enjoy a utility level equal to the one in the counterfactual policy scenario on the basis of BaU prices. A negative HEV hence indicates a welfare loss as compared to the BaU welfare. We aggregate welfare results from a utilitarian welfare perspective, that is, we adopt an agnostic position regarding cost distribution across regions when exposing global welfare results, and regarding cost distribution across households when exposing regional welfare results. Across all scenarios, we do not account for the (monetized) benefits from avoided climate damages acknowledging the wide spread of estimates on the social cost of carbon. Thus, negative welfare impacts must be interpreted as gross economic adjustment costs to emission reductions from BaU and can not be taken as an indicator for the desirability of emission reductions from a more comprehensive cost-benefit perspective. Global emission levels are constant across the different emissions trading variants such that we can perform meaningful global cost-effectiveness analysis at each respective ambition level *NDC*, *NDC+*, and *NDC-2C*. Note that our reduction targets relate to CO_2 emissions from fossil fuel combustion only, which is by far the most important source for greenhouse gas emissions.

Since important parameterizations are streamlined in common assumptions in the business-as-usual and the counterfactual climate policy scenarios, variations across models can be explained to a large extent by structural differences across models that capture the price responsiveness of production, consumption, and trade to CO_2 emission constraints. These differences drive the marginal and inframarginal costs of the represented economies to substitute away from carbon-intensive inputs. The abatement options include fuel switching, substitution of energy with non-energy inputs (energy efficiency), as well as output and demand reductions (energy savings). The costs of different abatement options are governed by cross-price elasticities and cost shares between various energy goods with different CO_2 intensities, as well as between energy and non-energy goods. Other important drivers of economic impacts triggered by emission constraints include the representation of existing or anticipated climate policies and assumptions about future international energy prices or technological change with respect to carbon and energy efficiency, that are employed to meet the streamlined regional GDP values and CO_2 emissions in the 2030 BaU projections. All these choices translate into model-specific marginal abatement cost (MAC) curves that provide a first-round approximation on the direct costs of emission abatement as the area under the MAC curve. The MAC curves are convex, indicating that it gets increasingly more expensive to abate the next unit of CO_2 as we decarbonize the economy. With the option for emissions trading the direct adjustment costs to domestic emission constraints will be adjusted by cost savings through exports or imports of emission allowances. Furthermore – as captured in a general equilibrium framework – there are potentially important income effects, most notably via policy-driven changes in international prices, the so-called terms of trade, that will increase or decrease the initial direct costs of emission restrictions depending on the structural characteristics of a specific economy in international trade.

In our exposition of the results, we focus on policy-induced changes from the BaU projection by IEO, and point to differences in results as compared to the BaU projection by WEO where relevant.

3.1. Global impacts

We report global impacts for the two polar cases in emissions trading, *ref* and *global*, across the three different ambition levels in emission reductions *NDC*, *NDC+*, and *NDC-2C*. The resulting six scenarios comprise the full range on where-flexibility in emissions trading and on the stringency in emission reductions. On the low-cost end we have the combination of least ambitious emission reduction targets (*NDC*) and full where-flexibility (*global*). On the high-cost end we have the most ambitious emission reduction targets (*NDC-2C*) and a purely domestic implementation (*ref*) which does not exploit cost savings from international emissions trading.

Figure 2 shows the global average CO_2 prices in *ref* and *global* for the different ambition levels. In *ref* this refers to the emission-weighted average across regional CO_2 prices, whereas in *global* it refers to the globally uniform (tradable) CO_2 price.

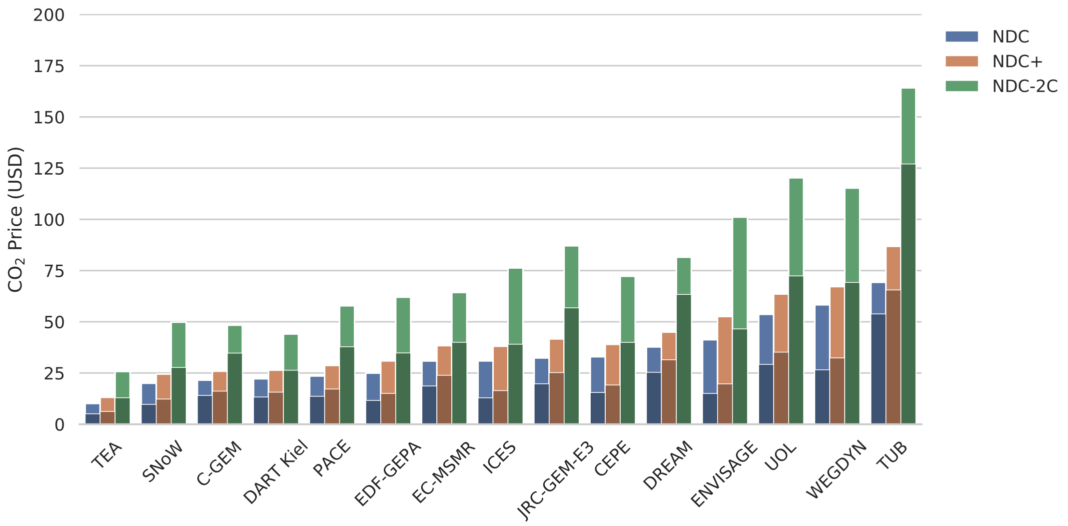
We first focus on *ref*, where regions implement their reduction targets domestically without international emissions trading. As expected, the global average CO_2 price increases with the ambition level reflecting the monotonicity of regional MAC curves. In the central case (*NDC/ref*), we find a range of 10 USD per tCO_2 to 69 USD, with a mean of 33 USD. For the most ambitious reduction targets in *NDC-2C/ref*, global average prices range from 26 USD per tCO_2 to 164 USD with a mean across models of 78 USD. These results are consistent with the range of findings of the High Level Commission on carbon pricing which "concludes that the explicit carbon-price level consistent with achieving the Paris temperature target is at least [..] USD 50–100/tCO_2 by 2030" (Stiglitz et al., 2017).

Considering comprehensive global emissions trading, note that for each ambition level, the global average CO_2 price is necessarily lower in *global* compared to *ref* and the wedge between the two prices indicates cost-saving potentials.[9] We find that moving to *global* roughly halves the required (then globally uniform) CO_2 price in most models.

Figure 3 shows the global welfare impacts in *ref* and *global* for the three different ambition levels on emission reduction *NDC*, *NDC+*, and *NDC-2C*. We find that at the global level welfare effects roughly mirror the results for CO_2 prices, where higher CO_2 prices correspond to higher economic adjustment costs. Under *NDC/ref*, we find a range of 0.07% up to 0.8%, and a mean of 0.43% for the global economic adjustment costs compared to the BaU. Under more restrictive emission caps that are in line with a 2°C path in 2030 (*NDC-2C*) global adjustment costs in most

[9]This is the case because for each ambition level the global emission reduction is the same in *ref* and *global*, but in *ref* marginal abatement costs (CO_2 prices) differ across regions. Given convex MAC curves, the emission-weighted average in *ref* must be higher than in *global*.

Figure 2: Global average CO_2 prices for three different ambition levels (*NDC*, *NDC+*, *NDC-2C*) and two polar cases of emissions trading (*ref*, *global*)



Note—. The lighter shaded bars represent CO_2 prices in *ref*. The darker shaded bars represent CO_2 prices in *global*.

models more than double, ranging from 0.16% to 1.84%, with a mean of 0.94%.[10] From a global perspective, *NDC+* leads to very similar adjustment costs as *NDC*, reflecting that conditional Paris pledges by individual regions only lead to roughly 2% additional global emission reduction compared to unconditional pledges.

Comprehensive international emissions trading (*global*) provides substantial global cost savings of 50%-90% in most models. The mean global welfare loss is 0.15% in *NDC/global* and 0.47% in *NDC-2C/global*.[11] Welfare gains through global emissions trading thereby increase with the stringency of the reduction targets. Under the actual Paris pledges (*NDC*) moving from *ref* to *global* increases global welfare on average by 0.28%. For the most stringent reduction targets under *NDC-2C*, this figure is 0.47%.[12,13]

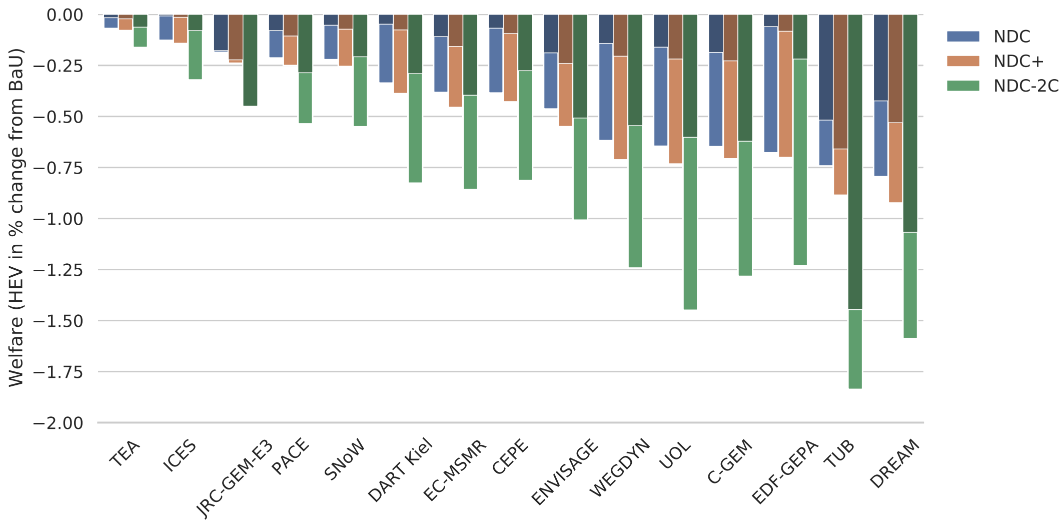
[10] This amounts to additional global costs in *NDC-2C/ref* of 0.5% percentage points compared to the central case (*NDC/ref*). For the alternative BaU based on WEO projections we find average global economic adjustment costs of 0.36% (*NDC/ref*) and 1.2% (*NDC-2C/ref*), which corresponds to slightly lower global reduction requirements under *NDC*, and to higher reduction requirements under *NDC-2C* (see Figure 1). The additional global adjustment costs thus amount to 0.84% percentage points.

[11] Note that we implicitly assume emissions trading in composite regions even in *ref*, compare footnote 7, meaning that our results provide lower bound estimates for the cost-saving potential of where-flexibility.

[12] As a subtlety it should be noted that cost savings from comprehensive international emissions trading tend to decrease in relative terms, i.e. as a fraction of *ref* adjustment costs with higher ambition levels. The logic behind is that it becomes increasingly expensive to substitute away from carbon when production and consumption patterns are getting less carbon intensive.

[13] TUB and DREAM find considerably lower cost savings from trading as indicated by their rather small CO_2 price wedges between *ref* and *global*, while JRC-GEM-E3 finds almost no differences

Figure 3: Global welfare effects for three different ambition levels (*NDC*, *NDC+*, *NDC-2C*) and two polar cases of emissions trading (*ref*, *global*)



Note—. The lighter shaded bars represent welfare changes in *ref*. The darker shaded bars represent welfare changes in *global*.

A policy-relevant message arises from the comparison between *NDC/ref*, which depicts the status quo of the Paris Agreement, and (*NDC-2C/global*). In most models, the global adjustment costs for *NDC-2C/global* are quite similar to the costs of *NDC/ref*. This gets reflected in the mean global adjustment costs, which are 0.43% in scenario *NDC/ref*, and 0.47% in *NDC-2C/global*. The key message here is that – from a global welfare perspective – the actual reduction pledges under the Paris Agreement can be ratcheted up roughly cost-neutrally towards much more stringent pledges in line with the 2°C temperature goal if at the same time the where-flexibility through international cooperation towards globally uniform CO_2 emissions pricing is fostered.[14] Hence, cost savings through where-flexibility pay the bill for a more ambitious international climate policy.

For the intermediate cases of where-flexibility *eur-chn*, *asia*, and *partial* (omitted in Figure 3 for the sake of clarity) most models prompt a ranking in terms of global welfare impacts that roughly mirrors the share of global CO_2 emissions eligible for international trading. In *global* the share by definition amounts to 100%, in *partial* to around 55%, in *eur-chn* to 25%, and in *asia* to around 20%.

between the reference case and full trading from a global perspective. Note that the JRC-GEM-E3 model incorporates lock-in effects in power generation technologies that might lead to second-best emission abatement choices.

[14] This finding becomes weaker in the BaU based on projections from WEO. Here, global adjustment costs are on average 1.8 times higher in *NDC-2C/global* compared to *NDC/ref*, see also footnote 10.

3.2. Regional incidence

Welfare effects at the regional level are driven by two effects. First, regions face abatement costs in line with their emission reduction targets and abatement options that are reflected in the regions' CO_2 prices (marginal abatement costs). Second, regions are subject to indirect spillover effects due to policy-induced price changes on international markets – i.e., terms-of-trade effects – both for energy and non-energy goods. Fossil fuel demand and thus fossil fuel prices decline under emissions pricing, which benefits fuel importers and hurts fuel exporters. Production costs for energy- and trade-exposed (EITE) goods increase due to emissions pricing. This does not only affect changes in comparative advantage, but the heterogeneous nature (imperfect substitutability) of traded commodities makes it possible for EITE exporters to pass through part of their domestic abatement costs via higher prices to the respective importers.

Variations across models can be traced back to modeling choices that govern the magnitude of these effects. Direct abatement costs are driven by the shape of the MAC curves that are in turn determined by cost and expenditure shares in production and consumption and the cross-price elasticities of substitution across production inputs and consumption goods. International spillovers are driven by cost shares and elasticities in international trade, which determine the ease of substitution away from more expensive imported goods in domestic production and consumption; terms-of-trade effects on international fuel markets are governed to a larger extent through the choice of supply elasticities in fossil fuel production.

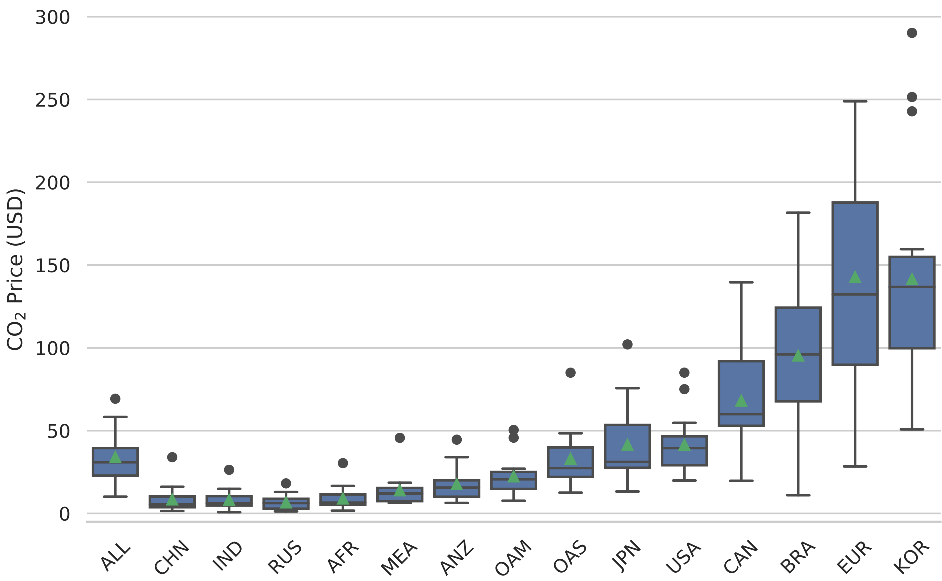
We begin our exposition of regional effects with the status quo of the Paris Agreement where regions implement their Paris emission reduction pledges without further international emissions trading (scenario *NDC/ref*). We then explore implications of increasing the ambition level and the degree of international cooperation.

3.2.1. Regional compliance with Paris pledges

Figure 4 shows a summary of regional CO_2 prices (marginal abatement costs), which depend on the effective reduction targets shown in Figure 1 and the regions' abatement abilities. As expected, regions with higher reduction targets face higher CO_2 prices. More specifically, the regions with the highest reduction targets (Brazil, Canada, Europe, and South Korea) also face the highest CO_2 prices, while regions with lower targets like Africa, China, India, the Middle East, and Russia exhibit low CO_2 prices.

Figure 5 shows a summary of regional welfare impacts across models. We find that

Figure 4: Regional CO_2 prices in *NDC/ref*



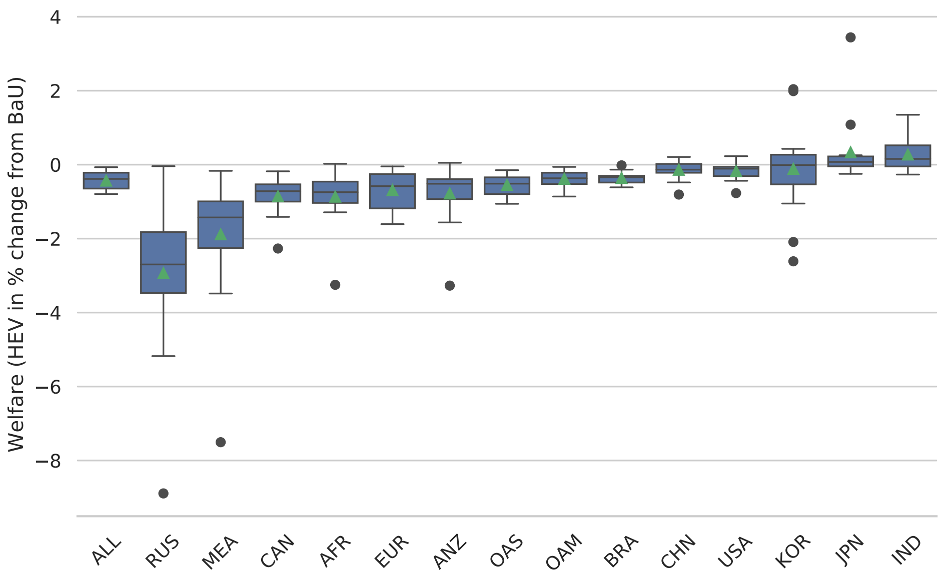
Note.—Box-Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Dots indicate outliers. Region keys: ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

direct abatement costs from compliance with the reduction target as inferred from the regional CO_2 prices (Figure 4) are strongly outweighed by terms-of-trade effects largely transmitted via changes in international fuel prices.[15] Individual regions may even benefit from emission reduction constraints. This is the case for India and Japan as large importers of fuels, where terms-of-trade gains more than offset the direct costs of emission abatement. The major share of the burden of global emission reductions falls on the fuel exporting regions Middle East and Russia, although both regions have relatively low reduction targets and associated CO_2 prices.

An interesting example showcasing the two effects driving regional adjustment costs is South Korea, where outcomes range from more than 2% gain in welfare to a loss of 2.6%. South Korea has the highest effective reduction target among all regions (33%, see Figure 1), leading to relatively high direct abatement costs. At the same time, South Korea is a fossil fuel importer, profiting from declining fuel prices, and an exporter of EITE goods. Which of these effects is dominating differs across models due to differences in the structure of the BaU economies and the choice of elasticities.

[15] Note that all participating models implement international trade based on the standard assumption of product heterogeneity (Armington, 1969), which gives rise to substantial terms-of-trade effects when parameterized with empirical estimates of trade elasticities (Balistreri et al., 2018).

Figure 5: Regional welfare across all models in *NDC/ref*



Note.—Box-Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Dots indicate outliers. Region keys: ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

We observe more heterogeneity across models on the regional level than on the global level. The cross-model variation in welfare is especially large for regions which have the most ambitious climate targets and regions where international feedback effects play an important role. The largest divergence is found for Russia and Middle East as large exporters of fossil fuels. However, South Korea and Europe, with strict targets and large imports of fossil fuels also show a huge variation.[16]

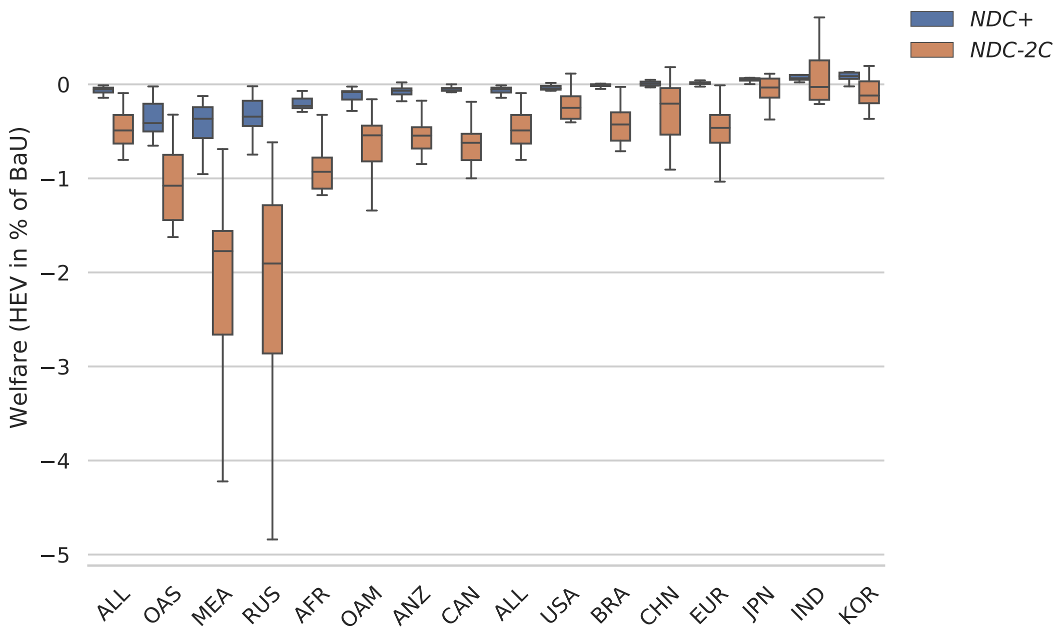
3.2.2. Ambition level and international cooperation

Figure 6 summarizes how regional welfare is affected as we move towards higher ambition levels *NDC+* and *NDC-2C*. Welfare effects are stated in percentage points from the respective values in *NDC/ref*.[17] Note that we still assume compliance via strictly domestic action, i.e., no international emissions trading. We observe that the difference between *NDC* and *NDC+* is rather small for most regions. For regions

[16] For most regions the alternative BaU based on WEO projections entails rather similar welfare impacts. Europe is better off under the WEO projections due to the lower effective emission reduction requirement (see Figure 1). That in turn slightly benefits Russia, as European oil and gas imports drop less. Only for South Korea is the incidence sharply more pronounced, as its effective reduction requirement is higher, and at the same time international oil and gas prices decline slightly less.

[17] As an example, a value of 1% would indicate that the region is better off by one percentage point measured in BaU welfare compared to the *NDC* case.

Figure 6: Differences in regional welfare under ambition levels *NDC+* and *NDC-2C* compared to *NDC* without emissions trading (*ref*)



Note.—Box-Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers omitted.
Region keys: ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

that step up their emission reduction pledges markedly in *NDC+* – Africa, Middle East, Other Americas and Other Asia – welfare declines; also fossil fuel exporters suffer slightly more under the additional negative demand shock. The highest emission reduction ambition level (*NDC-2C*) leads to additional global adjustment costs of 0.5% compared to *NDC*.[18] We find that the additional global adjustment costs for scaling up emission reduction targets towards a 2°C trajectory is unevenly distributed.[19] India, Japan, and South Korea do not face higher adjustment costs compared to the lowest ambition level (*NDC*). The gains from indirect international spillovers for these regions increase with the level of emission abatement, as direct abatement costs clearly increase as well. The fuel exporters Middle East and Russia lose overproportionally. All other regions lose roughly up to an additional 1% of BaU welfare compared to *NDC*.

Concerning regional welfare impacts of increased where-flexibility through international emissions trading two mechanisms are of paramount importance: (i) unequiv-

[18]Compare Section 3.1.

[19]Recall that the reduction targets in *NDC-2C* emerge from a uniform scaling of emission levels in *NDC+* and do not take into account more subtle fairness considerations.

ocal direct cost savings from emissions trading through the equalization of marginal abatement costs; and (ii) ambiguous indirect welfare effects through changes in the terms of trade on energy and non-energy markets that can play out both favorable or unfavorable for individual regions. More specifically, emission allowance selling countries face higher CO_2 prices under emissions trading variants compared to *ref*, while the opposite is true for allowance buying countries. These changes in the CO_2 prices affect the cost of EITE production and thereby the scope for terms-of-trade changes on EITE markets.

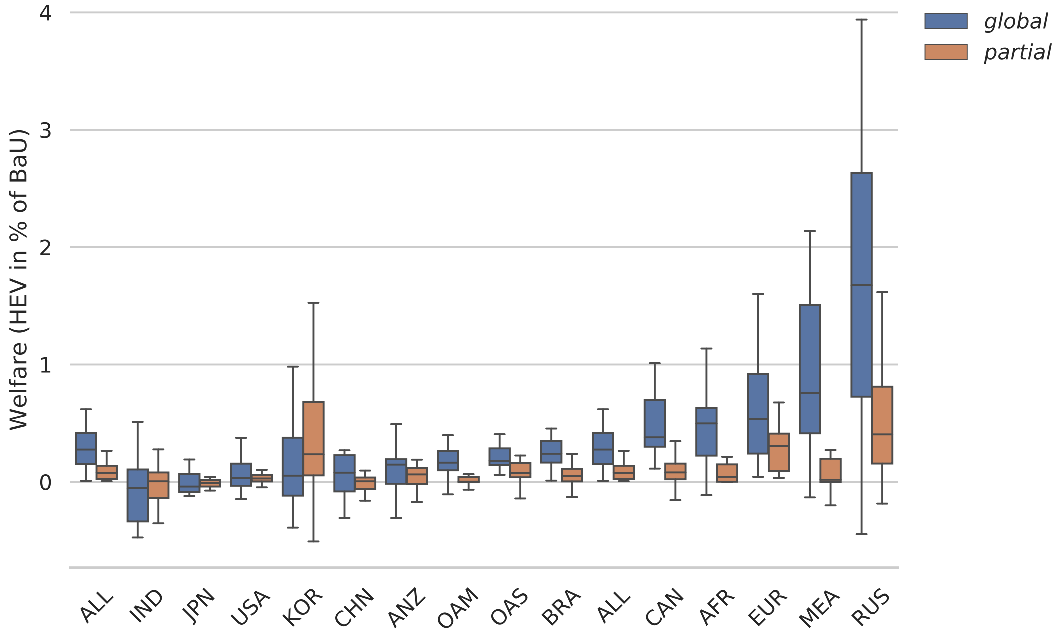
Figure 7 summarizes regional welfare impacts across models for the cases with worldwide trading schemes *global* and *partial* compared to *ref* for the case of the unconditional Paris pledges (*NDC*). We first focus on *global* and find that most regions gain through a comprehensive global emissions trading scheme as compared to the *ref* situation – gains are most pronounced for Russia, Middle East, and Europe. However, the only regions where we unambiguously find welfare gains through global cooperation are Brazil, Canada, Europe, and Other Asia. For all other regions, individual models find welfare losses from engaging in comprehensive global emissions trading, which points to the importance of terms-of-trade income effects when assessing the welfare impacts of climate policies in a more comprehensive (general equilibrium) manner.

We find, however, a robust pattern driven by changes in fossil fuel prices. Comprehensive global cooperation leads to a shift of global abatement to China and India, where cheap abatement options via reduced coal consumption can be exploited. This increases oil and gas prices and depresses coal prices vis-à-vis *ref*, and thereby leads to a shift in regional incidence from oil and gas producers (Middle East and Russia) to coal producers. India is even worse off under *global* compared to *ref* in most models, although still with a welfare gain compared to the BaU on average. Japan is in most models slightly worse off under *global* compared to *ref*, due to higher international oil and gas prices under *global*.

South Korea again shows a huge spread in results across models. On the one hand, South Korea can gain from emissions trading as it exhibits the highest CO_2 prices under *ref* (together with Europe). On the other hand, South Korea benefits substantially from depressed oil and gas prices under *ref*, an effect that is weakened under *global*.

When only EITE sectors and the power sectors are eligible for international emissions trading (*partial*), we find that Europe, South Korea, Middle East, and Russia can gain most compared to *ref*. While Europe and South Korea benefit from partial trading due to their high CO_2 prices in *ref*, the Middle East and Russia benefit from

Figure 7: Differences in regional welfare in *global* and *partial* compared to *ref* under *NDC*



Note.—Box-Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted.
Region keys: ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

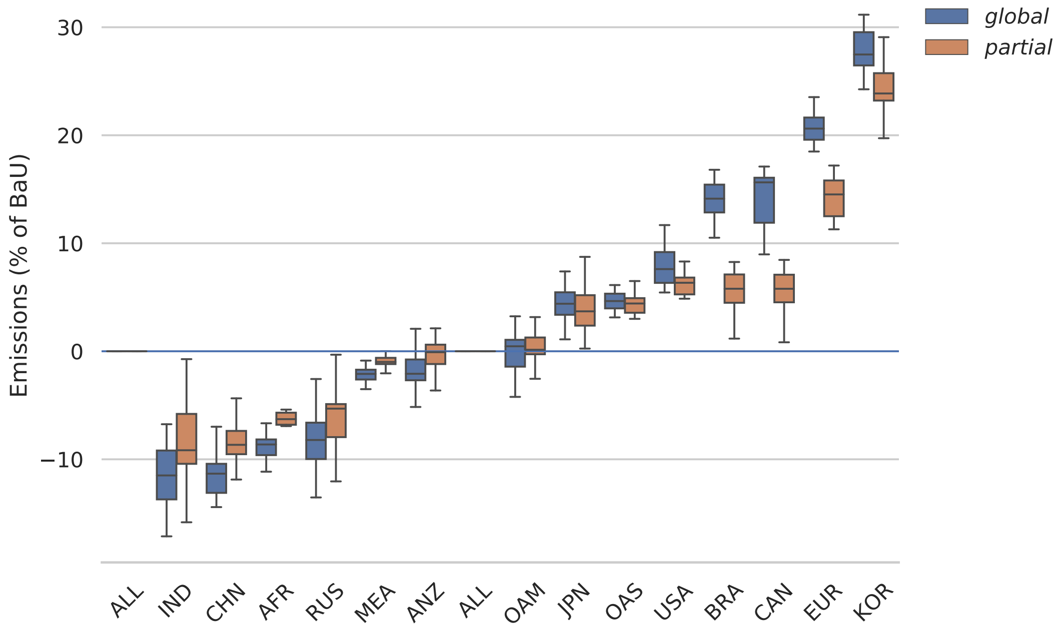
a shift towards coal abatement in *partial*. South Korea is thereby the only region that favors *partial* over *global*. The reason is that under partial trading, South Korea can reap gains from emissions trading, while the global shift from oil- and gas-related abatement towards coal is less accentuated. This is also reflected in welfare outcomes for Middle East and Russia, where we find the most pronounced gains under *global* attenuated under *partial*.

Emissions trading leads to an equalization of regional (or sectoral) CO_2 prices via exports and imports of emission allowances that constitute financial transfers between regions. For regions and sectors that form part of a trading coalition, their *ref* CO_2 price in relation to the tradable CO_2 price will determine whether the country becomes an exporter or importer of emission allowances and hence shows higher or lower emission reductions as stated in their Paris pledges. Figure 8 shows that regional buying and selling positions of emission allowances are rather stable across models: China, India, and Russia, which have the lowest CO_2 prices under *ref* (see Figure 4), become large exporters of emission allowances; South Korea, Europe, Canada, and Brazil become large importers.[20]

Figure 9 shows the differences in regional welfare in the club-trading scenarios *asia* and *eur-chn* compared to *ref*. We see that Europe and South Korea can gain from club trading, as they start off from very high CO_2 prices under *ref*. The other regions face only minor changes in economic adjustment costs triggered by club trading.

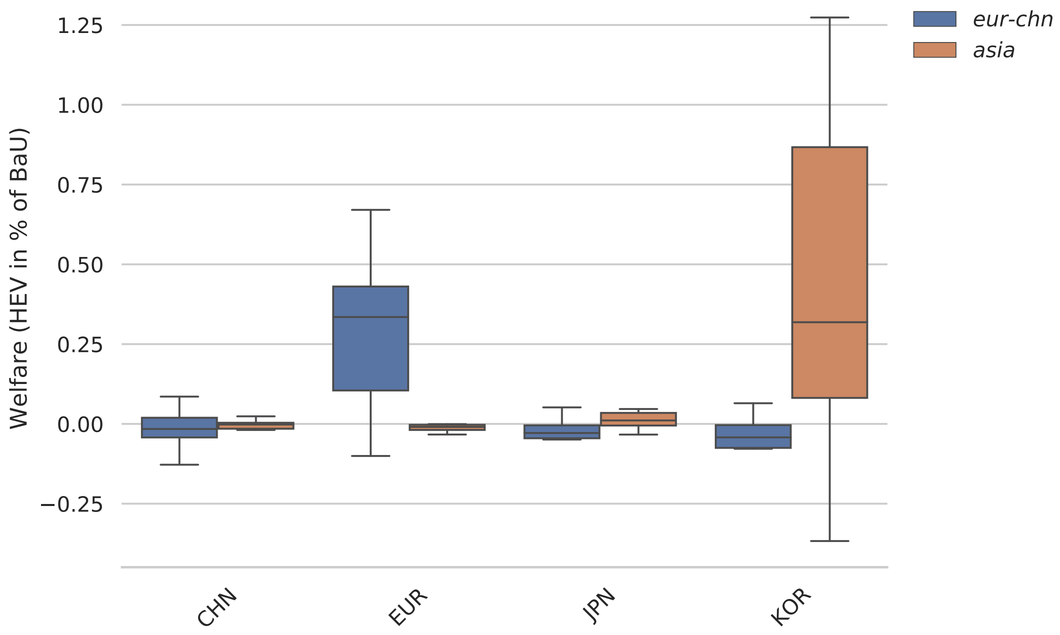
[20]Note that Brazil is a large importer of emission allowances as our analysis focuses on CO_2 emissions from fuel combustion. Accounting for emissions from agriculture, forestry, and land use (AFOLU) would most likely make Brazil a net exporter of emission allowances.

Figure 8: Differences in regional CO_2 emissions in *global* and *partial* compared to *ref* under *NDC*



Note.—Box-Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted.
Region keys: ALL - Global average; AFR - Africa; ANZ - Australia and New Zealand; BRA - Brazil; CAN - Canada; CHN - China; EUR - Europe; IND - India; JPN - Japan; KOR - South Korea; MEA - Middle East; OAM - Other Americas; OAS - Other Asia; RUS - Russia; USA - United States.

Figure 9: Differences in regional welfare in *eur-chn* and *asia* compared to *ref* under *NDC*



Note.—Box-Whisker plot shows the median (line), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers are omitted.
Region keys: CHN - China; EUR - Europe; JPN - Japan; KOR - South Korea.

3.3. Household level incidence

Our analysis on global and regional welfare implications of Post-Paris emissions pricing so far has been agnostic on the incidence across heterogeneous households *within* countries. For the political feasibility of emissions pricing reforms, however, a critical question is who bears the burden of higher energy prices. Taking into account distributional effects of CO_2 pricing across heterogeneous households is thus central to climate policy design.

Emissions pricing creates costs and rents which translate into incidence for households via changes in prices for consumption goods on the expenditure side and via changes in factor remuneration (plus potential transfers) on the income side. On the expenditure side emissions pricing is often found to be regressive to the extent that it drives up prices for consumption goods for which lower-income households tend to spend larger shares of their budgets. This is typically the case for electricity, home heating fuels, gasoline, and other energy-intensive goods whose prices will overproportionally increase under CO_2 pricing. On the income side emission pricing affects the productivity and thus the remuneration of the primary factors labor, capital, and specific resources (e.g., fossil fuel resources). Lower-income households tend to obtain larger shares of their income through labor and transfers, while higher-income households earn more through capital income. The incidence of climate policies on the income side hinges to a large extent on how governments will use revenues from emissions pricing. To address policy concerns on the regressive impacts of CO_2 pricing, we focus on revenue-neutral lump-sum transfers to households in equal shares. Such a rebating scheme is clearly progressive. Since each household receives an equal share of CO_2 revenues, the recycled amount marks a larger share of additional disposable for lower-income households. If sufficiently high, transfers can mitigate or even overcompensate the (expected) regressive effects of emissions pricing.

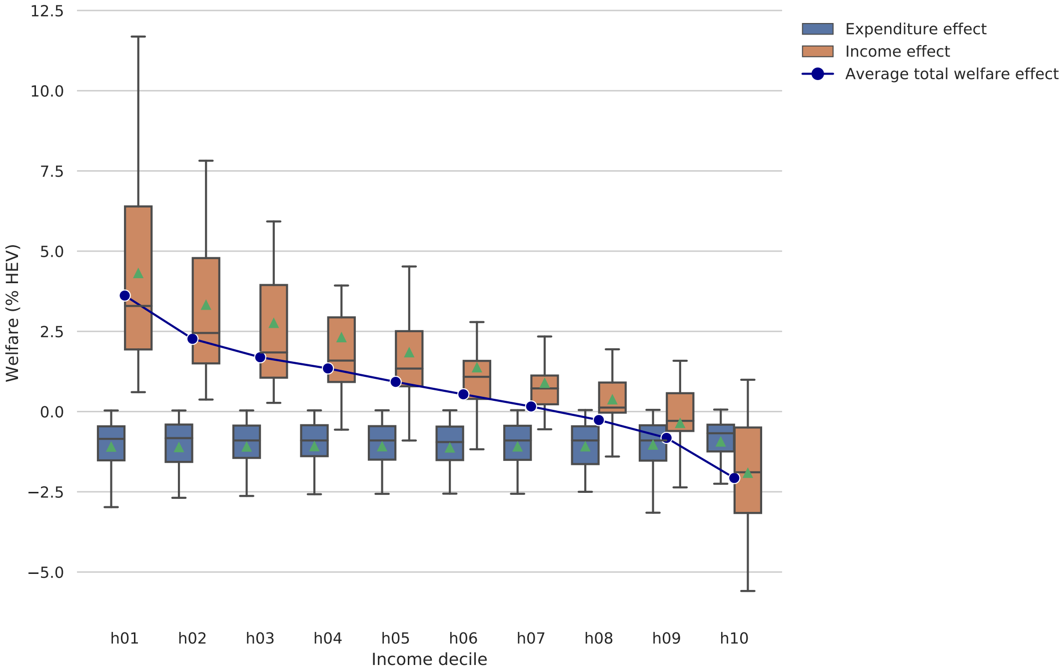
We present results for our central case scenario (*NDC/ref*) where regions meet their unconditional Paris pledges (*NDC*) through purely domestic action (*ref*). Figure 10 shows the total welfare impact on income deciles (*h01,...,h10*) as the mean across five models and 35 (partly overlapping) European countries (blue line with circle marker). On average, we find a progressive impact. While the lowest-income households gain more than 3% in real income (HEV), the highest-income households experience losses of roughly 2%. The underlying reason becomes clear if we decompose total welfare impacts into expenditure and income effects. The Box-Whisker plots in Figure 10 summarize expenditure and income effects across models and countries. We find that the expenditure effect – although varying sharply across countries due to different levels of CO_2 prices, emission intensities, and expenditure patterns – is negative and slightly regressive throughout. The income effect, on the other hand, which includes the lump-sum rebates received by households, is strongly progressive and dominates such that the overall welfare effect is progressive.[21]

We can summarize the individual effects on different households from a societal perspective when adopting a social welfare function where we capture alternative degrees of inequality aversion. We report social welfare as changes in the equally distributed equivalent income as defined by Atkinson (1970).[22] In Figure 11 we present social welfare changes for China, India, and Brazil, as well as for individual European countries Germany, the United Kingdom, France, Spain, and Norway. Countries are distinguished by color, and models are distinguished by markers, as for several European countries results are available from more than one model. With an inequality aversion of zero we adopt a utilitarian perspective where we are agnostic over the distribution of economic adjustment costs across different income deciles in

[21]Note that only European countries are represented in the Box-Whisker plots in Figure 10. In our central case, CO_2 prices in Europe are quite high, leading to high revenues and thus a strong income effect for households through lump-sum rebates.

[22]For a given degree of inequality aversion, the equally distributed equivalent income is defined as the level of income that – if obtained by every individual in the income distribution – would enable the society to reach the same level of welfare as is the case with actual incomes.

Figure 10: Summary on decomposition of households' total welfare into expenditure and income effects across models and regions



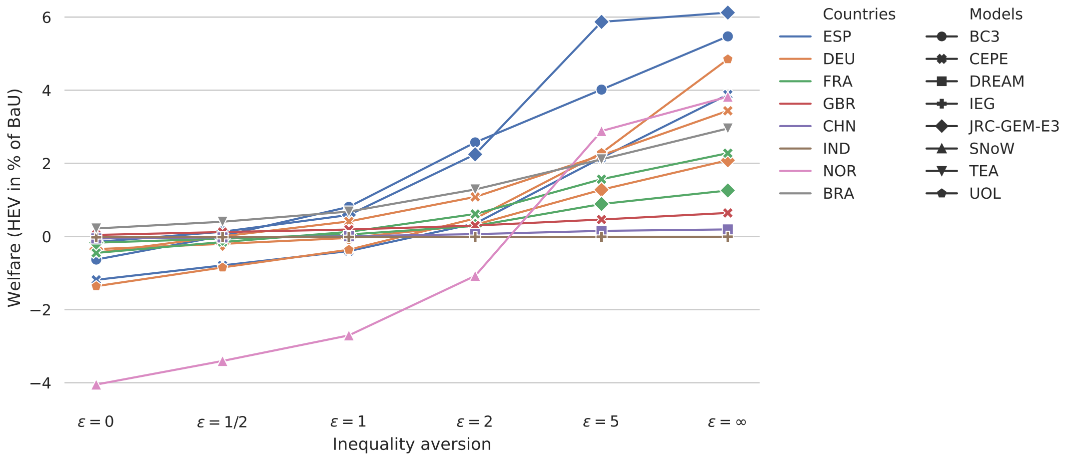
Note.—Box-Whisker plot shows the median (line), mean (green triangle), the first and third quartile (box), and whiskers showing the last datapoints within 1.5 times the interquartile range (IQR). Outliers omitted. Graph incorporates values from the models BC3 (Spain), IEG (India), UOL (Germany), SNoW (Norway), JRC-GEM-E3-EUROMOD-ITT (11 European countries), and CEPE (21 European countries).

social welfare. As we increase the inequality aversion, we find progressiveness of the lump-sum rebates in equal shares to households across all considered countries.[23] Higher degrees of inequality aversion imply higher values of social welfare. For an infinite aversion to inequality, i.e., when only the welfare of the lowest-income household matters, the associated social welfare actually increases beyond business-as-usual levels. Norway stands out for high productivity (efficiency) losses, which are due to very high CO_2 prices associated with a high emission reduction target and the low BaU emission intensity of the Norwegian economy. The redistributive effect of CO_2 pricing with lump-sum rebates to households is quite strong rendering initial efficiency losses from a utilitarian perspective into marked social welfare gains as inequality aversion increases, i.e. poorer households matter more and more. For China and India, on the other hand, the CO_2 pricing (at relatively low levels – see Figure 4) and lump-sum recycling involves very moderate economy-wide costs which leaves the income distribution across households relatively unaffected.

Our robust policy-relevant insight is that lump-sum recycling of revenues in equal shares to households can offset the regressive impacts of CO_2 pricing and even deliver social welfare gains with a reduction in CO_2 emissions if inequality aversion is sufficiently high.

[23]Note that for some countries in our cross-comparison CO_2 emissions pricing is already progressive without lump-sum rebates of CO_2 revenues. This can e.g. be the case when expenditure shares are rather homogeneous across households and emissions pricing leads to a significantly bigger impact on capital income than on labor income, burdening higher-income households stronger. However, the marked progressive effect illustrated in Figure 11 stems from the recycling mechanism.

Figure 11: Social welfare for different degrees of inequality aversion across models and regions



Note.—ESP - Spain; DEU - Germany; FRA - France; GBR - United Kingdom; CHN - China; IND - India; NOR - Norway; BRA - Brazil.

4. Concluding remarks

Most of the benefits of emission abatement will not materialize in terms of avoided climate damages before decades due to the inertia of the climate system. The costs of emission abatement on the other hand will occur in the short- to mid-term. It is therefore not surprising that the contemporary climate policy debate is still focused on the magnitude and distribution of economic adjustment costs of stringent emission constraints, as implied by the Paris Agreement in the pursuit of the 2°C temperature target. The United Nations Framework Convention on Climate Change has codified the challenge of international burden sharing as the principle of Common But Differentiated Responsibilities. However, the initial top-down approach on burden sharing applied in the Kyoto Protocol failed, not least due to the hardship to agree on common equity principles. The Paris Agreement inaugurated a new, bottom-up approach where countries pledge their emission reduction commitments voluntarily as so-called Nationally Determined Contributions (NDCs). The downside of such voluntary bottom-up approach is that it may not enforce sufficient collective abatement efforts to keep the average global temperature increase below 2°C from pre-industrial level. As a matter of fact, the individual abatement pledges under the Paris Agreement submitted so far fall substantially short off what is required to meet the long-run Paris temperature target. It is thus necessary to ratchet up the current NDCs towards much more restrictive targets even in the short run.

The unequivocal pressure to increase the ambition level in climate policy while securing societal approval calls for climate policy designs that are cost-effective and appear as fair to the citizens. Inherently, these two central requirements are intertwined since a reduction in compliance costs can substantially relax normative tensions on fair burden sharing.

The discipline of economics has identified two important instruments to decrease the overall compliance costs of emission reduction pledges and to increase societal support for stringent climate policies. Indeed, international emissions trading plays a decisive role in the cost effective containment of climate damages. Under purely domestic compliance to NDCs, there can be large differences in marginal abatement costs across countries, indicating a huge potential for cost savings. International emissions trading facilitates cost savings by allowing markets to identify where emissions reductions are the cheapest worldwide. With respect to equity concerns within societies, the recycling of additional revenues from emissions pricing is of critical importance. CO_2 pricing will at first glance have regressive impacts on households since poorer households tend to spend larger shares of their income on energy-related consumption categories such as electricity, heat or transport which will become more expensive. However, the regressive impacts of rigorous CO_2 emissions pricing can be alleviated, if not offset through lump-sum recycling of additional revenues to households in equal shares.

The findings of the EMF36 study confirm the potential of both instruments – international emissions trading and lump-sum revenue recycling to households – to facilitate ambitious Post-Paris climate policies that are in line with the 2°C temperature target. Under comprehensive global emissions trading, the 2°C target is placed within reach under approximately the same range of cost implicitly agreed upon by individual countries with their NDCs. CO_2 emission pricing can be implemented in a progressive manner when additional revenues are recycled lump-sum to households in equal shares. The progressive revenue-recycling effect dominates the regressive effects of higher energy prices. In the end, CO_2 pricing in combination with lump-sum recycling of additional revenues on an equal-per-household basis can not only make economies greener, but also societies fairer in terms of overall income distribution.

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A. Business-as-usual (BaU) projections and Nationally Determined Contributions (NDCs)

Our BaU projections are indexes for GDP and CO_2 from 1990-2030 (2011=1). We construct two alternative BaU projections denoted *IEO* and *WEO*. Against both BaU projections we derive effective reduction targets for CO_2 emissions from fossil fuel combustion in 2030 for our model regions for three different ambition levels covering (i) unconditional NDC pledges and lower bounds (*NDC*), (ii) conditional pledges and upper bounds (*NDC+*), and (iii) an ambition level called *NDC-2C* where we scale emission levels in *NDC+* uniformly across regions in order to comply with an emission reduction for 2030 which is on the 2°C emission trajectory path suggested by integrated assessment analysis. The notation used in this section is summarized in Table B1.

We map all the primary IEO and WEO data to GTAP regions, so the procedures described below apply to the individual GTAP regions from where we aggregate numbers towards the composite model regions (see Table 2). In what follows we sketch our data sources and the steps involved to establish BaU projections from *IEO* and *WEO* as well as the respective region-specific effective reduction targets in 2030. An Excel file with the data in use and the computational steps involved is available from the authors upon request.

A.1. BaU projections

We construct two alternative BaU projections based on *IEO* and *WEO* data for GDP and CO_2 emissions as indexes from 1990-2030 (2011=1) across all GTAP regions. *IEO* represents projections from the International Energy Outlook 2017 of the U.S. Energy Information Agency (EIA, 2017). *WEO* represents projections from the World Energy Outlook 2018 of the International Energy Agency (IEA, 2018). For historical data, we use WorldBank (2019) for GDP and EIA (2019) for CO_2. For years without data, we interpolate linearly.

We then aggregate the BaU data from the more disaggregate GTAP regions to our composite model regions using the weighted sum for the respective BaU items – here GDP and CO_2 emissions – indexed to 2011 as the base year (2011=1).

A.2. NDCs

Building on Kitous et al. (2016) we compile a dataset with regional NDCs as submitted by individual countries (see UNFCCC, 2020, for the NDC registry). The regions in our dataset cover more than 95% of global CO_2 emissions from fossil fuel combustion. The dataset includes for most countries a low and a high NDC pledge (equivalent to our *NDC* and *NDC+*) as well as the NDC base year, the target year for meeting the NDC, the coverage of greenhouse gas emissions, and the type of the target. Countries state their NDCs typically as a percentage reduction target against a certain base year (which can be historical or a future business-as-usual), or as a percentage reduction target for emission intensity of GDP (e.g., China and India). For countries that state their targets with respect to a business-as-usual in a future target year (typically 2030) and that provide a BaU projection for 2030 of their own, we use the implied physical emission level to go forward. We translate NDCs into percentage CO_2 emission reduction targets vis-a-vis the BaU in 2030.

For countries stating their NDC as an emission reduction target we calculate the effective emission reduction requirement as:

$$R^B_{r,c} = 1 - (1 - ndc^c_r) \cdot \frac{B^{CO2}_r(by_r)}{B^{CO2}_r(ty_r)}, \tag{1}$$

For countries stating their NDC as an intensity target we calculate the effective emission reduction requirement as:

$$R^B_{r,c} = 1 - (1 - ndc^c_r) \cdot \frac{B^{CO2}_r(by_r)}{B^{GDP}_r(by_r)} \cdot \frac{B^{GDP}_r(ty_r)}{B^{CO2}_r(ty_r)} \tag{2}$$

If the NDC target year is not 2030, the required percentage reduction from 2016 (last available historical year) to the NDC target year is linearly perpetuated to 2030.

For countries that have stated their NDCs for all greenhouse gas emissions (not only CO_2), we convert the reduction targets towards CO_2 emission reduction targets from fossil fuel combustion only as the latter constitute the relevant emission base for our model cross-comparison. The scaling factor is derived from Kitous et al. (2016):

$$F_r = \frac{1 - \frac{CO2^{NDC}_r}{CO2^{REF}_r}}{1 - \frac{GHG^{NDC}_r}{GHG^{REF}_r}}, \tag{3}$$

that is, the ratio of the %-reductions of CO_2 from fuel combustion over greenhouse gas emissions.[24] We only apply scaling factors lower than 1 being cautious on the scope for more stringent emission reductions. Brazil is adjusted based on expert

[24] E.g., if a country r in scenario *NDC* reduces 10% of GHG emissions and also 10% of CO_2 from fuel combustion, then $F_r = 1$.

opinion.[25] For countries with an intensity target, we set a minimum reduction target of 5% against the 2030 baselines, reflecting the assumption that such a target will lead to some degree of effective carbon pricing, even if baseline projections suggest that targets are reached without carbon pricing.

To define the *NDC-2C* scenarios we follow a budget approach, where we target a global level of CO_2 emissions that is 11.58% below 2011 emissions.[26] We apply a uniform scaling factor to the regional emission levels in *NDC+* in order to achieve that target.

The reduction requirements under *NDC-2C* then are

$$R^B_{r,NDC-2C} = 1 - S \cdot (1 - R^B_{r,NDC+}), \tag{4}$$

where S is the scaling factor.

Finally, we aggregate the effective reduction targets across GTAP regions towards our composite model regions based on CO_2 emission weighted averages of GTAP data for our base year 2011.

Table B1: Definitions and notations in NDC translation

Symbol	Description
r	Set of GTAP regions
B	Set of BaU projections $\{IEO, WEO\}$
c	Set of NDC scenarios $\{NDC, NDC+, NDC-2C\}$
$R^B_{r,c}$	Reduction requirement in region r and NDC scenario $c \in \{NDC, NDC+, NDC-2C\}$ as share of emissions in baseline $B \in \{IEO, WEO\}$ in 2030
ndc^c_r	Nationally intended contribution in region r and $c \in \{NDC, NDC+\}$
by_r	Base year of NDC in region r
ty_r	Target year of NDC in region r
$CO2^c_r$	CO_2 level in Kitous et al. (2016) in region r and scenario c
GHG^c_r	GHG level in Kitous et al. (2016) in region r and scenario c
F^c_r	Correction factor to scale from GHG to CO_2 reduction requirement in region r and $c \in \{NDC, NDC+\}$
S	Scaling factor to translate the implied emission level in *NDC+* to *NDC-2C*

[25] Experts from Brazil identify reduction potential of 100-210 Mt CO_2 in 2030 (excl. AFOLU). We stay rather conservative and use the lower value in order to calculate effective reduction requirements.

[26] This value is derived as an average emission trajectory suggested by integrated assessment analysis for scenarios that target a 2°C path (Huppmann et al., 2019).

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