The Great Carbon Arbitrage

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[1] The views expressed in this presentation are those of the authors and do not necessarily represent the views of the IMF, its Management, or its Directors.

[2] A computational tool and extra analysis can be found at https://greatcarbonarbitrage.com.

Motivation

- Two approaches to internalizing negative externalities
  1. Pigouvian taxation to fully reflect the social cost of an economic activity, Pigou (1920)
  2. Coase seeks to attain an efficient social outcome through bargaining and contracting, Coase (1960)
- We give a quantitative estimate of the social surplus that can be attained from avoiding emissions
- How much would the world benefit by phasing out fossil fuels and replacing them with renewable energy?

Motivation

- Focus on coal
- Measure the economic gains from phasing out coal as the social cost of carbon times the quantity of avoided emissions
- Compare the present value of benefits avoided carbon emissions to the present value of costs of ending coal plus the costs of replacing it with renewable energy

Overview of Results

- Baseline estimate of a net total gain of around $78 trillion
  - Represents around 1.2% of current world GDP every year until 2100
  - Carbon arbitrage per tonne of avoided coal production is $125
  - Carbon arbitrage per tonne of avoided CO_2 emissions is $55
- The net benefits from ending coal are so large that renewed efforts, carbon pricing, and other financing policies we discuss, should be pursued
  - In relation to the "The Great Energy Shock", the results of our Great Arbitrage Paper provide the economic rationale to invest big time in renewables *now*, also to establish energy independence (need to shorten permits and bureaucratic procedures)
  - We show that gas is not a good transition fuel. It delivers smaller net gains, by a magnitude! Should at most be a stopgap measure

List of Key Results

1. The net gain from replacing coal with renewables under a *conservative* estimate is 78 trillion.
2. To reap this Coasian bargain, as a complement to incomplete carbon taxation, we propose climate financing to replace coal with renewables.
3. We are the first ones to *quantify* how much climate financing would be needed to replace coal with renewables, in every country of the world.
    - Financing for expanding renewable capacity would be made conditional on the commitment to phase out coal.
    - Financing offered for the investment costs in renewables
    - Compensation offered for opportunity costs of coal.
        - This amounts, at a minimum, to the stranded asset value of coal. Could also include payments for lost wages and retraining workers.
4. We propose to use blended financing structures to draw financing from capital markets leveraging public money.
    - Creates a novel green asset class dedicated to replacing coal with renewables & increases the supply of ESG assets mitigating climate change

Data

- Asset Resolution and the 2 Degrees Investing Initiative (AR-2DII) data on historical and projected global coal production
- Captures plant-level data for each unique combination of:
  1. Energy use (power or non-power sector)
  2. Coal technology (lignite, sub-bituminous, bituminous, anthracite)
  3. Plant country (and country of parent(s))
- Captures ownership structure of plants
- Captures emission intensity (in tonnes of CO_2 per tonnes of coal) as of 2020, as well as historical production from 2013-2021 (in tonnes of coal) and projected production from 2022 to 2026 of each coal plant
  - Emission intensity of each coal-mining plant captures its scope I and III emissions

Data Comparison

Table: A comparison of 2020 global coal production between the estimate of AR-2DII and authoritative bodies.

	AR-2DII	NGFS	IEA	BP Statistical Energy Review	Global Energy Monitor
Coal production (giga tonnes of coal)	6.41	5.87	5.45	5.87	6,80
Coal emissions (giga tonnes of CO_2)	14.53	-	14.6	-	13.98

Coal Production Scenarios

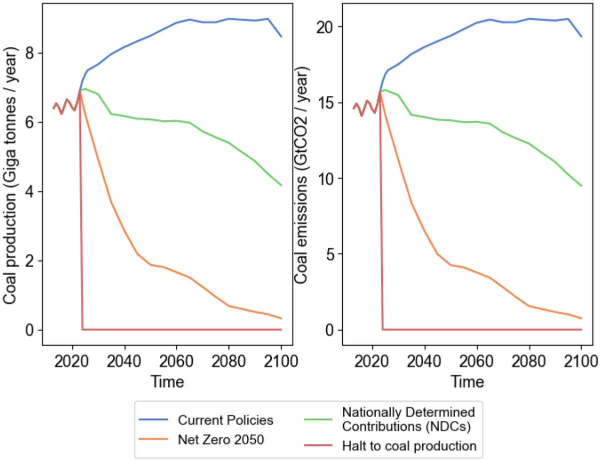


Figure: Global coal production scenarios and associated global emissions.

Investment Cost Scenarios

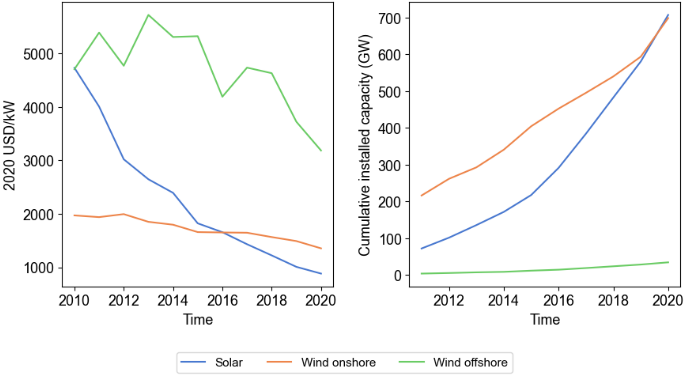


Figure: Investment costs in renewables and cumulative installed capacity in renewables over 2010-2020.

The Carbon Arbitrage

- The carbon arbitrage $A_{t,T}^{s_1,s_2,s_r,\theta}$ is given by any positive difference between the present value of benefits $B_{t,T}^{s_1,s_2,\theta}$ of avoiding carbon emissions from coal production minus the present value of costs $C_{t,T}^{s_1,s_2,s_r,\theta}$ of avoiding such emissions, taking into account opportunity costs of coal and investment costs in replacement renewable energy, i.e.

$$A_{t,T}^{s_1,s_2,s_r,\theta} = B_{t,T}^{s_1,s_2,\theta} - C_{t,T}^{s_1,s_2,s_r} \tag{1}$$

- We focus on estimating the global carbon arbitrage.

The Present Value of Benefits

- The present value of benefits $B_{t,T}^{s_1,s_2,\theta}$ that can be reaped if each coal company $i \in \mathcal{C}$ were to reduce its CO_2 emissions by $\Delta E_{i,\tau}^{s_1,s_2}$ each year $\tau \in [t+2, T]$ is given by

$$B_{t,T}^{s_1,s_2,\theta} = \theta \times \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \Delta E_{i,\tau}^{s_1,s_2} \tag{2}$$

  for avoided emissions priced at the social cost of carbon θ
- We conservatively assume a constant SCC θ over time. Fine as long as the real growth rate g of the SCC is larger than or equal to social discount rate r^s (i.e., if $g \geq r^s$).
- The emission reduction $\Delta E_{i,\tau}^{s_1,s_2}$ is given by the difference in emissions in year τ between the business-as-usual scenario s_1 and the phase-out scenario s_2; i.e.

$$\Delta E_{i,\tau}^{s_1,s_2} = E_{i,\tau}^{s_1} - E_{i,\tau}^{s_2} \tag{3}$$

The Amount of Emissions

- The emissions $E^s_{i,\tau}$ coal company i generates in year τ under scenario s is given by the product of its coal production $P^s_{i,l,\tau}$ in each of its plants $l \in \mathcal{L}_i$ under scenario s multiplied with the emission intensity $\epsilon_{i,l}$ of the plant

$$E^s_{i,\tau} = \sum_{l \in \mathcal{L}_i} P^s_{i,l,\tau} \epsilon_{i,l}. \tag{4}$$

- Benefits from avoided emissions, captured by the SCC, represent:
  1. Avoided damages from climate change
  2. Avoided adaptation costs
- Benefits from avoided emissions not captured by the SCC:
  - Avoided healthcare costs from air pollution (Rauner et al. (2020))

The Present Value of Costs

The present value of costs $C_{t,T}^{s_1,s_2,s_r}$ of avoiding coal emissions under scenario set $\{s_1, s_2, s_r\}$ and over time horizon $[t+2, T]$ is given by the sum of the present value of opportunity costs of avoiding coal emissions $O_{t,T}^{s_1,s_2}$ and the present value of investment costs in replacement renewables $I_{t,T}^{s_1,s_2,s_r}$, i.e.

$$C_{t,T}^{s_1,s_2,s_r} = O_{t,T}^{s_1,s_2} + I_{t,T}^{s_1,s_2,s_r} \tag{5}$$

The Opportunity Cost of Coal

- The present value of opportunity costs of coal $O_{t,T}^{s_1,s_2}$ is given by discounted missed free cash flows $O_{i,\tau}^{s_1,s_2}$ of each coal company $i \in \mathcal{C}$ in every year $\tau \in [t+2, T]$ resulting from its coal-production reduction in scenario s_2 relative to s_1, i.e.

$$O_{t,T}^{s_1,s_2} = \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \frac{O_{i,\tau}^{s_1,s_2}}{(1+\rho_i)^{(\tau-t)}} \tag{6}$$

- The missed free cash flow $O_{i,\tau}^{s_1,s_2}$ of i in year τ is given by the multiplication of its coal-production reduction $\Delta P_{i,\tau}^{s_1,s_2}$ in year τ in scenario s_2 relative to s_1 times the profit it makes per unit of coal production $\pi_{i,\tau}$, i.e.

$$O_{i,\tau}^{s_1,s_2} = \Delta P_{i,\tau}^{s_1,s_2} \times \pi_{i,\tau} \tag{7}$$

where $\Delta P_{i,\tau}^{s_1,s_2} = P_{i,\tau}^{s_1} - P_{i,\tau}^{s_2}$, and where $\pi_{i,\tau}$ is assumed to remain constant and equal to medium unit profit of top-10 coal companies (averaged over last 10 years of profits)

Missed Cash Flows

- We discount coal company i's missed cash flow $O^{s_1,s_2}_{i,\tau}$ at date τ by its weighted average cost of capital (WACC), i.e.

$$\rho_i = \lambda_i \rho^f (1 - \chi_i) + (1 - \lambda_i)(\rho^f + \beta_i \mathbb{E}[R^M]) \qquad (8)$$

  where λ_i is its average leverage, ρ^f is the risk-free rate, χ_i is its corporate income tax rate, β_i is its beta, and $\mathbb{E}[R^M]$ is the risk premium
- With $\rho^f = 2.08\%$, $\chi_i = 15\%$, $\lambda_i = 52\%$, $\beta_i = 0.9$, and $\mathbb{E}[R^M] = 1.99\%$, we obtain $\rho_i = \rho = 2.8\%$
- We conduct a sensitivity analysis based on $\rho = 3.6\%$, which uses the average risk-premium over the last 100 years, i.e. $\mathbb{E}[R^M] = 3.87\%$

The Present Value of Investment Costs

- The present value of investment costs $I_{t,T}^{s_1,s_2,s_r}$ in replacement renewable mix s_r is given by the present value of sum of investments that must be made in each country y to replace phased-out coal in scenario s_2 relative to s_1, i.e.

$$I_{t,T}^{s_1,s_2,s_r} = \sum_{y \in \mathcal{Y}} I_{y,t,T}^{s_1,s_2,s_r} \tag{9}$$

- We assume that phased-out coal in country y will be replaced by renewables in country y
- The investment cost $I_{\tau}^{s_1,s_2,s_r}$ in year τ in country $y \in \mathcal{Y}$ to build renewables to replace coal is given by the sum of replacement renewable capacity times unit investment costs of each renewable energy type $q \in \mathcal{R}$, i.e.

$$I_{y,\tau}^{s_1,s_2,s_r} = \sum_{q \in \mathcal{R}} G_{y,\tau}^{s_1,s_2,s_r,q} \times i_{\tau}^{q,s_1,s_2,s_r} \tag{10}$$

The Renewable Capacity

- The renewable capacity $G_{y,\tau}^{s_1,s_2,s_r,q}$ that must be built in year τ of renewable energy type q to replace phased out coal is given by

$$G_{y,\tau}^{s_1,s_2,s_r,q} = \omega_{\tau}^{q,s_r} \times h^{-1}(D_{y,\tau}^{s_1,s_2,s_r}) \times \frac{1}{f^q} \tag{11}$$

- How much renewable capacity $G_{y,\tau}^{s_1,s_2,s_r,q}$ of type q must be built in year τ in country y depends on the shortfall of energy $D_{y,\tau}^{s_1,s_2,s_r}$ created by the phase out of coal, i.e.

$$D_{y,\tau}^{s_1,s_2,s_r} = \max\{g(\Delta P_{y,\tau}^{s_1,s_2}) - R_{y,\tau}^{s_1,s_2,s_r}, 0\} \tag{12}$$

- $R_{y,\tau}^{s_1,s_2,s_r} = \sum_{q\in\mathcal{R}} R_{y,\tau}^{s_1,s_2,s_r,q}$ is the energy the existing stock of renewables $S_{y,\tau}^{s_1,s_2,s_r,q}$, built to replace coal, produces in country y at time τ, i.e.

$$R_{y,\tau}^{s_1,s_2,s_r,q} = h(S_{y,\tau}^{s_1,s_2,s_r,q}) \times f^q \tag{13}$$

where capacity factor f^q of renewable type q captures that a renewable plant typically does not run at theoretical capacity

Wright's Law

- Wright's law captures how investment costs of renewable energy type q fall (exponentially) according to learning rate γ_q as a function of global cumulative installed capacity in q (Schmidt et al. (2017)), i.e.

$$i_{\tau}^{s_1,s_2,s_r,q} = \alpha_q \left(\sum_{y \in \mathcal{Y}} \left(\sum_{\tau_b \leq t-1} G_{y,\tau_b}^{q} + \sum_{\tau_b = t+2}^{\tau-1} G_{y,\tau_b}^{s_1,s_2,s_r,q} \right) \right)^{-\gamma_q} \tag{14}$$

- The learning rate γ_q determines the percentage reduction Θ_q% in investment costs $i_{\tau}^{s_1,s_2,s_r,q}$ for each doubling of installed capacity, i.e.

$$\Theta_q = 1 - 2^{-\gamma_q} \tag{15}$$

- Samadi (2018) reviews the literature on empirically estimated learning rates and finds on average $\Theta_{q_{solar}} = 20\%$, $\Theta_{q_{wind-onshore}} = 5\%$, $\Theta_{q_{wind-offshore}} = 3\%$, corresponding to $\gamma_{q_{solar}} = 0.32$, $\gamma_{q_{wind-onshore}} = 0.07$, $\gamma_{q_{wind-offshore}} = 0.04$

Baseline Results

Table: Baseline settings of results.

Social cost of carbon	• θ_{IMF} = \$75 per tonne of CO_2
Time horizon [t+2,T] of carbon arbitrage	• $t = 2022,\ T = 2100$
Coal phase out scenario, s_2	• s_2 = Net zero 2050
Coal replacement scenario, s_r	• 50% solar, 50% wind (of which 50% onshore and 50% offshore)
Investment costs, I	• 30Y lifetime of renewable plants with depreciation and investment-cost experience curve
Opportunity costs, O	• Median unit coal profit of top 10 pure coal companies
Discount rate, ρ	• WACC ($\rho = 2.8\%$)

The Great Carbon Arbitrage

Table: The Great Carbon Arbitrage.

Present value of benefits of phasing out coal (in trillion dollars)		106.9
Present value of costs of phasing out coal (in trillion dollars)		29.03
	Opportunity costs	0.05
	Investment costs	28.98
Carbon arbitrage (in trillion dollars)		77.89
Carbon arbitrage relative to world GDP (%)*		1.2
Carbon arbitrage (in dollars) per tonne of coal production		125
Carbon arbitrage (in dollars) per tCO_2		55
Total coal production prevented (Giga Tonnes)		623.62
Total emissions prevented ($GtCO_2$)		1425.55
Further temperature increase – on top of 1.1 $^\circ C$ already observed – prevented **		2.14

Input your own assumptions and parameters to generate this table at:

https://greatcarbonarbitrage.com

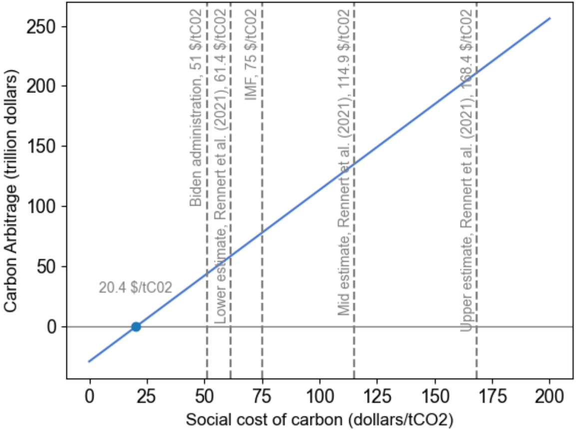


Figure: Net economic gain from replacing coal with renewables as a function of the social cost of carbon

Note: a recently published multi-year study by Resources for the Future puts SCC at $\$185/tCO_2$

Climate Financing by Region

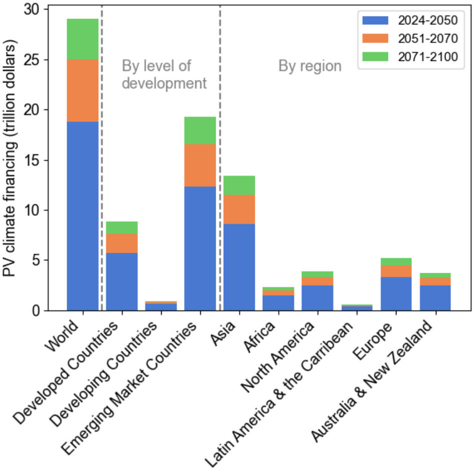


Figure: Present value of all climate financing needs.

Download the PV of climate financing needs at: https://greatcarbonarbitrage.com

Climate Financing Needs over Time

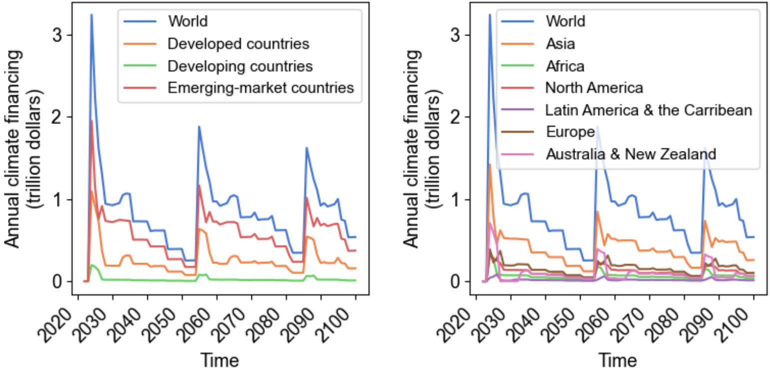


Figure: Annual climate financing needs (in trillion dollar; non-discounted).

Download annual climate financing needs at: https://greatcarbonarbitrage.com

World Map of Requisite Climate Financing

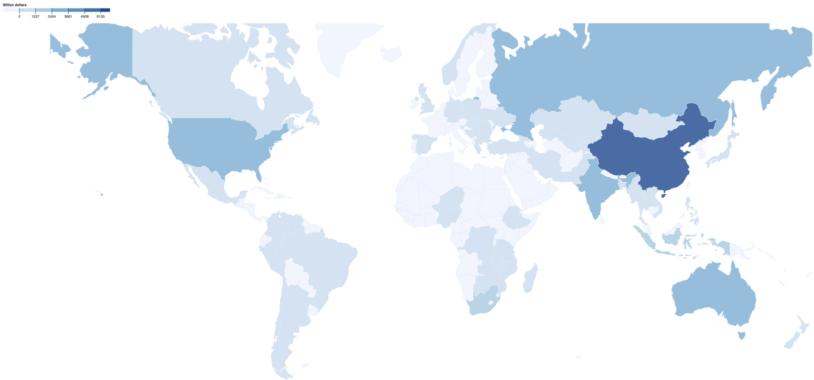


Figure: World map of climate financing needs (in present value terms; billion USD).

Download country-specific climate financing needs at:

https://greatcarbonarbitrage.com

World Map of Requisite Climate Financing (% of GDP)

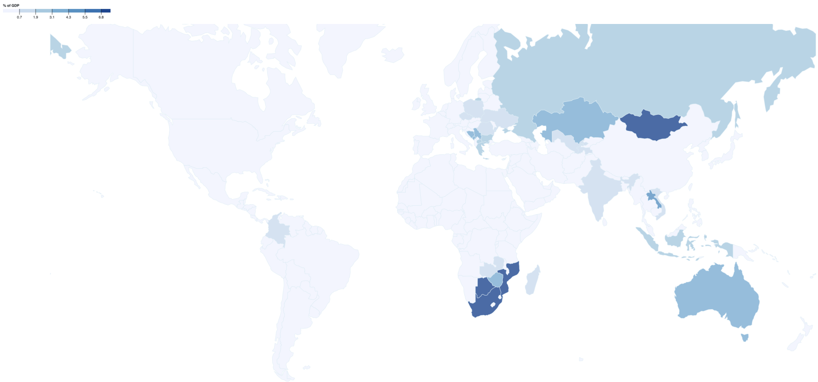


Figure: World map of climate financing needs (in present value terms; % of GDP).

Download country-specific climate financing needs at:

https://greatcarbonarbitrage.com

Link to Literature

Table: Comparison of the global present value of costs, benefits, and net benefits according to a Net Zero 2050 pathway (unless otherwise indicated).

	Paper	Present value of benefits	Present value of costs	Net Present Value
Coal	Adrian, Bolton & Kleinnijenhuis (2022)	\$106.92 trillion	\$29.03 trillion (\$1/2 – \$2 trillion dollars annually; with a front loading of investments of 3 trillion)	\$77.89 trillion (1.2% of GDP up to 2100)
	Rauner et al. (2020)	\$5.1 trillion, non-discounted in 2050	\$1.7 trillion, non-discounted in 2050	\$3.4 trillion, non-discounted (1.5% of GDP in 2050)
Energy sector	Mercure et al. (2021)		Stranded fossil fuel assets of \$7-\$11 trillion between [2021-2036]	
	IEA (2021)	x	\$4.5-5 trillion annual investment energy sector (4.5% of GDP in 2030, 2.5% in 2050)	x
Physical assets & land-use systems	McKinsey (2022)	x	\$275 trillion, non-discounted (\$9.2 trillion annually on average; with front loading of investments) (7.6% of GDP over 2022-2050)	x

Policies

- The global Coasian bargain we propose, in which the opportunity cost of coal and replacement cost in renewable energy are compensated, results in a Pareto improving deal in which every country in the grand coalition could be made better off. The world can reap a gain of around 78 trillion dollars by phasing out coal.
- In practice, the Coasian bargain we propose may fail because of high transaction costs
- But our point is that in light of such huge gains from phasing out coal, it makes sense for the world to seek to overcome any hurdles
- In the absence of global carbon taxation at the SCC, which we view as a first-best solution, such Coasian agreement would accelerate the green transition (as a complement to incomplete carbon pricing) by helping to make "finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (Article 2c of the Paris Agreement).

Policies: Case Study

- As US Climate Envoy John Kerry has pointed out, the requisite climate financing most likely cannot be paid by public funds alone (and may not be desirable) and must be supplemented by private funding
- We suggest that a public-private partnership model should be pursued to finance the phase out of coal.
- A highly innovative example of how our Coasian approach could work is the IFC-Amundi securitization deal (Bolton et al. (2020))
  - Constructed Asset Backed Security where development institution took first-loss tranche (of $125 million)
  - Senior tranches had investment grade rating (appealing to institutional investors)
  - Total size of the deal was about $2 billion
  - Senior tranche was 90% of the value of fund

Policies: Climate Financing the Coal Phase Out

- To finance the phase out of coal in a Coasian coalition it must be in the interest of three key stakeholders to participate in the four pillar public-private partnership described before:
  1. Governments $\rightarrow$ discussed now
  2. Coal companies
  3. Investors

Policies: Governments

- Taking the IFC-Amundi deal as a representative case study, a public-private partnership providing a total climate financing of 29 trillion dollars to phase out coal must be funded with roughly 10% by public funds
- Hence, governments must invest around 2.9 trillion dollars into the junior tranches of the ABS structures
- It is in the interest of individual governments to provide climate financing if their gross societal benefits are greater than their cost of doing so
- In our calculations, we take the global societal benefit of avoiding coal emissions to be equal to the SCC, representing the global average damage of emitting carbon, times the global quantity of avoided emissions
- In reality, the impacts of climate change are heterogeneously distributed across the world (IPCC (2021)). Hence, the country-specific SCC may deviate from the average

Policies: Governments

- Since regional estimates of the SCC are insufficiently reliable (Nordhaus (2017)), we have focused on the global carbon arbitrage, for which the global SCC more reliably accounts for climate damage estimates in aggregate
- The key point is that we find that the carbon arbitrage disappears only when the SCC is less than $\$20/tCO_2$, using conservative baseline parameters
- Countries that would only have to pay 10% of their climate financing costs would see their carbon arbitrage only disappear at a SCC less than or equal to $\$2/tCO_2$. Hence, it is in most countries' interest to provide climate financing.
  - Note: in the revised paper we make back-of-the-envelope calculation more precise and take into consideration country-specific net gains and inter-temporal net gains.
  - We will benchmark estimates of benefits against current physical damages from climate change accross the world.

Policies: Governments

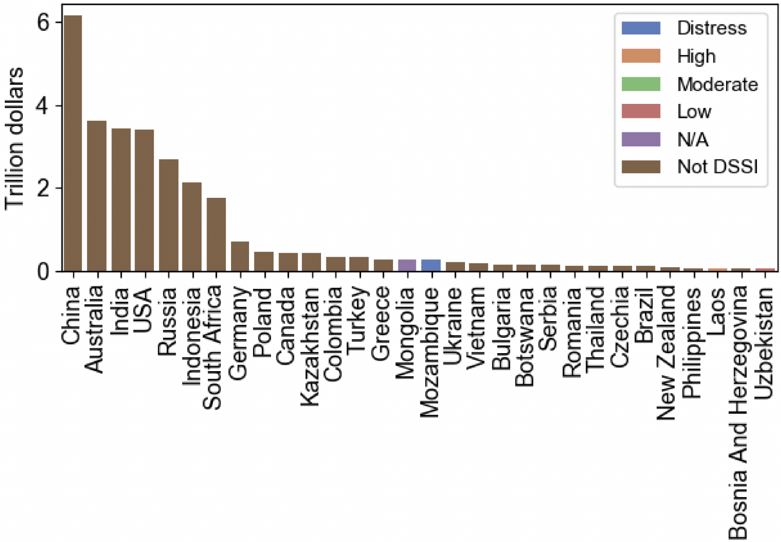
- As a baseline, it seems reasonable that countries pay for their own costs of replacing coal with renewables (i.e., their opportunity costs of coal and investment costs in replacement renewables)
  - Unlike what is commonly associated with climate financing, climate is not only needed for developing countries and emerging market economies, but also in the developed world (such as Australia, see world map)[3]!
- Distributional and historical fairness considerations, however, inevitably underlie the attainment of the Coasian bargain.
- It seems reasonable that the developed world would help pay for the lion share of energy transition in the developing world.

[3] https://greatcarbonarbitrage.com

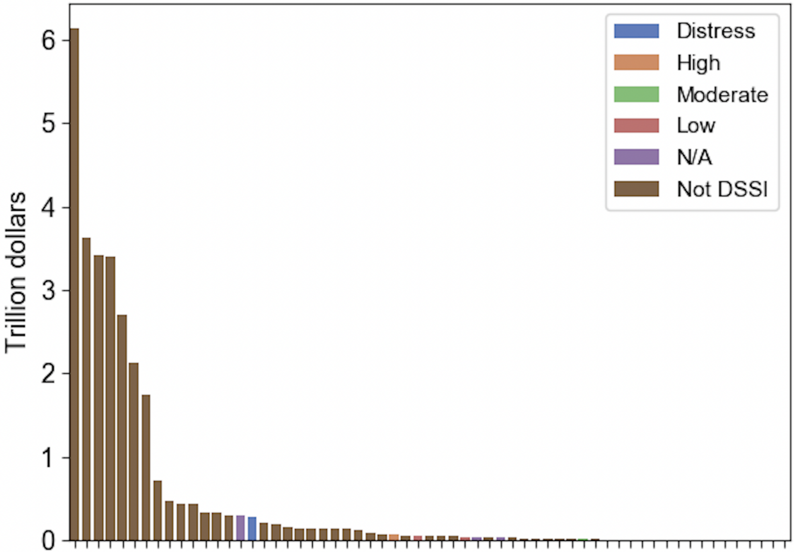
Policies: Governments

- The blended climate financing to phase out coal would be largely in the form of debt (roughly 26 trillion dollars), provided by capital markets but it would have a large grant element:
  1. Roughly 2.9 trillion dollars would be provided as grants by governments.
  2. The debt would be long-term.
  3. The debt would be provided at low interest rates, since it would be de-risked by government funding into the junior tranche.
- We estimate that most countries the climate financing would not increase debt-to-GDP levels by more than approximately 0-3%, with a few notable outliers (e.g, South Africa, Mozambique & Mongolia).
  - For some countries heavily reliant on coal, or with a weak existing fiscal position, debt restructuring or another solution might be necessary (see Bolton et al. (2022)).

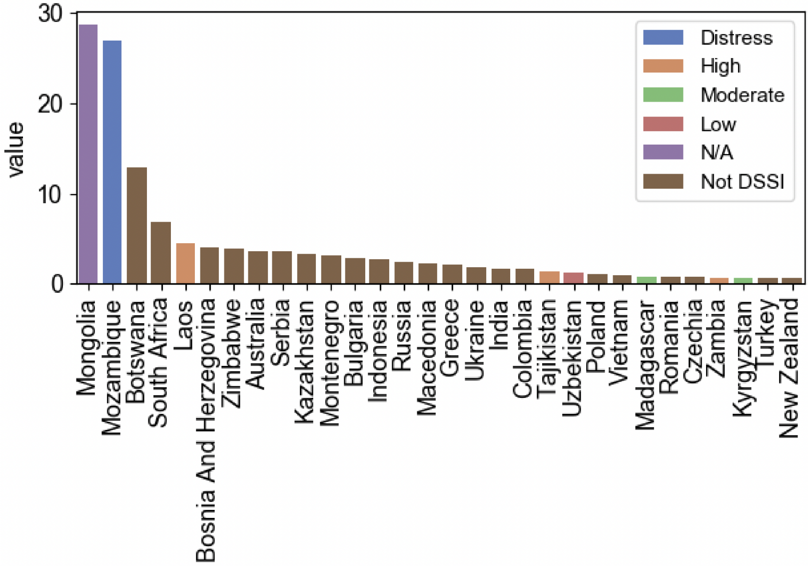
Climate Financing (trillion dollars) by Level of Debt Distress



Climate Financing (trillion dollars) by Level of Debt Distress



Climate Financing (as % GDP) by Level of Debt Distress



Policies: Debtors

An environmentally-friendly debt restructuring option (Bolton et al. (2022)):

- The sole motivation for a commercial creditor to consider giving any form of debt relief to a sovereign borrower carrying an unsustainable debt load is to improve the likelihood that the balance of the creditor's claim can be repaid on its restructured terms.
- The trick in marrying debt relief and environmental protection is to find a technique that will enhance the market's perception of a country with a sustainable post-restructuring debt position while at the same time freeing funds that can be deployed for environment-friendly projects.
- This could be achieved by giving the sovereign debtor an option to discharge a portion of the foreign-currency debt service due on the new bonds it issues ...

Policies: Debtors (continued)

An environmentally-friendly debt restructuring option (Bolton et al. (2022)):

- ... in connection with the transaction through the payment of the local currency equivalent of that portion to fund a conservation project within its own territory and approved in advance advance by the lenders.
- The project could be monitored and administered by an independent third party such as an NGO or a United Nations organization.
- A failure by the sovereign to fund the project with local currency on any payment date would mean that the sovereign debtor would owe the full amount of the foreign-currency debt service payment due under the new bonds on that date.

Policies: Governments

Climate financing should be provided conditional on the phase out of coal. The phase out of coal and phase in of renewables should happen concurrently.

1. Helps to ensure decoupled growth and macro-financial stability
   - Maintains energy supply (reduction in coal production is roughly matched with an increase in renewable energy)
   - Helps reduce volatility in energy prices
2. Creates a "carbon arbitrage"
   - Helps avoid carbon leakage (a shift of coal production to foreign countries), because energy demand can be met with renewables
   - Hence, the phase out of coal explicitly (and replacement with renewables) reduces emissions and enables the realization of a "carbon arbitrage"
   - Note: instead of a global Coasian deal, regional Coasian bargains that also be struck (potentially lowering transaction costs and obstacles to bargaining). Each will be effective in its own right (as local emission reductions can be achieved) and all will add up to a global deal

Policies: Climate Financing the Coal Phase Out

- To finance the phase out of coal in a Coasian coalition it must be in the interest of three key stakeholders to participate in the four pillar public-private partnership described before:
  1. Governments
  2. Coal companies $\rightarrow$ discussed now
  3. Investors
- Coal companies get compensated at a minimum their opportunity costs of coal.
- Hence, coal companies should be at a minimum *indifferent* between continuing coal operations and shutting coal mines down early.
  - Example: Germany achieved a "social equilibrium" by paying coal companies for their opportunity costs of coal in turn for shutting plants down early (see box in our paper)

Policies: Climate Financing the Coal Phase Out

- To finance the phase out of coal in a Coasian coalition it must be in the interest of three key stakeholders to participate in the four pillar public-private partnership described before:
  1. Governments
  2. Coal companies
  3. Investors → discussed now
- Investments by multilateral development banks (funded by governments) into the junior tranches of ABSs help de-risk investments by capital markets into senior tranches. These could then be sold with investment grade rating.
- As the renewable plants built to replace coal would generate a profit stream, the de-risked investments into renewables could become appealing from a risk-return perspective.
- Significant scaling of markets needed.
  - Currently ESG market is around \$3 trillion globally and the ABS market around \$2 trillion.
  - \$26 trillion needed from capital markets to replace coal with renewables (between approx. \$1/2 to \$2 trillion a year, with a front-loading of \$3 trillion).

Conclusion

- Our analysis makes a simple but powerful observation: phasing out coal and replacing it with renewables is not just a matter of urgent necessity to limit global warming to 1.5°C, it is also a source of considerable net economic and social gain
- From a Coasian perspective it is sound economic logic to compensate losses incurred from phasing out coal and to account for capital expenditures to replace the energy from coal, and to link these to social benefits of avoided emissions
- The world could realize a net total gain of around 78 trillion US dollars (1.2% of current world GDP every year until 2100)
- The *quantified* climate financing needs are indeed large ($\sim$29 trillion dollars), but our point is that they are nonetheless small relative to the social benefits ($\sim$107 trillion dollars) and could be financed in large part by capital markets.
- It is thus in our interest to seek to overcome any hurdles that prevent the great carbon arbitrage from being reaped.

References I

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Table: Units of variables in our model and standard conversion functions.

Name	Variable/Function	Unit/Definition
Social cost of carbon	θ	Dollars per tonne of CO_2 ($\$/tCO_2$)
Emissions	E	Tonnes of CO_2 (tCO_2)
Coal production	P	Tonnes of coal
Unit coal profit	π	Dollars per tonne of coal ($/tonne of coal)
Renewable capacity	S	Giga Watt (GW)
Renewable capacity addition	G	GW
Unit investment costs	i	Dollars per Giga Watt ($/GW)
Renewable energy per year	R	GJ
Function converting renewable capacity to energy per year	$h(x)$: GW $\rightarrow$ GJ/year	$x \times$ [#seconds per year], for $x = G, S$ *
Function converting energy per year to renewable capacity	$h^{-1}(y)$: GJ/year $\rightarrow$ GW	y/[#seconds per year], for $y = R, g(P)$ *
Function converting coal production to coal energy	$g(P)$: tonnes of coal $\rightarrow$ GJ	$P \times 29.3076$ **

* # seconds per year = $365.25 \times 24 \times 3600$.

** 1 tonne of coal equivalent is 29.3076 GJ.