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The Great Carbon Arbitrage

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Abstract

We measure the gains from phasing out coal as the social cost of carbon times the quantity of avoided emissions. By comparing the present value of the benefits from avoided emissions against the present value of costs of ending coal plus the costs of replacing it with renewable energy, our baseline estimate is that the world can realize a net gain of 77.89 trillion USD. This represents around 1.2% of current world GDP every year until 2100. The net benefits from ending coal are so large that renewed efforts, carbon pricing, and other financing policies we discuss, should be pursued.

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1 Introduction

When it comes to internalizing negative externalities, economists have adopted two different approaches. One is associated with Pigou and seeks to use taxation (or pricing of the social harm) to fully reflect the social cost of an economic activity (Pigou (1920)). The other approach is associated with Coase and seeks to attain an efficient social outcome through bargaining and contracting (Coase (1960)).

Much of the economic analysis on climate change (and the negative impact of greenhouse gas (GHG) emissions on the climate) has taken a Pigouvian approach, seeking to determine the optimal level of a carbon tax as indicated by the social cost of carbon (SCC) and then let markets freely respond to this tax. There is by now a sizeable literature on integrated assessment models (IAM) providing quantitative estimates of the size of the SCC (see e.g., Gollier (2012), Llavador (2015), Heal (2017), and Daniel et al. (2019)). It is a measure of the incremental harm from climate change caused by additional carbon emissions. As such the SCC is a measure that is conditional on the level of CO_2 in the atmosphere. The higher that level the more powerful is the greenhouse effect and therefore the higher are the expected physical damages.

We build on this literature here by giving a quantitative estimate of the social surplus that can be attained from avoiding emissions. We seek to provide an answer to the following question: how much would the world benefit from phasing out fossil fuels and replacing them with energy from renewable sources such as wind power and solar radiation?

We focus here on quantifying the gains from phasing out coal. Climate change mitigation involves many complex, multidimensional, policy interventions and it is impossible to quantify benefits of all these interventions in one study. It is also beyond the scope of this paper to determine how best to balance all these interventions. The focus on coal is natural given that coal emits roughly 2 times as much carbon into the atmosphere per unit of energy production as natural gas, and roughly 1.5 times as much as oil.[1] On this basis alone, a cost-benefit analysis would indicate that it is most economically efficient to begin the energy transition by phasing out coal.

Indeed, under a Coasian bargain coal companies would be compensated for losses

[1]See: https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

they incur from ceasing their operations, and the social benefits from avoided emissions would be assessed net of both opportunity costs of phasing out coal and capital expenditures required to install the replacement renewable energy capacity. Gross social benefits from all avoided emissions – capturing both the private economic gains of individuals directly involved in the transaction as well as the external economic gains of third parties not directly involved in the transaction – are measured by the SCC times the quantity of avoided emissions. Indeed, if an efficient global emissions trading system (ETS) were in place, the equilibrium carbon price in this market would be equal to the SCC. It would then be possible to reap a total gross revenue from phasing out coal equal to the carbon price (SCC) times total avoided emissions. Shorting coal and going long replacement renewables could then result in a net gain, or a carbon arbitrage.

We estimate that the net gain to the world of phasing out coal is very large indeed. By comparing the present value of benefits of avoided carbon emissions from phasing out coal, starting in 2024 on a phase-out schedule in line with the Net Zero 2050 scenario of the Network for Greening the Financial System (NGFS), to the present value of costs of ending coal plus costs of replacing it with renewable energy, our baseline estimate is that the world could realize a net total gain of 77.89 trillion US dollars. This represents an increase of around 1.2% of current world GDP every year until 2100. Per tonne of coal, this represents a net gain of around \$125, and per tonne of avoided coal emissions, this represents a net gain of \$55.

Our baseline estimate of social benefits of phasing out coal relies on a social cost of carbon of 75 dollars per tonne of CO_2 (tCO_2) – in line with the lower-end estimates of the SCC in Vernon et al. (2021) and consistent with IMF (2019). We also conduct a sensitivity analysis for all our main parameters, including the mix of replacement energy sources and different values of the SCC, ranging from a minimum of \$61.4/tCO_2 to a maximum of \$168.4/tCO_2. For the less conservative estimate of \$168.4/tCO_2 (Pindyck (2019)), we find that the carbon arbitrage grows from \$77.89 to \$211.03 trillion. The associated min-max estimates grow from (62.45, 120.97) to (195.60, 309.66) trillion dollars, or from (1.0, 1.9) to (3.0, 4.8) percentage points of GDP. Our baseline estimates are much closer to the minimum values than to the higher end values, indicating that we have not only chosen a conservative SCC in our baseline, but also chosen conservative estimates for our other parameters.

To determine the size and opportunity costs of avoided emissions we rely on a detailed dataset, put together by the Asset Resolution (AR), on companies' historical and projected global coal production based on the aggregation of production at the plant level, as well as financial data from Orbis. To calculate investment costs for different types of renewable energy investments needed to replace coal we use data from IRENA (2021b).

Our analysis in this paper makes a simple but powerful observation: phasing out coal is not just a matter of urgent necessity to limit global warming to 1.5°C. It is also a source of considerable economic and social gain. Faced with the prospect of such an enormous gain it is puzzling for any economist inculcated with the tenets of "there is no such thing as a free lunch" and "no money left on the table" how the world could indeed leave so much money on the table. Even faced with "high transaction costs" and "poorly defined property rights", to use the main notions behind the Coase Theorem (Coase (1960)), it is astonishing that a Coasian bargain of such proportions could be left untouched.

One of the main goals of the 26th Convention of Parties (COP26) held in Glasgow in November 2021 was to reach a global agreement to phase out coal. In the end this goal was not attained as a number of major emerging markets that heavily rely on coal for energy production did not sign on. The 197 parties of the convention could only agree on accelerating independent efforts towards the phase-down of unabated coal power.[2] A smaller group of forty countries, however, did agree to sign the Global Coal to Clean Power Transition accord. They noted that "coal power generation is the single biggest cause of global temperature increases", and "recognized the imperative to urgently scale-up the deployment of clean power to accelerate the energy transition."[3]

From a Coasian perspective it is sound economics to compensate losses incurred from phasing out coal and to account for capital expenditures needed to replace the energy from coal, as well as to link the social benefits of avoided emissions to these costs. If compensation was a more important part of global agreements, and if the yet to be fulfilled promise to transfer 100 billion dollars a year in green finance (and possibly much more) to developing countries had been made conditional on phasing out coal extrac-

[2]See Glasgow Climate Pact: https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf.

[3]See the Global Coal to Clean Power Transition Statement: https://ukcop26.org/global-coal-to-clean-power-transition-statement.

tion and keeping coal underground, a global agreement could be reached more easily. Conditioning climate financing to build renewables on phasing out coal not only makes sense from a Coasian perspective but also enhances macro-financial stability for at least two reasons. First, phasing in renewables and phasing out coal in tandem helps secure sufficient energy supply and avoid energy shortages and energy price spikes. Second, compensating the opportunity costs of phasing out coal is important to support local economies previously reliant on coal mining.

To gain further insight into the size of transfers that may be required to pay for the replacement of coal with renewable energy, we further break down on a regional basis where these costs would be incurred. We find that the present value of total conditional climate financing needs to end coal globally are around 29 trillion dollars, in line with renewable investment needs estimated in other studies (e.g., McKinsey (2022)).[4] This represents an annual global climate financing need between half a trillion and two trillion dollars, with a front-loaded investment this decade, which we estimate reaches up to around 3 trillion. Put differently, investment costs for the developed world to cover these global annual climate financing needs would be in the range of 0.5% to 3.5% of wealthy countries' GDP, with a front-loading at around 6% of wealthy countries' GDP.

This clearly represents a major challenge. But as the proverb goes, there is no gain without pain, and as we show here the gain is colossal, far larger than the pain. At the COP26 it was emphasized that no government in the world has enough money to make such sizeable investments and transfers, pointing to the difficulties in gaining sufficient political support for public funding of such a large investment program, and calling on the private sector to steer the required funding to renewable energy investments. Yet, more support could be obtained by pointing towards the enormous benefits to be gained from these investments and by not focusing only on costs.

The climate financing needs are indeed large, but our point is that they are nonetheless small relative to the social benefits. These social benefits are too easily forgotten, as is the case for example with the notion of "stranded assets". The valuation of these assets only reflects opportunity costs in terms of lost earnings from keeping the asset underground. But the correct valuation should also include benefits in terms of avoided

[4] Note that we refrain from making a statement as to whether existing or new climate finance commitments should be deployed to replace phased-out coal with alternative energy (e.g., renewables). We simply provide an estimate of costs to do so.

emissions. As we show, the "social stranded asset value" is large and positive when the resource is left unexploited, but negative when exploited, the opposite of how fossil fuel reserves are currently valued. The funds promised to poor countries for their energy transition are not a handout; they are an investment with an enormous social return that far exceeds the cost. Most of the funding of these investments can indeed come from the private sector, as we discuss in the policy section, but a significant amount of public money to enhance these investments will still be needed (see Arezki et al. (2016), and Bolton et al. (2020). In light of the enormous net gains from phasing out coal we identify in this paper, it is in everyone's interest to work to overcome current obstacles to striking a global agreement to phase out coal. In the absence of global carbon taxation at the SCC, which we view as a first-best solution, such 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).[5]

The outline of the remainder of the paper is as follows. Section 2 describes our data. Section 3 describes our methodology. Section 4 reports our results. Section 5 links our findings to the literature. Section 6 discusses policies to reap the carbon arbitrage. Section 7 provides concluding comments.

2 Data

We make use of a unique data set of Asset Resolution (AR) on the historical and projected global coal production aggregated from production at the asset level – henceforth referred to as "plant level". For each coal company, AR's company data capture the underlying plant-level characteristics for each unique combination of energy use (i.e. power or non-power sector), coal technology (e.g. lignite, sub-bituminous, bituminous, anthracite), coal technology sub-type (e.g. surface, underground), plant country, and geolocation. The data also capture for each coal plant its ownership structure, from its direct owner to any of its parents or ultimate parents.[6] The total number of coal companies in our

[5]See: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf.

[6]AR data also specifies the country in which the ultimate parent company is located.

data set is 2027, of which 1549 are ultimate parent companies, and its total number of coal plants is 6590. Of these coal plants, 4466 are directly linked to the ultimate parent company and 2124 are owned by subsidiaries. For each coal plant, the underlying data that feed into the company-level data specify its emission intensity (in tonnes of CO_2 per tonnes of coal) as of 2020, as well as its historical production from 2013-2021 (in tonnes of coal) and the projected production from 2022 to 2026. The emission intensity of each coal-mining plant captures its scope 1 and 3 CO_2e emissions.[7] The scope I emission intensity captures methane emissions from coal mining, which are converted into CO_2 emission equivalent (CO_2e).

These data cover at least 85% of global coal production according to AR. Based on this AR data our estimate of global coal production in 2020 is 6.41 Giga tonnes (Gt). In combination with the AR emission intensity data, our estimate of global scope I and III emissions from coal in 2020 is 14.53 Giga tonnes of CO_2e. Both the AR coal production and emission estimates are in line with the authoritative estimates of the Network for Greening the Financial System (NGFS (2021)), the BP Statistical Energy Review (BP (2021)), the International Energy Agency (IEA (2021e)), and the Global Enery Monitor[8]; see Table 1.[9]

Table 1: A comparison of the estimated global coal production (in giga tonnes of coal) and coal emissions (giga tonnes of CO_2e) in 2020 between the AR data and of a list of authoritative bodies. A dash indicates no estimate is available.

	AR	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

[7]Scope 1 covers direct emissions from owned or controlled sources. Scope 3 includes all other indirect emissions that occur in a company's value chain. The vast majority of Scope III emissions for coal mining companies consists of the combustion of thermal and metallurgical coal (or product end use). The AR data does not cover Scope 2 emissions, which capture indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company, since this is negligible for coal mining companies.

[8]See: https://globalenergymonitor.org/projects/global-coal-plant-tracker/.

[9]We also verified that the estimates of coal production and coal emissions by AR are consistent with those of the IEA for the years 2019 and 2021.

For comparison, 2020 global carbon emissions from the fossil fuels (i.e. gas, oil and coal) are estimated to be 34.81 $GtCO_2e$ by the Global Carbon Project. Hence, coal scope I and III emissions accounted for around 41.7% of fossil fuel emissions.

Table 2 shows the average scope I and III emission intensity (in tonnes of CO_2e per tonne of coal) globally for the different coal types in our AR data. We weigh the emission intensity of a coal company (derived from the weighted-emission intensity of its coal plants) by its 2020 coal production to get the weighted-average in Table 2, and also show the 5% and 95% quantiles. AR estimates the emission intensity of coal plants based on the capacity factor and cycle efficiency, where possible specific to the asset, whereas the combustion emissions intensity for the fuel is from a standard methodology by the Intergovernmental Panel on Climate Change (IPCC).[10] Variability among emission intensities of coal plants using the same type of coal arises from differences in the underlying assets across technologies, production processes, and regions. As Table 1 showed, combining AR emission intensity data with its production data, we obtain global coal emissions consistent with authoritative estimates, indicating AR emission intensity estimates can be relied upon.

Table 2: Average scope I and III emission intensity (in tonnes of CO_2e per tonne of coal) weighted by 2020 coal-plant production, as well as the 5% and 95% percent quantiles of the emission intensity.

Lignite	Bituminous	Sub-Bituminous	Anthracite
1.26	2.53	1.87	2.74
(1.25, 1.39)	(2.48, 2.64)	(1.86, 2.01)	(2.66, 2.82)

The AR carves out how much of global coal mining is deployed in the power sector. The total capacity in the coal power sector is 1938 GW in 2020, which again is consistent with 2020 estimates of NGFS, BP Statistical Energy Review, the IEA and the Global Energy Monitor. Since the coal mining emission intensities already capture scope III emissions, we should not separately count the amount of emissions that can be avoided

[10]See: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf. The emission intensity for stationary combustion, based on the low heat value approach, is 101,000 kg of carbon dioxide per terajoule ($kgCO_2/TJ$) for lignite, 94,600 $kgCO_2/TJ$ for bituminous coal, 96,100 $kgCO_2/TJ$ for sub-bituminous coal, and 98,300 $kgCO_2/TJ$ for anthracite.

by phasing out coal in the power sector, as this would result in double counting.[11]

Coal Production Scenarios

To determine the size of avoided emissions from phasing out coal, we must estimate what coal production would have been under a business-as-usual-scenario and compare that to coal production under a net-zero pathway in line with the Paris accords. To estimate these, we make use of future scenarios of coal production produced by the Network for Greening the Financial System (NGFS (2021)), whose scenarios have become an industry standard in the financial sector and beyond. The NGFS considers a variety of different climate scenarios (see Figure 1) capturing how future energy production might evolve, some of which reflect a phase out of coal to move to net zero by 2050 (e.g. the Net Zero 2050 scenario), whereas others present the continuation of coal production over the course of this century in line with current policies (i.e. the Current Policy Scenario). The NGFS Current Policy Scenario is a business-as-usual scenario.

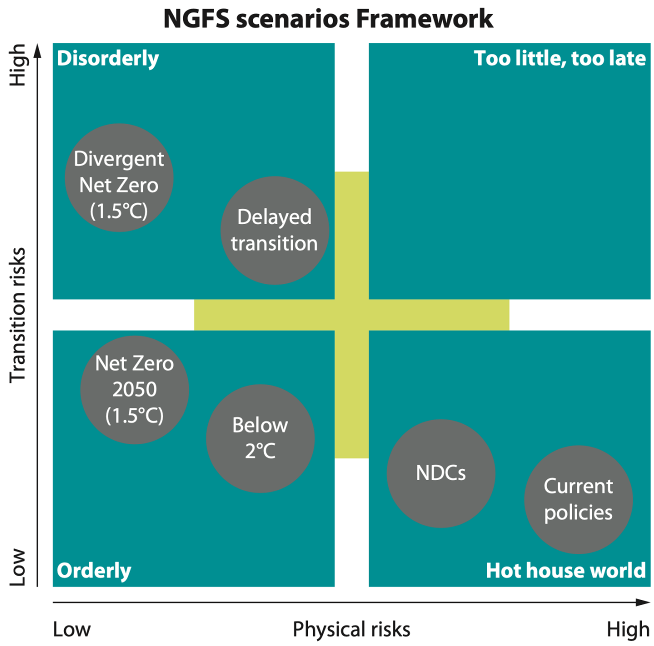

Figure 1: NGFS Climate Scenarios.

We use the quinquennial, global NGFS projections – based on the GCAM5.3-NGFS model – of annual coal production over the time period 2020-2100 for both the Current

[11]The AR data contains plant-level data on the capacity and emissions of coal power companies, numbering 3534 in total with 7735 plants. For each plant in the coal power sector, it captures its scope I and II emission intensity.

Policy and Net Zero 2050 scenario.[12] We linearly interpolate each quinquennial projection to obtain an estimate of the projected annual production amount. Since our plant level data of global coal production makes production projections only up to 2026, we use the NGFS scenarios to extrapolate how coal production of each coal plant would continue from 2027 onwards under the Current Policy Scenario scenario. In particular, we assume that the percentage change in coal production of a typical coal plant from 2027 onwards – using AR-2DDI data on its projected production in 2026 as a starting point – follows the same trend as that observed under the annualized NGFS Current Policy Scenario. Similarly, to obtain the pathway of coal production under the Net Zero 2050 scenario, we assume that the percentage change in coal production at the plant-level follows the trend of the Net Zero 2050 scenario from $t + 2$ onwards. We add a two-year lag to allow for sufficient time to implement the carbon arbitrage. We also consider a scenario where coal production is completely phased out from $t + 2$ onwards, representing the maximum gain in avoided emissions that could be obtained with a complete halt to coal production rather than a gradual phase-out as implied in the Net Zero 2050 scenario.

The projections above yield the following global coal production scenarios – as an aggregate of plant-specific production scenarios – depicted in Figure 2. We also plot the Nationally Determined Contributions (NDC) scenario as a benchmark compared to the Net Zero 2050 scenario. NDCs reflect promises made by each Party of the Paris Agreement (Article 4, paragraph 2) to reduce emissions, and is shown to fall far short of what is required to reach net zero by 2050. The right plot of Figure 2 shows how the various scenarios affect global coal emissions assuming – as we do – that the emission intensity of each coal plant remains equal to its 2020 value. The difference in coal production in a given year between the Current Policy Scenario and the Net Zero 2050 in the left plot of Figure 2 represents the annual amount of coal that must phased out to align with the Net Zero 2050 pathway. The same difference in the right plot of Figure 2 represents the amount of coal emissions that can be avoided annually by phasing out coal at this pace.

While we include the Halt to Coal Production scenario in Figure 2 as a theoretical case, it is unlikely that such scenario is feasible in practice. Instead the Net Zero 2050 scenario of the authoritative NGFS – our baseline – represents a feasible pace to phase out coal, as is widely acknowledged. Ending coal in the power sector, which our

[12] As a sensitivity analysis, we also study our results under the regional NGFS projections, based on the GCAM5.3-NGFS model, of these two scenarios.

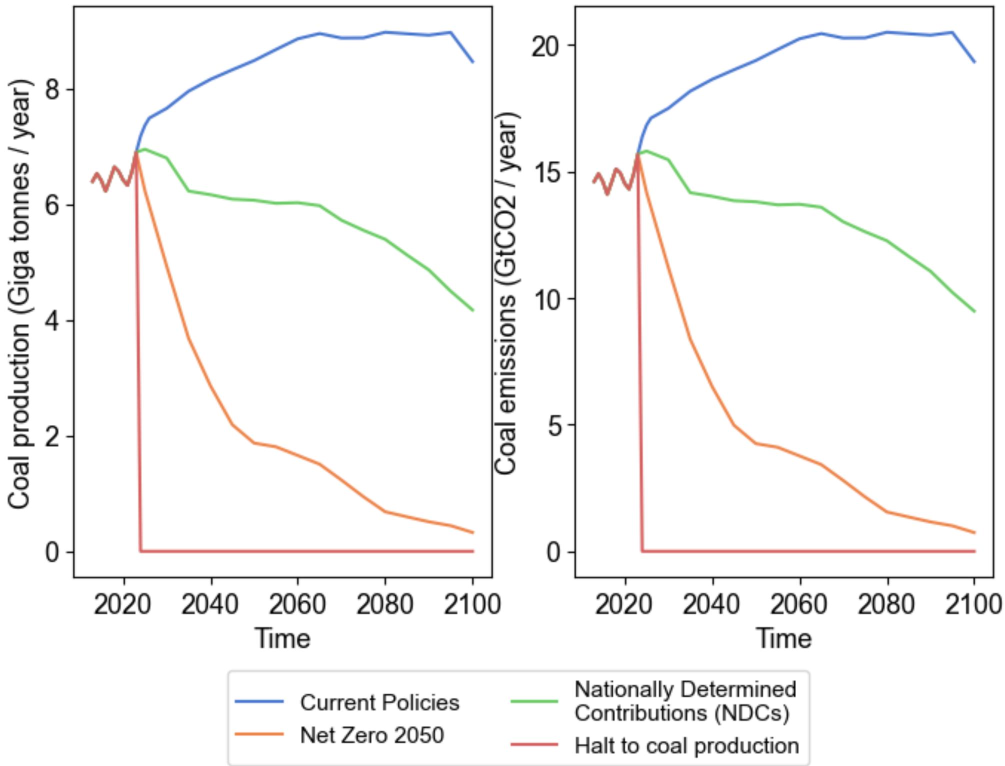

Figure 2: Global coal production under different scenarios (left plot) and associated annual global emissions (right plot).

phase out scenario encompasses, is the lowest hanging fruit, and must be largely realized this decade (IEA (2021d)). Coal will remain being deployed in the upcoming decades in certain hard-to-abate sectors, such as steel, as can be observed from the Net Zero 2050 scenario not dropping below 2 Gt of coal annually – even by 2050. We assume any coal use that the NGFS projects to be feasibly phased out under the Net Zero 2050 scenario can be replaced with renewables. Of course this is a strong assumption for some cases, but we view it as a realistic first-order approximation.[13]

Opportunity Costs of Coal

To calculate the opportunity cost of phasing out coal, we obtain the operating revenue, profit margin, taxes, interest payments, and depreciation allowances for each coal com-

[13]In the AR data, around 16.54% of global coal use in 2020 is in the power sector, using a capacity factor for coal power of around 50%, in line with IEA (2021a). The power sector can be made entirely coal free by switching to renewables (IEA (2021d)). Heating and industrial processes (including coal used for steel making) – two other major areas of coal consumption – can also largely be electrified and thus run on renewables (IEA (2021d)). Jacobson et al. (2017) provide a road map to power energy infrastructures (i.e., electricity, transportation, heating/cooling, industry, agriculture/forestry/fishing) on renewable energy. Implementation challenges in the timely phase out of coal and replacement with renewable energy could include a lack of suitable locations, long implementation cycles, and bottlenecks in the supply of inputs and raw materials.

pany over the period 2010-2020 from Orbis. This enables us to compute the free cash flow for each coal company over the period 2010-2020, given by the operating revenue times the profit margin plus depreciation allowances net of taxes and interest payments. For simplicity, we assume that the future coal profit per tonne of coal production remains constant over time for each coal company, and is equal to the median unit coal profit, averaged over [2010-2020], of the top-10 coal companies by 2020 coal production.[14] The unit coal profit of a coal company in a given year is taken to be its free cash flow divided by its coal production that year. This gives a median free cash flow of 0.34 dollars per tonne of coal production. To obtain the median, we focus only on pure coal companies to avoid mixing our estimate of free cash flows with cash flows generated by other segments of business outside of coal. We also apply the median free cash flow of 0.34 to state-owned coal companies in our AR data for which Orbis financial data is not available. As a robustness check, we in addition compute the opportunity costs under the assumption that the unit coal profit of each coal company is equal to the median of the top 100 pure coal companies, giving a free cash flow of 0.58 dollars per tonne of coal. We take the median as a robust proxy for the unit coal profit of individual coal companies, since individual coal company estimates by Orbis revealed unrealistically large outliers.

We discount expected free cash flows of each coal company with the weighted-average cost of capital (WACC), assuming a constant beta, constant risk premium and a constant risk-free rate. We take the risk-free rate to be the nominal 30Y US treasury yield, 2.08%, and the global risk premium to be the average excess CAPE yield over the last decade of around 3% minus 1% to account for the greater diversification benefits that an investor can obtain by being globally diversified.[15] Historically the risk premium on a global index has been around one percentage point lower than the risk premium on the S&P 500 (see e.g., Dimson et al. (2003)). To obtain a robust estimate of coal company betas, we regress the MSCI World/Metal & Mining Index against the MCSI World Index using time series data from January 1 2017 until January 1 2022, giving a beta of 0.91. We assume that target leverage of each coal company is equal to the the

[14]While our assumption that future coal profits remain equal to what they are today is admittedly strong, our results in Section 4 reveal that the opportunity cost of coal is roughly four magnitudes smaller than the benefits of phasing out coal, and roughly three magnitudes smaller than the investment costs in renewables. Hence, even if coal profits fluctuate somewhat in the future it is implausible that our central estimate of the carbon arbitrage would be much affected.

[15]See: `http://www.econ.yale.edu/~shiller/data.htm`.

weighed-average leverage of companies in the MSCI World/Metal & Mining index as of 2021, giving a target leverage of debt over enterprise value of 52%. We further assume that the corporate income tax rate is 15%.[16] As a robustness check, we use the average global risk premium over the last 100 years, which we take to be the excess CAPE yield of Shiller averaged over 1922-2022 minus 1%, giving 3.87%.[17] We obtain a discount rate of 2.8% (and 3.6% with the average risk premium).[18]

Investment Costs in Renewables

We obtain the global average of the investment costs in renewables – for solar PV, wind onshore, and wind offshore – as well as their respective global cumulative installed capacity up to 2020 from IRENA (2021b) and IRENA (2021a); see Figure 3. We assume that investment costs in renewables at the start date $t = 2022$ of our analysis are equal to the latest observed data of 2020. In practice, regional differences in investment costs exist, but since renewable investment costs are empirically shown to be driven down by global cumulative installed capacity – in a process of global "learning" or "experience" (Hepburn et al. (2020), Way et al. (2021)) – the global average represents a robust proxy.

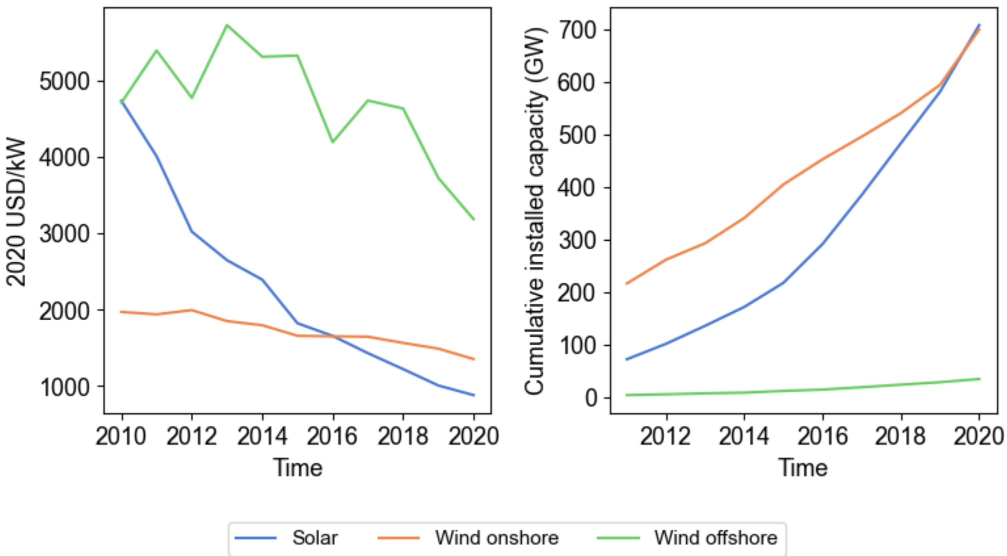

Figure 3: Investment costs in renewables (USD/KW) in the left plot and cumulative installed capacity in renewables (GW) in right plot, over 2010-2020.

[16]This is in line with the a global minimum corporate tax rate agreed in October 2021 by 137 countries and jurisdictions under the OECD/G20 Inclusive Framework on Base Erosion and Profit Shifting (BEPS). See: `https://www.oecd.org/tax/beps/`.

[17]This is in line with the global risk premium of 4.4% estimated by Dimson et al. (2003) over 1900-2003.

[18]We use the global risk premium over the last 10 years as our baseline to obtain a conservative estimate of the net gain of phasing out coal, since the discount rate applied to costs of phasing out coal is somewhat smaller than the historical average estimated by Dimson et al. (2003).

We next lay out the detailed model of our cost-benefit analysis. Units of variables and standard definitions of conversion functions in our model are summarized in Table 10 in the Appendix.

3 The Great Carbon Arbitrage

The size of the carbon arbitrage is given by any positive difference between the present value of benefits of avoiding carbon emissions from coal production minus the present value of costs of avoiding such emissions, taking into account opportunity costs of coal and investment costs in renewable energy. The global size of the carbon arbitrage $A_{t,T}^{s_1,s_2,s_r,\theta}$, our focus in this study,[19] is then given by the present value at time t of benefits $B_{t,T}^{s_1,s_2,\theta}$ minus costs $C_{t,T}^{s_1,s_2,s_r,\theta}$ of avoiding coal emissions, i.e.

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

The benefits $B_{t,T}^{s_1,s_2,\theta}$ of reducing coal production over the period $[t+2, T]$ from a business-as-usual production scenario s_1 to a lower production scenario s_2 are priced at the social cost of carbon θ. We assume for simplicity a constant SCC. As the climate is warming and more emissions are accumulated in the atmosphere the marginal social cost of an additional ton of CO_2 will be rising. As we explain further below, our constant SCC assumption essentially assumes that the discount rate is equal to the growth rate in the SCC. The present value of costs $C_{t,T}^{s_1,s_2,s_r}$ of avoiding coal emissions does not only depend on the coal-phase-out scenario s_2 relative to a business-as-usual scenario s_1, as well as the time horizon $[t+2, T]$ over which the coal phase out takes place, but also depends on the replacement scenario s_r specifying with what mix of renewables phased-out coal is substituted.

We examine the size of the carbon arbitrage implied by the difference in plant-

[19]The formulas can be easily adapted to estimate the size of the carbon arbitrage for individual firms, individual nations, or individual regions. This can be done under the assumption that the damages from emitting an additional tonne of carbon into the air, and thus the benefits of avoiding emissions, as captured by the SCC, are homogeneously distributed across the world. In practice this is not true, as the impacts from climate change are distributed heterogeneously across the world (IPCC (2021)). To estimate the carbon arbitrage for individual regions or countries, a regional SCC could be used (Nordhaus (2017)). Since regional estimates are insufficiently reliable (Nordhaus (2017)), we focus on the global carbon arbitrage, for which the global SCC properly accounts for climate damage estimates in aggregate.

level coal production between the Current Policy Scenario (CPS), s_1, and the Net Zero 2050 scenario, s_2. To quantify the upper bound of the carbon arbitrage, we also examine a scenario s_2 in which coal production is halted completely starting from $t+2$ and replaced with renewables.

We study the carbon arbitrage gain associated with an arbitrage that is executed over the period $t+2 = 2024$ up to $T = 2100$, since this is the horizon over which coal production is gradually phased out in the NGFS Net Zero 2050 scenario (recall Figure 2). The lag of two years is introduced to give time to set up the carbon arbitrage. We also study the size of the arbitrage opportunity from 2024 up to $T = 2050$ and $T = 2070$. The year 2050 is the net zero target for most developed countries, including the European Union, the United Kingdom, Canada, Japan, and New Zealand.[20] The year 2070, or earlier, e.g., 2060, is the net zero target for various emerging and developing economies, such as China, Saudi Arabia, and India. In practical terms, taking a shorter time horizon T for the carbon arbitrage means we evaluate only benefits of avoided emissions that accrue from costs made to avoid such emissions over [t+2,T]. Put simply, a shorter T means a shorter cost horizon.

We specify our parameter choices for the SCC θ and the replacement scenario s_r in detail in the remainder of the methodology section, which describes the present value of benefits $B_{t,T}^{s_1,s_2,\theta}$ of avoided coal emissions and its costs $C_{t,T}^{s_1,s_2,s_r}$.

3.1 Benefits of Avoiding Coal Emissions

The present value of global benefits $B_{t,T}^{s_1,s_2,\theta}$ that can be reaped if each coal company $i \in \mathcal{C}$ (where $\mathcal{C}$ is the set of coal companies) were to reduce its CO_2 emissions by an amount $\Delta E_{i,\tau}^{s_1,s_2}$ 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 that are priced at the social cost of carbon θ. The emission reduction $\Delta E_{i,\tau}^{s_1,s_2}$ in year τ is given by the difference in coal emissions in year τ between the business-as-usual scenario s_1 and the phase-out scenario s_2; i.e. $\Delta E_{i,\tau}^{s_1,s_2} = E_{i,\tau}^{s_1} - E_{i,\tau}^{s_2}$.

[20] See the Energy & Climate Intelligence Unit: https://eciu.net/netzerotracker.

The amount of 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

$$E^s_{i,\tau} = \sum_{l \in \mathcal{L}_i} P^s_{i,l,\tau} \epsilon_{i,l}. \tag{3}$$ [21][22]

Coal company i thus reduces its emissions by $\Delta E^{s_1,s_2}_{i,\tau}$ in year τ by reducing its coal production in each of its plants l from its business-as-usual amount $P^{s_1}_{i,l,\tau}$ to an amount $P^{s_2}_{i,l,\tau}$ specified by phase-out-scenario s_2.

As we have highlighted above, the SCC is expected to grow over time as more CO_2 emissions accumulate in the atmosphere, causing more rapid and extreme temperature rise with all attendant physical and economic damages (Daniel et al. (2016), Dietz and Stern (2015)). Nordhaus (2017) estimates that the SCC is likely to grow in real terms at 3% every year up to 2050. We do not consider a growing SCC in our calculations for simplicity. However, we also do not discount SCC. Given that the growth rate of the SCC in real terms is in all likelihood higher than the long-term market interest rate used to discount a future SCC, we are, thus, potentially underestimating by a significant margin the size of social benefits from avoided emissions. With a real growth rate of the SCC of 3%, in line with Nordhaus (2017), and a discount rate of 2%, consistent with the discount rate governments (e.g., Germany, England, and the Netherlands) typically use when they consider emission-mitigating investment projects, the benefits from phasing out coal on a present value basis would grow by 1% a year.[23] But the SCC is likely to grow non-linearly as we get closer to climate tipping points. So, even letting the SCC

[21] As noted in Section 2, we define a coal company's plant to be any unique combination of energy use, coal technology, coal sub-technology and plant country of a coal company. So in practice, we sum the product of coal production and associated emission intensity for each unique combination of these.

[22] In so far as coal companies decide to invest in abating emissions from coal production so as to lower their plants' emission intensities at future dates $\tau \in (t, T]$, we may slightly overestimate global benefits of reducing coal production, since we assume that the future emission intensity of coal production at the plant level will remain equal to what it is today. Abatement of coal emissions remains as of yet cost ineffective (see Section 4), even under optimistic technological advance assumptions. This is in part due to high costs of early-demonstration projects hindering large-scale deployment (Lu et al. (2022)). Abatement of coal emissions is especially problematic in emerging and developing economies, where regulatory uncertainties, lack of public financial support, and risks around long-term ownership and liability of stored CO_2, as well as complex chains of capture-transport-storage, hinder the cost-effective deployment (IEA (2021d)).

[23] Taking into account a net growth of the benefits over time updates the benefit formula to $B^{s_1,s_2,\theta}_{t,T} = \theta \times \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \Delta E^{s_1,s_2}_{i,\tau} \times (1+r)^{(\tau-t)}$, where $r = 1\%$ in this case.

grow on a net basis by 1% a year rather than keeping it constant, as we do, would still result in a conservative estimate of the benefits of phasing out coal. A second reason why we do not discount the SCC is that the SCC already embeds a discount rate, so discounting the SCC again would amount to discounting it twice.

Another reason why we potentially underestimate significantly social benefits is that we take a conservative estimate of the SCC to start with.[24] We set the social cost of carbon equal to $\theta = 75$ dollars per tonne of CO_2 emissions – in line with lower-end estimates of the SCC in Vernon et al. (2021) and consistent with IMF (2019). The central estimates of Rennert et al. (2021) suggest a range of the SCC reaching up to \$168.4 and starting from \$61.4 per tonne of carbon,[25] whose min-max values we use for our sensitivity analysis. Pindyck (2019) estimates the SCC could reach even higher. He finds that the *average* SCC exceeds \$200 per tonne of carbon and could reach up to \$326 or beyond, based on opinion elicitation and quantitative modelling. It is the possibility of a catastrophic climate outcome that is the main driver of his *average* SCC, which is not properly accounted for in *marginal* SCCs estimated by IAMs.[26]

On a final and key note, societal benefits of building renewable capacity over [t+2,T] extend beyond time T, the final year phase-out costs are accounted for. The reason is that a renewable plant with a lifetime of l years will still be operational beyond year T as long as it is built after time $T - l$. It can thus help avoid coal emissions after year T, since renewable energy, which compared to coal generates insignificant emissions over its

[24] An extra reason why we potentially underestimate the benefits of phasing out coal is that we do not capture in our calculations profits accruing to renewable energy plants that are built to replace coal plants. The main reason is that estimating future profits of renewable firms remains speculative, especially seeing that market shares of renewable companies are still expected to significantly shift as renewables are phased in. We do discuss in the policy section, Section 6, that profits from renewables could make private-sector financing to replace coal with renewables attractive from a risk-return perspective.

[25] The central SCC estimates of \$61.4 and \$168.4/tCO2 in Rennert et al. (2021) correspond to 3% and 2% near-term stochastic discounting. The lower estimate takes the parameters $\rho = 0.8\%$ and $\eta = 1.57$ in the model of Rennert et al. (2021) and the higher estimate uses the parameter values $\rho = 0.2\%$ and $\eta = 1.24$. Their distribution of the SCC reflects both socioeconomic and climate uncertainty. Rennert et al. (2021) implement key recommendations from the National Academies of Sciences, Engineering, and Medicine that are guiding the efforts of the Interagency Working Group on the Social Cost of Carbon, an Obama-era body re-established by executive order on President Biden's first day in office. The interagency working group currently uses an interim social cost of carbon of \$51/tCO_2 and is expected to announce an updated value in 2022.

[26] The *average* SCC provides a guideline for policy over an extended period of time and contrasts to the *marginal* SCC estimated by IAMs. Pindyck (2019) argues that as a guide for policy the marginal SCC is of limited use, as tells us only what carbon tax should be today, assuming that total emissions are on an optimal trajectory, whereas the SCC will change from year to year. Our constant SCC assumption is consistent with an *average* (albeit conservative) SCC that holds over an extended period of time.

life cycle (see e.g., Hertwich et al. (2016)),[27] can be used instead. Truncating benefits at T drastically underestimates benefits of replacing coal with renewable capacity.

We describe in detail how we capture benefits that accrue beyond T in the Appendix and now turn to discussing the present value of costs of avoiding coal emissions.

3.2 Costs of Avoiding Emissions from Coal

The present value of global 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 associated with 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.

$$C_{t,T}^{s_1,s_2,s_r} = O_{t,T}^{s_1,s_2} + I_{t,T}^{s_1,s_2,s_r}. \tag{4}$$

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

$$O_{t,T}^{s_1,s_2} = \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \frac{O_{i,\tau}^{s_1,s_2}}{(1+\rho_i)^{(\tau-t)}}. \tag{5}$$

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

$$O_{i,\tau}^{s_1,s_2} = \Delta P_{i,\tau}^{s_1,s_2} \times \pi_{i,\tau}. \tag{6}$$

The difference in i's coal production between scenario s_1 and s_2 is given by $\Delta P_{i,\tau}^{s_1,s_2} = P_{i,\tau}^{s_1} - P_{i,\tau}^{s_2}$, where its coal production $P_{i,\tau}^{s}$ in year τ under scenario s given by the sum of its coal production of each of its plants; i.e. $P_{i,\tau}^{s} = \sum_{l \in \mathcal{L}_i} P_{i,l,\tau}^{s}$. Since predicting future

[27] Since emissions from renewables pale in comparison to coal emissions, and thus would not significantly alter the size of the carbon arbitrage, we omit emissions from renewables in our analysis for simplicity of exposition.

coal profits under different climate trajectories is inherently speculative, we make the simplifying assumption that the profit margin $\pi_{i,\tau}$ per unit of coal production is constant across all firms and time, and that the unit profit in future years $\tau \in [t+2, T]$ is equal to the median coal profit of the top 10 pure coal companies averaged over the last ten years. As a sensitivity analysis we also take the median of the top 100 coal companies.

To obtain the present value of coal company i's missed cash flow $O_{i,\tau}^{s_1,s_2}$ at future date τ, we discount it by its weighted average cost of capital (WACC), ρ_i. Company i's WACC is given by its average leverage λ_i (which we assume to be equal to its target leverage) multiplied with the risk-free rate ρ^f (we assume for simplicity its debt is risk free) times one minus its corporate income tax rate χ_i. We add to this one minus its leverage λ_i multiplied by its cost of equity. Its cost of equity equals – under the capital asset pricing model (CAPM) of Sharpe (1964) – the risk-free rate ρ^f plus its beta β_i times the risk premium $\mathbb{E}[R^M]$.[28] Coal company i's discount rate is thus given by

$$\rho_i = \lambda_i \rho^f (1 - \chi_i) + (1 - \lambda_i)(\rho^f + \beta_i \mathbb{E}[R^M]). \tag{7}$$

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 takes instead the average risk-premium over the last 100 years (i.e. $\mathbb{E}[R^M] = 3.87\%$), as well as $\rho = 5\%$.

To break down the global opportunity costs of coal into the opportunity cost of coal per country, we also write the present value of the global opportunity costs of coal $O_{t,T}^{s_1,s_2}$ (as defined in equation 5) as the sum of the present value of the opportunity costs $O_{y,t,T}^{s_1,s_2}$ of coal per country y, i.e. $O_{t,T}^{s_1,s_2} = \sum_{y \in \mathcal{Y}} O_{y,t,T}^{s_1,s_2}$, where $\mathcal{Y}$ is the set of countries.[29] Here we assume that opportunity costs accrue to the country where the coal plant is located, since local coal production supports income and taxes in the local economy (Clark and

[28]For robustness, we do not include other Fama-French risk factors, since the premia and loadings on these factors tend to be unstable over long periods of time.

[29]The present value $O_{y,t,T}^{s_1,s_2}$ of opportunity costs of coal in country y is given by the present value of the sum of missed free cash flows $O_{i,y,\tau}^{s_1,s_2}$ of coal plants of each coal company $i \in \mathcal{C}$ in country y; i.e. $O_{y,t,T}^{s_1,s_2} = \sum_{i \in \mathcal{C}} \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho_i)^{(\tau-t)}} \times O_{i,y,\tau}^{s_1,s_2}$. The opportunity costs of coal in country y in year τ are given by $O_{y,\tau}^{s_1,s_2} = \sum_{i \in \mathcal{C}} O_{i,y,\tau}^{s_1,s_2}$. The opportunity costs of coal company i in country y in year τ is given by the difference in its coal production between scenario s_1 and s_2 in country y in year τ, $\Delta P_{i,y,\tau}^{s_1,s_2}$, times its unit coal profit π; i.e. $O_{i,y,\tau}^{s_1,s_2} = \Delta P_{i,y,\tau}^{s_1,s_2} \times \pi$. Company i's production in country y under scenario s is given by the sum of its coal production of each of its plants $l \in \mathcal{L}_i^y$ in country y ($\mathcal{L}_i^y$ is the set of plants of company i in country y); i.e. $P_{i,y,\tau}^s = \sum_{l \in \mathcal{L}_i^y} P_{i,y,l,\tau}^s$. Here $P_{i,y,l,\tau}^s$ denotes i's coal production in country y at plant l at time τ under scenario s. The difference in coal production of company i in country y between scenario s_1 and s_2 in year τ is given by $\Delta P_{i,y,\tau}^{s_1,s_2} = P_{i,y,\tau}^{s_1} - P_{i,y,\tau}^{s_2}$.

Zhang (2022)).[30] We next turn to the estimation of the present value of investment costs in renewables to replace phased-out coal.

3.2.2 Investment Costs in Renewable Energy

The present value of investment costs $I_{t,T}^{s_1,s_2,s_r}$ in 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 business-as-usual scenario s_1, i.e.

$$I_{t,T}^{s_1,s_2,s_r} = \sum_{y \in \mathcal{Y}} I_{y,t,T}^{s_1,s_2,s_r}. \tag{8}$$

The present value of investment costs in country y is given by the discounted value of investments that must be made in country y to compensate for the loss of $\Delta P_{i,y,\tau}^{s_1,s_2}$ coal production in each year $\tau \in [t+2, T]$, i.e. $I_{y,t,T}^{s_1,s_2,s_r} = \sum_{\tau=t+2}^{T} \frac{I_{y,\tau}^{s_1,s_2,s_r}}{(1+\rho)^{(\tau-t)}}$.[31] The production loss $\Delta P_{i,y,\tau}^{s_1,s_2}$ in country y is a function of the production loss of each plant in country y.

We compute annual investment costs $I_{y,\tau}^{s_1,s_2,s_r}$ in renewable energy per country y rather than per coal plant in country y, because it seems most reasonable to assume that replacing lost coal production with renewable energy does not happen at the level of the coal plant but at the level of the country. Coal companies do not necessarily have the right skills to morph partially or fully into a renewable company. Alternatively, we could assume that any shortfall in energy because of a coal phase out across the globe is compensated with renewable capacity built anywhere in the world. Our model could easily accommodate this by dropping the country subscript y in equations 9 to 14. We do not make this assumption, in part because individual countries typically want to ensure domestic renewable energy security without having to rely on imports, and in part because transmitting renewable energy over long distances, crossing multiple countries, is expensive or impossible. Indeed, increasing domestic supply capacity using local energy sources makes positive contributions to energy security (IEA (2007)).

[30] Our data easily accommodate doing the calculation based on the alternative assumption that opportunity costs accrue to the country of the headquarters of the ultimate parent company.

[31] Here we assume that the discount rate ρ for a renewable energy commodity is the same as that applying to coal companies, since both produce energy commodities. As a robustness check, we explore how our estimates change if coal companies faced a higher climate-risk premium of fifty basis points. We also assume for simplicity that the cost of capital of obtaining financing for renewables is the same across countries. Since the gross benefits from phasing out coal far exceed the costs, this simplification will not affect our headline result on the net gain from phasing out coal.

The investment cost $I_{\tau}^{s_1,s_2,s_r}$ that must be made in year τ in country $y \in \mathcal{Y}$ to build renewables to replace coal is given by the sum of renewable capacity that must be installed times the unit investment costs of each renewable energy type, i.e.

$$I_{y,\tau}^{s_1,s_2,s_r} = \sum_{q \in \mathcal{R}} G_{y,\tau}^{s_1,s_2,s_r,q} \times i_{\tau}^{q,s_1,s_2,s_r}. \tag{9}$$

Here $G_{y,\tau}^{s_1,s_2,s_r,q}$ is the renewable capacity that must be built in year τ of renewable energy type $q \in \mathcal{R}$ to make up for any shortfall in energy $D_{y,\tau}^{s_1,s_2,s_r}$ resulting from the phase out of $\Delta P_{y,\tau}^{s_1,s_2}$ amount of coal production that would have produced $g(\Delta P_{y,\tau}^{s_1,s_2})$ energy in country y in year τ (the function g converts coal production into coal energy). And i_{τ}^{q,s_1,s_2,s_r} gives the investment costs at time τ per unit of installed capacity of renewable energy type q.

The renewable capacity $G_{y,\tau}^{s_1,s_2,s_r,q}$ that must be built in year τ of renewable energy type $q \in \mathcal{R}$, where $\mathcal{R}$ is the set of renewable energy types, is given by

$$G_{y,\tau}^{s_1,s_2,s_r,q} = \omega_{\tau}^{q,s_r} \times h^{-1}(D_{y,\tau}^{s_1,s_2,s_r}) \times \frac{1}{f^q}. \tag{10}$$

We explain the interpretation of equation 10 in several steps below. 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. This shortfall is given by the positive difference between the coal energy $g(\Delta P_{y,\tau}^{s_1,s_2})$ that is not produced in year τ because of the phase out of $\Delta P_{y,\tau}^{s_1,s_2}$ coal production and the energy the existing stock $R_{y,\tau}^{s_1,s_2,s_r}$ of renewable energy in country y – built to replace coal[32] – produces in year τ, i.e.

$$D_{y,\tau}^{s_1,s_2,s_r} = \max\{g(\Delta P_{y,\tau}^{s_1,s_2}) - R_{y,\tau}^{s_1,s_2,s_r}, 0\}. \tag{11}$$

How much energy this stock produces is given by the sum of the energy that the existing stock of each renewable energy type $q \in \mathcal{R}$ produces in country y, i.e. $R_{y,\tau}^{s_1,s_2,s_r} = \sum_{q \in \mathcal{R}} R_{y,\tau}^{s_1,s_2,s_r,q}$. This is given by the renewable stock $S_{y,\tau}^{s_1,s_2,s_r,q}$ of type q in country y converted with function h into the annual energy that stock can produce. This number is then multiplied with the capacity factor $f^q \in [0, 1]$ applicable to type renewable q. The capacity factor f^q captures the fact that the renewable energy stock typically does not

[32] Note that our measure of renewable stock excludes renewable capacity built for other purposes outside of phasing out coal.

run at full capacity (e.g., because the sun does not shine, the wind does not blow, or these natural energy resources do not do so at full intensity).[33] The energy produced by the renewable stock of type q in country y at time τ is thus given by

$$R_{y,\tau}^{s_1,s_2,s_r,q} = h(S_{y,\tau}^{s_1,s_2,s_r,q}) \times f^q. \tag{12}$$

We take the 2020 global average estimate of the renewable energy capacity of solar PV, wind onshore, and wind offshore from IRENA (2021b). These are equal to: $f^{solar} = 16.1\%$, $f^{wind-onshore} = 36\%$, $f^{wind-offshore} = 40\%$, and assume these remain constant over time. In practice, different regions might have somewhat different capacity factors, as for instance some countries are naturally more sunny or windy than others. We do not account for this as no reliable, encompassing data exists at a granular level. The stock of renewable energy capacity of type q in country y at time τ is given by

$$S_{y,\tau}^{s_1,s_2,s_r,q} = \sum_{\tau_b=t+2}^{\tau-1} G_{y,\tau_b}^{s_1,s_2,s_r,q} \times (1-d_q)^{(\tau-\tau_b)} \mathbb{I}_{\{\tau-\tau_b \leq l_q\}}. \tag{13}$$

Equation 13 says that the stock of renewable energy capacity of type q at time τ is given by the renewable energy capacity $G_{y,\tau_b}^{s_1,s_2,s_r,q}$ of type q that has been built in each historical year τ_b from starting date $t+2$ when the coal phase out started up to the year before τ. The built renewable capacity experiences a degradation rate (henceforth referred to as depreciation rate) of d_q% per year and has a lifetime of l_q years.

Most of the literature takes the lifetime of solar and wind farms to be $l_q = 30$ years, since empirical data on longer lifespans is not widely available (as most wind and solar farms are built in the recent two decades). Jordan and Kurtz (2013) find that the depreci-

[33] In addition to the extra investments needed to account for the renewable capacity factor f^q being below one, intermittent renewable energy will typically also require complementary investments into energy storage and systems providing flexibility to the grid to manage supply and demand fluctuations (see e.g., Creutzig et al. (2017)) – especially as share of renewables on the power grid increases. Omitting this would admittedly result in an underestimate of the capex costs of renewables. A back-of-the-envelope calculation, based on a capex costs estimate by McKinsey (2021) (see data in Exhibit 13) and the LDES Council (launched at COP26) of energy storage and grid flexibility, however, reveals that including these would not significantly reduce our baseline estimate of the carbon arbitrage of $77.89 trillion dollars. In a scenario where strong (less strong) learning-by-doing effects apply, which drive down the capex costs of building out energy storage and grid flexibility, the present value of additional investment costs to create a net-zero power grid are approximately $1.89 trillion ($3.53 trillion). Capturing these extra capex costs would reduce our estimate of the carbon arbitrage to $76 trillion ($74.36 trillion). These capex cost estimates rely on the projection that long duration energy storage (LDES) technologies, which store and release energy through mechanical, thermal, electrochemical or chemical means, will be cost competitive with, or more cost competitive than, alternative technologies such as Li-ion batteries and hydrogen turbines.

ation of solar panels happens at a rate of approximately $d_{q_{solar}} = 0.5\%$ per year. Likewise, Staffell and Green (2014) finds an average depreciation rate of around $d_{q_{wind}} = 0.48\%$ for wind farms. Hence, both solar and wind farms could have a lifespan much longer than 30 years, albeit at reduced capacity (e.g., after 30 years a solar farm on average runs at 86% of original capacity). Therefore, we will also consider a life time of wind and solar farms of $l_q = 50$ years, while taking into account depreciation, as well as a lifespan dictated only by the degradation rate (i.e., l_q large).

We are now in a position to interpret equation 10. This equation says that the stock of green energy of type q that must be built in year τ is given by the shortfall of energy $D^{s_1,s_2,s_r}_{y,\tau}$ (resulting from the phase out of $\Delta P^{s_1,s_2}_{y,\tau}$ coal production) converted with inverse function h into the stock of renewable energy that corresponds to it. This is then weighted by the percentage $\omega^{q,s_r}_{\tau}\%$ of each renewable energy type q in the replacement renewable energy mix (specified by replacement scenario s_r). We divide this by the capacity factor f^q of renewable type q to reflect that more capacity must be built, because the capacity factor of renewable energy is less than a 100%. The lower the capacity factor of renewables is the more renewable capacity must be built to create enough renewable energy.

We focus on the set of renewables to replace phased-out coal given by $\mathcal{R}$ = {Solar PV, Wind Onshore, Wind Offshore}, even though other renewable energy types such as bio energy, geothermal, and hydro energy exists. The reasons are that solar PV and wind: (1) have received the most policy support in over 130 countries; (2) are currently the most competitive power generation technologies; and (3) experience a continuing trend of falling cost suggesting the highest potential to dominate most markets (IEA (2021e)). This is why the phase in of renewables in most net-zero-2050 scenarios is dominated by solar and wind (see e.g., NGFS (2021) and IEA (2021d)).

We pick a replacement scenario s_r in which any shortfall of renewable energy capacity is met with $\omega^{solar,s_r}_{\tau} = 50\%$, $\omega^{wind-onshore,s_r}_{\tau} = 25\%$, and $\omega^{wind-offshore,s_r}_{\tau} = 25\%$, which is broadly in line with the relative phase in of these renewables in IEA (2021d). As a robustness check, we use the relative percentage of solar, wind onshore, and wind offshore over time under the NGFS Net Zero 2050 scenario (generated from its projected quinquennial capacity additions and kept constant in the intermediate years) giving an average weight of $\omega^{solar,s_r}_{\tau} = 56\%$, $\omega^{wind-onshore,s_r}_{\tau} = 42\%$, and $\omega^{wind-offshore,s_r}_{\tau} = 2\%$. Our model easily accommodates other choices for the renewable set $\mathcal{R}$ and renewable mix s_r.

3.2.2.1 Experience Curves for Renewable Energy We could assume that future investment costs in renewables $i_\tau^{s_1,s_2,s_r,q}$ of type q remain equal to what they are today (i.e. $i_\tau^{s_1,s_2,s_r,q} = i_t^q$, $\forall \tau \in [t+2, T]$). Empirical evidence, however, suggests that this is a poor baseline. Renewable energy costs have fallen exponentially over the last decades, as a function of the cumulative installed capacity of renewables. As the world learns from the experience of building more solar (wind) farms, costs of building such solar (wind) farms will fall (Meng et al. (2021)). Recall Figure 3 depicting the investment cost decline associated with a corresponding increase in global cumulative installed capacity over 2010-2020.

The Wright's law captures how investment costs of renewable energy type q fall exponentially, according to learning rate γ_q, which can be found empirically, as a function of the global cumulative installed capacity in energy type q (Schmidt et al. (2017)). Under Wright's law future investment costs in year τ in renewable energy type q are given by

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

The value in between brackets over which the exponent is taken is the global cumulative installed capacity of technology q up to time $\tau - 1$. The first component in the brackets $\sum_{\tau_b \leq t-1} G_{y,\tau_b}^q$ is the cumulative installed renewable energy capacity of type q in country y up to time $t-1$ and the second component $\sum_{\tau_b=t}^{\tau-1} = G_{\tau_b}^{s_1,s_2,s_r,q}$ is the cumulative newly installed renewable energy capacity over time period $[t+2, \tau]$. The learning rate γ_q determines the reduction $\Theta_q\%$ in investment costs $i_\tau^{s_1,s_2,s_r,q}$ for each doubling of installed capacity (i.e. the value in between brackets), i.e.

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

Samadi (2018) reviews the literature on estimated learning rates of renewable technologies and finds on average $\Theta_{q_{solar}} = 20\%$, $\Theta_{q_{wind-onshore}} = 5\%$, $\Theta_{q_{wind-offshore}} = 3\%$, corresponding to $\gamma_{q_{solar}} = 0.32$, $\gamma_{q_{wind-onshore}} = 0.07$, $\gamma_{q_{wind-offshore}} = 0.04$, which are the values we use. To obtain the normalization constant α^q, we assume that the global cumulative installed capacity of type q at time $t - 1 = 2021$ is given by the latest available value in 2020 of IRENA (2021b), depicted in Figure 3. We further assume that investment costs $i_t^{s_1,s_2,s_r,q}$ of renewable type q at time $t = 2022$ are given by the average 2020 investment costs of type q, as estimated by IRENA (2021b), also depicted in Figure 3. The normalization constant α^q is obtained by equating the left and right hand side of equation 14 with these values.

Equation 14 gives a conservative estimate of the expected global drop in investment costs for renewable energy type q, as we only capture global capacity that is built in future years to phase out coal under scenario set $\{s_1, s_2, s_r\}$, and we do not capture future learning resulting from building renewable energy plants for other purposes.

The average drop of investment costs we observe globally under the Net Zero 2050 scenario (s_2), taking account only of learning from replacing coal with renewables, as a function of the cumulative build up of installed capacity is depicted in Figure 4.

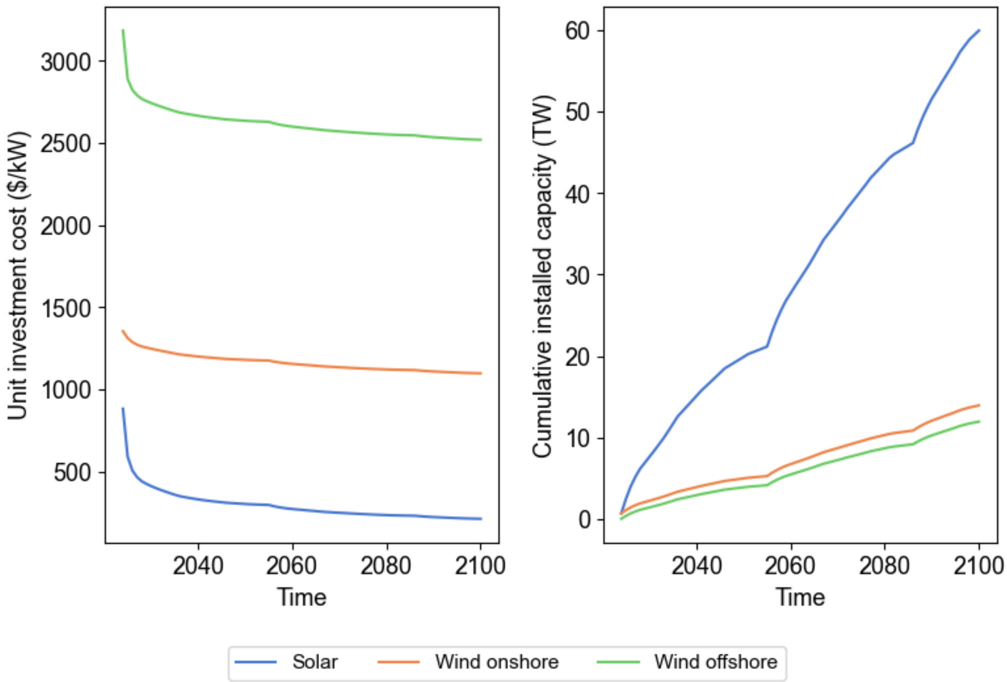

Figure 4: Drop in investment costs of each renewable (in dollars per KW) as a function of cumulative installed capacity (in TW).

This plot uses the baseline parameters used in the results, which include the above-mentioned baseline parameters of the Wright's law, depreciation rates, renewable mix weights, and renewable plant lifetime[34].

[34]A drop in investment costs resulting from learning-by-doing effects is not expected to shrink the

3.2.3 LCOE as Proxy for Investment Costs As a robustness check, we proxy requisite investment costs in renewable energy to replace coal energy by means of the levelized cost of energy (LCOE). The LCOE represents the minimum constant price at which electricity generated by a (renewable) power plant must be sold to break even over the lifetime of the plant. It is calculated as the ratio between all discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered, and includes not only annual investment expenditures, but also annual operations and maintenance expenditures, financing costs, as well as any fuel expenditures. Under the simplifying assumptions that the LCOE represents costs of producing one unit of energy and captures – spread out over time – investment costs to build the plant, we can proxy the present value of investment costs in renewables under scenario set $\{s_1, s_2, s_r\}$ as the discounted sum over time of the product of the coal energy $g(\Delta P_\tau^{s_1,s_2})$ that is phased out globally in year τ and the weighted average of the LCOE L_τ^q of each renewable energy type $q \in \mathcal{R}$, i.e.

$$I_{t,T}^{s_1,s_2,s_r} = \sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} \times g(\Delta P_\tau^{s_1,s_2}) \times \left(\sum_{q\in\mathcal{R}} \omega^{q,s_r} \times L_\tau^q \right). \tag{16}$$

The weights ω^{q,s_r} in the renewable mix are given by replacement scenario s_r. The coal production $\Delta P_\tau^{s_1,s_2}$ that is phased out globally in year τ is given by the sum of the coal production that is phased out by each coal company in that year, i.e. $\Delta P_\tau^{s_1,s_2} = \sum_{i\in\mathcal{C}} \Delta P_{i,\tau}^{s_1,s_2}$. We assume that the future LCOE of energy of type q remains equal to its global average in 2020, as estimated by IRENA (2021b), giving L_τ^{solar}=10.83, $L_\tau^{wind-onshore}$=15.83, and $L_\tau^{wind-offshore}$=23.33 (in dollars per GJ).[35]

3.3 Financial Costs of Phasing Out Coal

We now turn to the estimation of the estimation of the aggregate amount needed to finance the coal phase-out. The financing needed to phase out coal production according to phase-out scenario s_2 relative to a business-as-usual scenario s_1, and to replace coal

profitable life time of renewable plants compared to a scenario of no drop in investment costs. The reason is that maintenance costs are insignificant in comparison with capex costs. So once capex costs are made, it makes sense to keep renewable plants in operation for as long as possible.

[35]In dollars per MWh this is L_τ^{solar} =39, $\mathrm{L}_\tau^{wind-onshore}$ = 57, and $L_\tau^{wind-onshore}$ = 84.

energy with renewable energy mix s_r, is given by the present value of the costs $C_{t,T}^{s_1,s_2,s_r}$ of phasing out coal along this trajectory. The present value of the requisite global climate financing can be broken down into the sum of that of individual countries. The requisite climate financing of country y is in turn given by the sum of the present value of opportunity costs of coal $O_{y,t,T}^{s_1,s_2}$ in country y and the present value of investment costs in renewables $I_{y,t,T}^{s_1,s_2,s_r}$ in country y. Hence, the present value of the requisite global climate financing can be expressed as $C_{t,T}^{s_1,s_2,s_r} = \sum_{y \in \mathcal{Y}} O_{y,t,T}^{s_1,s_2} + I_{y,t,T}^{s_1,s_2,s_r}$ and the present value of country y's requisite climate financing as $C_{y,t,T}^{s_1,s_2} = O_{y,t,T}^{s_1,s_2} + I_{y,t,T}^{s_1,s_2,s_r}$.

The annual, non-discounted climate financing need of each country y is given by $O_{y,\tau}^{s_1,s_2} + I_{y,\tau}^{s_1,s_2,s_r}$, summing up to a global annual climate financing need of $\sum_{y \in \mathcal{Y}} O_{y,\tau}^{s_1,s_2} + I_{y,\tau}^{s_1,s_2,s_r}$.

4 Results

4.1 The Great Carbon Arbitrage

We provide below our estimates of the net present value of phasing out coal, what we refer to as the great carbon arbitrage. The baseline settings for our results are summarized in Table 3.

In our baseline, we use the IMF's estimate for the SSC of \$75/tCO_2. We focus on a time horizon from 2022 through 2100. The coal phase out scenario s_2 assumes reaching net zero by 2050. Concerning replacement energy sources, we assume 50% solar, 50% wind (of which half is onshore and the other half is offshore). The assumed investment cost I have an amortization over 30 years, and are subject to experience curves as investments are becoming gradually cheaper (Wright's Law). The opportunity costs O include the median per unit coal profit of the top 10 coal companies. The discount rate ρ is weighted-average cost of capital (WACC) of the MSCI World/Metal & Mining Index (see equation 7).

Table 3: 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 business-as-usual scenario, s_1	• Stated policy scenario (GCAM5.3-NGFS)
Coal phaseout scenario, s_2	• Net zero 2050 scenario (GCAM5.3-NGFS)
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 (\$0.34 per tonne of coal)
Discount rate, ρ	• WACC ($\rho = 2.8\%$)

Table 4 shows the main results of the paper. In order to compute the carbon arbitrage, we discount all calculations back to 2022, through the end of 2100. The present value of benefits of phasing out coal amount to $106.9 trillion, in 2022 dollars, while the present value of costs is only $29 trillion. This is a very large number for net present value of phasing out coal. As we will show below, the large size of this benefit is also robust to changes in our parameters. It would take an artificially low SCC to shrink this benefit to below a few billion. Clearly, the cost pales in comparison to the benefit. The value of preserving the planet, and limiting global warming by achieving a containment of coal emissions is highly valuable is naturally multiple times more than the cost of doing so.

The cost of phasing out coal can further be broken down into the investment cost, which at $28.98 trillion we estimate to be the lion share of the cost of phasing out coal, and an opportunity cost of only $50 billion. That is, by and large, the cost of phasing out coal consists in the additional investment required to shift to green sources of energy.[36] Netting costs out of benefits, we obtain a net carbon arbitrage of $106.9 - $29.03 = $77.89 trillion, or, as a fraction of current world GDP every year until 2100 a net benefit

[36]Note that we have not accounted for the investments needed to keep coal mines and plants running should there be no phase out. As a result our opportunity cost number of $50 billion may be somewhat overestimated.

of 1.2%.[37][38]

We estimate that the total stranded coal production from the phase out is 623.62 gigatonnes, and total emissions avoided are $GtCO_2$ of 1425.55. We can also express our estimate of the total net social benefit from the coal phase out of 77.89 trillion dollars, as both the net social value per tonne of avoided coal production and per tonne of avoided carbon emissions. Our per unit estimates are by approximately $125/tonne of coal and $55/$tCO_2$, respectively. The further temperature increase – on top of the 1.1 degrees already observed – that would be prevented by executing the coal phase out is estimated to be 2.14 degrees Celcius, which would obviously have a major impact on slowing down climate change.

Table 4: 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 $°C$ already observed – prevented **		2.14

* The world GDP in 2020 is 84.705 trillion US Dollars according to the World Bank.

** The best estimate of Matthews et al. (2009) for the temperature increase per trillion tonnes of carbon emitted is 1.5 $°C$. The 5th to 95th percentiles estimates are 1.0 $°C$ and 2.1 $°C$ per trillion tonnes of carbon emitted, associated with a further temperature increase prevented of 1.43 $°C$ and 2.99 $°C$, respectively.

[37] This fraction is taken over the cumulative discounted world GDP over the period $t + 2 = 2024$ to T, where in the baseline $T = 2100$. Since projecting the growth rate of GDP for over 50 years into the future is highly speculative, especially in the face of climate change and the transition, and since any growth rate will be (partially) offset by the risk-free discount rate, we think it most robust to assume future global and country GDP will remain equal to its latest available data in 2020, and thus neither not apply a growth rate nor discounting.

[38] We obtain the 2020 global and country GDP, as well as GDP per capita, from the World Bank Group. See here: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

4.1.1 Sensitivity Analysis on the Carbon Arbitrage In our baseline analysis, we use the IMF's estimate of the social cost of carbon of $\$75/tCO2$, see Figure 5. This is a fairly conservative estimate, which is well recognized in the literature, and among policy makers. However, clearly, other numbers for the social cost of carbon have been put forward. For example, the United States Biden administration uses an interim social cost of carbon of only $\$51/tCO2$. In a comprehensive study, Rennert et al. (2021) estimate that the social cost of carbon could vary between a lower estimate of \$61.4, and a higher estimate of $\$168.4/tCO2$, with a mid-point estimate of $\$114.9/tCO2$. The carbon arbitrage would disappear only if the social cost of carbon were to be less than or equal to $\$20.4/\mathrm{tCO}_2$. Hence, even under exceptionally conservative estimates of the social cost of carbon, a carbon arbitrage gain can be reaped from phasing out coal.

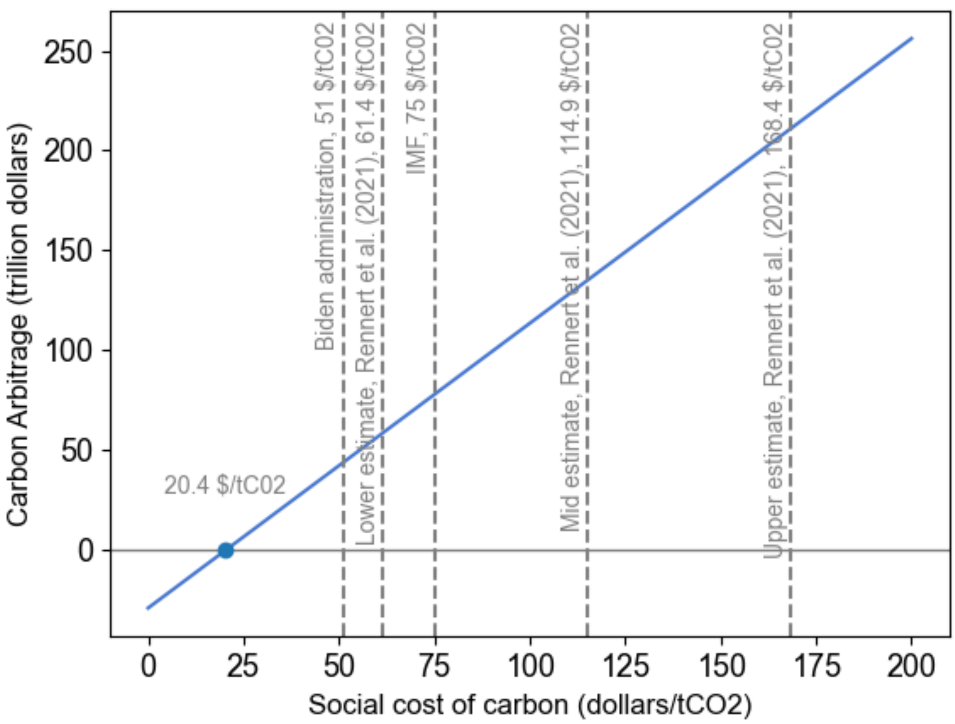

Figure 5: The carbon arbitrage as a function of the social cost of carbon.

We proceed by presenting robustness analysis in Table 5 with the midpoint estimate of θ_{IMF} =$\$75/\mathrm{tCO}_2$, the lower estimate of θ_{lower} =$\$61.4/\mathrm{tC0}_2$, and the higher estimate of θ_{higher} =$\$168.4/\mathrm{tC0}_2$. Clearly, the net benefit will be that much larger the higher the social value of the cost of carbon is assumed to be. In Table 5, we also show results for a time horizon of 2050 and 2070, in addition to the time horizon of 2100 which is our baseline. The longer the time horizon, the larger the present discounted value of the carbon arbitrage.

Table 5 shows that the great carbon arbitrage through 2100 could be as large as \$211.03 trillion if the higher estimate for the social cost of carbon of \$168.4/t$C0_2$ is assumed. On the other hand, if we use the lower estimate of a social cost of carbon of \$61.4/t$C0_2$, we obtain a net carbon arbitrage of \$58.50 trillion, which is of comparable magnitude. The net carbon arbitrage for shorter time horizons is mechanically smaller, but that is not surprising.[39] Rather than assuming a constant SCC, as we do in our baseline, we could also take a growth rate in the SCC of 3% a year (in line with Nordhaus (2017)) and discount benefits of avoiding coal emissions by 2% (in line with the discount rate governments typically use for climate mitigation investments). This results in a net growth rate of benefits of avoiding emissions of $r = 1\%$ per year. The estimate of the carbon arbitrage then growths from \$77.89 trillion to \$159.59 trillion, for a starting SCC of carbon of θ_{IMF} =\$75/tCO_2 in 2022 (not shown in the table). Given that the SCC is expected to grow non-linearly as we get closer to climate tipping points, resulting in a net growth of benefits of avoiding emissions of potentially more than 1% a year, our estimate of the carbon arbitrage using a constant SCC is highly conservative.

Table 5 highlights how our carbon arbitrage estimates depend on the projection of coal production under a business-as-usual (BAU) scenario s_1. We use the global stated policy scenario generated using the GCAM5.3-NGFS model as our baseline, which has become an industry standard. To understand the sensitivity of our results to different projections, we alternatively use the MESSAGEix-GLOBIOM 1.1 and REMIND-MAgPIE 2.1-4.2 models employed by the NGFS. The MESSAGEix-GLOBIOM 1.1 and REMIND-MAgPIE model only make BAU projections of coal production up to $T = 2050$, however, rather than up to $T = 2100$, which is used in our baseline. Taking a different BAU scenario does not substantially alter our main estimate for the net social gain from phasing out coal. For a SCC of θ_{IMF} =\$75/tCO_2 and a time horizon up to $T = 2050$, our estimate of the carbon arbitrage is \$15.73 trillion using the GCAM5.3-NGFS model (see Table 5), while the estimate of the carbon arbitrage is \$13.16 trillion using the MESSAGEix-GLOBIOM 1.1 model, and \$15.03 trillion using the REMIND-MAgPIE model (not shown

[39]In so far as the business-as-usual scenario, as stipulated by the NGFS Current Policy Scenario in Figure 2, is less reliable beyond $T = 2050$ since for instance the economic structure might change materially, it is nonetheless valuable to single out the carbon arbitrage opportunity over shorter time horizons.

in Table 5).

Table 5 further shows the alternative phase-out scenario where coal production is halted immediately, as of 2022. Of course, such a scenario is not very realistic as it is not obvious how coal can be replaced with renewables suddenly, especially for products such as steel use. For an immediate phase out, the baseline estimate of the net carbon arbitrage benefit is slightly higher, at \$87.06 trillion.

Table 5 furthermore shows that the relative mixture of solar, wind onshore, and wind offshore to replace phased-out coal does not significantly alter the carbon arbitrage. Our baseline setting to replace coal with 50% solar and 50% wind (of which 50% onshore and 50% offshore) results in a slightly lower carbon arbitrage, at \$77.89 trillion, than that obtained under the Net Zero 2050 scenario of the NGFS, at \$84.95 trillion, in which phased-out fossil fuels are on average replaced with a relative mixture of 56% solar and 44% wind (of which 42% onshore and 2% offshore). Our estimate is somewhat lower because investment costs in wind, especially offshore wind, are higher than those in solar (recall Figure 3 and 4). A replacement scenario s_r in which solar and wind are the dominant forms of energy to replace coal is the central scenario in most Net Zero 2050 pathways (see e.g. IEA (2021c)).

In the interim period during which the switch from coal to renewables is implemented, coal could in part be replaced with a less polluting fossil fuel, such as natural gas.[40] If coal would be replaced with 33% solar, 33% wind (of which 50% onshore and 50% offshore), and 33% natural gas, the carbon arbitrage for a SCC of \$75/tCO_2 sharply drops from our baseline estimate of \$77.89 trillion to \$0.78 trillion. If instead gas would fulfill a comparatively smaller role as an transition fuel and be replaced with 45% solar, 45% wind (of which 50% onshore and 50% offshore), and 10% natural gas, the carbon arbitrage for a SCC of \$75/tCO_2 shrinks to \$22.74 trillion. Clearly, replacing coal with gas results in a smaller net gain than doing so with renewables such as solar and wind. The reason is twofold. First, the present value of benefits of phasing out coal is smaller as benefits of reduced emissions from coal are partly offset by emissions from natural gas. Second, the median LCOE globally of gas is higher than that of solar PV and wind onshore, while being lower than that of wind offshore; this holds, for instance, in the

[40] In the Appendix, we explain how the formula of the present value of benefits of avoided emissions of coal production is updated to reflect that natural gas emits CO_2 into the atmosphere, albeit at a lower emission intensity than coal. We also provide the slightly updated formula of the present value of costs of replacing coal taking into consideration the LCOE of natural gas.

United States, Europe and China (IEA (2020)). Therefore, it is efficient to rely as little as possible on natural gas.

Of course, coal can also be replaced with other types of transition fuels, or renewables (once they become viable), as well as with nuclear energy. Coal emissions could alternatively be abated by means of carbon capture and storage once it becomes cost effective to do so.[41] It is straightforward to redo our calculations with alternative assumptions on the replacement scenario s_r, as our methodology does not depend on a specific replacement energy mix.

As would be expected, Table 5 shows that the longer the assumed lifetime of renewable plants is the greater the carbon arbitrage. If a 50Y lifetime rather than a 30Y lifetime (our baseline) is assumed, the carbon arbitrage rises from \$77.89 to \$98.01 trillion. The reason is that fewer investment costs have to be made to replace defunct renewable plants. The annual depreciation rate of renewables suggests that renewable plants could potentially live beyond even 50 years. Were the lifetime of a renewable plant only dictated by its depreciation rate, we obtain a much larger carbon arbitrage of \$214.07 trillion.

Even if we assume, unrealistically, that future investment costs in renewables will not fall further because of an absence of "learning", we still obtain a significant carbon arbitrage of \$62.49 trillion. It is logical that our estimate of the carbon arbitrage will drop (to \$12.41 trillion), if we use the LCOE as a proxy for investment costs in renewables. The LCOE not only captures investment costs, but also captures other costs including financing and operational costs. The LCOE proxy is nonetheless useful to benchmark our results. The LCOE proxy is best compared against our estimate

[41]Carbon capture, utilisation, and storage (CCUS) involves the capture of CO_2 from large emission sources or directly from the atmosphere. In 2021, the world's largest direct air carbon dioxide capture and storage system to date opened in Iceland and is called Orca. It can capture up to 4,000 tCO_2 a year and costs around \$1200/tCO_2 to be removed. The net gain from replacing coal with renewables under our baseline settings is estimated to be \$77.89 trillion dollars, whereas net gain from capturing emissions from coal production using direct air capture with a cost of \$1200/tCO_2 is \$-379.29 trillion (i.e., it is a net loss). The present value of costs of removing $\Delta E_{i,\tau}^{s_1,s_2}$ amount of CO_2 from the atmosphere per year over $[t+2,\bar{T}]$ is given by $C_{t,T}^{s_1,s_2,s_r} = \sum_{i\in\mathcal{C}} \sum_{\tau=t+2}^{\bar{T}} \frac{\Delta E_{i,\tau}^{s_1,s_2}\times c}{(1+\rho_i)^{(\tau-t)}}$, where $c = \$1200/tCO_2$ in this case, and $\bar{T}$ is the last year in which renewable plants built up to T can help reduce emissions. The present value of benefits $B_{t,T}^{s_1,s_2,\theta}$ of capturing emissions from coal is the same as the present value of benefits of reducing emissions by replacing coal with renewables (i.e., $B_{t,T}^{s_1,s_2,\theta}$=\$106.9 trillion). Based on current levelized costs, CCUS based on direct air capture is thus not an attractive alternative to replacing coal with renewables. Of course, CCUS levelized costs may fall further in the future (IEA (2022)) and also vary significantly by CO_2 source (IEA (2021b)). Under our baseline settings, we estimate that only once the levelized cost of CCUS from coal sources drop on average below \$266/tCO_2 a positive net gain from capturing coal emissions can be reaped.

Table 5: Sensitivity analysis of the great carbon arbitrage (in trillion dollars) around our baseline settings (see Table 3), shown for different estimates of the social cost of carbon θ.

		Carbon Arbitrage		
		θ_{lower}	θ_{IMF}	θ_{higher}
Time horizon [t+2,T] of carbon arbitrage	• $T = 2050$	9.48	15.73	58.66
	• $T = 2070$	28.27	40.06	121.04
	• $T = 2100$	58.50	77.89	211.03
Coal business-as-usual scenario, s_1	• s_1 = Stated policies (GCAM5.3-NGFS)	58.50	77.89	211.03
Coal phase out scenario, s_2	• s_2 = Net zero 2050	58.50	77.89	211.03
	• s_2 = Halt to coal production	61.87	87.06	260.04
Coal replacement scenario, s_r	• 50% solar, 50% wind	58.50	77.89	211.03
	• Static NGFS scenario 56% solar, 44% wind	65.56	84.95	218.09
	• Dynamic NGFS scenario	65.74	85.13	218.27
	• 33% solar, 33% wind, 33% natural gas	-13.69	0.78	100.16
	• 45% solar, 45% wind, 10% natural gas	4.84	22.74	145.65
Investment Costs, I	• 30Y lifetime of renewable plants with depreciation (experience curve)	58.50	77.89	211.03
	• 50Y lifetime of renewable plants with depreciation (experience curve)	75.81	98.01	250.46
	• Lifetime of renewable plants dictated by depreciation (experience curve)	172.65	214.07	498.57
	• 30Y lifetime of renewable plants with depreciation (no experience curve)	43.10	62.49	195.64
	• LCOE as proxy for investment costs (no experience curve)	-3.37	12.41	120.81
Opportunity costs, O	• Median unit coal profit of top 10 pure coal companies	58.50	77.89	211.03
	• Median unit coal profit of top 100 pure coal companies	58.46	77.85	210.99
Discount rate, ρ	• WACC ($\rho = 2.8\%$)	58.50	77.89	211.03
	• WACC with climate-risk premium coal companies ($\rho = \rho + 0.5\% = 3.3\%$, $\rho = 2.8\%$)	58.51	77.89	211.04
	• WACC with average risk premium over 1922-2022 ($\rho = 3.6\%$)	63.08	82.46	215.61
	• Benchmark ($\rho = 5\%$)	68.17	87.55	220.70

without learning, at $62.49 trillion, as we do not capture its experience curve.

The second last row of Table 5 shows that our assumption on future profits of coal companies does not alter the carbon arbitrage much, since opportunity costs of coal pale compared to the social gain of phasing out coal, as well as investment costs in renewables.

The last row of Table 5 shows the great carbon arbitrage with alternative discount rate assumptions. In the baseline, we are using a WACC of coal production of 2.8% based on a 2022 risk premium of 1.99%. When the average risk premium over the last 100 years is used of 3.87%, the discount rate rises from 2.8% to 3.6%, with an associated carbon arbitrage increase from $77.89 to $82.46 trillion. Hence, the results are relatively insensitive to this alternative assumption about the discount rate. As we have explained above, a simplifying assumption in our analysis is that the SCC on a present value basis is constant. This assumption implies potentially a sizable underestimate of the net social benefit from phasing out coal given that (based on other studies) the present value of the SCC is likely to rise as more CO2 is concentrated in the atmosphere.

Table 6 shows an additional sensitivity analysis. For our baseline of a \$75/$tCO2$, we find 62.45 to 120.97 trillion dollars, around the 77.89 that is our preferred estimate. Clearly, alternative assumption lead to different results, but as a fraction of GDP this 78.50 - 128.17 range reduces to a range of 1 - 1.9 percentage points of GDP. Hence, even relatively extreme assumptions about alternative parameters we obtain a sizeable carbon arbitrage.

Of course, when the lower and higher estimate for the cost of carbon is combined with the alternative parameters, the range widens from 43.07 to 309.66 trillion, which is fairly wide (it corresponds to a range as a percent of GDP from 0.7 to 4.8 percentage points).

However, we should emphasize that we view the central results as the most accurate, and present the alternative results only as robustness.

Table 6 also shows the carbon arbitrage estimates under the alternative parameter assumptions for the time horizons 2050, 2070, and 2100. Note that our central estimates, as shown in the table above, are much closer to the min settings (on the left) than to the max settings (on the right). This indicates that we have not only chosen a conservative SCC in our baseline, but also chosen conservative estimates for our other parameters. The min (max) settings correspond to picking the parameters associated with the smallest (largest) carbon arbitrage in each row of Table 5.[42]

Table 6: Sensitivity analysis of carbon arbitrage (in trillion dollars) across min-max of parameter settings.

		Carbon arbitrage			
		θ_{lower}	θ_{IMF}	θ_{higher}	
Time horizon [t+2,T] of carbon arbitrage	$T = 2050$	(1.97, 35.33)	(8.22, 49.58)	(51.15, 147.45)	**(1.97, 147.45)**
	$T = 2070$	(16.24, 49.16)	(28.03, 65.20)	(109.01, 175.33)	**(16.24, 175.33)**
	$T = 2100$	(43.07, 93.49)	(62.45, 120.97)	(195.60, 309.66)	**(43.07, 309.66)**

Table 7 shows that societal benefits of building a renewable plant should not only capture the emissions that the plant can avoid in the year it is built, or in the years up to the end of its estimated date of amortization, but should also include all coal emissions that the renewable plant can help avoid over its remaining lifetime past the date of amortization. Take as an example a time horizon $[t+2, T]$ with end date $T = 2070$, the year in which not only developed countries but also developing and emerging countries plan to be net zero. The year $T = 2070$ represents the last year investment costs are made to build replacement renewable plants as part of the carbon arbitrage strategy. Suppose a solar plant is built in year 2069. It will then run and produce renewable energy for 30 years (in our baseline), thereby enabling a reduction in coal production and associated coal emissions in the years 2069-2099. This results in a social gain over the period 2069-2099, priced at the SCC times the amount of avoided emissions.[43] This social gain stretches beyond the last year $T = 2070$ in which investments costs are made. Table 7 shows that the carbon arbitrage gain is underestimated by \$40.06-\$19.68=\$20.38 trillion, using $\theta_{IMF} = \$75/tC0_2$, if the benefits of avoided coal emissions are truncated at $T = 2070$, while these accrue up to 2099, the final year of the lifetime of the renewable plant.

[42] We exclude the carbon arbitrage estimate associated with the LCOE proxy from the min-max estimates presented in Table 6, since this is merely used as a benchmark. We also exclude the estimate under the assumption that the lifetime of a renewable plant is dictated only by its depreciation rate, as such assumption gives implausibly long lifetimes (i.e. greater than a hundred years). We deem neither of these benchmarks plausible.

[43] Recall that the methodology computing the social gain beyond T is found in the Appendix.

Table 7: Carbon arbitrage (in trillion dollars) with and without capturing avoided future coal emissions beyond $T = 2070$ for different choices of the SCC.

	Carbon arbitrage		
	θ_{lower}	θ_{IMF}	θ_{higher}
PV of benefits	28.27	40.06	121.04
PV of benefits truncated at T	11.59	19.68	75.29

4.2 The Coasian Bargain

From a Coasian perspective it is sound economic logic to provide climate financing to countries to compensate the losses incurred from phasing out coal and to account for the capital expenditures needed to replace the energy from coal, as well as to link social benefits of avoided emissions to these costs.

To gain further insight into the size of the transfers that may be required to pay for the replacement of coal with renewable energy, and compensate for opportunity costs of coal, we break down the requisite climate financing by geography, and state of development. Figure 6 shows the present value of all future conditional climate financing needs for developed countries, developing countries, and emerging markets.[44] There is also a breakdown into Asia, Africa, North America, Latin America and Caribbean, Europe, and Australia and New Zealand. The financing needs are by far largest for emerging markets, and particularly those in Asia.

The present value of the required global climate financing is around 29 trillion dollars, of which approximately 18 trillion dollars is needed up to $T = 2050$. The majority of climate financing needs occur thus between 2024 and 2050, with relatively lesser investment needs in the far future. This is in large part driven by a greater discounting of future costs and in a somewhat smaller part driven by falling investment costs in renewables as more capacity is built.

[44] We classify countries into developed countries, developing countries and emerging market countries according to the classification of the IMF World Economic Outlook.

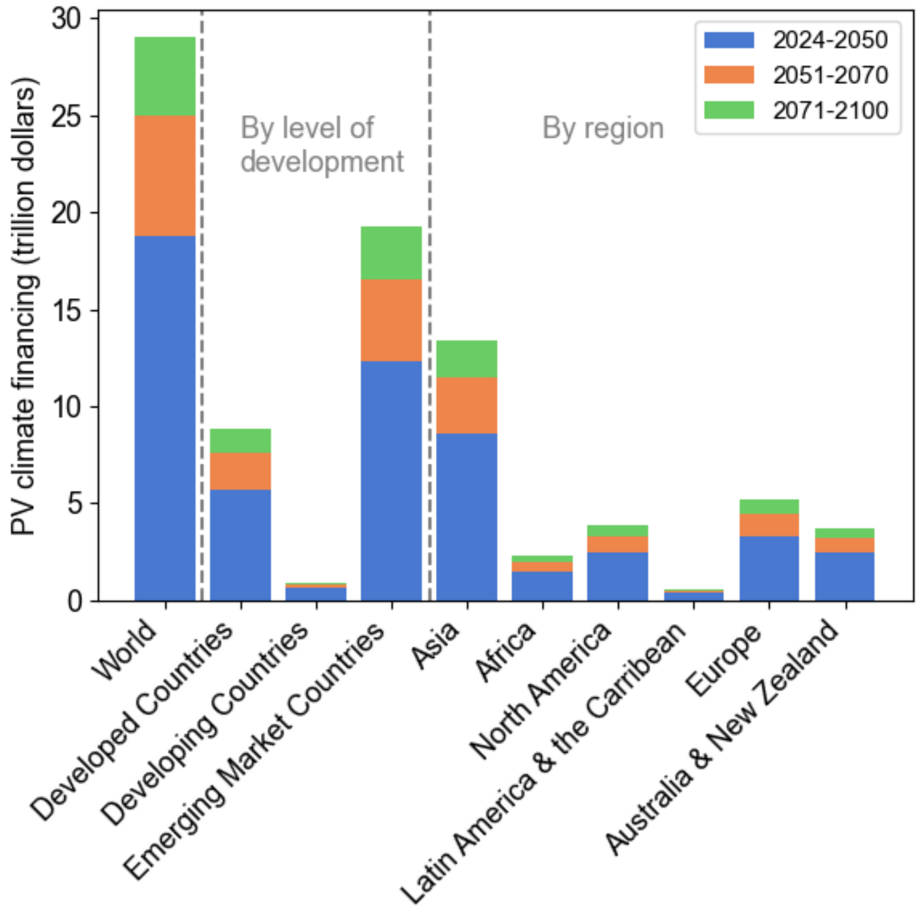

Figure 6: Present value of all future conditional climate financing needs.

Figure 7 gives the time series pattern of the financing needs by state of development and by region. Clearly, the largest financing needs are relatively early in all geographies. This is consistent with the findings of McKinsey (2022) that a front-loading of investments is needed this decade to reach net zero by 2050. There is also clearly an investment cycle, as we assume full depreciation after 30 years. We observe that investment peaks and then declines in 30 year cycles. The reason is that renewable capacity built in the first year of the cycle keeps producing energy for 30 years, albeit at a reduced amount every year because of depreciation. In the next year of the cycle, additional renewable energy capacity must be built only in so far as the existing stock of renewable energy falls short in compensating for the further phase out of coal. Under the Net Zero 2050 scenario, more coal is phased out every year. Hence, we observe an incremental annual need to build up more renewable capacity.

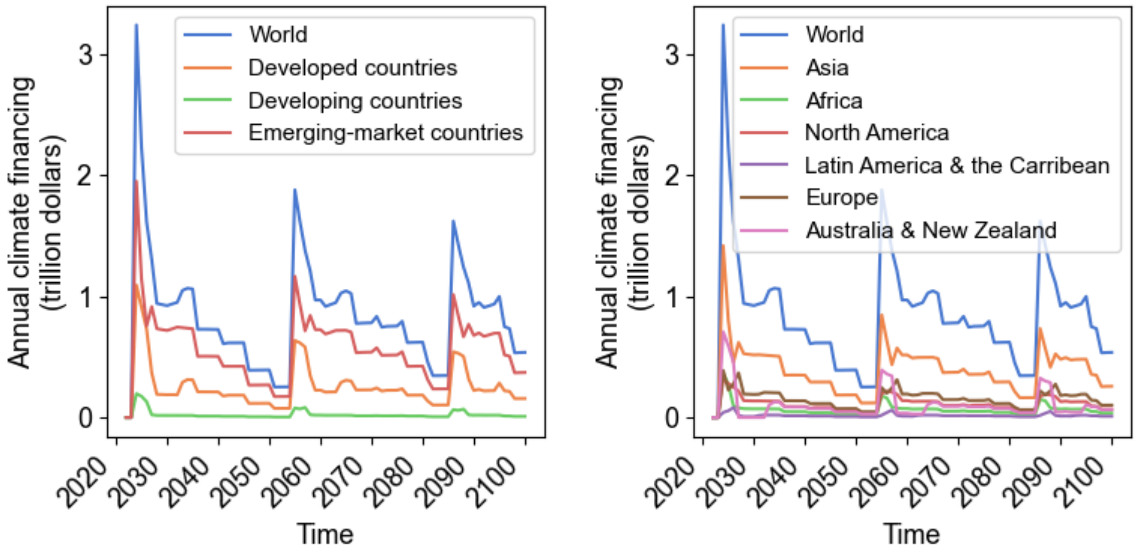

Figure 7: Annual conditional climate financing needs (in trillion dollars; non-discounted) broken down by level of development (left plot) and region (right plot).

Figure 8 shows the present value of the requisite climate financing over 2024-2100 (relative to cumulative GDP) plotted against GDP per capita.[45] Financing needs per GDP tend to be higher for countries with lower GDP per capita, with some notable outliers for emerging and developing countries. The right chart of Figure 8 shows that these outliers are

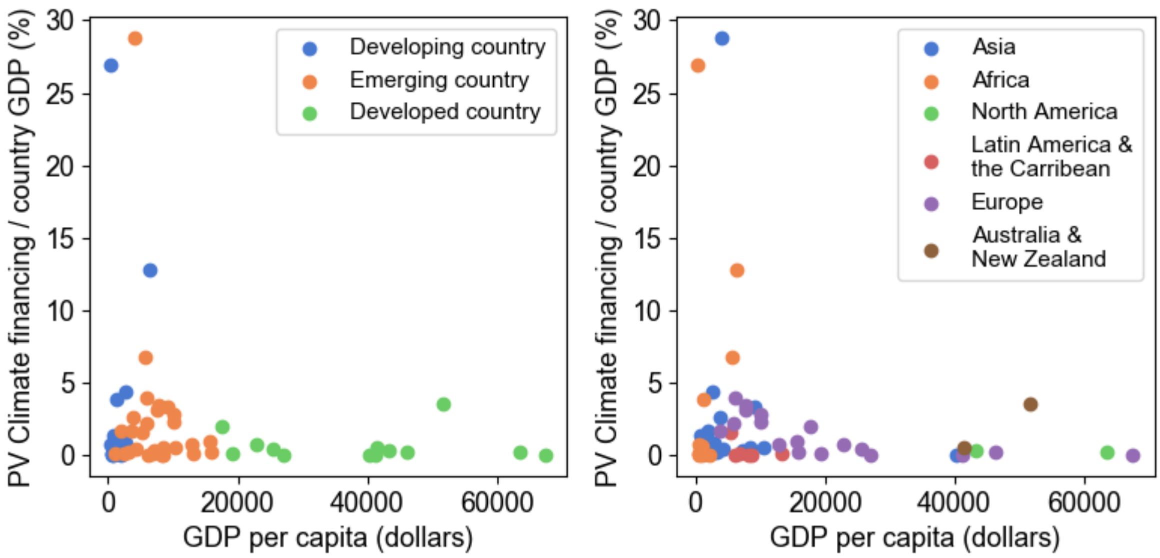

Figure 8: Present value of conditional climate financing need of each country relative to its GDP over 2024-2100. Countries are coloured either by level of development (in left plot) or by region (in right plot).

[45]We obtain the 2020 GDP and 2020 GDP per capita of each country from the World Bank. See: https://data.worldbank.org.

concentrated in Asia and Africa. Hence, a handful of countries have significantly higher financing needs than the average country. But even besides those notable outliers, financing needs represent a significant fraction of GDP for many countries. Hence, climate finance mechanisms to ensure a green transition appear as a first order policy goal.

Figure 9 shows the time series of annual requisite climate financing as a fraction of developed world GDP, for the developed world, emerging markets, and the developing world. Emerging market needs are clearly dominating the needs from the developed world, amounting to around 4% of the developed world GDP in the initial phase. But even developed world financing needs are 2% of the GDP of the developed world initially. Climate financing should thus not only consist of transfers to foreign countries but also of domestic subsidies in the developed world.

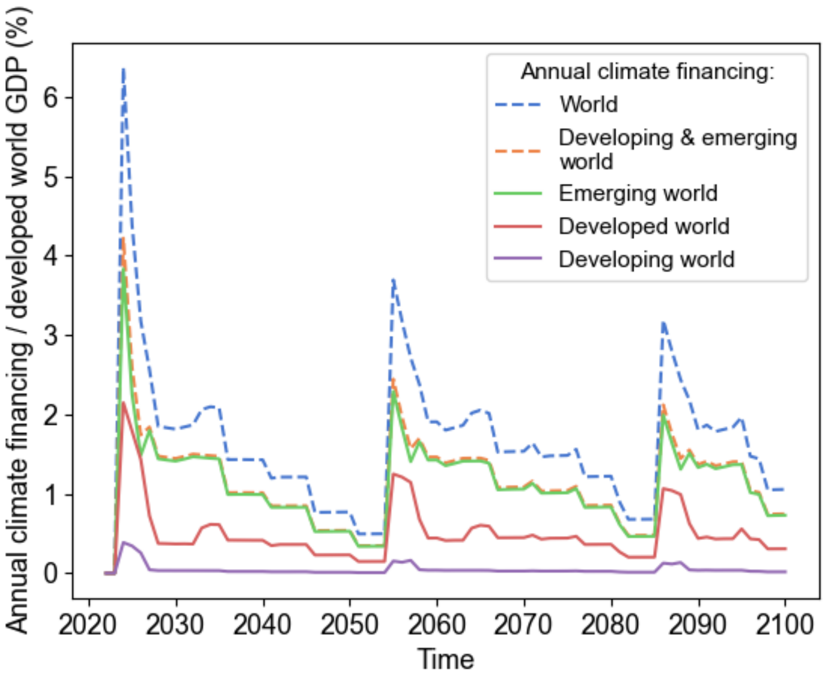

Figure 9: Annual conditional climate financing need of the world (blue line), the developing and emerging world (orange line), or the emerging world (green line) relative to developed world (DW) GDP (in %). The plot represents non-discounted values.

In the following box, we provide a case study of Germany. The German case provides a prototype for how the great carbon arbitrage can be practically realized. Rather than using the median unit profit of the top 10 coal *mining* companies globally, we use financial information from Orbis to estimate future missed revenues for each German coal *power* company.

Box 1: Germany Case Study of Coal Phase Out

In July 2020, the German government adopted the Act on the Phase-out of Coal-fired Power Plants and the Structural Reinforcement Act for Mining Regions.[a] This Act targets not only the end of power generated from coal by 2038 at the latest, but also introduces parallel structural policies to ensure energy security and compensate coal companies for missed revenues. The objective is to deliver legal certainty for power companies, that is based on sound economics and provides for a social equilibrium. Subsidies are available from 2020 to 2027 for those companies that are prepared to retire their coal-fired power plants early on a voluntarily basis, the payment mechanism of which takes place via auctions. After that year regulatory decommissioning may take place without compensation. The top price for the auction decreases from 165.000 Euro/MW in 2020 to 89.000 Euro/MW in 2027. The procedures for the award of contracts considers the bidding price of each company as well as the average yearly historical carbon emissions per MW of production (emission intensity). In the first auction round in September 2020, the total bid-size was 4.788 MW with biding prices reaching from 6.047 to 150.000 Euro/MW. The total subsidy disbursed was 317 million Euro. In total the German government will make available more than 4 billion Euro to compensate coal power plant companies for their earlier investment and to close plants before 2030.[b] The loss of electricity caused by the gradual phase-out of coal will be compensated for by a higher renewables target of 65% by 2030. Subsidies for proposed renewable installations include fixed above market prices and priority access for the power grid over a period of 20 years for small actors, as well as a more resource intensive market-based competitive auction for larger actors, where the government sets a fixed quantity of subsidized renewable power aligned with the target growth rate of renewables in Germany.[c] The renewable investments are partly financed through an add on cost in the individual energy bill (EEG-Surcharge) of German consumers and from 2021 on through government revenues from carbon taxes.

[a] See: https://www.bmwi.de/Redaktion/EN/Pressemitteilungen/2020/20200703-final-decision-to-launch-the-coal-phase-out.html.

[b] See: https://www.iea.org/reports/coal-fired-power.

[c] See: https://www.bmwi.de/Redaktion/DE/Downloads/G/gesetzentwurf-aenderung-erneuerbare-energien-gesetzes-und-weiterer-energierechtlicher-vorschriften.pdf? blob=publicationFile&v=4.

Box 1: Germany Case Study of Coal Phase Out – A Great German Arbitrage

The German government is in effect compensating coal companies for the opportunity cost of coal, via auctions, and investing in renewables to replace coal, via subsidies and auctions, to realize the great carbon arbitrage gain; or as they put it, to create the "social equilibrium". With the German phase-out schedule of 39GW 2020, 30GW 2022, 17 GW 2030, 0 GW 2038, we obtain a difference between coal capacity in the current policy scenario and in the German phase-out schedule of coal power as shown in Figure 10.

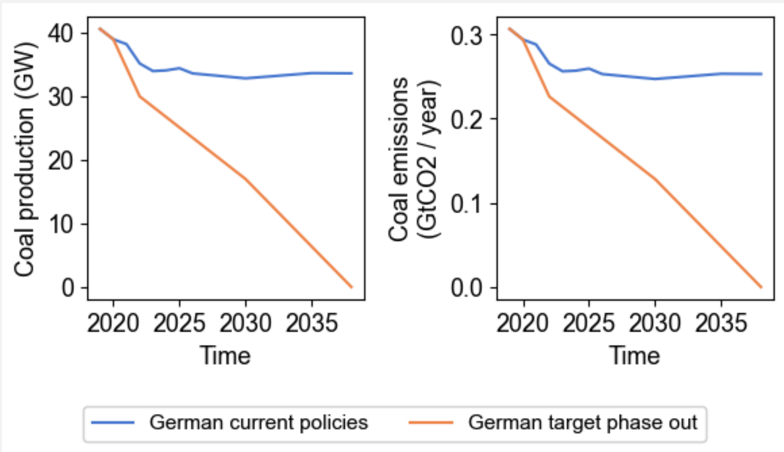

Figure 10: German coal phase out targets in the power sector.

With our standard methodology applied to the German case study, we estimate that the present value (from the perspective of $t = 2020$) of the costs to phase out coal in the power sector in Germany over [2020, 2038] is around 191 billion dollars, of around which 12 billion consists of opportunity costs and 179 billion consists of investment costs in renewables. The present value of the benefits are 518, 632 and 1419 billion dollars for θ_{lower}, θ_{IMF}, and θ_{higher} giving the carbon arbitrage as shown in Table 8. Our PV estimate of the opportunity costs up to $T = 2038$ aligns in magnitude with the 4 billion euros the German government is setting aside to compensate coal producers up to $T = 2027$.

Table 8: The German carbon arbitrage in the coal power sector.

Carbon arbitrage (billion dollars)		
θ_{lower}	θ_{IMF}	θ_{higher}
327	441	1228

4.2.1 Sensitivity Analysis of Requisite Climate Financing

Figure 11 presents sensitivity analysis of the requisite global climate financing. The left plot shows the required annual financing (in trillion dollars) and the right plot shows its the present value. Each plot has various assumptions on the effective lifetime of renewables and the presence or absence of “experience” driving declines in investment costs.

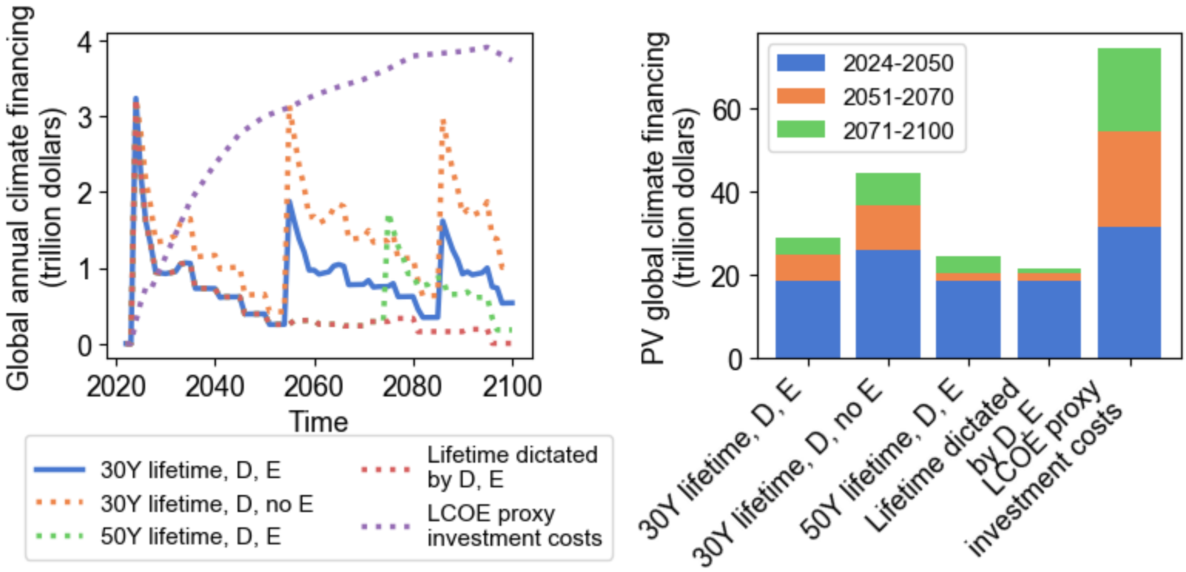

Figure 11: Annual global climate financing need (in trillion dollars; non-discounted) on the left plot and its the present value on the right plot, for different assumptions on the effective lifetime of renewables and investment costs.

The left plot of Figure 11 reveals that the investment cycle lengthens to 50 years if we lengthen the assumed lifetime of renewables from 30 to 50 years. It also shows that the investment cycle disappears, at least over the time horizon up to 2100, would renewable lifetime only be dictated by its depreciation (D) rate. Two immediate observations emerge from Figure 11. First, if we allow for experience (i.e., learning by doing) effects later investment cycles come with lower capex costs (compare blue and orange line). Second, LCOE is a misleading proxy for investment costs as it does not capture the front loading of capex investments (see purple line).

The assumption on the lifetime of renewables does not matter much for the present value of the requisite global climate financing, as shown on the right plot of Figure 11. What does matter is the degree of learning and the resulting fall in future investment costs. By construction, the present value will be higher with the LCOE proxy, since the LCOE also captures operational and financing costs.

In Figure 12, we conduct additional sensitivity analysis of the required financing, this time by comparing the estimates of the global against the regional scenarios of the NGFS. The global NGFS scenario assumes that the coal production trajectories under the Current Policy scenario and Net Zero 2050 scenario are homogeneous across countries in the world, whereas the regional NGFS scenarios (also using the GCAM5.3-NGFS model) capture that certain regions, such as Africa and Asia, will have a faster growth of energy demand, and therefore coal demand, over the course of this century under the current policy scenario. The regional NGFS scenarios furthermore capture that certain regions, such as the developed world, are expected to phase out coal faster than others.

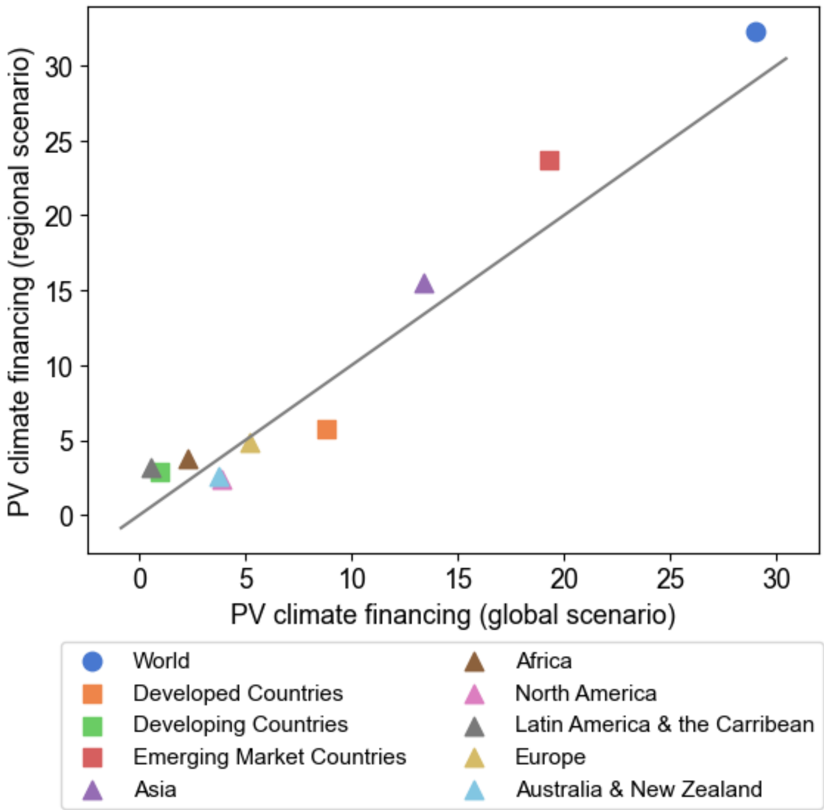

Figure 12: The present value of requisite climate financing under the global vs. regional NGFS scenarios. Regions are shown with a square and countries with a triangle.

While we find that the requisite annual climate financing in certain regions is higher (e.g., in emerging countries, developing countries; in particular Asia) and in other regions is lower (e.g., in developed countries; in particular America and Europe) in the regional than in the global NGFS scenario, the present value of requisite climate financing does not drastically differ. This is evident from the fact that the estimated present value of requisite climate financing in the regional and global scenario sit close to the diagonal in

Figure 12.

4.3 Social Stranded Asset Value & Carbon-Adjusted Earnings

The climate financing needs are indeed large, but our point is that they are nonetheless small relative to the social benefits. These social benefits are too easily forgotten, as is the case for example with the notion of "stranded assets". The valuation of these assets only reflects opportunity costs in terms of lost earnings from keeping the asset underground. But the correct valuation should also include the benefits in terms of avoided emissions. The "social stranded asset value" – a term we introduce – is large and positive when the resource is left unexploited, but negative when exploited, the opposite of how fossil fuel reserves are currently valued. Put differently, as shown in Figure 13, the opportunity costs of coal become negative once the social costs associated with coal emissions are taken into account. Rather than using the median unit profit of the top 10 coal companies, we use financial information from Orbis to estimate the (social) stranded asset value of each coal company.

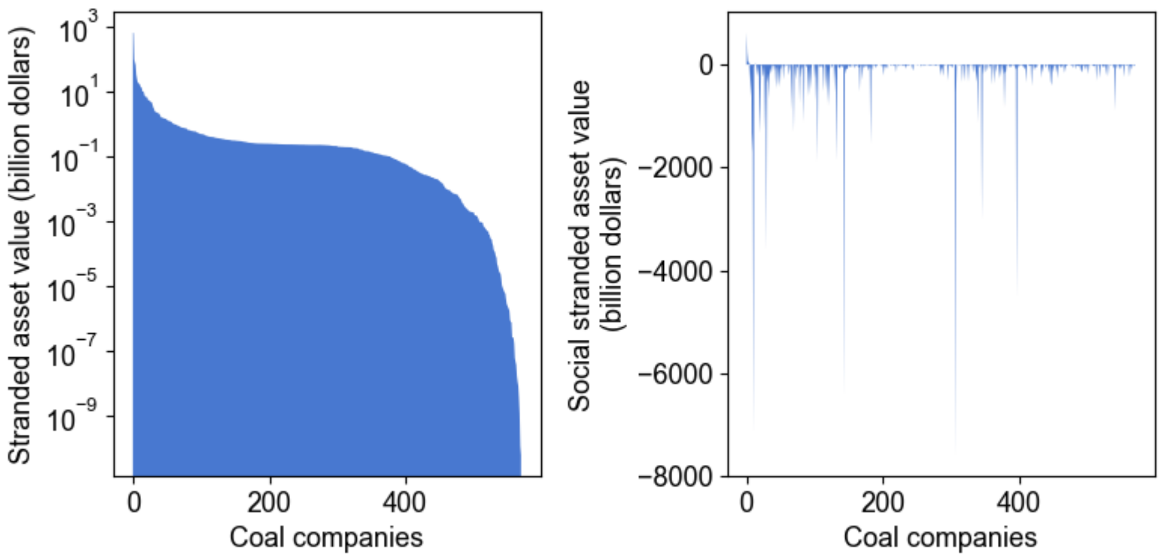

Figure 13: The distribution of the stranded asset value of coal companies (left plot) and the corresponding distribution of the "social stranded asset value" (right plot).

The stranded asset value $S^{s_1,s_2}_{i,t,T}$ of coal company i is given by the difference in its coal production between its business-as-usual scenario s_1 and the scenario where its coal assets are stranded, which amounts to our Halt to Coal production scenario s_2 (i.e., $P^{s_2}_{i,\tau} = 0$ for

$\tau \in [t+2, T]$). This gives a stranded asset value equal to $S_{i,t,T}^{s_1,s_2} = \sum_{\tau=t+2}^{T} \exp^{-\rho_i(\tau-t)} O_{i,\tau}^{s_1,s_2}$.

The "social stranded asset value" $S_{i,t,T}^{s_1,s_2,\theta}$ (with a superscript θ) of coal company i is given by the present value of its opportunity cost of coal $S_{i,t,T}^{s_1,s_2}$ (i.e., the stranded asset value) minus the present value of societal benefits $B_{i,t,T}^{s_1,s_2,\theta}$ of stranding its coal assets, i.e.,

$$S_{i,t,T}^{s_1,s_2,\theta} := S_{i,t,T}^{s_1,s_2} - B_{i,t,T}^{s_1,s_2,\theta}. \tag{17}$$

The present value of the societal benefit implied by stranding i's coal assets is given by

$$B_{i,t,T}^{s_1,s_2,\theta} = \sum_{\tau=t+2}^{T} \theta \times \Delta E_{i,\tau}^{s_1,s_2}. \tag{18}$$

Relatedly, we introduce the term "carbon-adjusted earnings" $\Pi_{i,\tau}^{s_1,s_2,\theta}$, and define it as the earnings $\Pi_{i,\tau}^{s_1}$ in year τ adjusted for the social damage generated by those earnings via its carbon emissions, given a social cost of carbon θ, i.e.,

$$\Pi_{i,\tau}^{s_1,\theta} := \Pi_{i,\tau}^{s_1} - E_{i,\tau}^{s_1} \times \theta.\text{[46]} \tag{19}$$

In our context earnings are defined by coal production times the profit per unit of coal production (i.e., $\Pi_{i,\tau}^{s_1} = O_{i,\tau}^{s_1} = P_{i,\tau}^{s_1} \times \pi$) under a business-as-usual scenario. The social harm is given by the social cost of carbon times emissions generated by coal production (i.e., $E_{i,\tau}^{s_1} \times \theta$). The carbon-adjusted earnings of coal companies are negative, rendering their social stranded asset value negative, even though their conventionally-defined earnings under a business-as-usual scenario s_1 are typically positive, rendering their stranded asset value positive.

5 Literature

Carbon emissions from burning coal are generating externalities that are far from being fully internalized. Much of the economic analysis on climate change has taken a Pigouvian approach, seeking to determine the optimal level of a carbon tax to internalize those externalities (see e.g., Gollier (2012), Llavador (2015), Heal (2017), and Daniel et al.

[46]Note that to obtain the present value of future earnings, we discount free cash flows from coal as before, but we do not discount the social cost of emissions from coal, as explained before.

(2019)). Related to the Pigouvian literature on carbon taxation and the SCC, there is also a literature on cap-and-trade systems (see e.g., the seminal treatment by Dales (1968) and Ellerman et al. (2003)). Under the Pigouvian approach, the price of carbon is set but the quantity adjustment is left to the market. Under cap-and-trade systems, which can also be seen as a variation of the Pigouvian approach, the quantity of emissions (i.e., the cap) is set, but the price of carbon is left to market forces. The social planner can thus set the price or the quantity to obtain an efficient social outcome (Weitzman (1974)).

We build on the Coasian approach and seek to attain an efficient social outcome through bargaining and contracting (Coase (1960)). Determining the appropriate level of the carbon price, as in the Pigouvian approach, is only a first step. It only suggests a marginal price to set for carbon emissions. It does not provide any information on the exact effect of the carbon price in reducing carbon emissions. We are going a step further by determining the size of avoided emissions from phasing out coal, and by using this to estimate the net social gain from phasing out coal. This requires in addition to the SCC an estimate of avoided emissions and the costs of replacing coal with renewables.

Table 9 summarizes our main findings on the net social gain from phasing out coal and compares these, as well as its break-down into benefits and costs, to the (sparse) literature. From Table 9 we observe that most studies, including the ones by IEA (2021d) and McKinsey (2022), focus solely on global costs to get to Net Zero by 2050 and fail to measure the sizable societal gain, which, as we show, outweigh these costs. To assess whether an action to meet the Paris accords is worthwhile to undertake, we argue that one should instead evaluate whether the net present value (NPV) of a mitigation or adaptation action positive. In the context of climate change, we propose to refer to this as the "social net present value" (SNPV). The one study that does evaluate both costs and benefits of phasing out coal offers point-in time-estimates (Rauner et al. (2020)), but does not estimate the net present value over the decarbonization horizon.

Table 9: Comparison of the global present value of costs and benefits, as well as the net benefits (unless otherwise indicated), found in the literature to decarbonize the coal sector, the energy sector, physical asset & land-use systems, and the broader economy according to a Net Zero 2050 pathway.

	Paper	Present value of benefits	Present value of costs	Net Present Value
Coal	Adrian, Bolton & Kleinnijenhuis (2022)	$106.9 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 (2021d)	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
Broader economy	Groves et al. (2020)	$62.6-$84.5 dollars in Costa Rica over 2020-2050	$20.8 -$36.4 billion in Costa Rica over 2020-2050	$29.8-$56.8 billion in Costa Rica over 2020-2050

We observe from Table 9 that our annual cost estimate of $1/2-$2 trillion to phase out coal is consistent with that of Rauner et al. (2020), and is less than cost estimates to decarbonize the broader energy sector ($4.5-$5 trillion annually, IEA (2021d)), and physical assets and land-use systems ($9.2 trillion annually, McKinsey (2022)) – as should be expected. The comparison of our results with the literature gives confidence that our cost estimates are reasonable. Moreover, our estimates are based on a fully transparent methodology, which easily lends itself to further sensitivity and scenario analysis (see our website). Mercure et al. (2021) estimate stranded assets value of fossil s to be between $7-$11 trillion dollars over 2021-2036. From a social perspective, those stranded asset values should be evaluated against the gains of phasing out fossil fuels, which is our main argument and point of departure.

Finally, none of the papers in Table 9 recognize that the Coasian approach provides a robust foundation for climate finance. Phasing out coal is not only a matter "of urgency for the planet" but it also makes economic sense. We show that the social gains far outweigh the costs of climate financing to end coal. This finding should provide extra impetus to implement a global carbon tax equal to the SCC. To complement incomplete carbon taxation, we argue that climate financing could be offered to countries to replace coal with renewables. We are the first to argue that such financing should be made *conditional* on a country's commitment to phase out coal, the opportunity costs of which should be compensated. This logic also applies to climate financing for phasing out carbon-intensive assets, more broadly.

6 Policies

The Pigouvian approach to phasing out carbon emissions via carbon taxation has dominated economic policy discussions on climate change. Carbon pricing will certainly play an essential role in the green transition. But in the absence of an adequate global carbon price, it is helpful to explore complementary mitigation policies that can have the same effect as carbon pricing.

The key point of our paper is that once the present value of the cost and benefits of phasing out coal are taken into account, the world can reap a social gain of 77.89 trillion dollars by phasing out coal. This represents around 1.2% of current world GDP every year until 2100.

In light of such huge gains from phasing out coal it is all the more important to keep alive any negotiations on an agreement to stop burning coal, and to pursue policies that help accelerate the replacement of coal with renewable energy. In the remainder of this section we point to several directions that could be explored to accelerate the financing of renewable energy investments to replace coal.

Financing the Coal Phase Out

We estimate that the present value of the requisite climate financing to globally phase out coal (representing a component of the broader need for "climate mitigation financing") is around 29 trillion dollars.[47] The global annual financing need varies between half a

[47] Our estimate of the requisite global climate financing $C_{t,T}^{s_1,s_2,s_r}$ depends on the pace at which coal is phased out s_2 relative to the business-as-usual scenario s_1, the replacement mix s_r of renewable energy with which phased out coal is replaced, the time horizon of the phase-out T, the degree to which renewable investment costs drop resulting from global "experience" in building renewable plants, the lifetime of renewables, and the projected free cash flows of coal companies. The conservative values we took for these are summarized in Table 3. We also conducted sensitivity analysis around our baseline estimate as shown in Section 4.1.1 and 4.2.1. The methodology to compute the requisite climate financing is given in Section 3.3.

trillion and 2 trillion dollars with a front-loading of around 3 trillion dollars (see Figure 7). We find that for a substantial number of countries, the climate financing they would need to provide to phase out coal domestically would be north of 5% of their GDP (see Figure 8). If the developed world were to fund the phase out of coal globally it would amount annually to between $\frac{1}{2}$% and 4% of its GDP with a front-loading of 6% of its GDP (see Figure 9). The requisite climate financing most likely cannot be paid by public funds alone 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. Public funding can help make private investments in creating a coal free world bankable and significantly amplify the total funds that can be attracted for ending coal.

IFC-Amundi Case Study: A Public-Private Partnership

A highly innovative example of how such a public-private partnership model might work in practice is the emerging market green bond fund described in Bolton et al. (2020), jointly implemented by the International Finance Corporation (IFC)[48] and the asset management firm Amundi. In that deal, an asset backed fund was constructed in which a development institution (IFC) took the first-loss tranche of $125 million. The senior tranches had investment grade rating, and were all successfully sold in the marketplace. Importantly, the fund invested in due time in climate-friendly assets. The total size of the deal was about $2 billion. Importantly, the senior tranche is 90% of the value of the fund, which indicates the enormous potential of public money provided by a multilateral institution in channelling private money to green projects.

A particularly promising model for scaling up renewable energy investments around the world is the four-pillar public-private partnership (PPP) model, outlined by Arezki et al. (2017). PPPs are typically thought of as bilateral contracts between a private concession operator and a government agency. Arezki et al. (2017) propose that four partners should be involved, and additionally include a development bank and institutional investors. Under this enlarged model for PPPs, development banks play a special role as "originate-and-distribute" banks for infrastructure projects structured as PPPs for at least three reasons. They reduce transaction costs of funding of infrastructure investments, by means of credit enhancement. With their technical knowhow, they can assist governments in identifying and structuring renewable energy projects under a co-

[48]The IFC is a sister organization of the World Bank and member of the World Bank Group.

ordinated plan. Further, they can monitor the implementation and operation of green projects, and alleviate political risk, thereby reducing moral hazard and adverse selection risk.

Various implementation features of the IFC-Amundi fund deal are worth noting for designing such deals. First, the Amundi Planet Emerging Green One (EGO) fund structure offered all assets in U.S. dollars, thereby eliminating exchange rate risk for investors. Second, it built an asset portfolio in a wide variety of emerging market countries across several continents, giving a unique diversification opportunity for investors. Third, green bonds were issued by emerging-market commercial banks, improving market access. As more funds such as EGO are launched high initial transaction costs in creating the new asset class will be amortized. A conveyor-belt of projects can then be originated and distributed to global investors, opening the gates for large pools of private money to be directed towards renewable energy investments, especially in poor and middle-income countries. The IFC-Amundi case study offers a promising model for financing green projects. We next outline how such a model could be applied to phase out coal specifically.

A Public-Private Partnership to Finance 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 above: (1) governments; (2) coal companies; and (3) investors.

Governments

Taking the IFC-Amundi deal as a representative case study, a public-private partnership providing a total climate financing of 29.03 trillion dollars[49] dollars to phase out coal must be funded with roughly 10% of public funds. Hence, governments must invest around 2.9 trillion dollars into the junior tranches of the ABS structures the phase out of coal. Such government investments could be seen as transfers given their high risk profile. The remaining investments, of around 26.1 trillion dollars, into the de-risked senior tranches must be financed by capital markets.

It is in the interest of an individual government to finance the junior tranche if its gross societal benefits from avoiding coal emissions is greater than its costs of doing so. Its

[49] 29.03 trillion represents the present value of future climate financing needs to phase out coal globally.

costs are roughly 10% of the total costs of phasing out coal in its country. The total costs – representing the country's climate financing needs to phase out coal – are given by the sum of the opportunity cost of coal and investment cost in renewables in its country. This is obtained by aggregating the opportunity costs of individual coal mines in that country and summing that with the investment costs in renewables, assuming that phased-out coal in a country is replaced with renewable energy in that country. The opportunity cost of a coal mine from phasing out coal is given by its expected discounted missed free cash flows from phasing out coal. In our calculations, we take the global societal benefit of avoiding coal emissions to be equal to the SCC times the global quantity of avoided emissions. The SCC captures the average damage across the globe from emitting one extra tonne of carbon into the atmosphere.

In reality, the impacts of climate change are heterogeneously distributed across the world (IPCC (2021)). Hence, the country-specific SCC might be higher than the average (e.g., India) and that to another lower than the average (e.g., New Zealand). We have focused on the global carbon arbitrage, for which the global SCC more reliably accounts for climate damage estimates in the aggregate. It is possible to redo our calculations, however, based on regional estimates of the SCC. A key observation is that we find that the carbon arbitrage disappears only when the SCC is less than or equal to \$20.4/tCO_2 (see Figure 5), using conservative baseline parameters. Countries that would only have to pay 10% of the climate financing would see their carbon arbitrage only disappear at a SCC less than or equal to \$2/tCO_2. Hence, even if the SCC for certain countries is less than our central estimate of \$75/tCO_2 the carbon arbitrage is unlikely to disappear in most countries. We thus expect that most countries should therefore find it in their interest to provide the necessary public funds to finance the phase out of coal. Even countries that are expected to experience mild climate impacts in absence of climate tipping points, amounting to a SCC below \$2/tCO_2, should find it in their interest to invest in renewables to phase out coal once the risk of climate catastrophic outcomes is taken into account.

Equity considerations inevitably underlie the attainment of the Coasian bargain we have identified. It seems reasonable that the developed world would pay for the lion share of the energy transition in the developing world, not least because developed countries are responsible for most historical emissions.[50] Providing the 10% of public funds needed for renewable investments in developing countries by our estimates amounts to approximately between 1.5 and 8 billion dollars annually (with a front-loading of around 19 billion), or between 0.003-0.01% of 2020 developed world GDP. (These numbers can be inferred from Figure 7 and 9 by taking 10%.) This represents a fraction of the 100 billion dollars of annual climate financing the developed world already promised to offer to the developing world for mitigation and adaption to climate change. The developed world could also pay for part of the climate financing of emerging market economies into the junior tranche. This may, for instance, be warranted to complement contributions into the junior tranche of those emerging-market economies that are unable to fully pay for 10% of their climate finance needs. The amount for emerging economies would come down to between approximately 20 and 120 billion annually (with a front-loading of 190 billion), representing around 0.04-0.24% of 2020 developed world GDP and 0.07-0.39% of 2020 emerging-market GDP.[51] The public financing the developed world must provide to phase out its own coal amounts to approximately between 10 and 60 billion dollars annually (with a front-loading of 110 billion) representing between 0.02-0.12% of 2020 developed world GDP. A special fund financed by countries contributing to the junior tranche might have to be set up to supplement financing into the junior tranche by countries heavily reliant on coal (see Figure 8), who might be unable to finance their own share in its entirety. Of course, the details of the respective investments of individual governments into the junior tranche will have to be ironed out in an international agreement. Instead of a global deal, regional bargains can also be made that add up to the global deal.

The blended climate financing to phase out coal would be largely in the form of debt (roughly 26.1 trillion dollars), but it would have a large grant element for at least three reasons. First, roughly 2.9 trillion dollars would be provided as grants by governments. Second, the debt would be long-term. Third, the debt would be provided at low interest rates, since it would be de-risked by government funding into the junior tranche. For most countries the climate financing would not increase debt-to-GDP levels by more

[50] See Wiegand (2021) for a discussion of equity and efficiency considerations that are relevant for the provision of climate compensation.

[51] Developed world and emerging-market GDP in 2020 are 50.8 and 30.7 trillion US dollars, respectively, according to the World Bank, and using the IMF World Economic Outlook classification of country development level.

than 5%, at most. (See Figure 8 and take 90%.) But for some countries heavily reliant on coal, or with a weak existing fiscal position, debt restructuring or another solution might be necessary.[52]

This climate financing should be provided conditional on the phase out of coal. Making the provision of climate financing offered to countries for building renewables to replace coal conditional on the phase out of coal enables these countries to achieve growth (in energy demand) that is decoupled from fossil fuels. It also helps to ensure macro-financial stability. Any drop in coal supply is roughly matched with a drop in coal demand as the demand for energy previously supplied by coal can be largely met with energy generated from newly built renewable plants, thereby helping to avoid volatility in coal prices, a shift of coal production to foreign countries, and shortfalls in domestic energy supply. Establishing conditionality of climate financing is thus also important to alleviate macro-financial stability issues arising from phasing out coal.[53] By phasing out coal and phasing in renewables, in tandem, energy demand can be met with renewables, thereby explicitly reducing coal emissions and consequent climate change damages.[54] A scenario is then avoided in which coal production simply shifts abroad to tap into unmet energy demand and coal emissions continue.

Coal Companies

It is in the interest of coal companies to phase out coal if they get compensated at least their opportunity cost of coal.[55] Compensation for the opportunity cost of coal companies is essential to avoid strong political headwinds hindering the implementation of domestic policies to phase out coal. That compensation can be paid out to the owners and operators of coal companies. Extra funding could be offered to pay for the lost income of coal workers and their retraining for employment in other sectors. Such compensation

[52]See Bolton et al. (2022) for a discussion of ways in which sovereign debt of countries with a weak existing fiscal position can be restructured to create sufficient fiscal space to take on additional debt for the purposes of climate adaptation or mitigation financing.

[53]The conditionality of climate financing could be built into contractual terms of ABSs. International agreements could also be struck in which countries enshrine into law the commitment to phase out coal in return of which they receive funding for renewables and compensation for missed coal profits.

[54]For many countries, such as China, the net gains from financing the phase out of coal extend beyond that captured by their SCC. Obtaining cleaner air is an especially salient concomitant benefit.

[55]Global climate financing F should be at least equal to the opportunity cost of coal and investment cost in renewables (i.e., $F = C^{s_1,s_2,s_r}_{t,T} = I^{s_1,s_2,s_r}_{t,T} + O^{s_1,s_2,s_r}_{t,T}$); recall Section 3.3. In the paper, we estimate the carbon arbitrage based on a climate financing cost of $F = C^{s_1,s_2,s_r}_{t,T}$. A carbon arbitrage can be reaped, however, as long as the provided climate financing remains less than the social gain from phasing out coal. That is, we must have that $C^{s_1,s_2,s_r}_{t,T} \leq F < B^{s_1,s_2,s_r}_{t,T}$.

alleviates harmful impacts of shutting down coal mines on the local economy. We estimate that the opportunity cost of coal represents around (0.05/106.9) 0.05% of the gross societal benefits of phasing out coal. Hence, even if governments would like to double, triple, or quadruple the compensation to the coal sector to better account for costs of job losses, the social gain from phasing out coal would remain large.

Investors

It is in the interest of investors to participate in the grand Coasian coalition to phase out coal if their investments are both bankable and sufficiently safe. The renewables that are built to replace coal would generate profits making phasing out coal bankable. The investments of governments into the junior tranche would sufficiently de-risk investments in renewables to appeal to institutional and other investors who can only invest in investment grade products. The senior, investment-grade tranches to phase out coal would represent a new green asset class, and significantly help increase the supply of *bankable* green projects, the lack of which presents a binding constraint on scaling up climate finance at present.

To scale up the capacity of capital markets to phase out coal (to around 26.1 trillion dollars), further collaboration between the public and private sector is necessary. International development banks (such as regional multilateral banks, IFC, and so on) would have to significantly scale up their capacity to invest in the junior (equity) tranches of ABSs, on the basis of increased government funding. Private sector initiatives, such as those led by the Glasgow Financial Alliance for Net Zero (GFANZ) – representing $130 trillion of assets under management (roughly 40% of global financial assets) – and the World Economic Forum, would have work with their members to develop markets for investment grade tranches.

To date, the market size for ABSs is not sufficient to finance a green transition at scale. Currently, the ABS market is only about $2 trillion globally. In principle, one could envision a substantial increase in market size over the next decade – especially in light of the growing appetite of (climate-concerned) investors and their clients to invest in bankable green projects – but it would remain to be seen how quickly such scaling could happen.[56] Asset managers, insurance companies, pension funds, and sovereign

[56]To globally phase out coal in line with the net zero 2050 pathway of the NGFS, we estimate that a front-loading north of 3 trillion dollars is needed this decade to phase out coal around the world (see Figure 7). Hence, the speed at which the ABS market can be scaled will matter for whether phasing out

wealth funds are potential investors in the senior tranches of ABS. The proposed structured would have to appeal to those institutions from an investment point of view, in terms of riskiness, yields, and ESG considerations. While many buy side institutions have adopted ESG type investment mandates, the total market size for ESG assets remains fairly small, below $3 trillion at the time of writing, globally. So, significant market development would be needed to create a large enough market for a new green asset class financing the phase out of coal.

We view this climate finance approach as complementary to Pigouvian carbon taxation approaches and cap-and-trade schemes.[57] Key to our argument is the recognition that there are large social benefits from ensuring the green transition. The global Coasian bargain we propose, in which the opportunity cost of coal and replacement cost in renewable energy are compensated, 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 to seek to overcome any such hurdles that prevent the great carbon arbitrage from being reaped. By unleashing capital markets, while gradually increasing the pricing of emissions, and establishing conditionality of climate financing for renewables with the phase-out of coal, we could soon reap most of the net benefits of the great carbon arbitrage we have estimated in this paper.

7 Conclusion

In this paper, we take a Coasian approach to the energy transition and climate finance. We measure the gains from phasing out coal as the social cost of carbon times the quantity of avoided emissions and weigh those gains against the present value of costs of ending coal plus costs of replacing it with renewable energy. In our central estimate, the world could realize a net total gain of 77.89 trillion US dollars. This represents around 1.2% of current world GDP every year until 2100.

These estimates of the net gain to the world of phasing out coal are very large indeed. Our baseline estimate of the social benefits of phasing out coal is based on a social cost of

coal along this pathway is feasible.

[57]Indeed, if a global carbon tax were to be in place, climate finance to phase out coal could be done at market prices and would not longer require government subsidies.

carbon of 75 dollars per tonne of CO_2 – in line with the lower-end estimates of the SCC in the literature. We also conduct a sensitivity analysis for all our main parameters and consider other values of the SCC, ranging from a minimum of \$61.4/tCO_2 to a maximum of \$268.4/tCO_2. For the less conservative estimate of \$168.4/tCO_2, which nonetheless rules out plausible catastrophic climate events with large costs (Pindyck (2019)), we find that the carbon arbitrage grows from \$77.89 to \$211.03 trillion. The associated min-max estimates grow from (62.45, 120.97) to (195.60, 309.66) trillion dollars, or from (1, 1.9) to (3, 4.8) percentage points of GDP.

To determine the size and opportunity costs of avoided emissions we rely on a detailed dataset on historical and projected global coal production at the affiliate level put together by the Asset Resolution (AR), as well as financial data from Orbis. To calculate investment costs for different types of renewable energy investments needed to replace coal we use data from IRENA (2021b).

We view our approach as *complementary* to the Pigouvian approach that is the basis for Carbon pricing. While we fully concur that, in principle, the optimal level of a carbon tax as indicated by the social cost of carbon could trigger an efficient reallocation of resources towards greening the economy, our analysis points towards the quantitative estimate of the social surplus that can be attained from avoiding emissions. We point out that the world could benefit from a Coasian bargain, in which policies and institutions are developed to complement carbon taxes, thus getting to the green transition more quickly.

Our policy discussion focuses on the possibility of using climate finance as an instrument. In particular, asset backed securities where international development banks invest in the junior, equity tranch and private investors hold the senior, investment grade tranch is an effective transfer of risk that could lead to potentially sizable investments into greener economic activity. The precise structuring and pricing of such instruments is left for future work, but we note that previous transactions point towards feasibility.

In sum, our analysis in this paper makes a simple but powerful observation: phasing out coal is not just a matter of urgent necessity to limit global warming to 1.5°C. It is also a source of considerable economic and social gain. From a Coasian perspective it is sound economic logic to compensate the losses incurred from phasing out coal and to account for the capital expenditures needed to replace the energy from coal, as well as to link the social benefits of avoided emissions to these costs. The climate financing needs are indeed large (around 29.03 trillion dollars), but our point is that they are nonetheless small relative to the social benefits (around 106.9 trillion dollars). These social benefits are too easily forgotten. Given the sizable social gains from phasing out coal, it is in our interest to seek to overcome any hurdles that prevent the carbon arbitrage from being reaped.

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A Appendix

Coal Replacement Benefits

The present value of benefits of phasing out coal extend beyond the cut-off year T, at which the last batch of investments (via climate financing) is made. How much energy renewable plants built over $[t+2, T]$ can still produce in years $\tau > T$ depends on their lifetime, their depreciation rate, and their capacity factor. $B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}}$ gives the present value of residual benefits that accrue over period $[T+1, \bar{T}]$ because of earlier-built renewable capacity in period [t+2,T]. It is given by the social cost of carbon θ times emissions

$\Delta E^{s_1,s_2,s_r}_{y,t,T,\tau}$ that are avoided in each year $\tau \in [T+1, \bar{T}]$ in each country $y \in \mathcal{Y}$ based on renewable capacity built over period $[t+2, T]$, i.e. $B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}} = \theta \times \sum_{\tau=T+1}^{\bar{T}} \sum_{y\in\mathcal{Y}} \Delta E^{s_1,s_2,s_r}_{y,t,T,\tau}$.[58] A natural choice for $\bar{T} - T$ is the lifetime of renewables (30 years in our baseline), since this is how long residual benefits accrue. Avoided emissions in year τ in country y from earlier-built renewable capacity are given by the energy $R^{s_1,s_2,s_r}_{y,t,T,\tau}$ that earlier-built capacity produces, converted with function g^{-1} to how much avoided coal production that amounts to, and multiplied with the weighted-average emission intensity $\tilde{\epsilon}_y$ of coal production in that country. This gives $\Delta E^{s_1,s_2,s_r}_{y,t,T,\tau} = g^{-1}(R^{s_1,s_2,s_r}_{y,t,T,\tau}) \times \tilde{\epsilon}_y$, where $R^{s_1,s_2,s_r}_{y,t,T,\tau} = \sum_{q\in\mathcal{R}} R^{s_1,s_2,s_r,q}_{y,t,T,\tau}$.

The quantity of avoided coal emissions relying on renewable energy produced by earlier-built stock in country y depends on which coal producers no longer need to produce coal and their emission intensity. We assume that each coal producer in country y reduces coal production proportionally, so we can use the weighted (by 2020 company-level production in country y) average emission intensity $\tilde{\epsilon_y}$.

The renewable energy that renewable type q built over $[t+2, T]$ can produce at a time $\tau > T$ is given by $R^{s_1,s_2,s_r,q}_{y,t,T,\tau} = h(S^{s_1,s_2,s_r,q}_{y,t,T,\tau}) \times f^q$, which represents a modification of equation 12. The renewable energy capacity $S^{s_1,s_2,s_r,q}_{y,t,T,\tau}$ of type q built in $[t+2, T]$ that still is effective at date $\tau > T$ is given by $S^{s_1,s_2,s_r,q}_{y,t,T,\tau} = \sum_{\tau_b=t+2}^{T} G^{s_1,s_2,s_r,q}_{y,\tau_b} \times (1-d_q)^{(\tau-\tau_b)} \mathbb{I}_{\{\tau-\tau_b \leq l_q\}}$, representing a modification of equation 13.

Coal Replacement with Natural Gas as Transition Fuel

Benefits of avoiding emissions from coal, including the residual benefits that accrue over period $[T+1, \bar{T}]$ because of earlier-built renewable capacity in period $[t+2, T]$, are given by $B^{s_1,s_2,\theta}_{t,T} + B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}}$. If we replace coal in part with natural gas, for a total of $\omega^{gas,s_r}\%$, then we must reduce these benefits by the incremental damage from climate change brought about by additional emissions from natural gas. The reduction in benefits that must be applied is $\theta \times \omega^{gas,s_r} \times \tilde{\epsilon}^{gas} \times \sum_{i\in\mathcal{C}} \sum_{\tau=t+2}^{T} g(\Delta P^{s_1,s_2}_{i,\tau})$, where the multiplication of the last three terms represent the gas emissions (in tCO_2), and where $\tilde{\epsilon}^G$ is the global weighted-average emission intensity of natural gas (in tCO_2/GJ). We obtain $\tilde{\epsilon}^G$ from AR by taking the company-weighted emission intensity of each gas power plant in the world and weighing this by its 2020 energy capacity (in GJ) relative to 2020 global energy capacity of gas plants.

The present value of costs of replacing coal with a mixture of renewables and natural gas is given by $C^{s_1,s_2,s_r}_{t,T}$ as before, except the present value of investment costs $I^{s_1,s_2,s_r}_{t,T}$ now must have an extra component to capture the present value of investment costs in natural gas plants. (Note that the weights ω^{q,s_r} of renewable types $q \in \mathcal{R}$ will now no longer sum to one, as part of the replacement of coal is with natural gas.) Since we do not have data on investment costs to build natural gas plants, we proxy requisite investment costs with the LCOE (as we did before in Section 3.2.3). The present value of investment costs in natural gas is then given by $\sum_{\tau=t+2}^{T} \frac{1}{(1+\rho)^{(\tau-t)}} \times g(\Delta P^{s_1,s_2}_{\tau}) \times \omega^{gas,s_r} \times L^{gas}_{\tau}$ (which represents a modification of equation 16). We take the 2020 global average estimated by IEA (2020) as the LCOE of natural gas (CCGT), of around L^{gas}_{τ}=\$19.4/GJ (equivalent to \$70/MWh). (Note that the 2020 global average LCOE of natural gas is higher than that of solar PV and wind onshore but lower than that of wind offshore. Revisit Section 3.2.3

[58] If we take into account that the growth rate of the SCC may exceed the discount rate applied to the benefits of avoided emissions by a net percentage of r%, then the residual benefits that accrue over period $[T+1, \bar{T}]$ are updated to $B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}} = \theta \times \sum_{\tau=T+1}^{\bar{T}} \sum_{y\in\mathcal{Y}} \Delta E^{s_1,s_2,s_r}_{y,t,T,\tau} \times (1+r)^{(\tau-t)}$.

for the LCOE of the aforementioned renewables.)

Table 10: Units of variables in our model (excluding those with no unit or a unit in dollars or percentages) and standard conversion functions.

Name	Variable/Function	Unit/Definition
Social cost of carbon	θ	Dollars per tonne of CO_2 ($/t$CO_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 $\to$ GJ/year	$x \times$ [#seconds per year], for $x = G, S$ *
Function converting energy per year to renewable capacity	$h^{-1}(y)$: GJ/year $\to$ GW	$y/$[#seconds per year], for $y = R, g(P)$ *
Function converting coal production to coal energy	$g(P)$: tonnes of coal $\to$ GJ	$P \times 29.3076$ **
Function converting MWh to GJ	$f(y)$: MWh $\to$ GJ	$y \times 3.6$ ***

* # seconds per year = $365.25 \times 24 \times 3600$.
** 1 tonne of coal equivalent is 29.3076 GJ.
*** 1 MWh is 3.6 GJ.