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 avoided carbon emissions to the present value of the costs of ending coal plus the 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 around 1.19% of current world GDP every year until 2100. We argue that policies and institutions should be construed to reap these large net benefits.

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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). 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)).

We build on this literature here by giving a quantitative estimate of the social surplus that can be attained from avoiding emissions. How much would the world benefit, how big is the Coasian bargain of phasing out fossil fuels and replacing them with energy from renewable sources such as wind power and solar radiation?

We focus here on quantifying 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 the losses 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 are measured by the SCC times the quantity of avoided emissions. Indeed, if an efficient global emissions trading system (ETS) were in

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

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.

We estimate that the net gain to the world of phasing out coal is very large indeed. By comparing the present value 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 a combination of renewable energy and natural gas, 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 1.19% of current world GDP every year until 2100.

Our baseline estimate of social benefits of phasing out coal is based 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 and consider other 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, which nonetheless remains conservative in the face of 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 (0.96, 1.85) to (3.00, 4.75) percentage points of GDP. Our central estimates are much closer to the min settings than to the max settings, 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 on historical and projected global coal production at the plant level put together by the Asset Resolution and 2 Degrees Investment Initiative (AR-2DII), 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 neither India nor China, who both heavily rely on coal for energy production. 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 economic logic 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. The missed opportunity in Glasgow was that an agreement to phase out coal might have been possible if compensation had been a more important part of the agreement, and if the yet to be fulfilled promise to transfer 100 billion a year in green finance (and possibly much more) to developing countries had been made conditional on phasing out coal.

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)). 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

[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`.

countries' GDP, with a front-loading at around 6% of wealthy countries' GDP.

This is 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 US Climate Envoy John Kerry emphasized the inconvenient and sobering truth 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 – as also IEA (2021b) has done. Yet, more support would be gained by also pointing to enormous benefits to be gained from these investments and not obnubilate the issue with an exclusive focus on the 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 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. Much of the funding of these investments can indeed come from the private sector, but a significant portion of public money to enhance these investments will still be needed (see Arezki et al. (2016), and Bolton et al. (2020)).

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 17 defines the notions of "social stranded asset value" and "carbon-adjusted earnings" and provides quantitative estimates of social stranded asset values. Section 5 links our findings to the literature. Section 7 provides concluding comments.

2 Data

We make use of a unique asset-based company data set of Asset Resolution (AR) and the 2 Degrees Investing Initiative (AR-2DII) on the historical and projected global coal production at the asset level – henceforth referred to as "plant level". For each coal company, these data capture plant-level data 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, specifying its direct owner, as well as any of its parents or ultimate parents.[4] The total number of coal companies in our 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 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 I, II, and III emissions.[5]

These data cover at least 85% of global coal production according to 2DII-AR. Based on this AR-2DII data our estimate of global coal production in 2020 is 6.41 Giga tonnes (Gt). In combination with the AR-2DII emission intensity data, our estimate of global scope I and III emissions from coal in 2020 is 14.53 Giga tonnes of CO_2. Both the AR-2DII 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 (2021d)), and the Global Enery Monitor[6]; see Table 1. For comparison, 2020 global carbon emissions from the fossil fuels (i.e. gas, oil and coal) are estimated to be 34.81 $GtCO_2$ by the Global Carbon Project. Hence, coal scope I, II and III emissions accounted for around 41.7% of these.

[4]AR-2DII data also specifies the country in which the ultimate parent company is located.

[5]Scope 1 covers direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company. Scope 3 includes all other indirect emissions that occur in a company's value chain.

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

Table 1: A comparison of the estimated global coal production (in giga tonnes of coal) in 2020 between the AR-2DII data and of a list of authoritative bodies. A dash indicates no estimate is available.

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

Table 2 shows the average scope I, II, and III emission intensity (in tonnes of CO_2 per tonne of coal) globally for the different coal types in our AR-2DII data. We weigh the emission intensity of a coal plant by its 2020 coal production get the weighted-average, and also show the 5% and 95% quantiles. AR-2DII 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).[7] 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-2DII emission intensity data with its production data, we obtain global coal emissions consistent with authoritative estimates, indicating AR-2DII emission intensity estimates can be relied upon.

Table 2: Average scope I, II, and III emission intensity (in tonnes of CO_2 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-2DII carves out how much of global coal mining is deployed in the power

[7]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.

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 by phasing out coal in the power sector, as this would result in double counting.[8]

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.

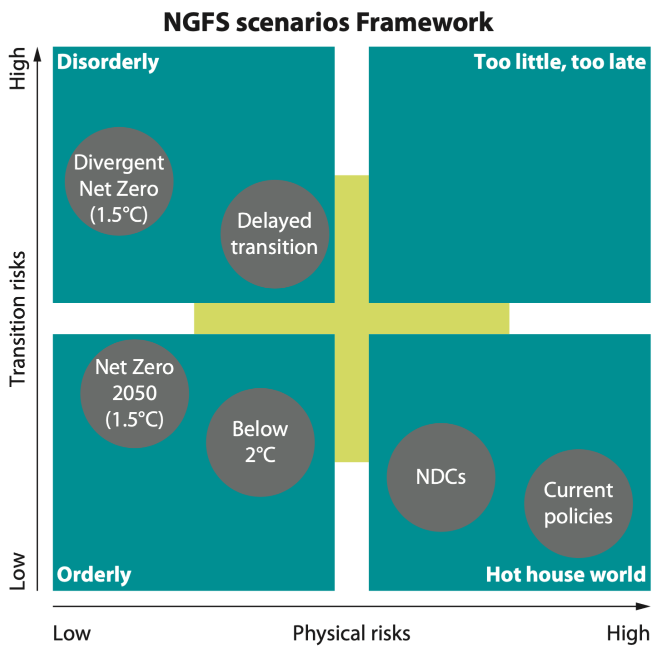

Figure 1: NGFS Climate Scenarios.

[8]The AR-2DII 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.

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 Policy and Net Zero 2050 scenario.[9] 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, taking as a starting point the projected coal production at the plant-level at time $t+1$ of 2DII-AR. 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,[10] 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 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.

[9] 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.

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

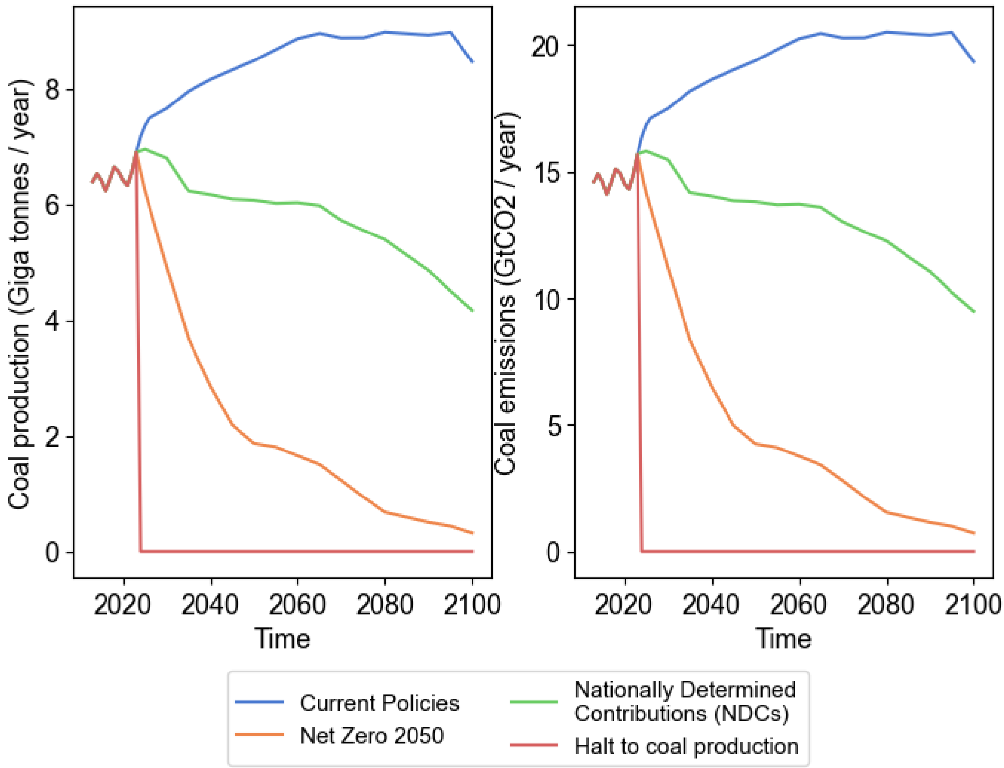

Figure 2: Global coal production under different scenarios (left plot) and associated annual global emissions (right plot).

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 phase out scenario encompasses, is the lowest hanging fruit, and must be largely realized this decade (IEA (2021c)). 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.[11]

Opportunity Costs of Coal

To calculate the opportunity cost of phasing out coal, we obtain the operating revenue,

[11] The AR-2DII data sample around 16.54% of global coal use in 2020 to be 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 (2021c)). 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 (2021c)).

profit margin, taxes, interest payments, and depreciation allowances for each coal company 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. 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 on pure coal companies only to avoid mixing our estimate of free cash flows with cash flows generated by other segments of business outside of coal. As a robustness check, we also 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 30Y US treasury yield, 2.08% and the global risk premium to be the excess CAPE yield of 2.99% of Shiller minus 1%.[12] 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)). We take these two numbers as of January 2022, which corresponds to the start year of our analysis. 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 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%.[13] As a

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

[13]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/.

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%. We obtain a discount rate of 2.8% (and 3.6% with the average risk premium).

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.

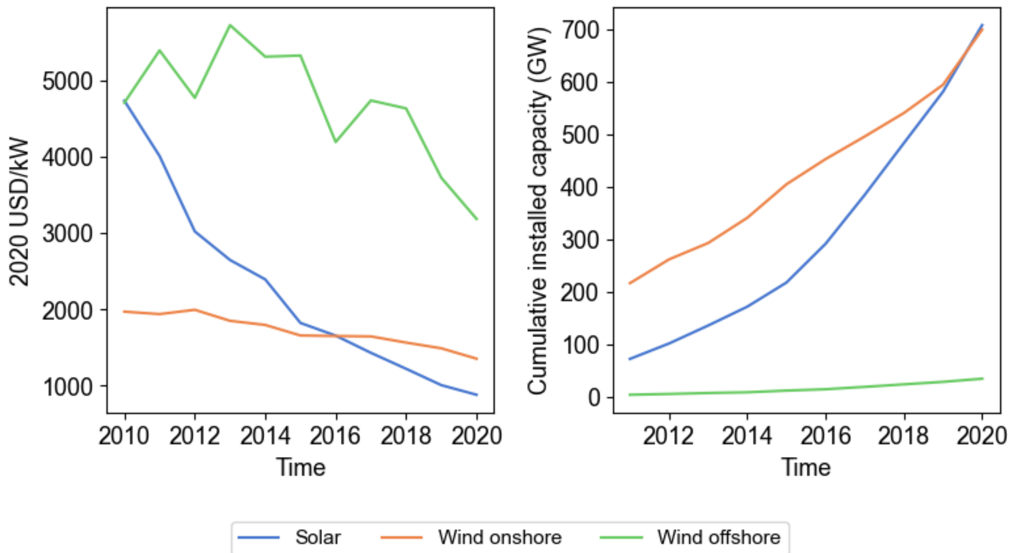

Figure 3: Investment costs in renewables (USD/KW) in the left plot and cumulative installed capacity in renewables (GW) in right plot, over 2010-2020.

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,[14] 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. The SCC θ captures economic costs, or damages of emitting one additional ton of carbon dioxide into the atmosphere, and thus benefits of reducing emissions. 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 CO2 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-phased-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-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

[14] 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.

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.[15] The year 2070 is the net zero target for various emerging and developing economies, such as China, Russia, 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 choice the SCC θ and the replacement scenario s_r in detail when we describe 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 of 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. $\Delta E_{i,\tau}^{s_1,s_2} = E_{i,\tau}^{s_1} - E_{i,\tau}^{s_2}$. The amount of emissions $E_{i,\tau}^{s}$ coal company i generates in year τ under scenario s is given by the product of its coal production $P_{i,l,\tau}^{s}$ in each of its plants $l \in \mathcal{L}_i$ under scenario s

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

multiplied with the emission intensity $\epsilon_{i,l}$ of the plant

$$E^s_{i,\tau} = \sum_{l \in \mathcal{L}_i} P^s_{i,l,\tau}\epsilon_{i,l}.^{1617} \tag{3}$$

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 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 CO2 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 the 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.[18]

Another reason we potentially underestimate significantly social benefits is that we take a conservative estimate of the SCC to start with. 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,[19] whose min-max values we use for

[16] 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 practise, we sum the product of coal production and associated emission intensity for each unique combination of these.

[17] 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-effective, 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 CO2, as well as complex chains of capture-transport-storage, hinder the cost-effective deployment (IEA (2021c)).

[18] Add a footnote: The avoided emissions from phasing out coal arguably could lower the growth rate in the SCC. Since we are using a conservative SCC value and since we are underestimating the present value of avoided emissions by not allowing for a 3% real growth rate in the SCC we do not attempt to account for the positive feedback on the future growth in SCC from avoided emissions from coal.

[19] 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 $\eta = 1.57$

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.[20]

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 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

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.

[20]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.

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 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 $\mathbb{E}[R^M]$. 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.[21] 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 Zhang (2022)).[22] 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. $I_{y,t,T}^{s_1,s_2,s_r} = \sum_{\tau=t+2}^{T} I_{y,\tau}^{s_1,s_2,s_r}$.[23] 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

[21]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 $\Delta P_{i,y,\tau}^{s_1,s_2} = P_{i,y,\tau}^{s_1} - P_{i,y,\tau}^{s_2}$.

[22]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.

[23]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.

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)).

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[24] – 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 that renewable energy stock typically does not 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). 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 $l_q = 30$

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

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 depreciation 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 farmers 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 $D_{y,\tau}^{s_1,s_2,s_r}$ (resulting from the phase out of $\Delta P_{y,\tau}^{s_1,s_2}$ coal production) converted with inverse function h into the stock of renewable energy that corresponds to it. This is then weighted by the percentage $\omega_{\tau}^{q,s_r}\%$ of each renewable energy type q in the replacement renewable energy mix (specified by replacement scenario s_r). We divide 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 $\mathcal{R} = \{\text{Solar PV, Wind Onshore, Wind Offshore}\}$, 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 (2021d)). 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 (2021c)).

We pick a replacement scenario s_r in which any shortfall of renewable energy capacity is met with $\omega_{\tau}^{solar,s_r} = 50\%$, $\omega_{\tau}^{wind-onshore,s_r} = 25\%$, and $\omega_{\tau}^{wind-offshore,s_r} = 25\%$, which is broadly in line with the relative phase in of these renewables in IEA (2021c). 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 $\omega_\tau^{solar,s_r} = 56\%$, $\omega_\tau^{wind-onshore,s_r} = 42\%$, and $\omega_\tau^{wind-offshore,s_r} = 2\%$. 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. 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.

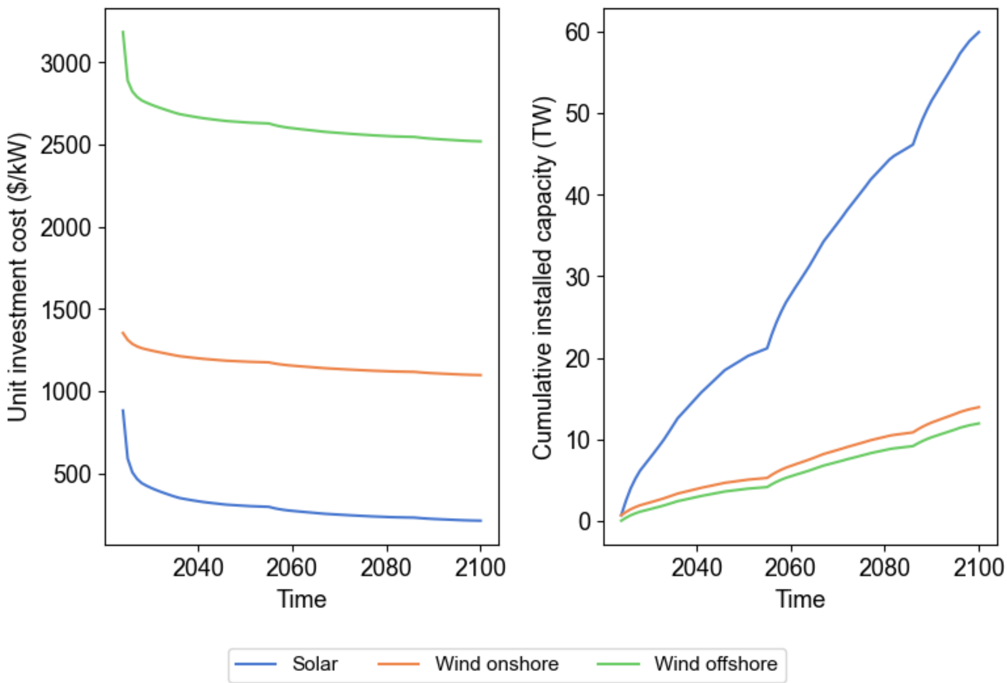

Figure 4: Drop in investment costs of each renewable (in dollars per KW) as a function of cumulative installed capacity (in TW).

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 $L_\tau^{solar} = 0.039$, $L_\tau^{wind-onshore} = 0.057$, and $L_\tau^{wind-onshore} = 0.084$ (in dollar per KWh).

3.3 Financing the Coal Phase Out

To achieve the great carbon arbitrage financing conditional on the commitment to phase out coal and to replace coal with renewables must be provided – ensuring energy availability. We turn to the question of who should and can pay for this in Section 7, and focus our attention on estimating the aggregate amount needed to finance the coal phase-out. The present value of 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 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. This in turn is 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 financing can be expressed as $C_{t,T}^{s_1,s_2,s_r} = \sum_{y \in \mathcal{Y}} O_{y,t,T}^{s_1,s_2} + I_{y,t,T}^{s_1,s_2,s_r}$.

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.

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 phase out scenario, s_2	• s_2 = Net zero 2050
Coal replacement scenario, s_r	• 50% solar, 50% wind (of which 50% onshore and 50% offshore)
Investment costs, I	• 30Y lifetime of renewable plants with depreciation and investment-cost experience curve
Opportunity costs, O	• Median unit coal profit of top 10 pure coal companies
Discount rate, ρ	• WACC ($\rho = 2.8\%$)

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 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 \$106.92 trillion, in 2022 dollars, while the present value of costs is only \$29.03 trillion. This is a very large number for social 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. Netting costs out of benefits, we obtain a net carbon arbitrage of \$106.92 - \$29.03 = \$106.92, or, as a fraction of current world GDP every year until 2100 a net benefit of 1.19%.[25][26]

[25] 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 do not apply discounting.

[26] 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.

Table 4: The Great Carbon Arbitrage.

Present value of benefits of phasing out coal (in trillion dollars)		106.92
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 (%)*		1.19
Total coal production prevented (Giga Tonnes)		506.79
Total emissions prevented ($GtCO_2$)		1160.61
Further temperature increase – on top of 1.1 $°C$ already observed – prevented **		1.74

* 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 1.16 $°C$ and 2.44 $°C$, respectively.

As a result of the shift to green energy, we estimate that the total coal production avoided is of the order of 587.81 gigatonnes, and total emissions avoided are GtCO2 of 1721.12. The further temperature increase – on top of the 1.1 degrees already observed – that would be prevented by executing the great carbon arbitrage is estimated to be 1.74 degrees Celcius. Needless to say, these are very substantial results for global warming.

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 $/$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.

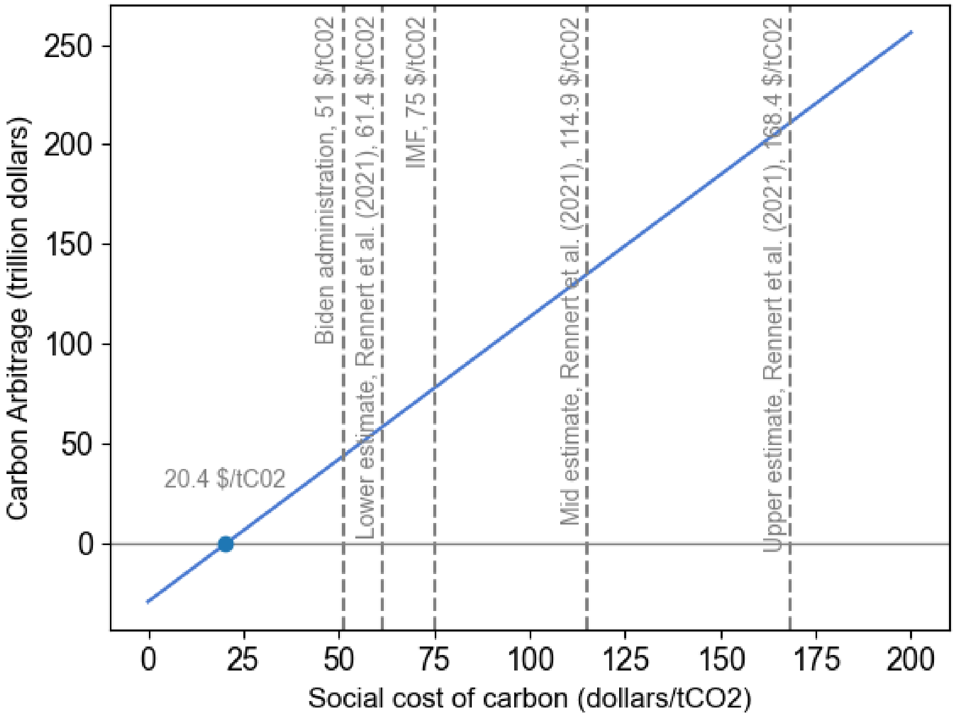

Figure 5: The carbon arbitrage as a function of the social cost of carbon.

We proceed by presenting robustness analysis in Table 5 with the midpoint estimate of θ_{IMF} =\$75/tCO_2, the lower estimate of θ_{lower} =\$61.4/tC0_2, and the higher estimate of θ_{higher} =\$168.4/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/tC0_2 is assumed. On the other hand, if we use the lower estimate of a social cost of carbon of \$61.4/tC0_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.[27]

[27] 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.

Table 5 also 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 further 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 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 42% wind. Our estimate is somewhat lower because investment costs in wind are higher than those in solar (recall Figure 3 and 4).

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 \$11.42 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 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 current 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.

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 0.96 - 1.85 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 0.66 to 4.75 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.[28]

[28]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.

Table 5: Sensitivity analysis of the great carbon arbitrage (in trillion dollars), 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 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 (of which 50% onshore and 50% offshore)	58.50	77.89	211.03
	• Static NGFS scenario 56% solar, 44% wind (of which 42% onshore and 2% offshore)	65.56	84.95	218.09
	• Dynamic NGFS scenario	65.74	85.13	218.27
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)	-4.36	11.42	119.82
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

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 the carbon arbitrage is underestimated if avoided carbon emissions resulting from replacement renewable stock beyond year $\tau > T$ are not taken into account, where T is the last year investments in new renewable plants are made. Take $T = 2070$, the year in which not only developed countries but also developing and emerging countries plan to be net zero, as an example. If a solar plant is built in year 2069, it will run for 30 years (in our baseline). This enables a reduction in coal production in the years 2069-2099, while meeting energy demand, thereby helping to bring down coal emissions priced at the social cost of carbon. The carbon arbitrage gain over the cost horizon from 2024 up to $T = 2070$ is underestimated by \$40.06-\$19.68=\$20.38 trillion if avoided emissions from coal, by having built renewable plants in 2069, are truncated at $T = 2070$. Put differently, the 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 the renewable plant can help avoid for its remaining lifetime past the date of amortization.

Table 7: Sizable underestimation of the carbon arbitrage (in trillion dollars) if future coal emissions that built renewable plants over [t+2,T] can help avoid are only counted up to time $T = 2070$, the last year investment costs in renewables are made.

	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. 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.

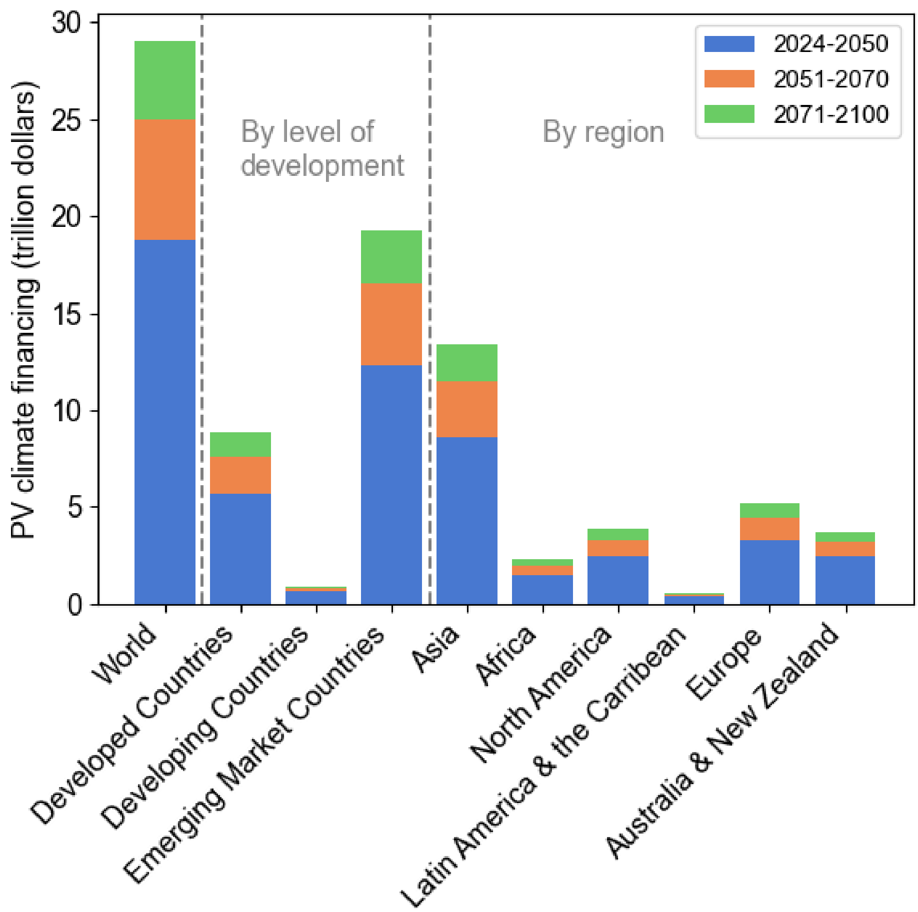

Figure 6: Present value of all future conditional climate financing needs.

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.

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.

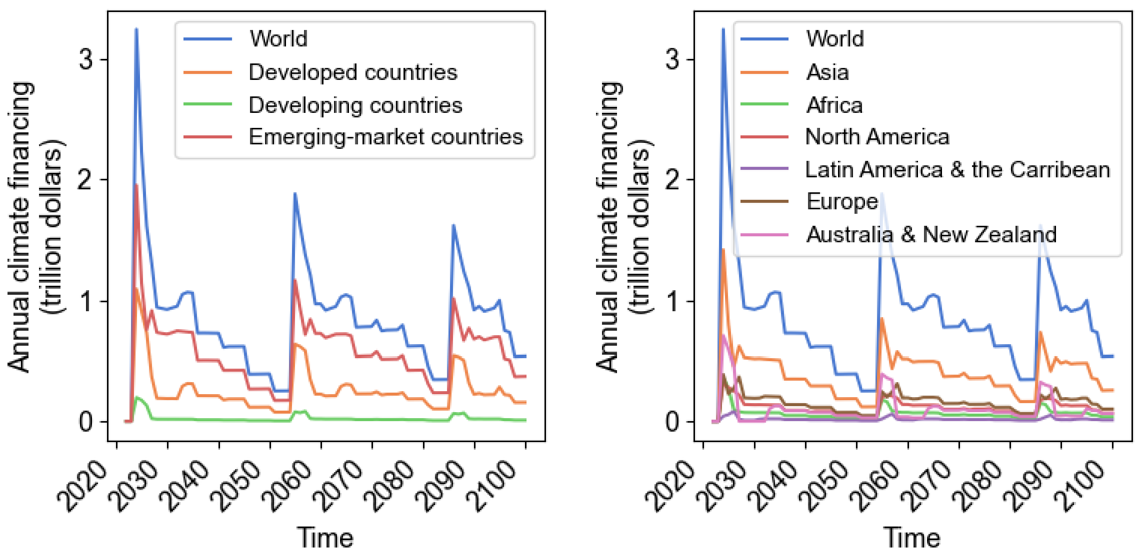

Figure 7: Annual conditional climate financing needs (in trillion dollars; non-discounted) broken down by level of development (left plot) and region (right plot).

Figure 8 shows the non-discounted, requisite climate financing over 2024-2100 (relative to cumulative GDP) plotted against GDP per capita. 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 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 appears as a first order policy goal.

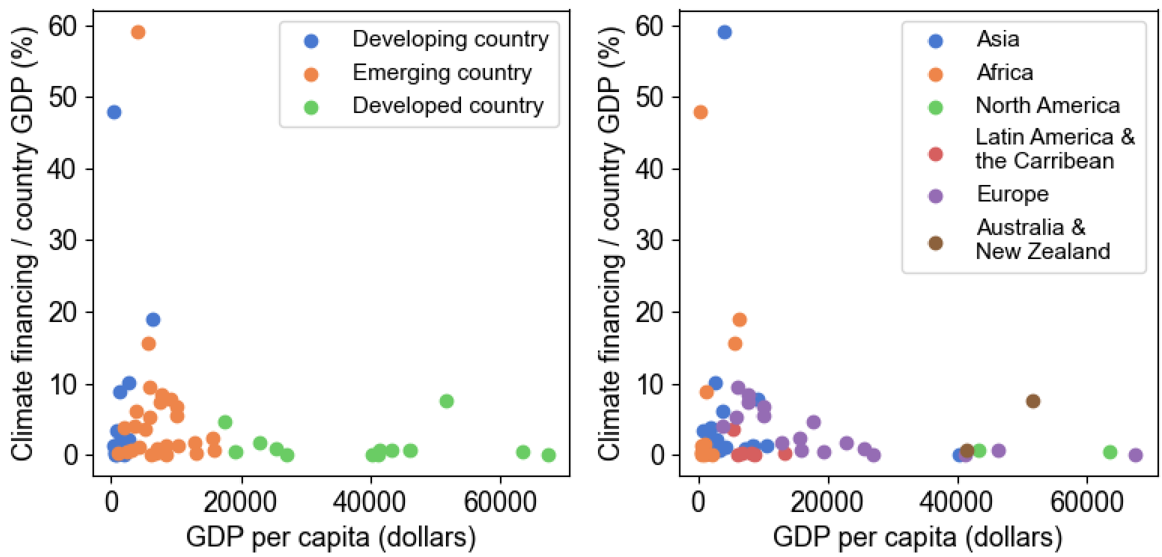

Figure 8: Present value of conditional climate financing need of each country relative to its GDP. Countries are coloured either by level of development (in left plot) or by region (in right plot).

Figure 9 shows the times series of annual climate financing needs 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.

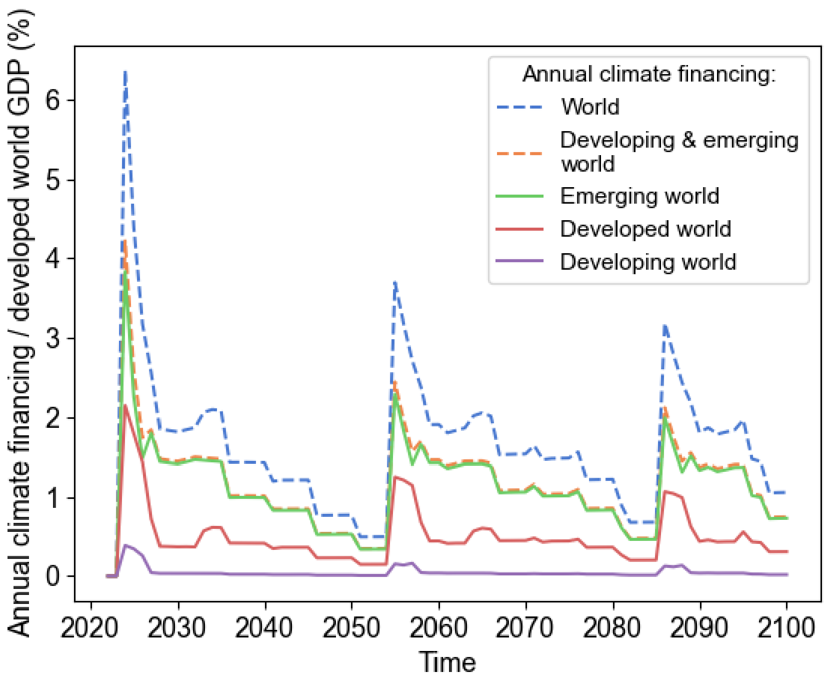

Figure 9: Annual conditional climate financing need of the world (blue line), the developing and emerging world (orange line), or the emerging world (green line) relative to developed world (DW) GDP (in %). The plot represents non-discounted values.

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.

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.

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.

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.

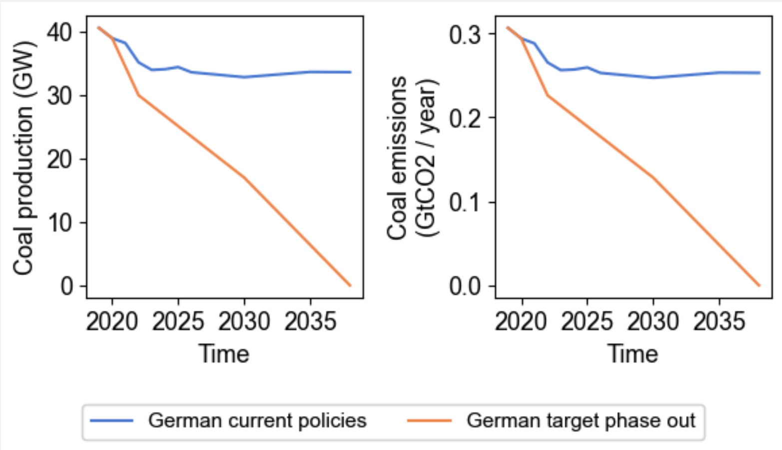

Figure 10: German coal phase out targets in the power sector.

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

Comparing the blue line (our baseline) with the dashed orange line, moreover reveals that in absence of "experience" (E) curves of renewables each next investment cycle would be as expensive as the previous. Whereas with learning, the next cycle will be less expensive because of fallen investment costs. The left plot furthermore reveals that using the LCOE as a proxy for investment costs gets the intertemporal dynamics of when capital expenditures for new renewables must be made completely wrong. It simply shows an increase in costs as coal is phased out in line with the Net Zero 2050 pathway.

The key point is that 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 it also captures operational and financing costs.

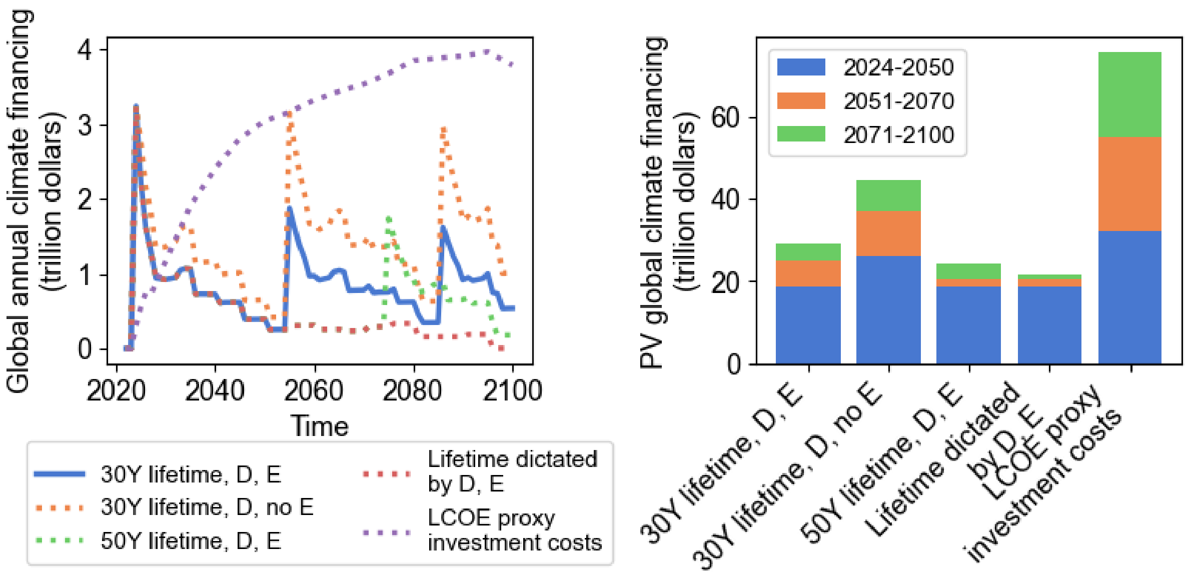

Figure 11: Annual global climate financing need (in trillion dollars; non-discounted) on the left plot and its the present value on the right plot, for different assumptions on the effective lifetime of renewables and investment costs.

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 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.

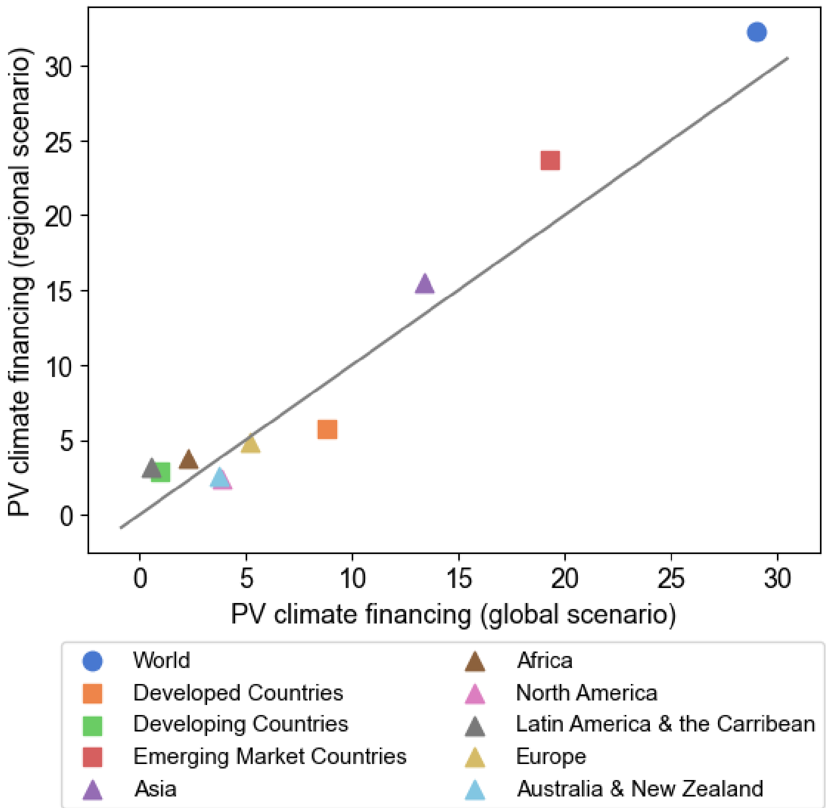

Figure 12: The present value of requisite climate financing under the global vs. regional NGFS scenarios. Regions are shown with a square and countries with a triangle.

While we find that the requisite annual climate financing in certain regions is higher (e.g., emerging countries, developing countries; Asia in particular) and in other regions is lower (e.g., developed countries; America and Europe in particular) 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.

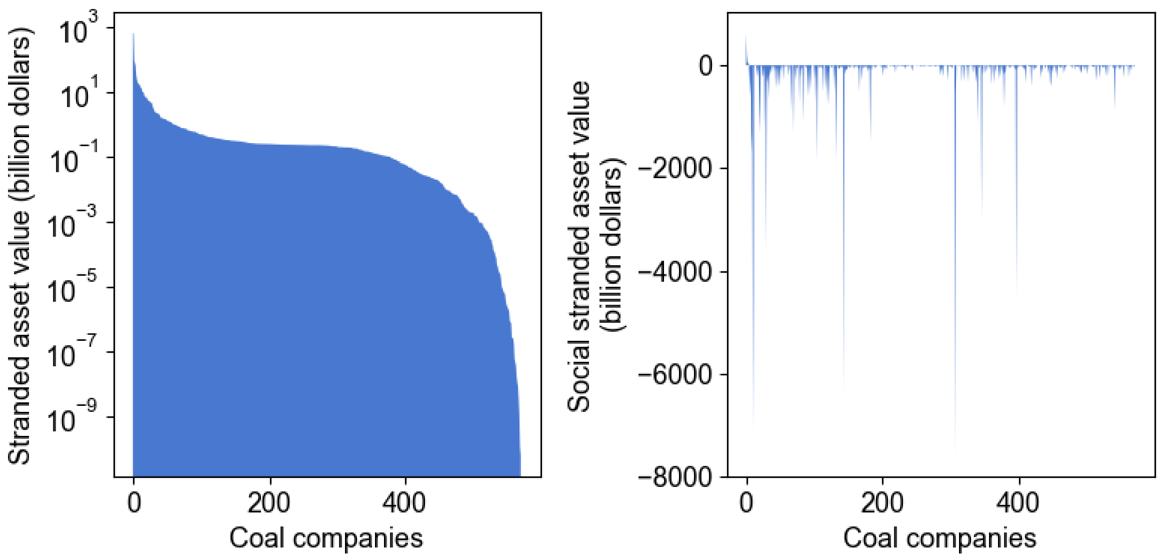

Figure 13: The distribution of the stranded asset value of coal companies (left plot) and the corresponding distribution of the "social stranded asset value" (right plot).

The stranded asset value $S_{i,t,T}^{s_1,s_2}$ of coal company i is given by the difference in its coal production between a business-as-usual scenario s_1 and a scenario where its coal assets are stranded, which amounts to our Halt to Coal production scenario s_2 ($P_{i,\tau}^{s_2} = 0$ for $\tau \in [t+2, T]$), i.e. $S_{i,t,T}^{s_1,s_2} = \sum_{\tau=t+2}^{T} \exp^{-\rho_i(\tau-t)} O_{i,\tau}^{s_1,s_2}$.

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 $S_{i,t,T}^{s_1,s_2}$ minus the present value of societal benefits $B_{i,t,T}^{s_1,s_2,\theta}$ of stranding its coal assets, i.e.

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

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

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

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.

$$\Pi_{i,\tau}^{s_1,\theta} := \Pi_{i,\tau}^{s_1} - E_{i,\tau}^{s_1} \times \theta.^{29} \quad (19)$$

In our context the earnings are defined by the 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 fuel pollution and ultimately global warming. Economists have very much focused on the Pigouvian approach that uses taxation to internalize those externalities (Pigou (1920)). 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 (see e.g., Stern and Stern (2007), Stiglitz et al. (2017)), seeking to determine the optimal level of a carbon tax

[29] Note that we discount free cash flows from coal as before, but we do not discount the social cost of emissions from coal, as explained above.

as indicated by the social cost of carbon (SCC). The SCC reflects the social marginal damages, i.e., the net damages arising from one additional ton of emissions. 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)). Nordhaus (2013) defines IAMs – such as DICE (Nordhaus (1993)) and PAGE (Hope et al. (1993)) – as approaches that integrate knowledge from two or more domains into a single framework". Related to the IAM-based Pigouvian literature on carbon taxation and the SCC, there is also a more Coasian literature on cap-and-trade systems (see the seminal treatment by Dales (1968) and Ellerman et al. (2003)).

Another approach to climate externalities is based on Coase, who thought to attain an efficient social outcome through bargaining and contracting (Coase (1960)). We build on the IAM literature by also giving a quantitative estimate of the social surplus that can be attained from avoiding emissions. We estimate how much the world would benefit, if coal was phased out and replaced with alternative energy sources such as wind power and solar radiation. Table 9 summarizes our main finding – i.e. the great carbon arbitrage $91.09 trillion when coal is phased out in line with a Net Zero 2050 pathway – and compares these to the (sparse) literature.

From Table 9 we observe that most studies, including the ones by IEA (2021c) 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 a point-in time-estimate (Rauner et al. (2020)), but does not estimate the net present value over the decarbonization horizon.

We further observe from Table 9 that our annual cost estimate of $1/2-$2 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 (2021c)), and physical assets and land-use systems ($9.2 trillion annually, McKinsey (2022)).

Mercure et al. (2021) estimate stranded asset value of fossil fuel 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 recognizes that the Coasian approach provides a foundation for climate finance. The social gains far outweigh the costs of climate financing to end coal. We are the first to argue that climate financing offered to countries for renewables should be made *conditional* on their 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.

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)	$106.92 trillion	$29.03 trillion ($1/2 – $2 trillion dollars annually; with a front loading of investments of 3 trillion)	$77.89 trillion (1.19% 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 (2021c)	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

6 Policies

The Pigouvian approach to phasing out carbon emission via carbon pricing is in many respects dominating the policy discussion today. It will certainly play an important part in the green economic transition. However, it is unlikely to be the only policy approach to phasing out coal and transitioning to a greener economy.

An alternative to the Pigouvian approach is Coasian. The main policy debate using elements of the Coasian approach is centered on cap-and-trade emission trading systems to date. Such systems seek to establish property rights of emissions that can be traded. However, under an ETS, the price of carbon does not necessarily equal the social cost of carbon.

The approach of this paper is also Coasian. Under our scheme, compensation for the opportunity cost of coal and investment costs in renewables would be resultant from a reduction in emissions, i.e. conditional on the commitment to phase out coal, giving rise to a social gain. Our calculation is centered around the "social net present value" (SNPV) – and depends not only on the social cost of carbon, informing avoided damages from climate change by decarbonizing, but also on costs of decarbonization. We argue that policies can be construed to reap the SNPV. This section is discussing one such policy approach.

A highly innovative example of how the Coasian approach might work is the securitization deal described in Bolton et al. (2020) and jointly implemented by the International Finance Corporation (IFC)[30] and the private-sector firm Amundi. In that deal, an Asset Backed Security (ABS) was constructed in which development institution (IFC) took the first-loss tranche of $125 million. The senior tranches had investment grade rating, and were successfully sold in the marketplace. Importantly, the ABS invested its funds in due time into climate-friendly investments. 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.

In our view, such investments could be done at bigger scale. To get to significant scale, 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. 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 to work with

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

their members to develop markets for investment grade tranches, to make investments sufficiently appealing to (institutional) investors. To date, the market size for ABSs is not sufficient to finance a green transition at scale, and significant market development would be needed.

There could be co-investments in the equity tranche. Private sector institutions – especially those with a high risk appetite and long investment horizons – could co-invest in the junior tranch, to enhance incentive alignment. Governments of countries where green investments occur could also co-invest in equity.

A promising model for scaling up renewable energy investments around the world, deploying ABS funds with credit enhancement, is a 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 coordinated 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 worthwhile of note for designing new 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. A large green asset class financing the energy transition is then created.

Of course, we view this climate finance approach as complementary to Pigouvian carbon taxation approaches and cap-and-trade schemes. Key to our argument is the recognition that there are large social benefits from ensuring the green transition. Losing sight of these gains, or a lack of appreciation of the enormous gains from avoided emissions, can result in bad policy choices. 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 argue for the importance of 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 the costs of ending coal plus the costs of replacing it with renewable energy. In our estimate, the world could realize a net total gain of 77.89 trillion US dollars. This represents around 1.19% 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 carbon of 75 dollars per tonne of CO2 – 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 to a maximum of 268.4. 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 and 2 Degrees Investment Initiative (AR-2DII), 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 (29.03 trillion dollars), but our point is that they are nonetheless small relative to the social benefits (106.92 trillion dollars). These social benefits are too easily forgotten.

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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. $B^{s_1,s_2,s_r,\theta}_{t,T+1,\bar{T}} = \theta \times \sum_{\tau=T+1}^{\bar{T}} \sum_{y \in \mathcal{Y}} \Delta E^{s_1,s_2,s_r}_{y,t,T,\tau}$. 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 plant coal production) 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.

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 $\rightarrow$ GJ/year	$x \times$ [#seconds per year], for $x = G, S$ *
Function converting energy per year to renewable capacity	$h^{-1}(y)$: GJ/year $\rightarrow$ GW	y/[#seconds per year], for $y = R, g(P)$ *
Function converting coal production to coal energy	$g(P)$: tonnes of coal $\rightarrow$ GJ	$P \times 29.3076$ **

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